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The role of CD38 expression on NAD levels and cell physiology in a leukaemia model

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The role of CD38 expression on NAD levels and cell physiology in a leukaemia model

by

Zainab Nejim Al-Abady

A thesis submitted to Plymouth University in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

School of Biomedical and Biological Sciences

Faculty of Science and Technology

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Dedication

I dedicate this thesis to my beloved mother and to my beloved family:

My husband, Abbas Al-Shabany

My lovely daughter, Ayiat

My sons, Haider and Abdu-Allah

The role of CD38 expression on NAD levels and cell physiology in a leukaemia model

Zainab Nejim Al-Abady

Abstract

CD38 is a transmembrane glycoprotein with both ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase activities; it is also known as a cell surface receptor. CD38 utilizes NAD(P) as a substrate to produce the second messengers, Nicotinic acid adenine dinucleotide phosphate (NAADP) and Cyclic adenosine diphosphate ribose (cADPR). CD38 has been implicated in several diseases. For instance, in chronic lymphocytic leukemia (CLL), it is known as a poor prognostic marker and as a disease modifier. Also, abundant data are available on the receptor functions of CD38 in CLL. However, the aim of the work described in this thesis was to investigate the enzymatic functions of CD38 in leukemia. The work also addresses the question of why CD38⁺ subset leukemia patients are characterised by poor outcome.

It has been postulated that CD38 is the major NADase in cells, and that knocking it down increases NAD levels significantly. Thus, it was hypothesized that NAD levels might be depleted and result in detrimental consequences on cell physiology when CD38 is significantly expressed. Also, it was suggested that a similar linkage might be also present in leukemia, contributing to poor outcome. To test this hypothesis, a human leukaemia cell line (HL60) was used as a convenient model that differentiates into CD38⁺ cells when stimulated using all-*trans* retinoic acid (ATRA). It is shown that CD38 is expressed extracellularly and intracellularly in the differentiated cells, as evaluated by qPCR, FACS, Western blotting and the NGD cyclization assay. However, one of the major consequences of the early expression of CD38 (at 3 h) was a substantial depletion of intracellular NAD⁺ levels that was apparent by 4 h after treatment with ATRA. These novel data suggest a major role for CD38 as a main regulator of

NAD during the differentiation. The main role of CD38 in degradation of NAD was confirmed by using a CD38 inhibitor (kuromanin). Interestingly, the drop in NAD⁺ levels during the differentiation was reversed after treatment with kuromanin. Furthermore, the CD38 homologue, CD157, and other NAD-consuming enzymes (PARP and SIRT) were all investigated, and it was found that there are no substantial roles of all these enzymes on the NAD⁺ degradation during the differentiation. In contrast, qPCR results for NAD-biosynthesis enzymes during the differentiation process showed a significant rise in indolamine 2,3-dioxygenase (IDO) mRNA expression, with lesser increases in nicotinamide nucleotide adenytransferase (NMNAT) and nicotinamide phosphoribosyl transferase (NAMPT) mRNA levels.

The consequences of low NAD levels on cell metabolism were also assessed; the results show a reduction in lactate production and glutathione levels with an elevation of TBARS levels. However, the NAD⁺:NADH ratio remained relatively constant. Moreover, the effects of low NAD levels on DNA repair and cell death were also investigated in response to DNA damage caused by UVB. Preliminary findings show that, in CD38⁺ cells, there is a resistance to apoptotic cell death. Additionally, CD38 expression was also investigated in leukaemia cells, and was found to be regulated in response to hypoxic environment, or the change in NAD⁺ levels following FK866, kuromanin and NAD⁺ application. Altogether, these studies raise the possibility that the impact of CD38 enzymatic function on NAD levels and the negative consequences on NAD(P)-dependent processes might play an important role in the poor prognosis in CD38⁺ leukemia patients.

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Abbreviations

Abbreviation Glossary

9-cis RA	9-cis retinoic acid
ADH	Alcohol Dehydrogenase
ADPR	Adenosine diphosphate ribose
ADPRP	ADP-ribose 2' - phosphate
ALDH	Aldehyde dehydrogenase
AML	Acute myeloblastic leukaemia
ANOVA	Analysis of variance
APL	Acute promyelocytic leukaemia
ARTs	ADP-ribose transferases
ATL	Adult T-cell leukemia-lymphoma
ATO	Arsenic trioxide
ATP	Adenosine triphosphate
ATRA	All <i>trans</i> retinoic acid
BCR	B-cell-receptor
BER	Base excision repair
BM	Bone marrow

BSA	Bovine serum albumin
BST-1	Bone marrow stromal cell antigen 1
cADPR	Cyclic adenosine diphosphate ribose
CAMs	Coronary arterial myocytes
CCD	Charge-coupled device
CCL19	CC ligand 19
cGDP	Cyclic guanosine diphosphate ribose
CICR	Ca ²⁺ -induced Ca ²⁺ release
cIDPR	Cyclic inosine diphosphate ribose
CLL	Chronic lymphocyte leukaemia
CNT	Concentrative nucleoside transporters
CPD	Cyclobutane pyrimidine dimer
CtBP	C-terminal binding protein
CX43	Connexin-43
CXCL12	CXC ligand 12
CXCR4	CXC receptor 4
DC	Dendritic cells
DMSO	Dimethylsulfoxide

ECL	Electro generated chemiluminescence
ECCAC	European collection of cell culture
eNAMPT	Extracellular NAMPT
ENT	Equilibrative nucleoside transporters
ER	Endoplasmic reticulum
ETC	Electron transport chain
FACS	Fluorescence-activated cell sorter
FCS	Fetal Calf Serum
FDC	Follicular dendritic cells
FKBP	FK506-binding protein
FSC	Forward scatter
G6P-DH	Glucose 6-phosphate dehydrogenase
GM-CSF	Granulocyte-macrophage colony-stimulating factor
GSH	Reduced glutathione
HAE	4-hydroxyalkenals
HASM	Human airway smooth muscle
HEB	Hypertonic extraction buffer
HIF	Hypoxia inducible factors

HL60	Human leukaemia cells
HLA	Human leukocyte antigen
HLB	Hypotonic lysis buffer
HMW	High molecular weight
HPV	Hypoxic pulmonary vasoconstriction
HRP	Horseradish Peroxidase
IDO	Indoleamine 2, 3-dioxygenase
IDP	Isocitrate dehydrogenase
IFN	Interferons
IgV	Immunoglobulin variable
IL	Interleukin
IP3	Inositol trisphosphate
KO	Knock out
LDH	Lactate dehydrogenase
LN	Lymphoid nodes
LPS	Lipopolysaccharide
mAbs	Monoclonal antibodies
MAPK	Mitogen-activated protein kinase

MDA	Malondialdehyde
ME	Malic enzyme
MFI	Mean fluorescence index
MMPs	Matrix metalloproteinases
MPT	Mitochondrial permeability transition
MTT	3-(4, 5-dimethylthiazole-2-yl)-2, 5-diphenyl tetrazolium bromide
NA	Nicotinic acid
NAADP	Nicotinic acid adenine dinucleotide phosphate
NAD	Nicotinamide adeninedinucleotide
NADase	NAD glycohydrolase
NADK	NAD kinase
NADP	Nicotinamide adeninedinucleotide phosphate
NADs	NAD synthetase
Nam	Nicotinamide
NaMN	Nicotinic acid mononucleotide
NAMPT	Nicotinamide phosphoribosyltransferase
NAPRT	Nicotinic acid phosphoribosyl transferase
NBT	Nitroblue tetrazolium

NER	Nucleotide excision repair
NGD	Nicotinamide guanine dinucleotide
NHD	Nicotinamide hypoxanthine dinucleotide
NIDDM	Non-insulin dependent diabetes
NK	Natural killer cells
NLC	Nurse-like cells
NMNAT	Nicotinamide mononucleotide adenylyltransferase
NOD	Non-obese diabetic
NOX4	NAD(P)H oxidase
NRK	Nicotinamide riboside kinase
NuT	Nucleoside transporter
PAGE	Polyacrylamide gel electrophoresis
PAR	Poly ADP-ribose
PARPs	Poly-ADP-ribose-polymerases
PBS	Phosphate buffered saline
PCs	Proliferation centre
PE	Phycoerythrin
PECAM-1	Platelet endothelial cell adhesion molecule-1

PES	Phenazine ethosulfate
PGC-1 α	Peroxisome proliferator-activated receptor δ co-activator-1 α
PI3-K	Phosphoinositide 3-kinase
PMA	Phorbol 12-myristate 13-acetate
PML	Promyelocytic leukemia
PVDF	Polyvinylidene difluoride
QPCR	Quantitative polymerase chain reaction
RAR	Retinoic acid receptor
RARE	Retinoic acid response element
RAS	Retinoic acid syndrome
ROS	Reactive oxygen species
RPMI	Roswell Park Memorial Institute
RXR	Retinoid x receptor
RyR	Ryanodine receptor
SAP	Saponin and PBS
SDS	Sodium dodecyl sulphate
SSBR	Single strand break repair
SSC	Side scatter

TBA	Thiobarbituric acid
TBARS	Thiobarbituric acid reactive substances
TBS	Tris-buffered saline
TCA	Tricarboxylic acid cycle
TCR	T-cell receptor
TGase	Transglutaminase
TLR	Toll-like receptors
TNB	5-thio-2-nitrobenzoate
TNF- α	Tumor necrosis factor- α
TPCs	Two-pore channels
TRPM2	Transient receptor potential cation channel member 2
TTBS	TBS-Tween
ZAP-70	Zeta1-associated protein of 70 kDa

Author's Declaration

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CHAPTER 1

GENERAL INTRODUCTION

1. GENERAL INTRODUCTION

1.1 Nicotinamide adenine dinucleotide (NAD)

Nicotinamide adenine dinucleotide (NAD) and its phosphorylated form, NADP (Fig 1.1) were first discovered by Harden and Young (1906); NAD and NADP have long been known to be essential co-enzymes in some of the most fundamental redox reactions of basic metabolism, such as glycolysis, the tricarboxylic acid (TCA/Krebs') cycle and the pentose phosphate pathway (Mathew *et al.*, 2000; Ziegler, 2000). The oxidized and reduced forms of NAD (NAD⁺ and NADH, respectively) regulate glycolysis by acting as cofactors for the glycolytic enzyme glyceraldehyde-3-phosphate dehydrogenase. NAD(H) also mediates important energy metabolism-related reactions, such as the lactate dehydrogenase-catalyzed lactate-pyruvate conversion in the cytosol (Stryer, 1995; Berger *et al.*, 2004). Generally, NADH is the substrate of over 300 cellular dehydrogenases, including those located in the inner mitochondrial membrane that catalyzes the transfer of electrons from NADH to coenzyme Q during oxidative phosphorylation (Li and Chen, 2002). Hence NAD(H) is essential for the synthesis of ATP (Stryer, 1995; Berger *et al.*, 2004). Moreover, beyond the function of NAD in energy metabolism, its phosphorylated form (NADP⁺) has important functions in the cellular antioxidant capacity through its role as a precursor for synthesizing the major reducing molecule NADPH; the latter provides several cell protective functions (Stryer, 1995; Pollak *et al.*, 2007).

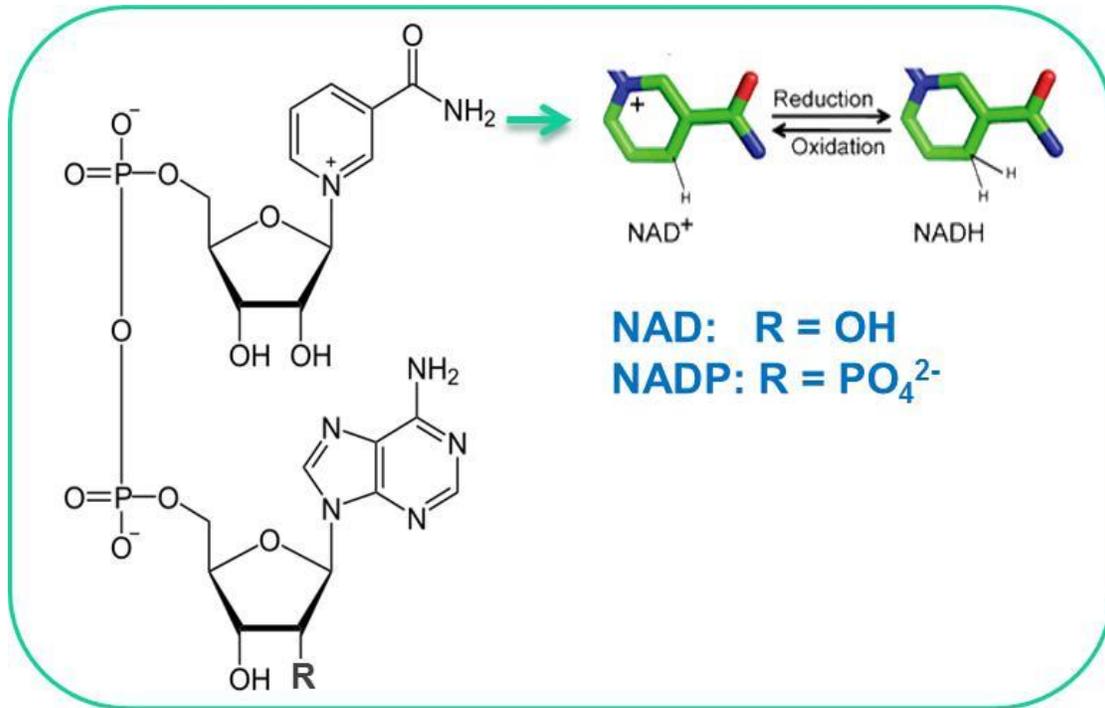


Figure 1.1 The structures of the nicotinamide nucleotides, NAD, NADP and NADH.

Interestingly, NAD has other important functions, as a signalling molecule, via acting as substrate for several NAD-consuming enzymes. These enzymes are represented by the CD38/CD157 system, poly-ADP-ribose-polymerases (PARPs), mono-ADP-ribose transferases (ARTs) and sirtuins (NAD-dependent protein deacetylases) in cells. NAD mediates post-translational protein modification by serving as substrate for the ADP-ribosylation reaction (via ARTs; Koch-Nolte *et al.*, 2008). It also controls DNA repair (via PARP; Kim *et al.*, 2005). This group of enzymes uses NAD as a substrate to catalyze the addition of a polymer of ADP-ribose to the protein. Further, NAD mediates gene silencing and longevity (via sirtuins; Michan and Sinclair, 2007). These enzymes catalyse the deacylation of proteins, in which the acetyl group is transferred from the protein to the ADP-ribose portion of NAD, releasing the nicotinamide group from NAD in the process. Additionally, in the late 1980s, NAD(P) was discovered to be a key substrate in producing two novel Ca²⁺ messengers; cADPR and NAADP (Lee *et al.*, 1989; Lee

and Aarhus, 1995). These messengers are involved in a wide range of biological functions. Thus, NAD mediates Ca^{2+} -signalling (via CD38/CD157; Malavasi *et al.*, 2008). In fact, extracellular and intracellular NAD levels may be regulated by CD38; EC 3.2.2.6 (Adebanjo *et al.*, 1999), which has been defined both as an ectoenzyme and as a receptor molecule (Howard *et al.*, 1993; Malavasi *et al.*, 1994).

Extracellular NAD^+ as a signalling molecule for CD38 and ARTs has additional functions. It may work like a cytokine, deriving rapid and functional responses through binding to specific purinergic type 2 receptors. It may also induce cell proliferation, migration, chemotaxis and apoptosis. For example, NAD^+ activates the purinergic receptor P2Y11, which results in cell activation in human granulocytes (Moreschi *et al.*, 2006). In human monocytes, NAD^+ binds different receptors such as P2X1, P2X4, and P2X7, which trigger Ca^{2+} influx (Klein *et al.*, 2009). Furthermore, NAD^+ induces cell proliferation, migration and release of prostaglandin E2 and cytokines in mesenchymal stem cells (Fruscione *et al.*, 2011). NAD^+ is involved in immunoregulation through the extracellular enzymatic network that control NAD^+ levels, which may be responsible for providing an essential second signal for chemotaxis through the two intracellular Ca^{2+} mobilizers, cADPR and ADPR (Berridge, 1993; Meszaros *et al.*, 1993; Perraud *et al.*, 2001). Furthermore, the mechanism to control regulator T lymphocytes cells is mediated through the immunomodulatory functions of NAD^+ that are mainly linked to the activation of ART enzymes. This can be done by transferring the ADP moiety of NAD^+ to specific amino acids in target proteins; P2X7 receptor (Koch-Nolte *et al.*, 2008), which causes activation signalling, leading to apoptotic cell death (Adriouch *et al.*, 2001; Seman *et al.*, 2003).

In contrast, while several NAD-dependent enzymes catalyse consumption of NAD in cells, resynthesis of NAD is necessary to maintain the functions of a wide variety of these enzymes. Thus, cellular NAD is synthesized either via a *de novo* pathway from tryptophan or via one of two possible recycling pathways: from nicotinic acid (NAc) or nicotinamide (NAM); vitamin PP, or niacin (Fig. 1.2; Magni *et al.*, 2004), and from nicotinamide riboside (NR; Bieganowski and Brenner, 2004).

There are two important enzymes, nicotinamide phosphoribosyltransferase (NAMPT) and nicotinamide mononucleotide adenylyltransferase (NMNAT), that constitute an NAD salvage recycling pathway in mammalian cells (Rongvaux *et al.*, 2003). Specifically, NAMPT catalyzes the conversion of NAM to nicotinamide mononucleotide (NMN), and localizes to both the cytosol and nucleus (Rongvaux *et al.*, 2002). NMN produced from NAM (via NAMPT) or from NR (via nicotinamide riboside kinase (NRK)) is further converted into NAD by NMNAT. NAD can be also synthesized from NAc, by nicotinic acid phosphoribosyl transferase (NAPRT), in addition to other enzymes such as NAD synthetase (NADs) via the intermediate nicotinic acid mononucleotide (NaMN; Wilhelm and Hirrlinger, 2012). In the nucleus, NAMPT and NMNAT have been observed to produce NAD as a substrate for NAD-dependent enzymes, including SIRT1 and PARP1 (Zhang *et al.*, 2009a). On the other hand there are three different enzymes that catabolise tryptophan in the endogenous *de novo* pathway, including tryptophan dioxygenase (TDO), indoleamine 2,3-dioxygenase (IDO) and indoleamine 2,3-dioxygenase-2; IDO2 (Ball *et al.*, 2009). Specifically, IDO activity is inducible in multiple cell types (Mellor and Munn, 2004), and it is chronically activated in many cancer patients (Schroecksadel *et al.*, 2007).

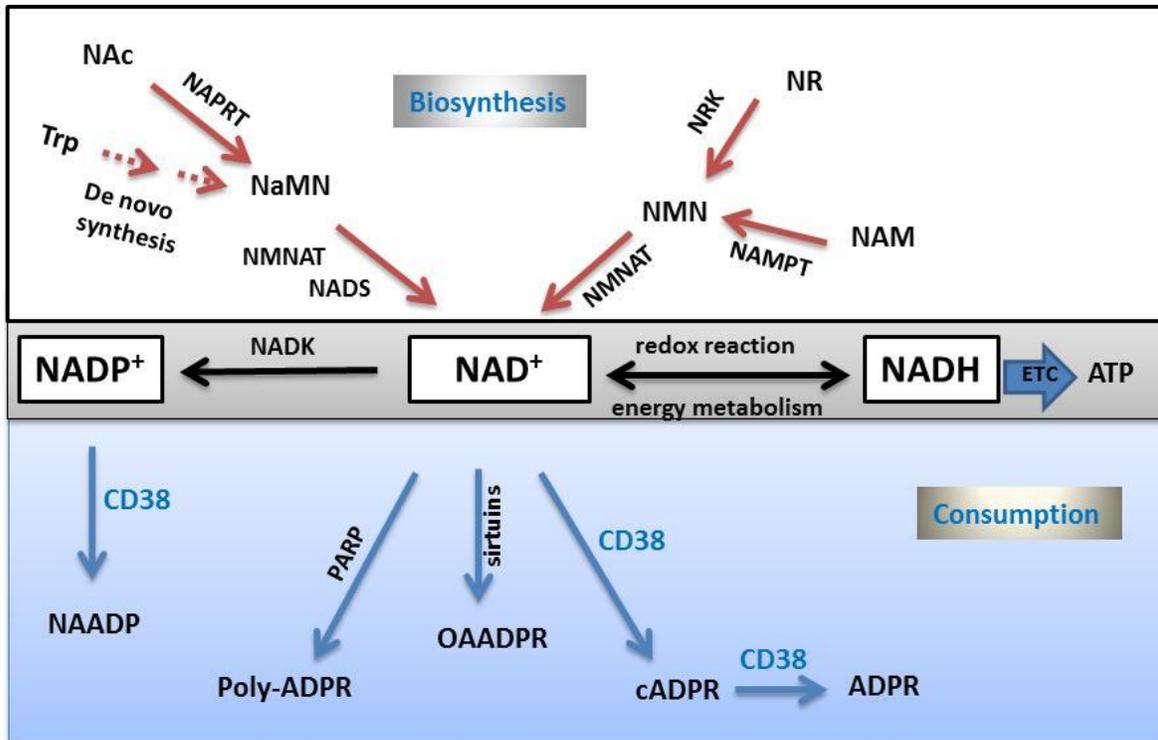


Figure 1.2 NAD metabolism represented by the biosynthesis pathways (the de novo pathway and salvage pathway), in addition to a network of NAD-consuming enzymes included (CD38, PARP, and sirtuins). NAD is shuttling between its oxidized form NAD⁺ and the reduced form NADH. The electrons bound by NADH can be transferred to the electron transport chain (ETC) of mitochondria. The reaction catalyzed by NAD kinase (NADK) links NAD to the redox pair of NADP⁺ and NADPH (adapted from Wilhelm and Hirrlinger, 2012).

In humans, the distribution of NAD⁺ levels in plasma and tissue is different; the concentration of NAD⁺ in human plasma ranges between 10 and 50 nM (De Flora *et al.*, 2004). NAD⁺ levels may depend on the balance between the opposing processes of dinucleotide release from cells and its enzymatic degradation (De Flora *et al.*, 2004). However, NAD⁺ levels in specific tissue regions may be significantly higher than those in plasma, such as during inflammation (Scheuplein *et al.*, 2009). Investigation of cellular NAD⁺ and NADH levels in response to different environmental stimuli has been an important subject of several studies. For instance, the intracellular NAD⁺/NADH ratio reflects the cellular metabolic status and redox state. It has been reported that under oxidative stress some cell types (for example, erythrocytes) increase their intracellular

NADH/NAD⁺ ratio or the NADH level, in order to resist possible oxidative damage (Liang *et al.*, 2007; Ying, 2007). However, the change in nucleotide (NAD(H)) levels has also been linked to several diseases, such as sickle cell disease (Zerez *et al.*, 1990), neoplasia and ischaemia (Lohmann *et al.*, 1989), several age-associated diseases such as diabetes, cancers and neurodegenerative diseases; Parkinson's disease (Soriano *et al.*, 2001; Greenamyre *et al.*, 2001; Zhang *et al.*, 2002; Lin and Guarente 2003). Notably, several studies suggest that the change in NAD levels might modulate protein activities, and have an effect on cell functions (Ying, 2006; 2008). For instance, an augmentation of intracellular NAD⁺ levels following CD38 knock out leads to SIRT activation with positive consequences on cell physiology (Barbosa *et al.*, 2007). One possible explanation is that CD38, as a member of the cyclase family, appears to be a major NAD consuming enzyme in cells. Thus, CD38 limits the availability of NAD to all other consumers.

1.2 Members of the ADP-ribosyl cyclase family

As mentioned above, NAD⁺ is a substrate in the production of a novel Ca²⁺ messenger, cyclic ADP-ribose (cADPR; Lee *et al.*, 1989). Generally, cADPR is produced from NAD⁺ by ADP-ribosyl cyclase activity, and there are three main members of the ADP-ribosyl cyclase family. The first ADP-ribosyl cyclase was described in the ovotestis of a marine invertebrate, the sea slug (*Aplysia californica*). The ADP-ribosyl cyclase from *Aplysia* is a soluble protein with a molecular weight of ~30 kDa. It generates cADPR as the predominant product of its enzymatic activity (Clapper *et al.*, 1987; Lee *et al.*, 1989). The second member of the ADP-riboysl cyclase family is CD38, which is the mammalian homologue of the *Aplysia* cyclase, with a single chain of 45 kDa (Mehta *et al.*, 1996; Ortolan *et al.*, 2002). CD38 was discovered by Reinherz *et al.*

(1980), while working on T lymphocytes by using the monoclonal antibody OKT10, and it was known then as a surface antigen (T10; Katz *et al.*, 1983). Several years later, T10 came to be known as ‘cluster of differentiation 38’ (CD38; Pallesen and Plesner, 1987). The third member of the cyclase family is CD157, a mammalian homologue of CD38, with a crystal structure that shows a high degree of structural homology with CD38 and the *Aplysia* cyclase as well (Yamamoto-Katayama *et al.*, 2002). CD157 is a 42-45 kDa surface molecule, identified as a bone marrow stromal cell antigen-1 (BST-1), also known as Mo-5 (Kaisho *et al.*, 1994). Each of the CD38 and CD157 glycoproteins has a polypeptide core of 280-300 amino acids (Liu *et al.*, 2005).

In addition to the well-known members of the ADP-ribosyl cyclase family, recent reports indicate the presence of CD38- and CD157-independent ADP-ribosyl cyclases. The next addition to the ADP-ribosyl cyclase family is an NAD(P)-catabolising enzyme from *Schistosoma mansoni* (*Sm*NACE; Kuhn *et al.*, 2006).

1.3 Distribution of CD38

CD38 is distributed in a number of human and non-human tissues. It has been detected on the sarcolemma in skeletal and heart muscle, in addition to CD38 localization in the human brain (Mizuguchi *et al.*, 1995; Fernandez *et al.*, 1998). The CD38 molecule has been also found at various locations, including the normal prostatic epithelial cells (Kramer *et al.*, 1995); pancreatic islet cells (Koguma *et al.*, 1994; Mallone *et al.*, 2002); cornea (Sizzano *et al.*, 2007); the kidney; and intra-parenchymatous fibrous septa in the thyroid (Fernandez *et al.*, 1998). Moreover, CD38’s presence has been also documented in the inner nuclear envelope, for instance, in the rat hepatocytes, in addition to its localization in the plasma membrane (Khoo and Chang, 2000).

CD38 as a cell surface receptor is expressed in cells of hematopoietic origin (Terhorst *et al.*, 1981). However, its expression has been most appropriately termed ‘discontinuous’ (Jackson and Bell, 1990) since CD38 expression is repeatedly changeable as bone marrow precursors develop into mature elements of the various lineages. For instance, in B cells, CD38 expression is tightly regulated during B cell ontogenesis and is highly present in bone marrow (BM) precursors. However, it is down-regulated in resting normal B cells and then is expressed in terminally differentiated plasma cells (Malavasi *et al.*, 1994). CD38 expression is also changeable in T cells (Deaglio *et al.*, 2001). Furthermore, studies suggest that CD38 is down-modulated during differentiation into immature human monocyte-derived dendritic cells and expressed again upon maturation induced by Lipopolysaccharide (LPS; Fedele *et al.*, 2004). CD38 is also expressed by cells of the innate immune system, including circulating and residential natural killer (NK) cells (Mallone *et al.*, 2001). Collectively, in the immune system, CD38 is expressed by immature hematopoietic cells, down-regulated by mature cells and re-expressed at high levels by activated lymphocytes; T cells, B cells, dendritic cells and NK cells (Funaro *et al.* 1990). CD38 is also expressed in the BM (Byk *et al.*, 2005), granulocytes (Fujita *et al.*, 2005), circulating monocytes (Zilber *et al.*, 2000), on the surface membrane of erythrocytes and platelets (Zocchi *et al.*, 1993; Ramaschi *et al.*, 1996) and circulating osteoclast precursors (Shalhoub *et al.*, 2000). CD38 has been also detected in lamina propria cells in the gut (Fernandez *et al.*, 1998). Finally, it is worth mentioning that CD157 expression is also involved in most tissues, including the hematopoietic system, like CD38 expression, but the tissue distribution of CD157 is limited compared to CD38 (Ortolan *et al.*, 2002).

1.4 CD38 (the type-II & -III glycoprotein) and cyclase crystal structures

The cyclase crystal structure reveals a homo-dimer; the enzyme is a bean-shaped molecule with most of the β sheets in the carboxyl domain, while the helices are in the amino domain (Fig. 1.3 A; Prasad *et al.*, 1996). The two domains are separated by a central cleft, with the active site located in a pocket near the cleft, as shown by crystallography and site-directed mutagenesis (Munshi *et al.*, 1999), with a catalytic residue identified as Glu179. It is interesting to note that for the ADP-ribosyl cyclase, 86 of its 256 amino acid are identical to those in CD38, and an additional 110 amino acids are conservative substitutions (States *et al.*, 1992). However, the structure of human CD38 is more complicated than the cyclase structure (Jackson and Bell, 1990). The structure of CD38 consists of an amino tail of 21 residues, a transmembrane segment of 23 residues and a large carboxyl domain of 256 residues that contains four glycosylation sites (Fig. 1.3 B; Jackson and Bell, 1990). The equivalent residue of Glu179 in CD38 is Glu226, which represents the catalytic residue of CD38 (Munshi *et al.*, 2000).

The crystal structure of CD38 has revealed a molecule with a high degree of structural conservation with the cyclase. Thus, it was suggested that the overall homology between the two proteins is 69% (States *et al.*, 1992). However, Liu and others (2005) reported that these proteins have about 34% protein sequence identity. CD38 has a single binding pocket for multiple enzymatic activities, and it was observed that CD38's critical residues are localized in the carboxyl terminal and spread out in the last 100 amino acid residues of the protein (Munshi *et al.*, 2000). Other studies have shown that the CD38 active site is constructed by helices $\alpha 5$ and $\alpha 6$ from the N-terminal domain and helix $\alpha 7$ and strand $\beta 5$ from the C-terminal domain (Fig. 1.3

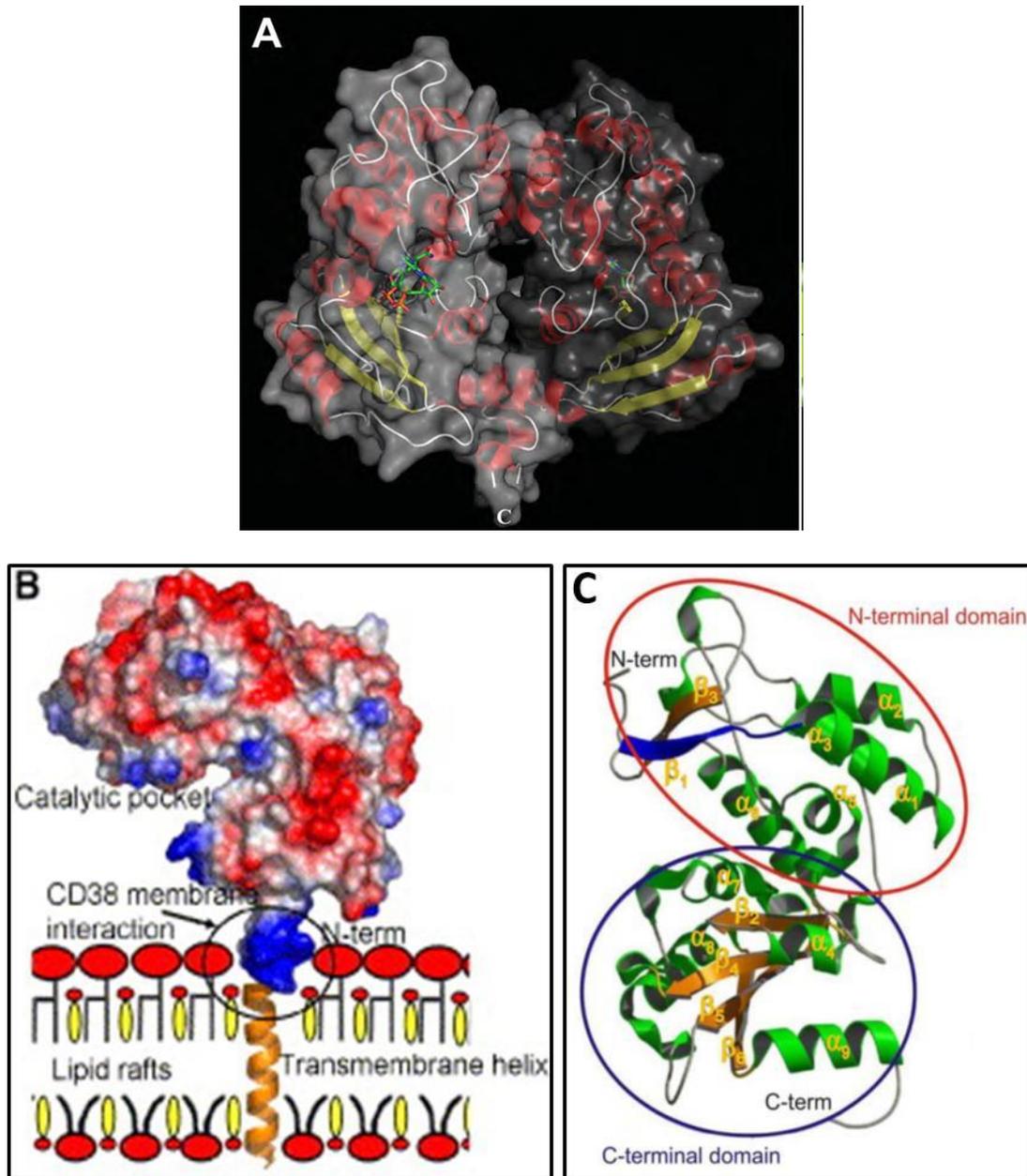


Figure 1.3 Structures of ADP-ribosyl cyclase and CD38. (A) The *Aplysia* ADP-ribosyl cyclase is a homo-dimer and the surfaces of the two monomers are coloured differently. Transparent grey revealing the secondary structures underneath. The colour code is: helix-red, β -sheet-yellow, coil-grey. The NAD molecules bound at the active sites are rendered using sticks. Colour code is: nitrogen-blue, oxygen-red, phosphorus-yellow, carbon-green. The letter C indicates the carboxyl end (adapted from Lee, 2012). (B) CD38 structure shows its membrane interaction. (C) The overall structure of human CD38. The N-terminal structures (in the red circle) and the C-terminal structure circled in blue (adapted from Liu *et al.*, 2005).

B). These two distinct domains are connected by a hinge region composed of three peptide chains including: residues 118-119, 143-144, and 200-201 (Liu *et al.*, 2005).

It is important to note that there are many types of membrane proteins with different arrangements, as shown in Fig. 1.4, and CD38 is one of these proteins that spans from the internal to the external surface of the biological membrane (integral protein). Moreover, CD38 was initially classified as a type II transmembrane glycoprotein (Fig. 1.4b), with an extracellular carboxyl active domain (Jackson and Bell, 1990), expressed both the cADPR synthesizing and hydrolyzing activities. However, a recent thorough study by Zhao *et al.* (2012) showed that CD38 has the characteristics of a type III integral membrane protein, in which the C-terminus would be in opposite orientation to that in a type II membrane protein, so that the active site of CD38 would face the cytoplasm, with an extracellular N-terminal tail (Fig. 1.4a). Furthermore, some considerable studies have reported that the full-length CD38 can form dimers on the cell surface (Moreno-Garcia *et al.*, 2004) or even oligomers (Ferrero and Malavasi, 1999; Fig. 1.5).

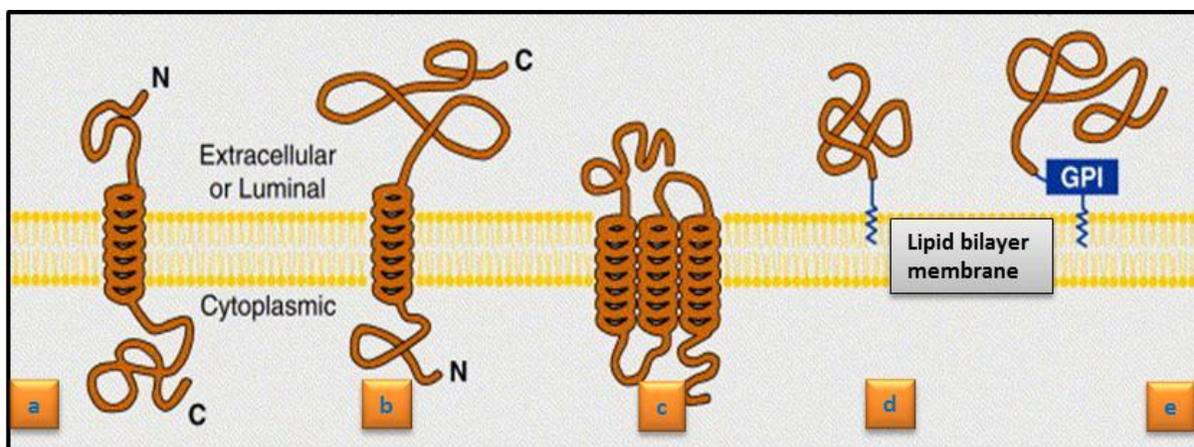


Figure 1.4 Schematic representation of different types of integral membrane proteins as follows (a) type-1 transmembrane, (b) type-2 transmembrane, (c) multipass transmembrane, (d) lipid-chain anchored membrane, and (e) GPI-anchored membrane (modified from Cai and Chou, 2006).

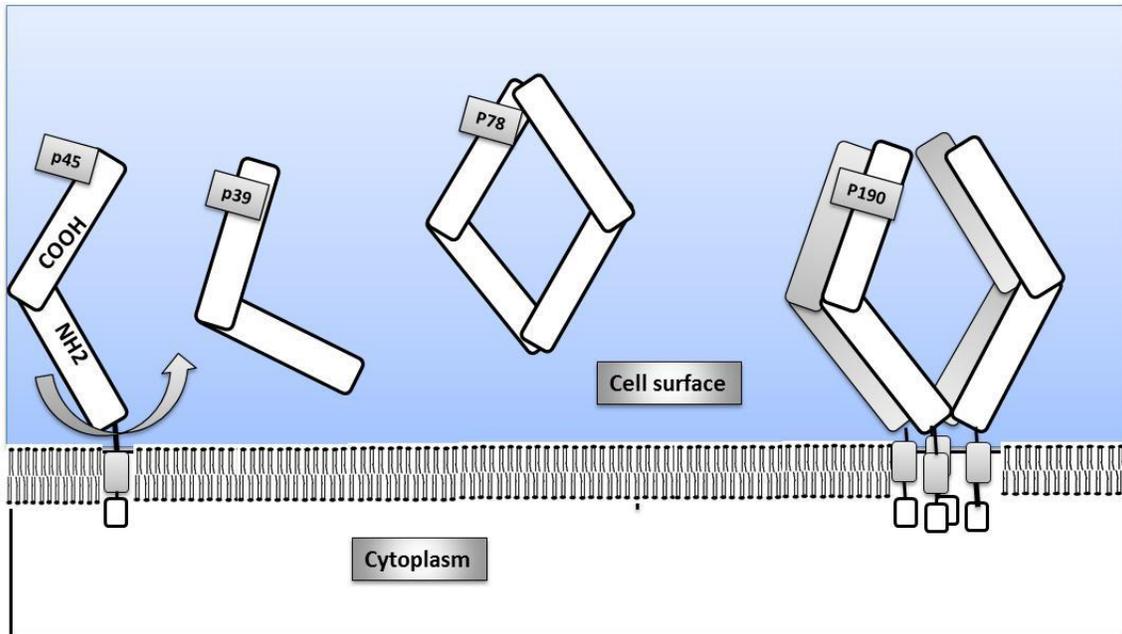


Figure 1.5 Simplified diagram representing monomeric, dimeric and oligomeric forms of CD38. Cleavage of the surface membrane form gives rise to p39 (soluble), its dimeric form is p78 and p190 represents a tetramer of the membrane form (modified from Ferrero and Malavasi, 1999).

The similar glycoprotein to CD38, CD157, also exhibits both monomeric and dimeric forms (Malavasi *et al.*, 2008). The C-terminal end of CD157 is anchored to the plasma membrane, by a glycosphosphatidylinositol (GPI) molecule, while the N-terminal region, which includes the catalytic domain, is out of the membrane (Funaro *et al.*, 2009). Therefore, and on the cell surface membrane, the two molecules (CD38, CD157) are oppositely oriented with respect to one another (Ferrero and Malavasi, 1999).

1.5 CD38 as a cell surface receptor

CD38 has multiple functions through its roles as an enzyme and a receptor (Deaglio *et al.*, 1996). As a receptor, CD38 is expressed in various cell lineages, where it mediates cell-cell interactions and delivers transmembrane signals. The role of CD38 as a receptor was first identified by means of agonistic monoclonal antibodies (mAbs), which suggested the existence of a non-substrate surface ligand, namely CD31/platelet endothelial cell adhesion molecule-1; PECAM-1 (Deaglio *et al.*, 1998). CD38 receptor functions are regulated through interactions with its non-substrate ligand, CD31, which is expressed in a variety of cells including endothelial cells, platelets and nurse-like cells (for example, macrophages and epithelial cells; Deaglio *et al.*, 2000; 2005). CD38/CD31 crosstalk has been extensively analyzed in a number of different environments, ranging from T lymphocytes to B, NK, and myeloid cells, from normal to pathological situations (reviewed in Deaglio *et al.*, 2000). For instance, CD31 interaction with CD38 induces activation, proliferation, cell adhesion and cytokine release in lymphocyte subsets (Deaglio *et al.*, 1998). CD38/CD31 interactions also lead to increased B-cell proliferation and survival, through direct cooperation with CD100, a cell surface receptor member of the semaphorin family known as sema 4D (Kikutani and Kumanogoh, 2003). Other proposed ligands for CD38 include hyaluronate in humans (Nishina *et al.*, 1994), and an unidentified 130-kDa glycoprotein in mice (Wykes *et al.*, 2004).

Several lines of evidence indicate that the receptor functions mediated by CD38 are regulated at multiple levels (Malavasi *et al.*, 1984). The first level involves the dynamic structure of CD38, which allows a monomer to dimer transition, which modulates the functions of the molecule (enzyme and receptor functions). Additional control is provided by the dynamic localization of

CD38 in lipid microdomains of the plasma membrane (Pavon *et al.*, 2006). A significant fraction of the membrane CD38 pool is localized in cholesterol-rich regions, while the remaining fraction of CD38 is localized in the raft pool (Deaglio *et al.*, 2007a). That localization makes it possible for CD38 to expand its interaction horizontally and frontally with molecules other than its substrate (NAD), forming large supramolecular complexes; thus it attracts transducers in spite of its short tail (Rah *et al.*, 2007).

Extensive observations that were made on CD38 receptor functions suggest that CD38 controls specific signalling pathways in B cells, T cells, NK cells, and monocytes. However, CD38 associations with surface molecules are lineage-dependent, and they also vary according to the maturation steps within each lineage (Deaglio *et al.*, 2001). For instance, CD38 signalling in B cells and in human or murine systems (Funaro *et al.*, 1993; Lund *et al.*, 1996) depends on the presence of a functional B-cell–receptor (BCR) complex. CD38-associated molecules in human B cells include the CD19/CD81 complex, the chemokine receptor CXCR4, and adhesion molecules, such as CD49d (Deaglio *et al.*, 2007a; 2010). The ability of CD38 to deliver its signals in B cells appears completely linked to the stage of maturation. Thereby, the presence of blocking mAbs in cultures of CD19⁺ B-cell precursors suppresses B-cell proliferation and induces apoptosis (Kumagai *et al.*, 1995). However, in mature circulating B lymphocytes, CD38 ligation is followed by activation, apoptosis inhibition, proliferation and cytokine secretion (Zupo *et al.*, 1994; Funaro *et al.*, 1997).

Furthermore, in T cells, the CD38 molecule is also associated with the T-cell receptor (TCR)/CD3 complex (Zubiaur *et al.*, 1999), and it has been shown that CD38 initiated functional signals in a subset of membrane rafts containing CD3 (Zubiaur *et al.*, 2002; Munoz *et al.*, 2003).

The observation in immature T cells indicated that CD38 enhances apoptosis when it is cross-linked with a goat anti-mouse antiserum or interacts with CD31 (Tenca *et al.*, 2003). However, it has been shown that following T-cell activation, the final outcome includes cytokine secretion and cell proliferation (Malavasi *et al.*, 2008).

In monocytes, CD38 signalling has been shown to be associated with HLA class II and CD9 molecules. The CD38/HLA class II/CD9 complex shares a common pathway of tyrosine kinase activation, and cytokine secretion in human monocytes (Zilber *et al.*, 2005). CD38 expression in human monocytes was found also to be regulated in response to proinflammatory cytokines (Musso *et al.*, 2001). CD38 expression is also known as a marker of the transition of monocytes to dendritic cells (DC) induced by inflammatory processes (Fedele *et al.*, 2004). Furthermore, CD38 mediates important signalling that is involved in dendritic cell migration; the CD38/cADPR signalling pathway is required for the migration of immature dendritic cells to CXC ligand 12 (CXCL12) and of mature dendritic cells to CC ligand 19 (CCL19) and CCL21 (Partida-Sanchez *et al.*, 2004a; 2004b).

CD38 is also expressed by resting and activated natural killer (NK) cells; it forms part of a supramolecular complex that includes CD16. Indeed, CD38-CD16 association controls an activation pathway that includes Ca^{2+} fluxes, increased expression of HLA class II and CD25, tyrosine phosphorylation of cytoplasmic substrates (such as ZAP-70 and ERK), release of cytokines and cytotoxic responses (Mallone *et al.*, 2001). Collectively, the general events that take place after CD38 activation in several cell lineages include calcium (Ca^{2+}) mobilization from cytosolic stores, as well as the triggering of the phosphorylation of a cascade of intracellular substrates, including phosphatidylinositol 3-kinase, leading to the activation of

nuclear factors (such as the nuclear factor- κ B complex), and the secretion of cytokines (Kitanaka *et al.*, 1997; Deaglio *et al.*, 2000).

Additionally, in neutrophils, CD38 signalling plays an important role in the regulation of cell trafficking; it has been shown that trafficking of neutrophils to sites of infection and inflammation is dependent on CD38 expression (Partida-Sanchez *et al.*, 2001; 2003). This process is controlled through cADPR production, which is triggered by the release of intracellular Ca^{2+} (Partida-Sanchez *et al.*, 2004b). Finally, as with CD38 receptor functions, CD157 also transduces activation signals, but no non-substrate ligand equivalent to CD31 has been described for CD157 (Malavasi *et al.*, 2006).

1.6 CD38 as active enzyme

CD38 is pleiotropic in function (Malavasi *et al.*, 1994); it is considered as the major NAD-consuming enzyme in humans (Malavasi *et al.*, 2008). CD38 is capable of catalyzing four major enzymatic reactions: NAD glycohydrolase (NADase), cyclic adenosine diphosphate ribose (cADPR) hydrolase, base-exchange reactions and ADP-ribosyl cyclase activity (Fig. 1.6 A, B). The ADP-ribosyl cyclase activity generates cADPR, and the NADase activity generates adenosine diphosphate ribose (ADPR) directly from NAD (Lee, 2006), while the cADPR hydrolase activity generates ADPR from cADPR (Howard *et al.*, 1993). However, it has been observed that the majority of the NAD (~95%) is converted to ADPR, and only a minor fraction of the total product appears to be cADPR (Howard *et al.*, 1993). Finally, CD38 can also use NADP^+ as a substrate and, in the presence of nicotinic acid (NA), to catalyze the exchange of the nicotinamide (Nam) group of NADP^+ with nicotinic acid, producing NAADP and nicotinamide (Lee, 2006). This reaction predominates in acidic conditions, while at neutral and alkaline pH the

enzyme mainly catalyzes cyclization of NAD^+ (Aarhus *et al.*, 1995). Furthermore, Graeff *et al.* (2006) documented that CD38 may also catalyse the hydrolysis of NAADP to ADP-ribose 2'-phosphate (ADPRP) at acidic pH. CD38 is also known to metabolize analogs of NAD, such as nicotinamide guanine dinucleotide (NGD) and nicotinamide hypoxanthine dinucleotide (NHD), releasing cyclic compounds (Cyclic guanosine diphosphate ribose (cGDPR) and cyclic inosine diphosphate ribose (IDPR), respectively) with fluorescent properties, but without calcium-releasing activity (Graeff *et al.*, 1994a). cGDPR, unlike cADPR, is a poor substrate for the hydrolase activity of CD38, and thus its measurement provides the basis of a continuous assay of cyclization for distinguishing CD38-like enzymes (with cyclase activity) from classical NADases (Graeff *et al.*, 1994a).

It is noteworthy that there are a number of critical residues that are highly conserved across the ADP-ribosyl cyclase family, and that have an essential role in the major enzymatic activities. For example, there are twelve conserved cysteine residues in the cyclase family, with only four of them (Cys119, Cys160, Cys173 and Cys201) having an essential role in the cADPR synthetic and hydrolytic activities of CD38 (Tohgo *et al.*, 1994). Moreover, the carboxylic domain of CD38 contains Cys275, which contributes to the NAD glycohydrolytic activity of CD38 (Hoshino *et al.*, 1997). Disulfide bonds between cysteine residues are important for the catalytic activity of CD38, as it has been shown that CD38 enzymatic activity can be inhibited by reducing agents such as dithiothreitol, 2-mercaptoethanol or reduced glutathione (Tohgo *et al.*, 1994; Zocchi *et al.*, 1995). Furthermore, three of the critical residues, Trp125, Trp189 and Glu226, are also highly conserved across the ADP-ribosyl cyclase family, with two of them (Trp125 and Trp189) essential for positioning NAD in the CD38 binding pocket, via hydrophobic interactions (Munshi *et al.*, 2000). However, a unique critical residue to CD38 is

Lys129; it is known to form a hydrogen bond with cADPR (Tohgo *et al.*, 1997). Additionally, there are two critical acidic residues in the catalytic domain of CD38 that are necessary for the pH-dependent base-exchange reaction: Glu146 and Asp155 (Graeff *et al.*, 2006).

It has been reported that CD157 shares a similar enzymatic function with CD38 (Malavasi *et al.*, 2006), except that CD157 does not produce NAADP. Surprisingly, CD38 knockout mice studies suggest that CD157 might undergo modification to enhance its cyclase activity to produce cADPR in some cells and tissues (Partida-Sanchez *et al.*, 2001; Lee, 2012). However, CD157 catalytic activity is one hundred-fold lower than that of CD38 (Hussain *et al.*, 1998).

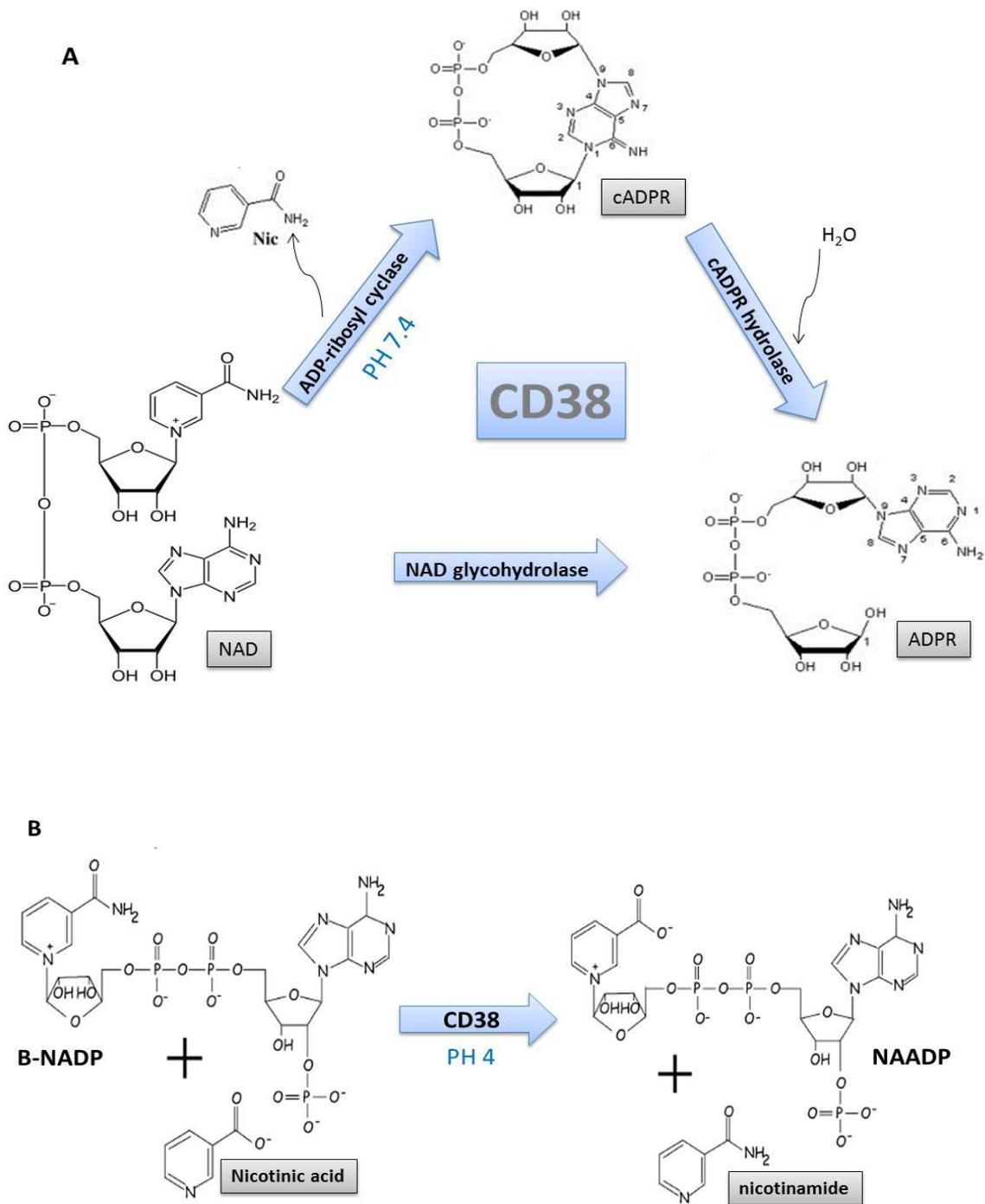


Figure 1.6 Schematic representation of CD38 (A) cyclase and hydrolase reactions by using β -NAD as substrate (Modified from Zhang *et al.*, 2011). (B) Base exchange reaction in the presence of β -NAD with the pH optimum of 4 (modified from Yamasaki *et al.*, 2005).

1.7 The interdependence between CD38 enzymatic and receptor functions

CD38 as a cell surface receptor and a multifunctional enzyme has drawn the attention of several studies, focusing on how it is that the single molecule (CD38) has a multifunctional role (receptor and enzymatic functions), and what the role of the enzymatic activity of CD38 is in the initiation of the signalling cascade. Indeed the answer to these questions is still not completely known, because the possibility of finding CD38 inhibitors is still limited, in addition to the complexity of CD38 being a multifunction enzyme with a variety of enzymatic products. However, the initial hypothesis is that they are completely unrelated, as enzymatic mutants and enzyme inhibition of CD38 have no effect on its receptor functions in human B, T, and myeloid cells (Lund, 2006; Congleton *et al.*, 2011).

The alternative hypothesis by Malavasi *et al.*, (2011) and Vaisitti *et al.*, (2011), is that CD38 enzymatic functions are regulated through interactions taking place between CD38 and different proteins or molecules that are critical for cell homeostasis. This suggests that the human CD38 enzymatic activity is not only limited in function by the availability of the substrate (NAD), but also by the opening or closing of the enzymatic site that is further controlled by the interactions with other non-substrate ligands (Malavasi *et al.*, 2011; Vaisitti *et al.*, 2011). Indirect evidence in support of this hypothesis comes from the crystal structure of CD38, which has shown CD38 as a dimer coupled to different ligands (Zhang *et al.*, 2011). In addition, the study by Liu *et al.*, (2005) suggested that CD31 binding regulates the access of NAD to its enzymatic site. A possible explanation is that CD31 acts as modulator of CD38's three-dimensional structure and thus alters its propensity to bind the substrates or to initiate signalling (Liu *et al.*, 2005).

The membrane localization of CD38 in close association with signalling receptors is suggested to initiate enzymatic and receptorial coupling machinery important for signal transduction (Munoz *et al.*, 2008). Moreover, the products of the enzymatic activities of CD38 might be necessary for the receptor functions. For instance, it is believed that a direct contribution of cADPR to the signalling process is induced after CD38 binds with agonistic mAbs in humans (Hoshino *et al.*, 1997; Munshi *et al.*, 2000). Thus, CD38 provides a connection between Ca²⁺-modulation via cADPR and the classical signalling cascades that are responsible for the activation of Ca²⁺-dependent kinases and initiating antigen receptor signalling (Deaglio and Malavasi, 2006). Collectively, the functions attributed to CD38 are linked either to enzymatic or receptor functions. However, the final outcome is dependent on the interactions with other ectoenzymes and/or signalling molecules, which vary according to tissue and sub-cellular localization (Deaglio *et al.*, 2008).

1.8 Visualization of the cyclization reaction (enzyme-NAD interaction)

Until recently, it was not possible to visualize the wild type cyclase complexes with its substrate NAD, or to visualize cADPR formation, without modification. The excellent study by Kotaka *et al.* (2012) solved the previous difficulties of visualizing CD38 with its substrate, without limitations, by crystallography. The previous restriction was that CD38 converted NAD to its products during crystallization, and hence the only option was to use an inactive mutant of CD38, e.g. E226Q or E179G, or even to use substrate analogs that are resistant to enzymatic conversion. However, even with the limitations in the previous results, they were still consistent with the results recently obtained by Kotaka *et al.* (2012). Generally, the cyclization can proceed with either NAD, to produce cADPR, or with its analog, ara-2'FNAD, which, like NAD, is a

substrate for the *Aplysia* cyclase and CD38, except with the substitution of a fluorine atom at the 2'-position of the adenylyl ribose (Liu *et al.*, 2008; Zhang *et al.*, 2011; Kotaka *et al.*, 2012). It has been found that ara-2'F-NAD, or NAD enters the active site pocket with its nicotinamide-end first, which interacts with the catalytic residue Glu226 in CD38 and Glu179 in the cyclase. The interaction is not via the anomeric carbon (C1) of the terminal ribose, the cyclization site, but through the two -OH groups of the ribose, forming hydrogen bonding with the carboxyl group of the catalytic residue (Liu *et al.*, 2006; Kotaka *et al.*, 2012). This leads to straining of the ribose ring and a cleavage of the glycosidic bond to release the nicotinamide group.

Moreover, Lee (2012), using cyclase crystallographic information, identified 22 folding conformations (folding states) during the interaction of NAD with the enzyme to produce a cyclic compound, of which only 3 are shown in Figure 1.7. The conformations started from an extended (initial) state (coloured yellow) in which the adenine ring stacks parallel and interacts hydrophobically with Tyr81. During the intermediate state (transparent) the N1 of the adenine brings closure to the anomeric carbon C1 of the terminal ribose. In the fully folded state (coloured cyan) the adenine interacts with Trp140 and the N1 of the adenine is only 5.2 Å from C1 in order to form the cyclization linkage (Lee, 2012). The same crystallography technique has also been applied to CD38 to visualize the folding process (Zhang *et al.*, 2011).

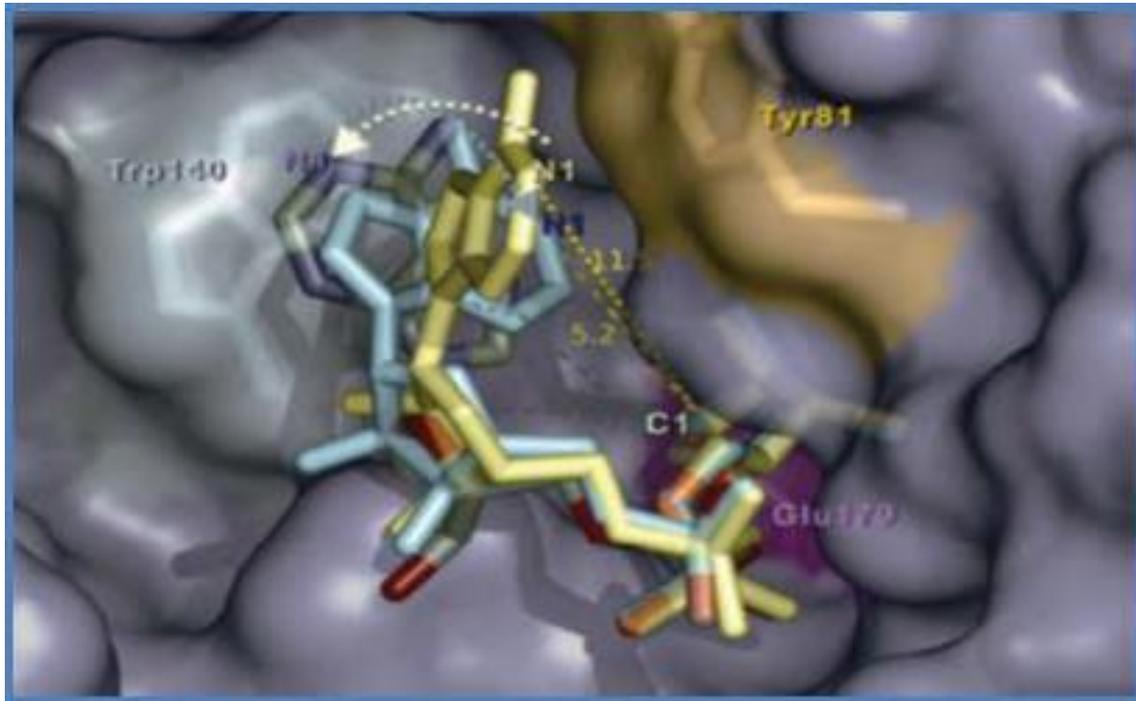


Figure 1.7 Visualization of the ara-2'FNAD cyclization reaction catalyzed by the cyclase. Adapted from Lee (2012).

1.9 The Second Messengers (cADPR and NAADP)

There are several known calcium mobilizers. First, inositol trisphosphate (IP₃), a second messenger that facilitates Ca²⁺ mobilization from its endoplasmic reticulum (ER) stores, was first shown in pancreatic acinar cells after activation by carbachol (Streb *et al.*, 1983, Churchil *et al.*, 2002). Several years later, a second active calcium inducer (cADPR) was purified by Lee *et al.* (1989). cADPR as a second messenger was found to induce calcium release from sea urchin egg homogenates through a variety of mammalian cells, including human cells (Dargie *et al.*, 1990; Lee, 2002). Evidence suggests that cADPR is an endogenous modulator of the Ca²⁺-induced Ca²⁺ release (CICR) mechanism in cells, which is known to be mediated via the ryanodine receptor,

RyR (cADPR main target) in the endoplasmic reticulum (Lee *et al.*, 1995a). The activation of RyR by cADPR requires the presence of accessory proteins, such as calmodulin (Thomas *et al.*, 2002) and FK506-binding protein; FKBP (Zhang *et al.*, 2009b).

The third and the fourth calcium mobilizers are NAADP (Lee and Aarhus, 1995) and ADPR, which also play important roles in Ca^{2+} signalling (Lee, 2006). While ADPR acts on plasma membrane transient receptor potential cation channel member 2 (TRPM2), the NAADP channels have been identified as the two-pore channels (TPCs) in lysosomes, and the main role of NAADP in Ca^{2+} releasing correlates positively with the expression of TPC proteins (Perraud *et al.*, 2001; Brailoiu *et al.*, 2009; Calcrafft *et al.*, 2009).

Indeed, CD38 activity to produce either NAADP or cADPR is dependent on its environment and is regulated by pH (Lee, 2006). For example, at physiological pH, CD38 cyclises NAD to produce cADPR, and also breaks it down to ADP-ribose, inactivating its signalling function. However, that it is able to synthesise and hydrolyse NAADP only at acidic pH, confirms that CD38 could be located in two separate environments in cells and perform different Ca^{2+} signalling functions. Therefore, CD38 is known as a unique Ca^{2+} -signalling enzyme that is responsible for cADPR and NAADP production in various cells (Lee, 2012). The first demonstration was in sea urchin spermatozoa, which contain micromolar concentrations of NAADP (Billington *et al.*, 2002). It has been shown that the synthesis of NAADP can be stimulated by several stimuli, including those that elevated cADPR synthesis (extensively reviewed by Lee, 2012). Furthermore, it was proposed that NAADP may serve as an initial Ca^{2+} inducer, whose signal may be amplified by cADPR- and IP_3 -dependent Ca^{2+} release (Guse and Lee, 2008).

Interestingly, studies revealed that these two novel Ca^{2+} messengers (NAADP and cADPR) can act either individually or in coordination, depending on stimulus type, suggesting a crosstalk between the two calcium-mobilizing pathways (Park *et al.*, 2011; Kang *et al.*, 2012; Lee, 2012). Also, it is worth mentioning that the entry of cADPR into cells is either mediated via CD38, or by members of the equilibrative (ENT2) and the concentrative nucleoside transporters; CNT2 and CNT3 (De Flora *et al.*, 2004) as suggested mechanisms to resolve the CD38 ‘topological paradox’. However, the NAADP transporter has not been identified, although it has been suggested that the proteins involved in NAADP transport are different from those characterized for cADPR transport (Billington *et al.*, 2006). In conclusion, these messengers bind via different receptors and channels involved in the regulation of Ca^{2+} , and activate important signalling pathways, for instance, muscle contraction (uterus and bronchi) and gland secretion (pancreas). These functions were initially identified in CD38 knockout mice studies or mice modified to over-express CD38 (Jin *et al.*, 2007). They have also been confirmed in human disease models (Munesue *et al.*, 2010).

1.10 Role of CD38/second messengers in pathophysiological conditions

1.10.1 CD38 and obesity

Obesity is a major disease, defined as an increase in the body’s storage of fat, causing health problems leading to increased mortality (Sorensen *et al.*, 2010). It increases the risk of a number of health conditions, including hypertension, adverse lipid concentrations, and type 2 diabetes (National Institutes of Health, 1998). However, the biochemical explanation for this disease is still unclear. Recently, Barbosa *et al.* (2007) described a novel and unique role for the enzyme CD38 as a necessary molecule in the biochemical pathway that leads to the development of

obesity, as confirmed by CD38 knockout mice studies. CD38 has been implicated in the regulation of a wide variety of signalling pathways in numerous cell types (Galione and Churchill, 2000). For instance, CD38 hydrolase activity (NADase) has a key role in the regulation of intracellular NAD levels and subsequently regulates NAD-dependent deacetylases such as sirtuins; also known as SIRT enzymes (Aksoy *et al.*, 2006). Importantly, SIRT enzymes have been implicated as regulators of energy metabolism, cell life span (longevity) and activation of peroxisome proliferator-activated receptor γ co-activator-1 α (PGC-1 α ; Rodgers *et al.*, 2005). The latter is known as a co-activator with pleiotropic function (Knutti and Kralli, 2001). It plays a significant role in energy metabolism and reduces the problems of obesity (Baur *et al.*, 2006), by controlling the function and biogenesis of the mitochondria (Lin *et al.*, 2005). Recent studies have shown that activation of SIRT (by resveratrol) can protect laboratory animals from a high fat diet-induced obesity and its deleterious effects, by increasing levels of PGC1-1 α , cellular mitochondrial numbers, and energy expenditure (Lagouge *et al.*, 2006).

However, in the case of CD38-deficient mice, one of the possible mechanisms for mice's resistance to diet-induced obesity is mediated via activation of the NAD-dependent deacetylase (SIRT)/PGC1 α pathway (Baur *et al.*, 2006). It has been proposed that increasing intracellular levels of NAD following CD38 deficiency will promote activation of the SIRT enzymes. SIRT activation leads to the activation of PGC1 α (Fig.1.8), which is involved in protection from obesity (Barbosa *et al.*, 2007).

Furthermore, several reports have highlighted a crucial role of CD38 as a novel pharmacological target to treat metabolic diseases via NAD⁺-dependent pathways. Thus, the manipulation of NAD⁺ metabolism has emerged as a reasonable strategy to improve metabolic syndromes, such

as protecting against obesity. More recently, a study by Escande *et al.* (2013), reported that *in vitro* and *in vivo* inhibition of CD38 activity (via quercetin and apigenin) results in elevated cellular NAD levels, decreased overall protein acetylation and improved lipid homeostasis.

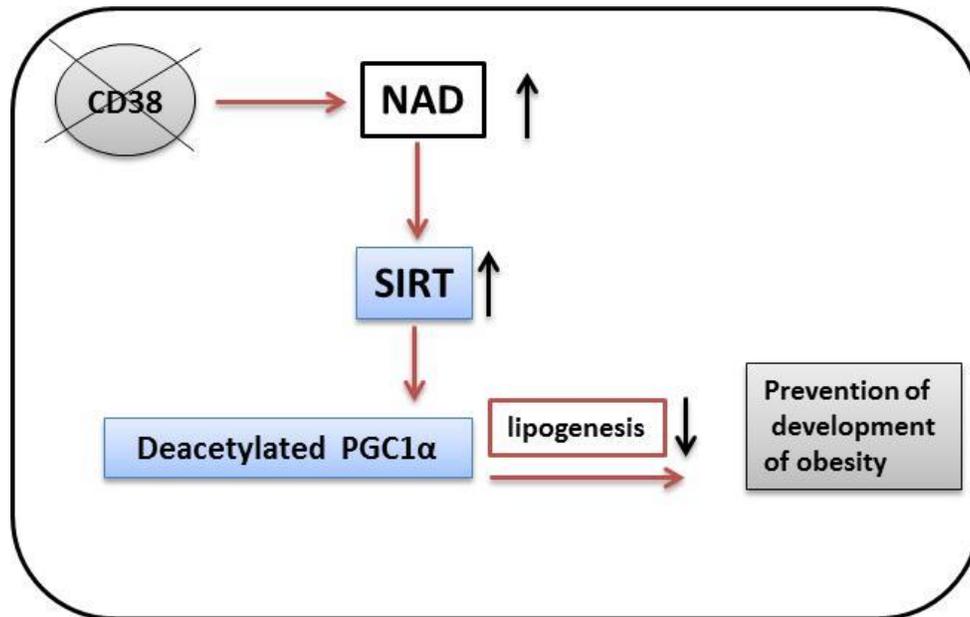


Figure 1.8 The crucial role of CD38 deficiency in preventing the development of obesity through activation of SIRT/PGC1 α following NAD elevation.

In summary, in addition to the knockout of CD38, the inhibition of CD38 activity, and elevation of sirtuin activity were successful mechanisms for preventing the development of obesity, which is part of the NAD manipulation strategy. Another suggested mechanism that might have a beneficial effect is through the activation of one of the NAD biosynthesis pathways to increase NAD levels, which again could activate the SIRT enzymes, consequently leading to an increase in PGC1 α activity and reduce the problems of obesity. Successful completion of these proposed

studies will lead to a better understanding of obesity and may lead to new therapeutic approaches for this condition.

1.10.2 CD38 and diabetes

Diabetes is a metabolic disorder characterised by chronic hyperglycaemia with disturbances of carbohydrate, fat and protein metabolisms, resulting from the destruction of insulin production by beta cells in the islets of Langerhans (type 1 diabetes), or from an impairment in insulin secretion; type 2 diabetes (Harris, 1989; Atkinson and Maclaren, 1994). The role of CD38 products in insulin signalling has been demonstrated in diabetes patients by several studies. The first pathway proposed for insulin secretion by glucose is mediated by the CD38-cADPR system in pancreatic β -cells (Okamoto *et al.*, 1997). It is suggested that in the process of glucose metabolism, the generation of ATP induces cADPR accumulation by inhibiting the cADPR hydrolase activity of CD38, since the ATP produced competes with cADPR for the binding residue, Lys129, of CD38 (Kato *et al.*, 1995). cADPR then stimulates insulin secretion by mobilizing intracellular Ca^{2+} from the endoplasmic reticulum (Noguchi *et al.*, 1997). The CD38/cADPR system prevents β -cell apoptosis through activation of RyR2 in diabetes (Paraskevas *et al.*, 2001). The evidence shows that the Arg140Trp mutation on CD38 might be responsible for the development of type II diabetes mellitus, via the impairment of glucose-induced insulin secretion (Yagui *et al.*, 1998). Furthermore, CD38-deficient mice studies have shown an alteration in Ca^{2+} levels, in addition to a reduction in the responsiveness to insulin, which is regarded as a survival factor; consequently CD38 deficiency increased islet apoptosis (Paraskevas *et al.*, 2001; Johnson *et al.*, 2006). The apoptosis leads to decreased β -cell mass, and a disruption of islet architecture (Bonner-Weir, 2000). Another pathway involves the CD38/NAADP system, which mediates Ca^{2+} mobilization by insulin in human pancreatic β -

cells. It has been shown that NAADP-generating enzymes may be involved in insulin signalling. Thus, CD38 has important roles in controlling the anti-apoptotic signalling pathway in pancreatic β -cells (Johnson *et al.*, 2006).

The causal relationship between CD38 and insulin release in humans has been further investigated, showing that auto-antibodies (a marker of autoimmunity in human diabetic patients) to CD38 might be playing a key role in impaired glucose-induced insulin secretion (Ikehata *et al.*, 1998). Auto-antibodies against CD38 have been found in sera from Caucasian type 1 (insulin-dependent, 13.1%) and type 2 (non-insulin dependent, 9.7%) diabetic subjects (Pupilli *et al.*, 1999). They have also been found in 13.8% of Japanese non-insulin dependent diabetes (NIDDM) patients along with abnormalities of both the CD38-cADPR signal system and effects on insulin secretion (Ikehata *et al.*, 1998; Mallone *et al.*, 2001a). The different results of studies may result from the use of different types of islet samples.

Altogether, these studies might indicate that the auto-antibodies altered the *in vivo* ADP-ribosyl cyclase activity of islet CD38 and impaired glucose-induced insulin secretion. Further studies have confirmed that the absence of CD38 accelerates development of autoimmune diabetes in non-obese diabetic (NOD) mice (Chen *et al.*, 2006). In summary, CD38 has a regulatory role in insulin secretion by glucose in β -cells, via its metabolites, the calcium mobilizers (NAADP, cADPR), and that CD38 deficiency may contribute to the pathogenesis of diabetes (Fig. 1.9).

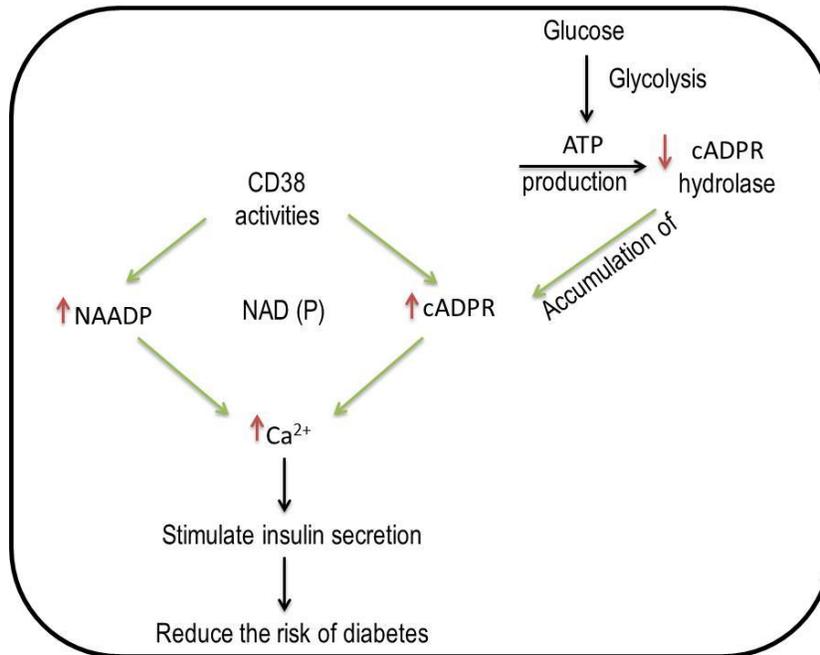


Figure 1.9 Simple diagram showing the role of CD38 activities and its products in protection against diabetes.

1.10.3 CD38 and Chronic Lymphocyte Leukaemia (CLL)

Chronic lymphocyte leukaemia (CLL), a B-cell malignancy, is the most frequent leukaemia in the western world, and is characterised by increased lymphocytosis (an increase in the number of lymphocytes) that results from the accumulation of a population of $CD5^+/CD19^+/CD23^+$ mature B lymphocytes in the peripheral blood, bone marrow (BM) and lymphoid nodes; LN (Rozman and Montserrat, 1995; Van Bockstaele *et al.*, 2009). It is also defined as a disease characterized by a dynamic balance between cells circulating in the blood and cells located in permissive niches in lymphoid organs (Zenz *et al.*, 2010).

There are two subgroups of CLL patients, according to CD38 expression, which correlates with different clinical outcomes (Damle *et al.*, 1999). CLL patients show either an indolent or a progressive course (Caligaris-Cappio and Hamblin, 1999). The two patient subgroups, with CD38⁺ or CD38⁻ CLL, differ clinically in several ways, including overall survival (Ibrahim *et al.*, 2001), time to first treatment (Morabito *et al.*, 2002), bias toward male gender (Damle *et al.*, 1999), number of leukaemic cells with atypical morphology (Morabito *et al.*, 2002), extent and level of adenopathy, lactate dehydrogenase, β -microglobulin levels (Ibrahim *et al.*, 2001; Domingo-Domenech *et al.*, 2002) and absolute lymphocyte counts (Del Poeta *et al.*, 2001). Hence, CD38⁺ CLL patients have an unfavourable clinical course with a more advanced stage of the disease, poor responsiveness to chemotherapy, and a shorter survival state compared to CD38⁻ CLL patients (Morabito *et al.*, 2002). Initial studies indicated that CD38 might be useful as a surrogate marker for the absence of mutations in immunoglobulin variable (IgV) genes in CLL patients (Damle *et al.*, 2007). Furthermore, the correlation between CD38 expression levels and cells' susceptibility to apoptosis makes this molecule a valuable prognostic marker and a disease modifier in leukaemia; CLL (Malavasi *et al.*, 2008).

Researchers have confirmed that in combining CD38 with other negative prognostic markers, such as the cytoplasmic kinase zeta1-associated protein of 70 kDa (ZAP-70) and CD49d (Morabito *et al.*, 2009), cytogenetic abnormalities, CD23, b2m, p53 function and cell size (Shanafelt *et al.*, 2004), all together provide complementary prognostic information in CLL. It has been documented that CD38 ligation leads to phosphorylation of the activatory tyrosines within the proliferation marker ZAP-70 (Roos *et al.*, 2008). It has been suggested that CD38 in association with ZAP-70 in CLL may contribute to the signals mediated by the B cell receptor complex (BCR; Chen *et al.*, 2002). This relation may explain why the simultaneous expression

of the two molecules is considered an efficient identifier of the high-risk patient subset (Schroers *et al.*, 2005). Therefore, patients with CD38⁺ ZAP-70⁺ clones are more responsive to activation of intracellular proteins than CD38⁺ ZAP-70⁻ patients (Deaglio *et al.*, 2007a). Moreover, CD38⁺ CLL clones express specific activation markers in addition to ZAP-70⁺, that are not found in CD38⁻ CLL clones (Damle *et al.*, 2002), such as expressing high levels of CD69 and human leukocyte antigen (HLA)-DR (Damle *et al.*, 2007). Another characteristic of the CD38⁺ and CD38⁻ CLL subgroups is variable telomerase levels (Damle *et al.*, 2004). Lastly, they differ in high-risk genomic abnormalities (Krober *et al.*, 2002) in the development of new DNA mutations (Ottaggio *et al.*, 2003).

The earliest investigations of the role of CD38 in CLL pathogenesis and progression, was *in vitro* activation of CD38, elicited by agonistic mAbs that induced a portion of the CLL clone (10%-30%) to proliferate (Deaglio *et al.*, 2003). The following studies substituted the mAb with the CD31 ligand, which proved the same proliferation effect (Deaglio *et al.*, 2005). Noticeably, there are many indications of the significant association between CD38 expression and chemotaxis in CLL (Deaglio *et al.*, 2007a; Vaisitti *et al.*, 2010). The first indication came from a functional cooperation between CD38 and CXC receptor 4 (CXCR4), using a CD38 agonistic mAb which was able to enhance the chemotaxis of CLL cells in response to CXCL12 chemokine. However, this effect was inhibited by blocking mAbs. This functional cooperation was partial, owing to the co-localization of CD38 and CXCR4 in the same membrane region (Vaisitti *et al.*, 2010). Furthermore, a recent study has confirmed that co-expression of CXCR4 and CD5 creates a percentage of newly born cells that is proximally 10 times higher in CD38⁺ than in CD38⁻ clones (Calissano *et al.*, 2009).

A strong relationship between CD38 expression, CLL cell migration to solid tissues and clinical outcome exists, and that CD38 expression might reflect *in vivo* CLL cell activation (Fig. 1.10). Interestingly, the variable activation status may decline over time, leading to the conversion of CD38⁺ cells to CD38⁻ cells, but is reactivated again when the cells are recruited into lymphoid tissues (Calissano *et al.*, 2009).

The most favourable conditions for expansion of CLL clones exist in two separate proliferation centre (PCs) sites; in lymphoid nodes (LN) and BM (Jaksic *et al.*, 2004), where a favourable microenvironment which provides growth and survival signals mediated by CD38 is available (Deaglio *et al.*, 2005). In the proliferation centres, Leukaemic cells come into contact with accessory cells, such as T lymphocytes (Patten *et al.*, 2008), follicular dendritic (FDC), stromal, endothelial, and mesenchymal cells (Malavasi *et al.*, 2011) and some cytokines and chemokines, as shown in Figure 1.10.

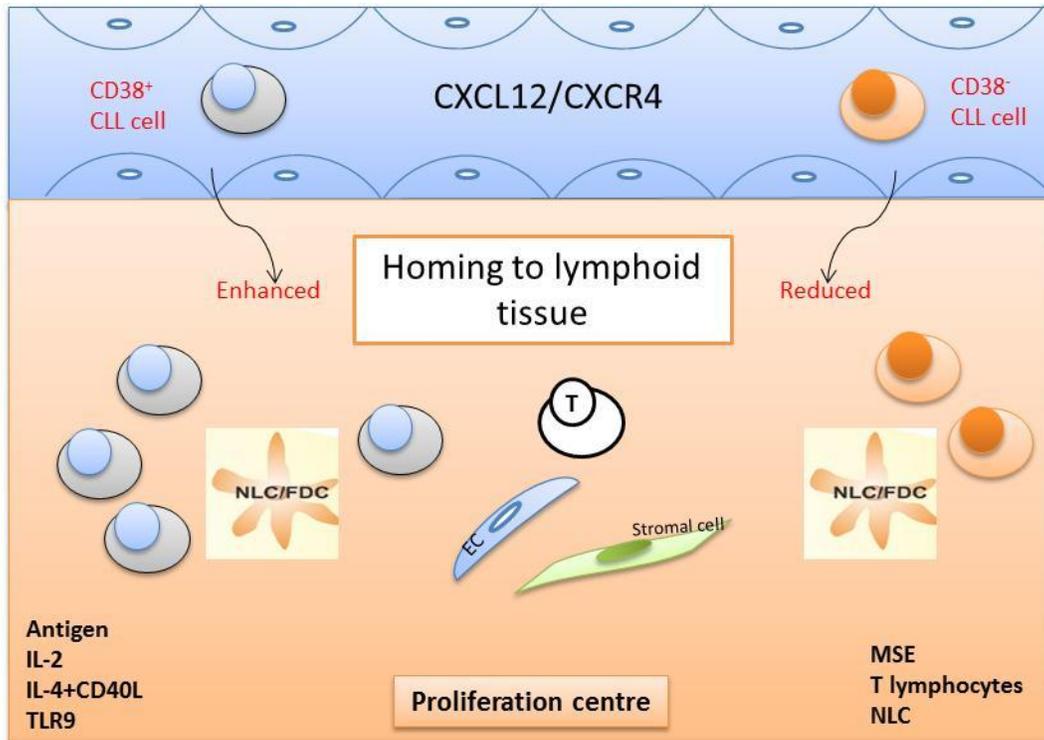


Figure 1.10 Hypothetical model of the interactions between CLL cells and distinct environments, suggesting a role for CD38 in the pathogenesis of CLL. CD38⁺ CLL cells (grey) are more sensitive to CXCL12 signals, with a higher propensity to home to lymphoid tissues than the CD38⁻ (orange). CLL lymphocytes in LN (PCs) come into contact with nurse-like (NLC) cells, follicular dendritic (FDC) cells, stromal cells, endothelial cells (EC), mesenchymal, and T cells. The presence of these environments, in addition to the cytokines and toll-like receptors (TLR) lead to CLL cell proliferation and disease progression; these events are more apparent in the CD38⁺ subsets (adapted from Malavasi *et al.*, 2011).

The initiating event for this activation is still unclear, though a study by Chiorazzi and Ferrarini (2011) which has suggested BCR signalling as a factor promoting cellular stimulation, as CD38⁺ CLL cells are generally more responsive to BCR signalling *in vitro*, which is not always the case in CD38⁻ clones (Morabito *et al.*, 2010). However, evidence for involvement of CD38 in the BCR signalling pathway is indirect and linked to lateral associations with CD19 and CD81 and to the co-localization in the same lipid rafts as the BCR (Deaglio *et al.*, 2007b). Hence, besides BCR signalling, CD38⁺ cells also respond to signals coming through chemokine and other receptors (Lopez-Giral *et al.*, 2004). For instance, nurse-like cells (NLC) that are present in solid

lymphoid tissues *in vivo* express CD38 ligand (CD31), and the interaction between CD38 and CD31 in this system promotes proliferation and survival (Deaglio *et al.*, 2005; Burger *et al.*, 2009). Several reports have shown that CD31/CD38 signals that regulate the adhesion and chemotactic response of CLL cells are part of a molecular circuit involving the CCL3 and CCL4 chemokines, and the integrin CD49d (α4), the latter being a negative prognostic marker in CLL (Zucchetto *et al.*, 2009). Collectively, trafficking of a CLL cell to the proliferation centre might affect the cell's capacity to express more activation markers such as ZAP-70 and CD49d. Moreover, the percentage of CD38⁺ CLL cells might also be extended, favouring survival/proliferation of CLL cells over apoptosis (Malvasia *et al.*, 2011). Additionally, the ability of leukaemic cells to recirculate from blood to lymphoid organs (the homing process) is also regulated by specific subsets of adhesion (integrin) molecules and by matrix metalloproteinases (MMPs). The latter play a significant role in mediating cell proliferation and prevention of apoptosis in association with chemokine receptors (Vaisitti *et al.*, 2011) by degrading the extracellular matrix to facilitate cell migration. One example of MMPs in CLL is MMP-9 (Kamiguti *et al.*, 2004), which is found to be involved in CLL cell migration and survival (Vaisitti *et al.*, 2011). However, targeting the CLL MMPs is suggested, to block cell trafficking to LN and BM (Deaglio *et al.*, 2010).

Recently, studies have indicated that nicotinamide phosphoribosyl transferase (NAMPT), the rate-limiting enzyme in the salvage NAD biosynthesis pathway in leukocytes, also exerts pro-survival activity in CLL, as recently confirmed from *in vitro* and *vivo* studies, suggesting the existence of a CD38/extracellular NAMPT (eNAMPT) loop in CLL cells, where CD38 consumes NAD and generates nicotinamide, triggering eNAMPT expression and activation to

resynthesize extracellular NAD levels. Finally, by this pathway pro-survival and activation signals will be generated in CLL (Audrito *et al.*, 2012).

In summary, the coexistence of a large supra-molecular complex, derived from the formation of extracellular and intracellular molecules in B-CLL cells, where CD38 looks to be a bridging element cooperating with all these molecules, might be one of the reasons for the higher migratory potential of CD38⁺ CLL (Willimott *et al.*, 2007). This might provide an initial explanation for the clinical observation that patients with CD38⁺ CLL clones have more aggressive disease with poor patient outcome. However, whether CD38 expression can affect the CLL homing process, through modulation of extracellular NAD⁺ levels, or the generation of Ca²⁺ active compounds, or through structural re-organization of the membrane, still needs to be completely investigated (Vaisitti *et al.*, 2011).

Altogether, CD38 has been implicated in multiple pathological conditions. Therefore, to further assess CD38's physiological functions and to investigate the role of its products in other pathophysiological environments, several CD38 ablation and knockdown studies have been established. For instance, CD38-knockout mice studies have shown a highly depleted level of endogenous cADPR (Partida-Sanchez *et al.*, 2001). The consequence of cADPR depletion and the impairment of its metabolism caused multiple abnormalities and defects (reviewed in Lee, 2012), including in neutrophil chemotaxis and bacterial clearance (Partida-Sanchez *et al.*, 2001); bone resorption (Sun *et al.*, 2003); aortic muscle contraction (Mitsui-Saito *et al.*, 2003); regulation of airway tone in response to agonists (Deshpande *et al.*, 2005); oxytocin secretion and social behaviour (Jin *et al.*, 2007); fibrosis after hepatic damage (Kim *et al.*, 2010); and inflammation after cerebral ischemia (Choe *et al.*, 2011). Recently, Xu *et al.* (2012) suggested a

beneficial role for the CD38/cADPR pathway in mouse coronary arterial myocytes (CAMs). In addition to the interesting role of cADPR, the functions regulated by NAADP/TPC are also significant (reviewed in Galione *et al.*, 2011). All these functions might also be disrupted in CD38 knockout mice, referring to the importance of the NAADP role in addition to cADPR as the main CD38 products. In conclusion, most previous and recent studies have supported the role of CD38/cADPR signalling cascade in various pathophysiological conditions in human and animal models.

1.10.3.1 CD38 as a possible therapeutic target in human leukaemia

The distinct differences in CD38 expression between normal cells and their leukaemic counterparts has made it attractive for the design of therapeutic protocols driven either by cells or by monoclonal antibodies (mAbs; Fig.1.11). These mAbs have a high ability to select CD38⁺ tumour cell lineages, in addition to the stability of the complex (mAb-target) on the cell surface (Maloney *et al.*, 1999). However, in addition to the positive points, the limitation with *in vivo* use of anti-CD38 mAbs, is its widespread expression in multiple cell types and differentiation stages, in addition to a presence of CD38 expression in the brain, pancreas, and retina (reviewed in Malavasi *et al.*, 2008). These substantial limits, however, have not prevented the design of models for *in vivo* applications. One of these designs includes antibody-dependent cellular cytotoxicity against CD38⁺ lymphoid cell lines (Stevenson *et al.*, 1991).

Additional studies have developed anti-CD38 immunotoxins capable of killing human myeloma and lymphoma cells (Bofill *et al.*, 1994). Other models are based on either the use of antibodies alone (Tesar, 2007), or conjugated to toxins; mostly for purging applications (Bolognesi *et al.*, 2005), or conjugated to radiopharmaceuticals. In this design the mAbs are used as carriers of

radiopharmaceuticals delivering a lethal hit either by surface or cytoplasmic irradiation (Mehta *et al.*, 2004). These models have been applied in myeloma and acute leukaemia cases (Stevenson, 2006). The mechanisms of action for using antibodies alone as a therapy include the inhibition of the migration function that is considered critical for CLL progression. This inhibition might be the result of the action of a mAb binding a specific domain of CD38 and disturbing ligation of a chemokine (CXCL12) to its receptor. Alternatively, a divalent anti-CD38-anti-CXCR4 therapeutic reagent might also provide simultaneous binding to CD38 and CXCR4, thereby increasing ligand specificity (Deaglio *et al.*, 2008).

CD38 can also be used as a target for gene therapy by using oncolytic viruses as anticancer drugs. These viruses propagate in tumour tissue and destroy it without causing excessive damage to normal or non-cancerous tissues, through selective targeting of CD38 (Nakamura *et al.*, 2005). The tumour cell is killed by the oncolytic virus as it takes over the cellular translational and transcriptional machinery, ultimately leading to an induction of cell necrosis or apoptosis (Parato *et al.*, 2005).

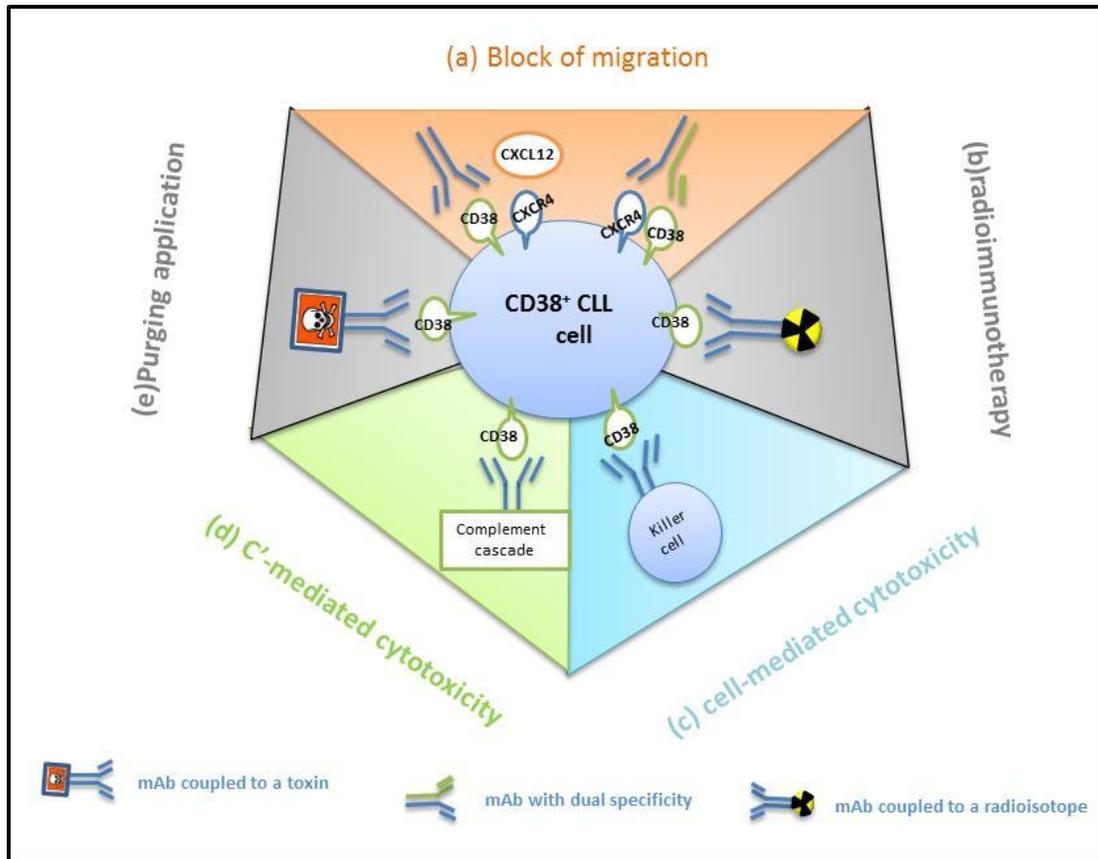


Figure 1.11 Potential applications of CD38 as a therapeutic target (adapted from Deaglio *et al.*, 2008).

Recently, two CD38 mAbs have been in clinical development: a humanized mAb; SAR650984 and a human mAb; daratumumab (de Weers *et al.*, 2011; van der Veer *et al.*, 2011). Alternatively, a useful and distinct approach could rely on the use of inhibitors of the enzymatic activities of CD38 instead of the mAbs strategy (Kellenberger *et al.*, 2011). This might be a useful strategy when CD38 inhibition is used as a therapeutic target in leukaemia and obesity patients. On the other hand, using activators of CD38 enzymatic activity might be important for other diseases, for instance diabetic patients.

In summary, several observations have suggested that CD38 is a potential therapeutic target for leukemia. Generally, targeting of CD38 may impair the proliferation of leukaemia cells, and might also render it more susceptible to conventional chemotherapy. However, more studies are still needed to investigate the role of CD38 as a therapeutic target in leukemia, and probably other diseases.

Finally, it is worth noting that CD38 regulation induced by all *trans* retinoic acid (ATRA) was interestingly involved in the induction of human leukaemia cells' (HL60) differentiation to neutrophil-like cells, as well as restricted cell proliferation. It has been documented that ATRA-induced CD38 expression is mediated by direct transcriptional regulation via activation of a retinoic acid receptor (RAR) and retinoid x receptor (RXR) (Kishimoto *et al.*, 1998). However, it has also been indicated that phosphoinositide 3-kinase (PI3-K) is involved in the modification of CD38 antigen expression in the ATRA-induced granulocytic differentiation of HL60 cells (Lewandowski *et al.*, 2002). Another study by Shen and Yen (2008) documented a causal role for Cbl-CD38 interaction in promoting ATRA-induced differentiation of HL60; this interaction enhances mitogen-activated protein kinase (MAPK) signalling, leading to myeloid differentiation.

1.11 The HL60 cell line and induction of differentiation

The HL60 cell model was derived from a patient with acute promyelocytic leukaemia (Collins *et al.*, 1977). These myeloid-restricted precursor cells are a well-characterized model for studying the terminal differentiation processes. HL60 cells exhibit the typical properties of leukaemia: unlimited proliferation capacity, inability to respond to normal differentiation stimuli, and increased obstruction of apoptosis (Palis *et al.*, 1988). However, many agents are known to induce differentiation in HL60 cells, with the hope of treating cancer cells by overcoming their blocked differentiation through several suggested mechanisms. These include: inhibiting histone deacetylase, inhibiting topoisomerase, interfering with DNA and RNA synthesis, and disturbing signal transduction (Tsiftoglou *et al.*, 2003). For instance, induction of promyelocytic HL60 cells to mature into neutrophil-like cells has been shown after 5-7 days culture with DMSO (Collins *et al.*, 1978) or 5 days culture with ATRA (Breitman *et al.*, 1980). In contrast, exposure of HL60 cells to phorbol 12-myristate 13-acetate (PMA) or to sodium butyrate under a mild alkaline condition induces differentiation into monocyte- and eosinophil-like cells, respectively (Fischkoff, 1988; Ahmed *et al.*, 1991). Interestingly, the differentiated HL60 cells have many of the functional characteristics of normal peripheral blood granulocytes, including phagocytosis, complement receptors (such as CR1, the C3b receptor, and CR3), chemotaxis, and the ability to reduce nitroblue tetrazolium; NBT (Collins *et al.*, 1978; Newburger *et al.*, 1979).

One of the recognised myeloid differentiation agents is all-*trans* retinoic acid (ATRA), the acid form of vitamin A. ATRA treatment has been shown to modulate the secretion of certain cytokines as well as the expression of different adhesion molecules, for instance CD38 (Gao *et al.*, 2007). CD38 upregulation was observed in several types of myeloid cells, for instance

human myeloid leukaemic cell lines HL60 and KG-1, as well as in freshly isolated cells from acute promyelocytic (APL) and myeloblastic (AML) leukaemia when exposed *in vitro* to ATRA and *in vivo* during oral treatment with ATRA (Breitman *et al.*, 1981; Drach *et al.*, 1993, 1994). It has been observed that this effect is mediated by the activation of nuclear receptors, RAR and RXR, which act as ligand-inducible transcription factors. It has been suggested that ATRA-induced CD38 expression is mediated via a RAR-RXR heterodimer, rather than an RXR-RXR homodimer (Mehta *et al.*, 1997). Indeed, the nuclear receptors, RAR and RXR are encoded by distinct genes and bind to specific ligands and response elements. Each RAR and RXR family of receptors consists of three subtypes, each subtype being encoded by a distinct gene (Pfahl *et al.*, 1994; Sporn *et al.*, 1994). RAR subtypes can bind both ATRA and its isomer, 9-*cis* retinoic acid (9-*cis* RA), whereas RXR subtypes bind only 9-*cis* RA (Heyman *et al.*, 1992). Thus, each may specifically regulate the expression of subsets of retinoid target genes, such as CD38, during ATRA-induced granulocytic differentiation of HL60 cells (Drach *et al.*, 1994). These observations were confirmed by a study by Kishimoto *et al.* (1998) in which the presence of a retinoic acid-response element (RARE), known as a DR5 repeat, was described, in intron 1 of the CD38 gene.

ATRA has been used in clinical therapy for promyelocytic leukaemia (PML) patients with satisfactory results (Warrell *et al.*, 1991). ATRA was either used alone in APL therapy or in a combination regimen of ATRA with cytotoxic chemotherapy (Tallman *et al.*, 2002). Another example includes ATRA/ATO (arsenic trioxide) and anthracycline-based chemotherapy (Sanz *et al.*, 2009). However, the differentiation of APL cells by ATRA shows a side effect known as retinoic acid syndrome (RAS), the most dangerous side-effect of ATRA treatment (Mehta, 2000). RAS is marked by acute respiratory distress and pulmonary oedema (Gruson *et al.*, 1998).

Interestingly, an interaction between CD38 and CD31 might be involved in the pathophysiology of this syndrome (Lewandowski *et al.*, 2002). The differentiation of APL cells by ATO has also shown a side effect similar to that found with ATRA (Sanz *et al.*, 2009).

1.12 CD38 and HL60 differentiation

Studies on CD38 expression during ATRA-induced HL60 differentiation are quite varied, as some of them suggest that for ATRA-induced CD38 expression during myeloid leukaemia cells differentiation, this effect is independent of differentiation and is mediated by RAR activation in HL60 cells (Drach *et al.*, 1994). Meanwhile, a further study has demonstrated that the degree of the cellular response to retinoic acid (cell differentiation or loss of viability) depends on the CD38 expression level (Lamkin *et al.*, 2006). Recently, Congleton *et al.* (2011) have confirmed that induction of CD38 expression promotes myeloid maturation, whereas knocking it down has an inhibitory effect on ATRA-induced differentiation, and that effect is mediated through CD38 receptor functions rather than its enzymatic functions. Hence, CD38 either enhanced or blocked cellular differentiation.

It has been shown that granulocyte differentiation inducers in HL60, including dimethylsulfoxide (DMSO), failed to induce CD38 expression, unlike the case with ATRA (Guida *et al.*, 2004). However, not only is CD38 expressed in ATRA-induced HL60 differentiation, but the differentiation of HL60 is also accompanied with expression of CD11b, CD45RO, CD11c, CD54 and CD36, and suppression of CD117 and CD44, as investigated in immunophenotyped studies using a CD antibody microarray (Barber *et al.*, 2008). Finally, in most previous studies on the link between CD38 expression and the differentiation process, one theme remains clear: CD38 expression affects the differentiation status and might cause this abnormal differentiation.

Therefore, by studying this process, an understanding of extracellular/intracellular CD38 levels is gained, and even how its role in regulating other intracellular factors might affect the differentiation process against a proliferation.

1.13 The strengths of the HL60 model

The HL60 cell line is a well-characterized model that is possible to differentiate into cells morphologically similar to normal neutrophils, monocytes, macrophages, and eosinophils (Breitman *et al.*, 1980; Fischkoff *et al.*, 1984). However, the promyelocytes would normally differentiate terminally into only granulocytes. Importantly, the HL60 cell line provides a continuous source of human cells expressing CD38 (neutrophil-like cells), after being stimulated with ATRA. These cells are grown in culture, and therefore a large number of cells are available for experimentation. This would be of high importance for assays that require large numbers of cells.

Additionally, it is well known that peripheral blood neutrophils are short-lived cells and once removed from the blood their viability is limited to several hours (Mauer *et al.*, 1960). Therefore, a long-lived cell line such as HL60 cells has been found to overcome such a shortcoming. These cells are stimulated to neutrophil-like cells in a manner similar to blood neutrophils, and stay alive for several days, which is especially important for researchers who are only interested in neutrophil studies. Finally, the HL60 cell line is a model of acute myelocytic leukaemia (APL), so use of these cells to study terminal differentiation allows one to discover new factors that might affect this maturation. Additionally, they might be used as a potential therapy for differentiation diseases like APL.

1.14 Objectives of the study

As a receptor and a multifunction enzyme, CD38 plays important roles in the pathophysiology of several human diseases. Several human studies suggest a potential key role for CD38 receptor functions in the development of leukemia (for instance CLL). However, the effect of the enzymatic function of CD38 on leukemia development needs to be established to find a relevant therapy for CD38⁺ leukemia patients. In the current study it was hypothesized that inducing CD38 expression or its enzymatic activity might significantly degrade intracellular NAD levels and hence have effects on several NAD dependent processes in cells. To test this hypothesis, HL60 cells were used as a model for human leukaemia that is able to express CD38 when treated with ATRA. The hypothesis that CD38 might control NAD levels and its related metabolic reactions might be one of a number of possible mechanisms that are responsible for poor prognosis and other consequences in CD38⁺ leukemia patients. The specific objectives were:

- a) to develop methods for determination of NAD levels and CD38 activity;
- b) to determine whether CD38 levels are differentially elevated, both intracellularly and extracellularly, during the time course of HL60 differentiation induced by ATRA, by measuring cyclase activity of CD38 (cyclase assay), CD38 protein expression by flowcytometry and Western blotting, in addition to measuring CD38 gene expression by qPCR;
- c) to determine the intracellular NAD(H) levels during a time course of HL60 differentiation, using a cycling assay;
- d) to develop a novel inhibitor of CD38 activity, in order to test our hypothesis;

- e) to determine the physiological consequences of the effect of low NAD levels in the cells by measuring the NAD/NADH ratio, lactate levels, total glutathione, the lipid peroxidation state, DNA damage and cell apoptosis.; and
- f) to investigate the possibility of regulating CD38 gene expression under multiple conditions, such as using a CD38 inhibitor (kuromanin), NAD biosynthesis inhibitor (FK866), increasing NAD levels, and using several hypoxia conditions.

CHAPTER 2

GENERAL MATERIALS & METHODS

2. Materials and Methods

2.1 Materials

The HL60 cell line was a kind gift from Anwar Al-mzaiel (University of Plymouth, UK), and the human B-lymphocyte-derived cell line (RAJI Cells) was obtained from ECCAC (European collection of cell culture). RPMI-1640, Fetal Calf Serum (FCS), L-glutamine, penicillin, streptomycin, and trypan blue were all from Lonza, Slough, UK. NGD; kuromanin and all-trans-retinoic acid (ATRA) were from Sigma-Aldrich Ltd. (Poole, UK); and PBS and NAD were from Melford Laboratories (Ipswich, UK). Antibodies for Western blotting, anti-human CD38 mouse monoclonal antibody was from BD Bioscience (Oxford, UK) and mouse monoclonal (10H) to PADPR was from Abcam (Cambridge, UK). M-MLV reverse transcriptase, dNTPs, random nonamers, SYBR Green, and other PCR reagents were purchased from Sigma-Aldrich Ltd. (Poole, UK).

2.2 Culture of HL60 and RAJI cells

The cells were maintained in suspension in Roswell Park Memorial Institute (RPMI-1640) medium supplemented with 10% heat-inactivated fetal calf serum, 100 U/ml penicillin and 100 µg/ml streptomycin, 2 mM L-glutamine, and kept at 37 °C in a 5% CO₂ humidified incubator. Cultures were passaged twice weekly by dilution in fresh medium to a density of 0.3×10^6 cells/ml in both 25 and 75 cm² flasks.

2.3 HL60 and all-trans retinoic acid (cell differentiation)

To induce HL60 differentiation with ATRA (Breitman *et al.*, 1980), the cells (2.5×10^5 cells ml⁻¹) were incubated with 1 μ M ATRA at 37 °C in a humidified atmosphere of 5% CO₂ for up to 5 days (Fig. 2.1). The cells were then washed twice in RPMI-1640, centrifuged at $200 \times g$ for 5 min, and subsequently counted and assayed for further analysis. ATRA stock solution was dissolved in pure ethanol (99% v/v) at a concentration of 10 mM and diluted into the growth media to a final concentration of 1 μ M ATRA; the final ethanol concentration in cultures was 0.01%. HL60 cells were also treated with ethanol (0.01%) as a control.

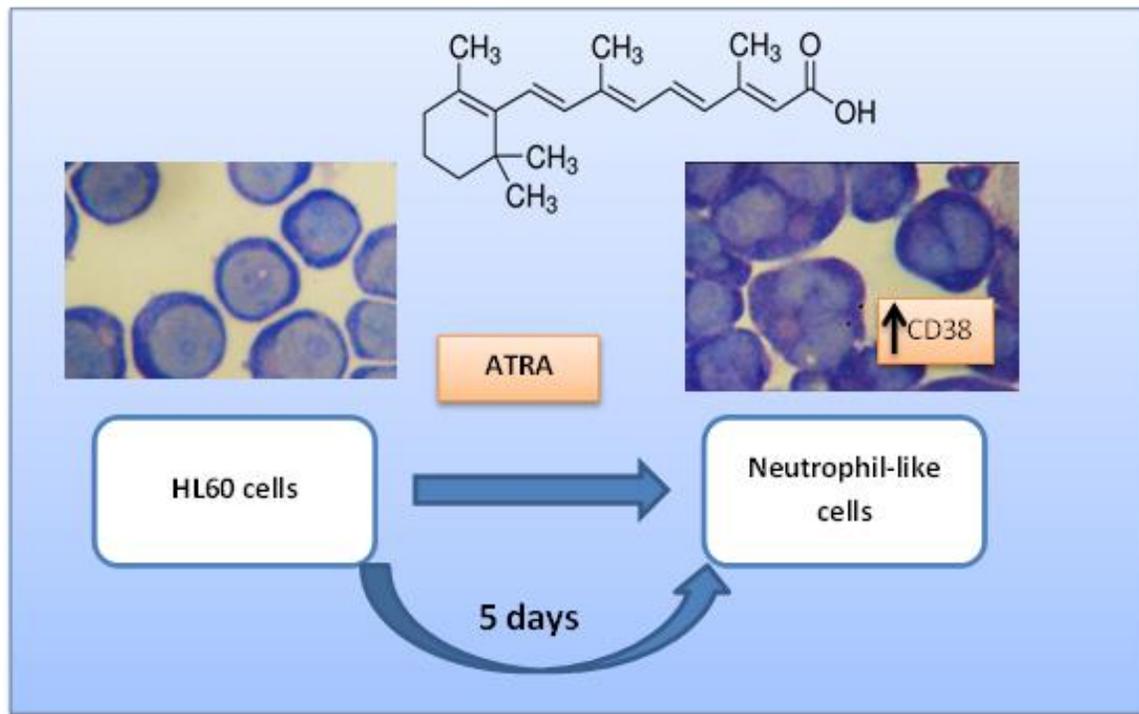


Figure 2.1 Diagram illustrating HL60 differentiation by ATRA over 5 days.

2.4 NBT differentiation assay

Differentiation of HL60 cells was assessed using the nitroblue tetrazolium (NBT) reduction test. Briefly, 100 μl of 1×10^6 cells ml^{-1} in RPMI media were incubated in 96 well plates with 100 μl of 2 mg/ml (0.2% w/v) NBT and 100 μl (200 ng/ml) of freshly prepared phorbol myristate acetate (PMA) in RPMI. After 30-60 min incubation at 37 °C in 5% CO_2 a humidified incubator, cells then were dissolved in 100 μl DMSO to solubilise the reduced NBT (formazan product). The absorbance of the solution was measured at 590 nm on a plate reader (VersaMax, Molecular Devices, Sunny Vale, CA).

2.5 Assessment of viability

A viability test was used to determine the number of viable cells present in cell suspensions; it was carried out on all cell samples before they were assayed in each experiment. This assay is based on the principle that live cells possess intact cell membranes that exclude the dye, trypan blue, whereas dead cells take up the dye.

In this test, cell suspension (10 μl) was mixed with 90 μl of 0.1% trypan blue, and then (after 5 min incubation) 10 μl from the mix (cells with trypan blue) were visually examined to determine whether cells had taken up or excluded the dye. In this assay, viable cells have clear cytoplasm whereas nonviable cells have a blue cytoplasm.

2.6 Cell proliferation assay (MTT)

To carry out the MTT assay, 10 μl of 5 mg ml^{-1} 3-(4,5-dimethylthiazole-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) was added to 100 μl of cell suspension at a density of 1×10^6 cells

ml⁻¹ in PBS (137 mM NaCl, 2.7 mM KCl and 10 mM phosphate, pH 7.4) in 96 well plates. The plate was incubated in a humidified incubator for 2-3 h at 37 °C to allow reduction of MTT. The reduced MTT was solubilized by the addition of 100 µl DMSO to each well and each sample was pipetted several times to aid dissolution. Plates were read in a plate reader (VersaMax, Molecular Devices, Sunny Vale, CA) set to 540 nm.

2.7 mRNA isolation and Quantitative Real-Time PCR

Levels of mRNA for CD38, GAPDH, CD157, IDO, NMNAT and NAMPT were determined in ATRA-treated and untreated HL60 cells during the time course of differentiation using quantitative real-time PCR. After cell incubation, total RNA was isolated using a commercially available GenElute™ mammalian total RNA miniprep kit (Sigma, Poole, UK), which utilizes a column based technique to isolate and purify RNA. An On-column DNase-I treatment step was used to remove genomic DNA. RNA quantity (A₂₆₀) and purity (A₂₆₀:A₂₈₀) was measured using a Nandrop spectrophotometer (ND-1000; Labtech, UK). RNA (1 µg) from control and ATRA-treated HL60 cells was reversed transcribed to cDNA using M-MLV reverse transcriptase in thin-walled PCR tubes (Sigma, Poole, UK) using a GeneAmp PCR System 9700 instrument. RNA was denatured at 70 °C for 10 min in the presence of dNTPs (dATP, dCTP, dGTP, TTP; 0.5 mM) and random nonamers (1 µM); following the Sigma reverse transcription protocol.

Reaction mixes were cooled on ice for 5 min and then 1 unit of MMLV-reverse transcriptase was added to each. Reaction mixes were then incubated at room temperature for 10 min, 37 °C for 50 min and 94 °C for 5 min. cDNA samples were stored at 4 °C until use. Primer sequences were designed using the NCBI website and according to the mRNA sequence of each gene published

in the same website using primer Blast software. Primers (Table 1) were purchased from Eurofins MWG Operon (Germany), and all primers produced 100-105 bp products.

Quantitative RT-PCR was performed using a 96 well plate using the StepOne plus sequence detection system (Applied Biosystems, UK) and using the DNA-binding dye SYBR green for detection of PCR products. GAPDH was used as a housekeeping gene to normalise mRNA levels. cDNA was amplified by adding 2 μ l to a final reaction volume of 25 μ l containing SYBR green, 0.05 U/ μ l Taq polymerase, 300 nM reference dye and 0.2 μ M of the specific primers. Reactions were performed under the following conditions: 94 °C for 2 min followed by 40 cycles of 94 °C for 30 s, 60 °C for 30 s and 72 °C for 30 s. The fluorescence obtained in the reaction was normalized using the reference dye included in the master mix. Results of the levels of CD38, GAPDH, CD157, IDO, NMNAT and NAMPT expression were indicated by the number of cycles required to achieve the threshold level of amplification. The C_t (cycle at threshold) value from control HL60 was compared with that of ATRA-treated cells using the $\Delta\Delta C_t$ methodology to determine the relative target quantity in samples (Livak and Schmittgen, 2001).

Genes	Primers	Size	Product (bp)
GAPDH	For: CCCACTCCTCCACCTTTGAC	20	100
	Rev: CTGTTGCTGTAGCCAAATTCGT	22	
CD38	For: GCACCACCAAGCGCTTTC	18	100
	Rev: TCCCATACACTTTGGCAGTCTACA	24	
CD157	For: GGGAAGGCAGCATGAAAGTC	20	105
	Rev: GGTCACGCACTGTAAGAGCTT	22	
IDO	For: GCCTGCGGGAAGCTTATG	18	100
	Rev: TGGCTTGCAGGAATCAGGAT	20	
NMNAT	For: TCATTCAATCCCATCACCAACA	22	105
	Rev: AGGAGAGATGATGCCTTTGACAA	23	
NAMPT	For: TCCGGCCCGAGATGAAT	17	105
	Rev: TGCTTGTGTTGGGTGGATATTG	22	

Table 2.1 Primers used for qPCR experiments, the size and product was shown for each primer.

2.8 Assessment of CD38 expression during HL60 differentiation by western blotting

2.8.1 Plasma membrane and whole cell lysate preparation

75-100 µl pre-cooled lysis buffer (consisting of; 1% Nonidet (NP-40), 150 mM sodium chloride and 50 mM Tris HCl (pH 8.0) with freshly added a protease inhibitor (AEBSF 104 mM, Aprotinin 80 µM, Bestatin 4 mM, E-64 1.4 mM, Leupeptin 2 mM, Pepstatin A 1.5 mM)), were added to the cell pellet (2.5×10^6 cells ml⁻¹) with constant agitation for 20 min at 4° C. Cell lysate was centrifuged for 30 min at $6000 \times g$, 4° C. The supernatant was harvested in a fresh tube and stored at -20° C for further assays, and the pellet was discarded.

2.8.2 Preparation of Nuclear Extract

Cells nuclear extracts were prepared as described by Whiteside *et al.*, (1992). Cells were harvested in ice-cold PBS by centrifugation ($6000 \times g$ for 30 s) and washed once with ice-cold PBS. Cell pellets were then lysed in 150 µl hypotonic lysis buffer (HLB; consists of 10 mM HEPES, 1.5 mM MgCl₂, 10 mM KCl, 0.125% NP-40 with freshly added protease inhibitor and 1 mM DTT, pH 7.9). After incubation on ice for 5 min, lysates were centrifuged at $6000 \times g$ for 1 minute, 4 °C. Cleared lysates (supernatant) were then moved to fresh tubes, frozen and stored at -20 °C for further estimation of cytosolic protein concentration.

The nuclei pellets were washed in HLB to remove contaminating cytosolic proteins. After washing the pellets, they were resuspended in 100 µl of hypertonic extraction buffer (HEB; consisting of 5 mM HEPES, 1 mM MgCl₂, 0.5 M NaCl, 0.2 mM EDTA and 25% glycerol with freshly added protease inhibitor cocktail (100 µl per 1 ml of lysis buffer; P8340, Sigma, Poole, UK) and 1 mM DTT, pH 7.0) for 1 h at 4 °C under agitation. After centrifugation ($6000 \times g$ for

10 min at 4 °C), supernatants containing the nuclear protein were moved to fresh tubes and stored at -70 °C.

2.8.3 Determination of protein concentration

Protein concentrations were assessed according to a simple protocol described by Bradford (1976). In this assay, 200 µl Bradford reagent was added to 50 µl of each sample and standard solutions of bovine serum albumin in 96 well plates. After 5 min incubation the absorbance was read at 595 nm using a plate reader. As blank, water was mixed with the Bradford reagent

The reference standard for the protein under test was bovine serum albumin (BSA), and concentrations between 0-20 µg protein ml⁻¹ were used to generate a standard curve for each run of the assay. The concentration of protein in each sample was then interpolated from the standard curve.

2.8.4 Western blot assessment of protein expression

Total protein samples (20 µl containing 50 µg or 100 µg) were mixed with 5 µl of 5× loading buffer (60 mM Tris-chloride, pH 6.8, containing 2% (v/v) SDS, 10% (v/v) glycerol and 0.1% (v/v) bromophenol blue), and subsequently denatured by incubation for 5 min at 100 °C under reducing conditions with freshly added 5% (v/v) mercaptoethanol.

Equal amounts of protein were electrophoresed on 12% sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE) gels using standard conditions. The gel was run in 1 × SDS running buffer (192 mM glycine, 25 mM Tris base and 0.1% w/v SDS, pH 8.3) for 45-50 min. The voltage was set to 200. After electrophoresis, the protein-containing gel was sandwiched

between buffer-soaked filter papers. Polyvinylidene fluoride (PVDF) membranes were used and were placed immediately next to the gel. The sandwich was placed in the blotting tank full of 1× pre-cooled blotting buffer (192 mM glycine, 25 mM Tris base and 20% methanol) with the gel towards the anode, and the blot was run at 100 V for 36 min. Two sets of molecular weight markers were used to calibrate the gels as well as to assess transfer efficiency; prestained markers (10 kDa to 190 kDa; from Bioline Reagents Ltd., London, UK) and biotinylated (unstained) protein ladder (9 kDa to 200 kDa; from New England Biolabs, Hitchin, UK).

When blotting was complete, the membrane was blocked at room temperature by shaking in Tris-buffered saline-0.05% Tween 20 (TBS-T) solution containing 5% skimmed milk (w/v) for 1 h. The proteins were then (after blocking) probed overnight at 4 °C with the primary antibody (CD38 or PAR antibody) at a dilution 1:500 in 2.5% blocking buffer. After the incubation with the primary antibody, the membranes were washed 3 times for 5 min in TBS-T before the 1 h incubation with the HRP-conjugated secondary antibody (goat polyclonal anti-mouse IgG; Abcam Cambridge, UK), which was used with dilution (1:1000) and prepared in 2.5% blocking buffer.

The same washing steps were performed with TTBS before the membrane was soaked briefly for 5 min in the detection reagents. Before images were captured (exposed for a maximum of 10 min) the excess detection reagent was drained off by holding the membrane with forceps and touching the edge against a tissue. The plot, protein side down, was placed onto a fresh piece of Saran Wrap, wrapped up and any air bubbles gently smoothed out with the protein side up. Bands were visualized by electro generated chemiluminescence staining (Amersham

Biosciences, UK). Digital imaging with a charge-coupled device (CCD) camera-based imagery system was used (UVP EC3 Imaging system, Cambridge, UK).

2.9 *NAD*⁺ assays

Multiple enzymatic cycling assays have been used for the determination of *NAD*⁺ levels as follows.

2.9.1 Glucose 6-phosphate dehydrogenase (G6PDH)/diaphorase cycling assay

This assay was used to determine *NAD*⁺ levels fluorimetrically; it consists of two enzymatic reactions. In the first reaction, *NAD*⁺ is reduced to *NADH* catalysed by glucose 6-phosphate dehydrogenase (G6PDH). This reaction was conducted in the presence of an excess of glucose 6-phosphate. In the second part of reaction *NADH* is reoxidized to *NAD*⁺, catalyzed by diaphorase. Diaphorase catalyzes the conversion of resazurin into the highly fluorescent resorufin (indicator reaction). Fluorescence was measured with excitation wavelength 530 ± 25 nm and emission wavelength 590 ± 35 nm.

2.9.2 Alcohol dehydrogenase cycling assays

This cycling assay involves a single enzyme catalysed reaction (Fig. 2.2). This assay was previously described by Bernofsky and Swan (1973), Self (1988) and Leonardo *et al.* (1996). In this system *NAD*⁺ is first reduced to *NADH* catalysed by yeast alcohol dehydrogenase utilizing ethanol as cosubstrate, after which *NADH* reduces phenazine ethosulfate (PES), regenerating *NAD*⁺ for the next cycle. The PES is then oxidized by passing electrons to a tetrazolium dye ; MTT (Self, 1988). The signal from the *NAD* is then amplified using an enzyme-cycling system.

The product of the reaction, a formazan dye, is measured spectrophotometrically at 565 nm. However, the method used for NAD determination in this thesis was a slight modification of alcohol dehydrogenase cycling assay described by Leonardo *et al.* (1996).

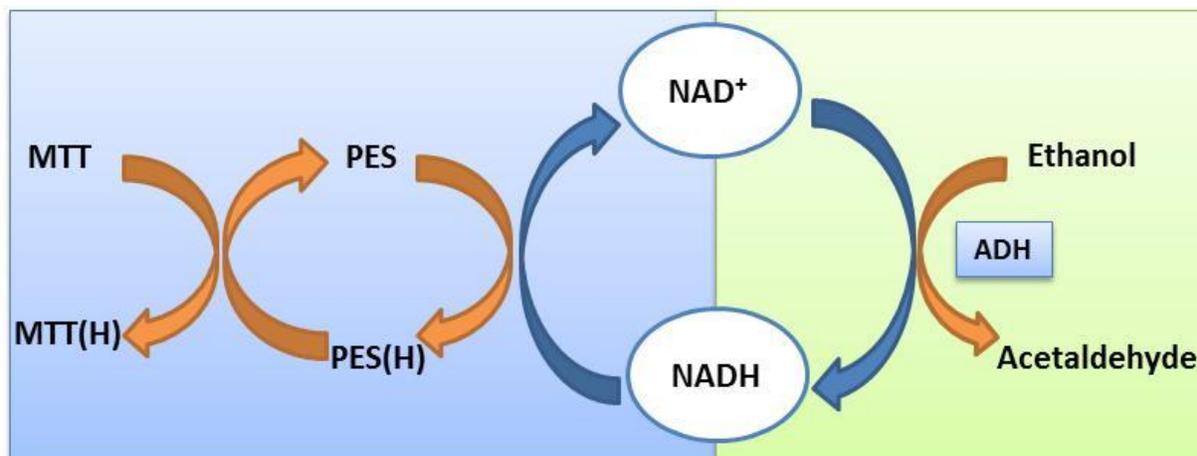


Figure 2.2 The principle of enzymatic cycling reaction for the colorimetric determination of NAD⁺.

2.9.2.1 Modified NAD(H) cycling assay

NAD⁺ and NADH were extracted (Fig. 2.3) by a modification of the protocol described by Leonardo *et al.* (1996). Cells with and without treatment were placed in microcentrifuge tubes and centrifuged at $7000 \times g$ for 1 min. After removal of the supernatant, the pellets were immediately frozen in a dry ice-ethanol bath. For NAD⁺ extraction, 250 μ l of 0.2 M HCl were added to the frozen pellets or 250 μ l of 0.2 M NaOH for NADH extraction. To extract NAD(H), samples were placed in a 100 °C water bath for 10 min and then centrifuged at $4000 \times g$ for 5 min to remove cellular debris. NAD⁺ or NADH-containing supernatants were transferred to fresh tubes and stored in -20 °C until needed. Extracted NAD⁺ or NADH were assayed as described below.

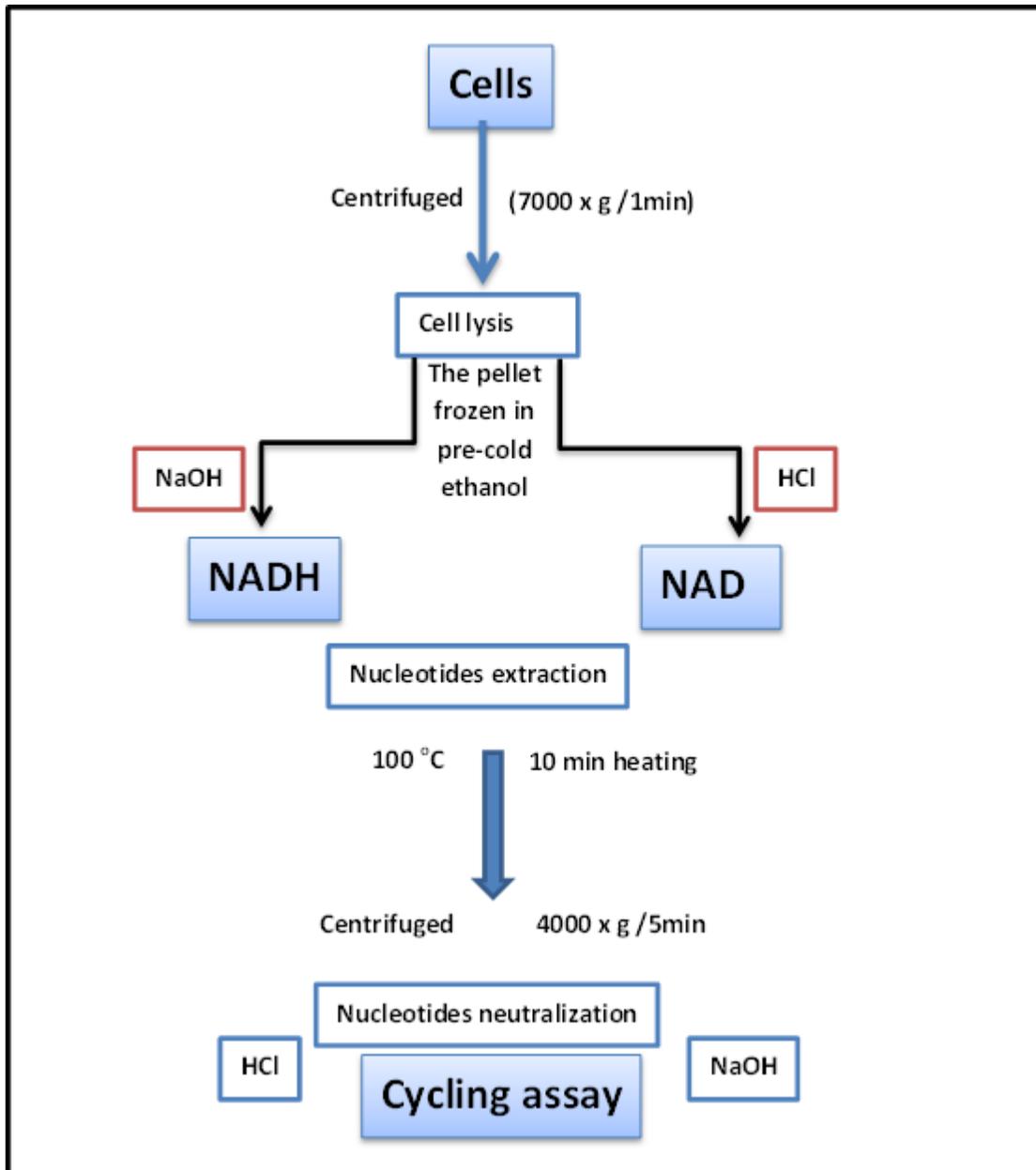


Figure 2.3 A simple diagram for nucleotides extraction and assay illustrating NAD^+ extraction by HCl and NADH extraction by NaOH.

For NAD(H) determination, the NAD^+ , NADH recycling assays were performed in triplicate as follows: 49 μl of extracted NAD^+ (or NADH) was added to the following reaction mixture containing 151 μl of 98 mM of sodium bicine, pH 8.0, 24 mM of either NaOH (neutralizing base for NAD^+) or HCl (neutralizing acid for NADH), 1.63 mM of PES, 0.412 mM MTT, 19.6 μl of absolute ethanol, 3.92 mM of EDTA and 5 μl of yeast ADH (400 U/mg in 0.1 M bicine buffer, pH 8.0). The absorbance at 565 nm was recorded in a plate reader (VersaMax, Molecular Devices, Sunny Vale, CA), after 30 min incubation in the dark. NAD^+ and NADH standards from 5 to 60 μM were repeated with each separate experiment, to calibrate the assay (Fig. 2.4 A, B).

The reaction specifically detects NADH and NAD^+ , but not NADPH nor NADP^+ . The enzyme cycling reaction significantly increases the detection sensitivity and specificity. NAD^+ or NADH can be easily quantified by comparing with standards of NAD^+ and NADH. The NAD^+/NADH ratio was calculated by dividing intracellular NAD^+ levels by NADH levels in the same sample after they had been normalized to the cell number.

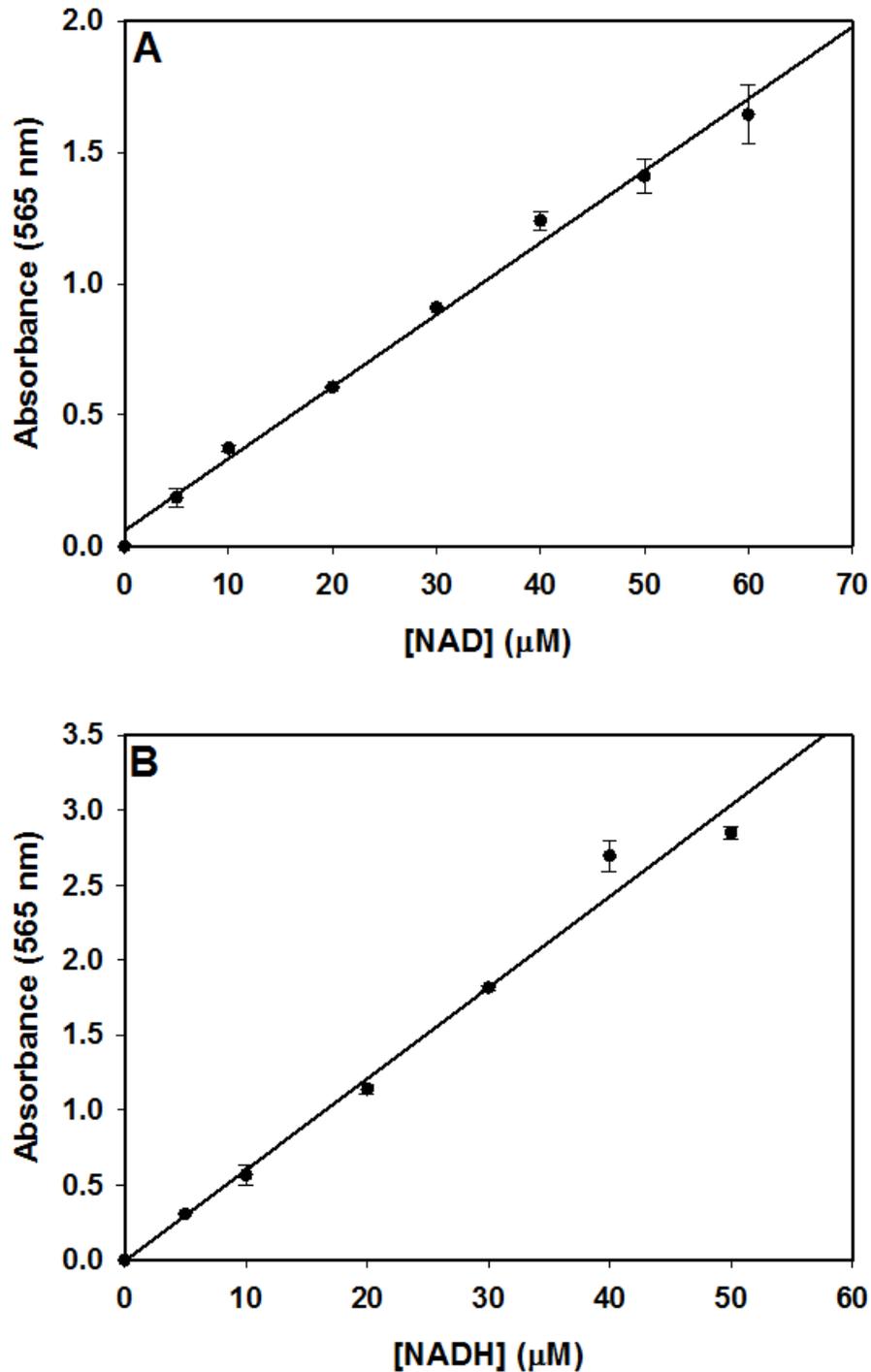


Figure 2. 4 (A) The NAD cycling assay. NAD (5-60 μM) extracted with HCl, the mixture was equilibrated in the dark at 25°C for up to 30 min ($r=0.99$). (B) The NAD(H) cycling assay. NADH (5-30 μM) extracted with NaOH, the mixture was equilibrated in the dark at 25°C for up to 30 min ($r=0.99$). Change in absorbance is recorded at 565 nm. Data are means \pm SEM, $n=3$.

2.9.2.2 Effect of cell number on the sensitivity of the NAD assay

Intracellular NAD was determined in the HL60 cell line to examine the possibility of an effect of differences in cell number on NAD levels, which might potentially interfere with the results of treatment effects on NAD levels. Thus, different cell numbers were used to assess variations in NAD levels in HL60 cells. As shown in Figure 2.5, there were no apparent differences in NAD levels in HL60 cells observed using different cell numbers. Therefore, in subsequent studies, final cell numbers between $0.24 \times 10^6 \text{ ml}^{-1}$ and $0.98 \times 10^6 \text{ ml}^{-1}$ were routinely used in the experiments.

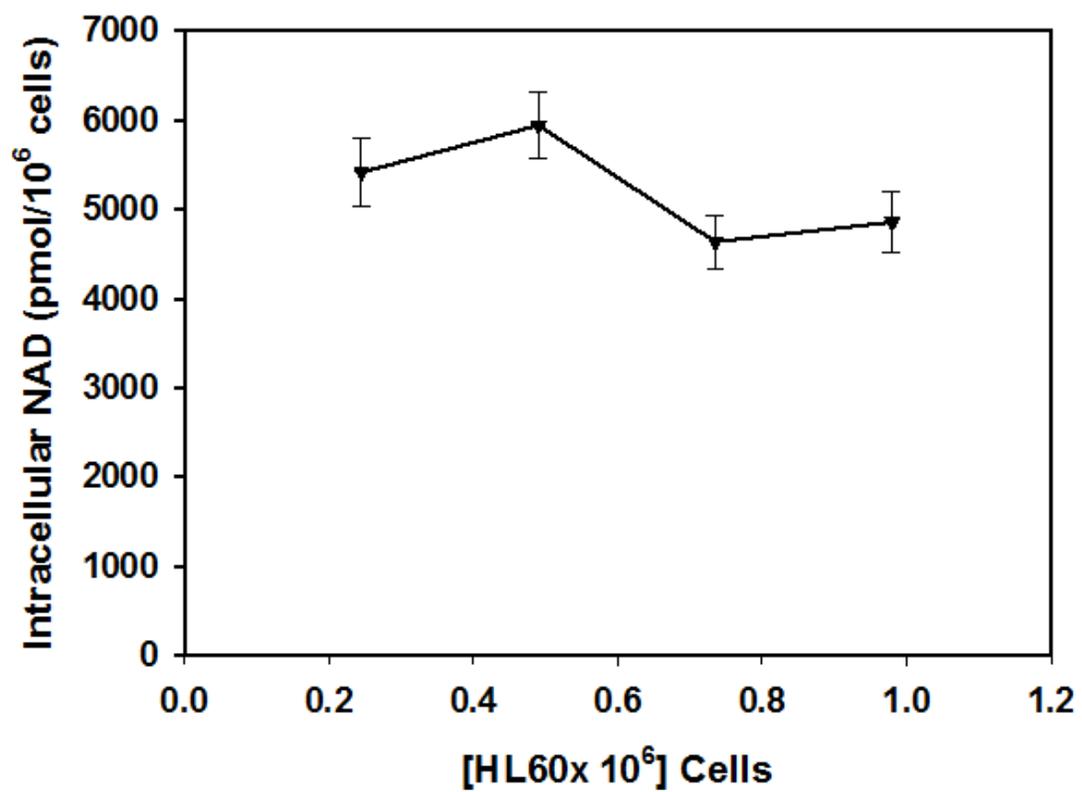


Figure 2. 5 Intracellular NAD levels determined in HL60 cells with cell density ($0.24\text{-}0.98 \times 10^6$ cells ml^{-1}) and incubation time 30 min. Data are means \pm SEM, $n = 3$ (7 measurements).

CHAPTER 3

THE EFFECT OF CD38 EXPRESSION ON NAD LEVELS IN HUMAN LEUKEMIA CELLS

3.1 Introduction

CD38 has a dual behaviour, with enzymatic and receptorial functions. As a receptor, CD38 controls signalling pathways involved in the activation, growth and survival of lymphoid and myeloid cells (Mallone *et al.*, 2001). The role of CD38 as a negative prognostic marker in CLL has also been widely confirmed (Matrai, 2005). The CLL published data, in which the levels of CD38 expression correlated inversely with patient outcome have generated much attention. In CLL, CD38 measurements have become more straightforward than those of IgVH mutation and other negative prognostic markers (Damle *et al.*, 1999). While much accumulated data has shown a distinct role of the CD38 receptor functions in the poor prognosis in CLL patients, to this author's knowledge nothing is known about the role of CD38 enzymatic functions in leukemia. To address this issue, HL60 cells, which express CD38 when treated with ATRA, were used as an available model for human leukaemia. Another leukemia cell line was also used in this study; RAJI cells (Burkitt lymphoma) also express the CD38 molecule (Trubiani *et al.*, 2008). Our hypothesis was based on the previous findings of Barbosa *et al.* (2007), who reported that in CD38 knockout (KO) mice, intracellular NAD levels are increased. Furthermore, another study in macrophages has shown that when CD38 is genetically deleted, an increase in intracellular NAD levels occurs (Iqbal and Zaidi, 2006). This might reflect the major role that CD38 has as an endogenous and extracellular regulator of NAD levels. Therefore, the hypothesis of this study was that NAD levels might be depleted in the case of CD38 upregulation. It was also expected that low levels of NAD, an important coenzyme for the network of enzymes involved in vital metabolic pathways in the cell, might have physiological consequences, such as in the case of leukemia patients where the CD38⁺ subset of patients show poor prognosis and short survival.

It is worth mentioning that CD38 receptor functions in CLL have been well documented over many years by different groups (Deaglio *et al.*, 2008; Malavasi *et al.*, 2008). However, the purpose of the current study was to draw attention to the cellular enzymatic function of CD38 in the poor prognosis in leukemia. To do this, a number of approaches were used: HL60 cells were differentiated to neutrophil-like cells using ATRA, and CD38 protein levels, cyclase activity and CD38 mRNA levels were all investigated by different methods; the intracellular NAD levels were evaluated during the differentiation process by using a modified NAD cycling method; the levels of other enzymes that catalyse NAD-consuming reactions such as CD157, PARP, and sirtuins, in addition to the expression of NAD biosynthesis enzymes were all determined during the differentiation. The current study shows for the first time that when CD38 expression is induced by ATRA, intracellular NAD decreases significantly and that this high degree of NAD degradation correlates with CD38 expression.

3.2 Material and methods

3.2.1 Materials

RPMI-1640 medium, fetal calf serum (FCS), L-glutamine, penicillin, streptomycin, trypsin and trypan blue were all purchased from Lonza Ltd. (Slough, UK). NAD was from Melford (Ipswich, UK). NGD, kuromanin, ATRA, M-MLV reverse transcriptase, dNTPs, random nonamers, SYBR® Green and other PCR and western blotting reagents were all purchased from Sigma-Aldrich Ltd. (Poole, UK). FACS antibodies; phycoerythrin (PE)-conjugated anti-CD38 antibody and mouse IgG1 K isotype control (PE) were all from eBioscience Ltd. (Hatfield, UK). The MCF-7 cell line was a kind gift from Niketa Ferguson (University of Plymouth, UK).

3.2.2 Culture of the MCF-7 cell line

The adherent breast cancer cell line, MCF-7, was cultured in RPMI-1640 medium supplemented with 10% fetal bovine serum, 100 U/ml penicillin, 100 µg/ml streptomycin, and 2 mM L-glutamine. The confluent cells were passaged by treating them with 0.05% trypsin-EDTA (Life Technology, UK). The cells were maintained in culture at 37 °C and under a 5% CO₂ atmosphere with cell viability greater than 95% as assessed by trypan blue exclusion.

3.2.3 Measurement of the cyclase activity of CD38

CD38 cyclase activity was assayed by monitoring the conversion of nicotinamide guanine dinucleotide (NGD) to cyclic GDP-ribose (cGDPR), essentially as described previously (Graeff *et al.*, 1994; Genazzani *et al.*, in: Putney, 2005). This method was applied to measure the cyclase activity for $1.3 - 2.0 \times 10^6$ cells ml⁻¹ from both whole and lysed cells, and in nuclear extracts (see Sections 2.8.1 and 2.8.2). The enzyme assay was started by adding $1.3 - 2.0 \times 10^6$ cells to a

reaction mixture containing 100 μM NGD and phosphate buffered saline (PBS), pH 7.4, to final volume of 0.75 ml in a UV-cuvette. The production of fluorescent cGDPR was monitored for 5-10 min fluorimetrically with an excitation wavelength of 300 nm and an emission wavelength of 410 nm, using an LS50B luminescence spectrophotometer (Perkin Elmer, UK). The initial rate was expressed as the change in fluorescence intensity per second ($\Delta\text{F/s}$).

3.2.4 Detection of surface and intracellular CD38 during HL60 differentiation by fluorescence-activated cell sorter (FACS)

3.2.4.1 Flow cytometry for extracellular staining

Following treatment of HL60 cells (Section 2.3) with ATRA (1 μM), 1.5×10^6 cell ml^{-1} were washed twice with PBS. After this, pellets were resuspended in 100 μl of FACS staining buffer (PBS containing 1% w/v bovine serum albumin) and then incubated for 30 min at 4 $^{\circ}\text{C}$ followed by washing three times by centrifugation at $200 \times g$ for 5 min. The pellets (1.5×10^6 cells) were resuspended in 100 μl FACS staining buffer, and 15 μl aliquots of cell suspension were incubated with either conjugated monoclonal anti-CD38 antibody (HIT2-PE, 0.25 $\mu\text{g}/100$ μl ; 1:20 dilution), or isotype control-PE (0.25 $\mu\text{g}/100$ μl ; 1:20) for 30 min at 4 $^{\circ}\text{C}$ in the dark. After incubation, cells were washed twice with 500 μl of FACS buffer and resuspended in 500 μl PBS. Samples were incubated on ice after mixing and kept in the dark to avoid photo bleaching until they were analysed. The samples were sorted on a BD FACSAriaTMII flow cytometer (Becton-Dickinson, USA), and data from 10,000 events were collected and analyzed by the BD FACSDiva version 6.1.3 software.

In each experiment, CD38 antibody conjugated to a fluorochrome (PE) was used to distinguish CD38 positive cells (cells that bind antibody) from CD38 negative cells (cells that did not bind

antibody) or from the isotype control (negative control). CD38 positive cells give much greater fluorescence intensity than CD38 negative or unstained and control cells.

Before analysis, cells were gated and the cell debris was discounted using the forward scatter (FSC) and side scatter (SSC) profiles (Fig. 3.1). Data were analyzed using WinMDI 2.8 software (Joe Trotter, Pharmingen, CA). Mean fluorescence index (mfi) was calculated as: $mfi = \frac{\text{fluorescence (test)} - \text{fluorescence (isotype control)}}{\text{fluorescence (isotype control)}}$.

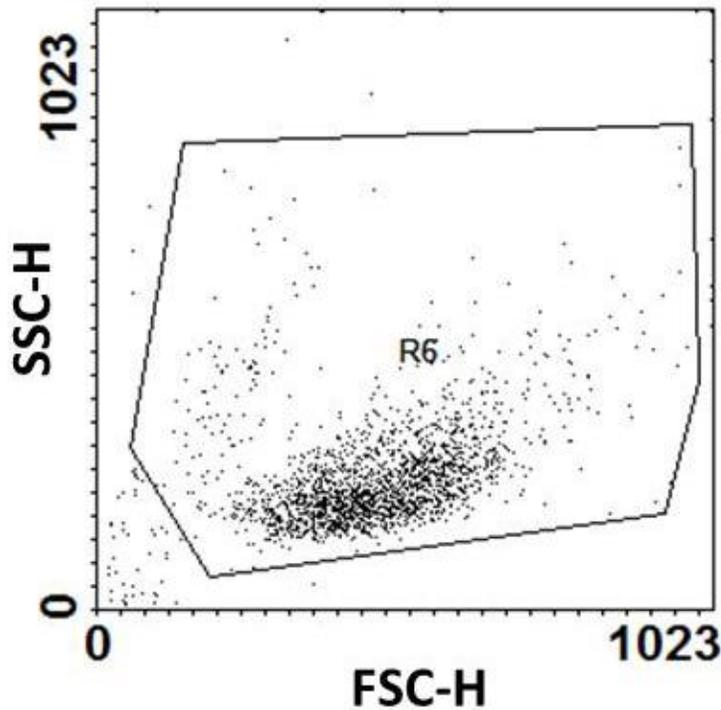


Figure 3.1 cells were gated and cell debris was gated out based on forward scatter (FSC) and side scatter (SSC) profiles as shown in the SSC-FSC dot plot, to analyse data by using WinMDI 2.8 software and to calculate mean fluorescence index.

3.2.4.2 Flow cytometry for intracellular staining

Intracellular staining was performed according to the protocol described by Jacob *et al.* (1991). Cells were harvested, washed twice with PBS at $200 \times g$ for 5 min, and resuspended at approximately 1.5×10^6 cells ml^{-1} of PBS. Cell viability was assessed using trypan blue, and was not less than 99%. Cells were fixed with a $1 \times$ fixation buffer containing 4% paraformaldehyde (eBiosciences, UK) for 20 minutes on ice. For permeabilization, cells were washed twice with SAP buffer (PBS containing 2% v/v fetal calf serum and 0.3% w/v saponin). The cells were then stained for 30 min at 4 °C with the anti-human CD38 PE (0.25 $\mu\text{g}/100 \mu\text{l}$, clone-HIT2) in SAP buffer or with 0.5 $\mu\text{g}/100 \mu\text{l}$ of mouse IgG1 K isotype control PE. After two washes in PBS containing 1% BSA and 0.1% saponin, cells were resuspended in 500 μl PBS and analyzed on a BD FACSAriaTMII flow cytometry (Becton-Dickinson, USA). For each case studied, 10,000 events were processed, and data were analyzed using BD FACSDiva version 6.1.3 software. For negative controls, the primary antibody was omitted.

3.2.5 Co-culture of differentiating cells with MCF-7 cells and measurement of cell proliferation by MTT assay

The cell lines (HL60, RAJI, MCF-7 and differentiating cells) were maintained in culture at 37 °C under a 5% CO₂ atmosphere at cell viability greater than 95%. For the co-culture experiments, the adherent MCF-7 cells (2×10^5 cells/ well) were grown in six-well plates and incubated for 24 h. On the day of the experiment, 1 ml of 3×10^6 HL60 cells (3 days differentiated) were added to plates containing the adherent cells, and cultured for a further 24 h in the same medium and incubated at 37 °C. The supernatant containing the suspended, differentiated cells was collected

and washed with PBS. Cell proliferation was measured using the MTT cell proliferation assay as previously described (Section 2.6).

3.2.6 Determination of intracellular NAD levels in cells treated with CD38, PARP and Sirtuin inhibitors

HL60 cells ($2.5 \times 10^5 \text{ ml}^{-1}$) were seeded in a 25 cm² culture flasks and incubated with 1 μM ATRA for 3 days in the presence or absence of a PARP inhibitor (4-amino-1,8-naphthalimide, 1-30 μM) or a sirtuin inhibitor (sirtinol). The cells were then harvested and collected by centrifugation, washed and counted. The intracellular NAD was extracted and the level determined by the enzymatic cycling assay as previously described (Section 2.9.2.1).

The intracellular NAD levels was determined in HL60, RAJI or differentiating HL60 cells ($2.5 \times 10^5 \text{ cells ml}^{-1}$) treated with 1-30 μM kuromanin, an inhibitor of CD38 cyclase activity, at times up to 6 h. In addition to measuring NAD levels, both cell proliferation (MTT assay) and nitroblue tetrazolium reduction (NBT assay) were also determined in all cell lines after being treated with kuromanin at various concentrations and for different incubation times.

3.2.7 Statistical analysis

Statistical analysis of the data was assessed using Fisher's one way analysis of variance (Statview 5.0.1; Abacus concepts, USA) or Student's t-test as appropriate. Data are expressed as means \pm SEM for three separate experiments in triplicate, unless otherwise stated. A difference of $P < 0.05$ was considered statistically significant.

3.3 Results

3.3.1 ATRA-induced HL60 mature granulocyte cell differentiation and inhibited cell proliferation

HL60 cells can terminally differentiate to granulocytic (neutrophil-like) cells after incubation with 1 μ M ATRA for 5 days. To confirm this characteristic, the NBT assay was used to evaluate cell differentiation. NBT, a water-soluble dye, is widely used to detect the production of superoxide anions within phagocytic cells, and in the process it is reduced to an insoluble intracellular blue-black formazan. The measurement of superoxide anions is considered to be an accurate method for estimating the ability to generate a respiratory burst (Baehner *et al.*, 1976).

The results showed a significant increase (1-way ANOVA, $p < 0.01$) in the NBT reduction capacity (Fig. 3.2) in HL60 cells treated with ATRA for 5 days (0.51 ± 0.15), compared with treated cells at time zero (0.23 ± 0.068) and undifferentiated HL60 cells (0.14 ± 0.04), indicating mature granulocyte differentiation. These results are consistent with the previous reports that indicated that approximately 70-80% of HL60 cells matured towards granulocyte like cells after day 4 of differentiation (Imaizumi *et al.*, 1987).

Further evidence for cell differentiation induced by ATRA is provided by the morphological change of HL60 cell to neutrophil-like cells as determined by Wright-Giemsa-stained cytospin slide preparations. HL60 cells were successfully differentiated to neutrophil-like cells (Fig. 3.3). HL60 cells cultured without ATRA are predominantly promyelocytes with characteristic cytoplasmic granules, large nuclei. However, after 5 days of incubation with 1 μ M ATRA, a high percentage of HL60 cells resembled mature granulocytes (mainly segmented neutrophils). Thus,

the results (Fig. 3.3) confirm that ATRA induces relatively extensive morphological differentiation of HL60 cells.

The proliferation capacity of HL60 cells after incubation with 1 μ M ATRA was determined using the MTT assay. As illustrated in Figure 3.4, ATRA inhibited HL60 cell proliferation; reduction of cell vitality, compared with the untreated control ($100 \pm 0.2\%$), was evident after 24 h ($87.8 \pm 11.1\%$) and was significant on the 3rd ($75.2 \pm 2.0\%$) and 5th ($74.9 \pm 2.0\%$) days of differentiation. These results indicate that ATRA induces HL60 differentiation, but inhibits the proliferation process.

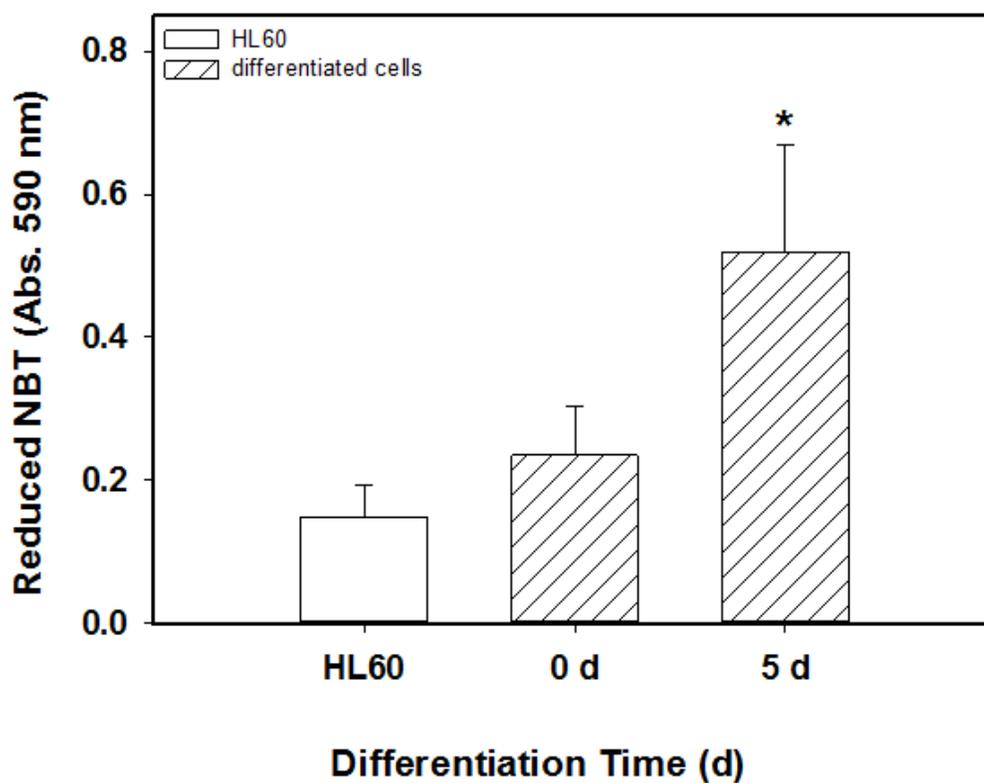


Figure 3.2 The NBT reduction ability of ATRA treated HL60 cells for 5 days comparing to untreated HL60 cells (as control). Data are means \pm SEM, $n = 3$ (3-5 measurements per replicate). * denotes significant difference from the control, $P < 0.05$.

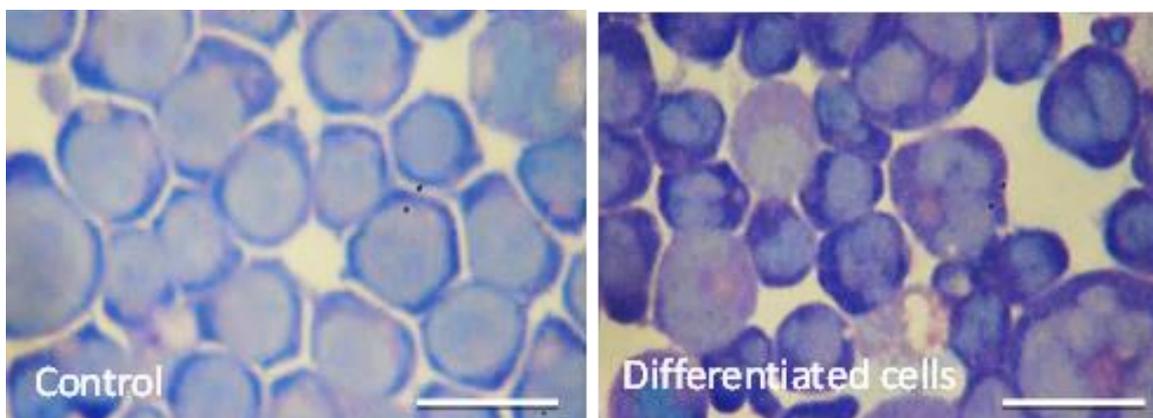


Figure 3.3 Morphology of undifferentiated (control) and differentiated HL60 cells. Differentiation was induced using ATRA for 5 days. Cytospin slide preparations of cell culture suspensions were stained with Wright-Giemsa stain and examined using light microscopy ($\times 1000$ magnification). Scale bar: 30 μm .

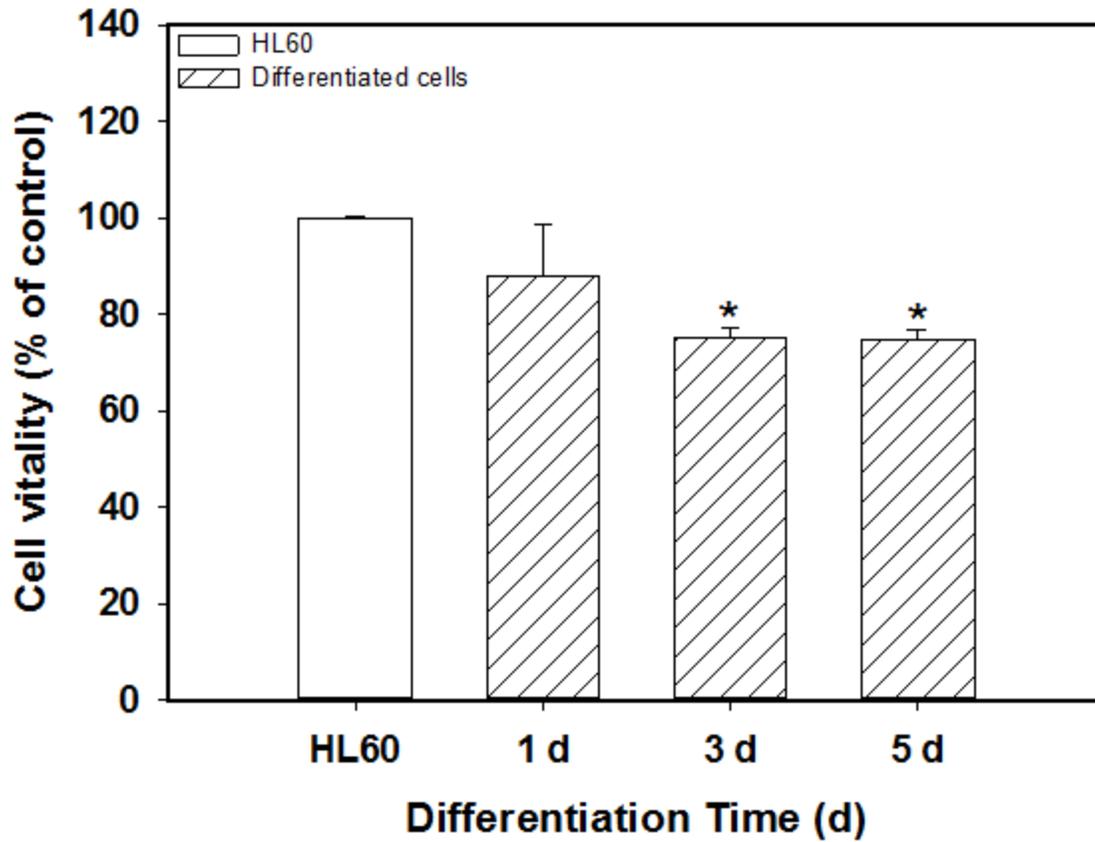


Figure 3.4 Effect of ATRA-induced HL60 differentiation over 5 days on cell vitality (MTT assay) as compared to the untreated control (HL60). Data are means \pm SEM, n = 3 (3 measurements per replicate). * denotes significant difference from the control (HL60), $P < 0.05$.

3.3.2 ATRA-induced HL60 differentiation is accompanied by CD38 induction

Treatment of HL60 cells with ATRA was accompanied with upregulation of CD38 expression (Munshi *et al.*, 2002). However, the full mechanisms of CD38 regulation, and the initial induction time for its mRNA expression, cyclase activity and protein levels were not fully investigated during ATRA-induced HL60 differentiation. Therefore, in this Chapter, a time course of CD38 expression during HL60 differentiation was obtained. Also, a comparison of surface and intracellular CD38 protein levels and cyclase activity has been determined, which is first reported in this Chapter.

3.3.2.1 Measurement of CD38 mRNA expression by qPCR

The level of CD38 mRNA expression during cell differentiation was measured using real time PCR coupled with reverse transcription. qPCR analysis demonstrated that CD38 mRNA is expressed early, from 3 h of differentiation, and reached a maximum at 24 h in a time-dependent manner (Figure 3.5); thereafter it remained at a constant level. This finding suggests that ATRA induced transcriptional regulation of the CD38 mRNA, and also supports a previous finding of Uruno and colleagues (2011) that showed an early-phase increase of CD38 mRNA expression at 1.5-6 h after incubation of HL60 cells with ATRA. Furthermore, it was of particular interest to test whether the second member of the NADase/ADP-ribosyl cyclase gene family (Ferrero and Malavasi, 1997), CD157, would also show changes in gene expression during the differentiation. Therefore, CD157 mRNA expression in HL60 after treatment with ATRA was analyzed for up to 120 h. It was found that CD157 showed only a slight but significant increase after 3 and 5 days of differentiation (Fig. 3.5). Hence, CD157 does not appear to be upregulated during HL60

differentiation. These results suggest the possibility of CD38 being the major NAD-consuming enzyme that is expressed during HL60 differentiation, rather than its homologue, CD157.

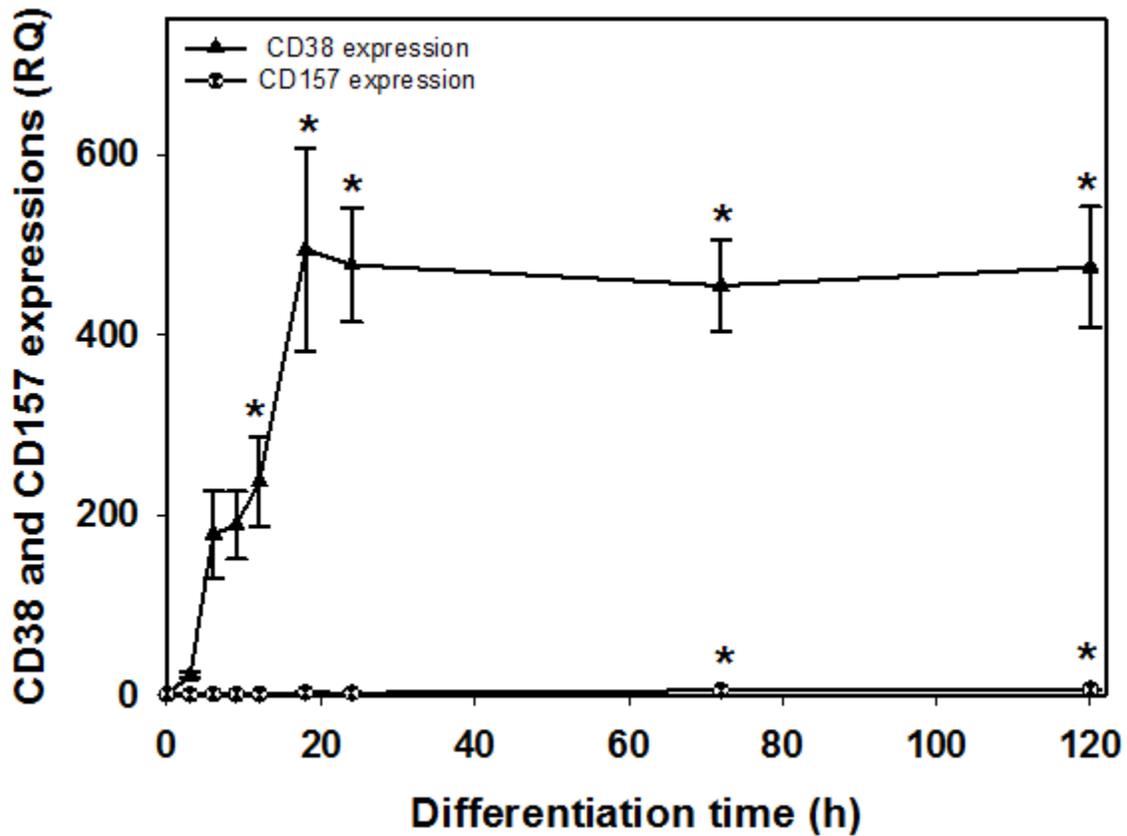


Figure 3.5 Time-course analysis of CD38 mRNA induction in HL60 cells treated with ATRA over 5 days differentiation showing the increase in CD38 expression, but not in CD157 expression comparing to untreated control (HL60). Data are means \pm SEM, $n = 3$ (4-7 measurements per replicate). * denotes a significant difference from the control (HL60), $P < 0.05$.

3.3.2.2 Surface and whole cell lysate CD38 cyclase activity during HL60 differentiation

In light of previous evidence which showed that CD38 mRNA was upregulated during differentiation of HL60 cells, the relationship between gene expression and the active form of the protein was investigated. Therefore, in this study, the intracellular and extracellular cyclase activities of CD38 were explored. CD38 cyclase activity was measured for whole cell lysate (representing intracellular and extracellular cyclase activity), and viable differentiated cells (representing extracellular cyclase activity) as shown in Figure 3.6. There was a significant increase in the CD38 cyclase activity during the first 24 h of differentiation. CD38 activity reached its maximum level in both cases at 6 h during the differentiation, with lower activity seen at 8 - 12 h. However, at 24 h, a twofold increase activity was seen in both the cell lysate ($200.0 \pm 8.2\%$) and live cells ($260.0 \pm 29.7\%$) compared to the untreated control. It is noteworthy that CD38 cyclase activity in cell lysate was found to be (unexpectedly) lower than that of viable cells. One explanation is that using a lysis buffer might result in lowered enzymatic activity in comparison to that for viable cells. In addition, if it is possible that extracellular nucleotides (in this case NGD) are able to enter cells as previously reported by Billington *et al.* (2008a), then the NGD cyclization activity in viable cells might represent whole CD38 cyclase activity.

As confirmed above, CD38 is active during the early stages of differentiation. Therefore, the extracellular CD38 cyclase activity was further measured on the 1st, 3rd and 5th days both in HL60 cells and in differentiated HL60 cells. A significant increase in cyclase activity was shown (Fig. 3.7) on the third day of differentiation. Thereafter, the activity increased gradually up to day 5, as compared to the appropriate control. Altogether, the data presented in this section

confirm a continuing increase in CD38 activity during the *in vitro* differentiation process. This increase is initiated within 4 hours and progresses over the 5 days of differentiation.

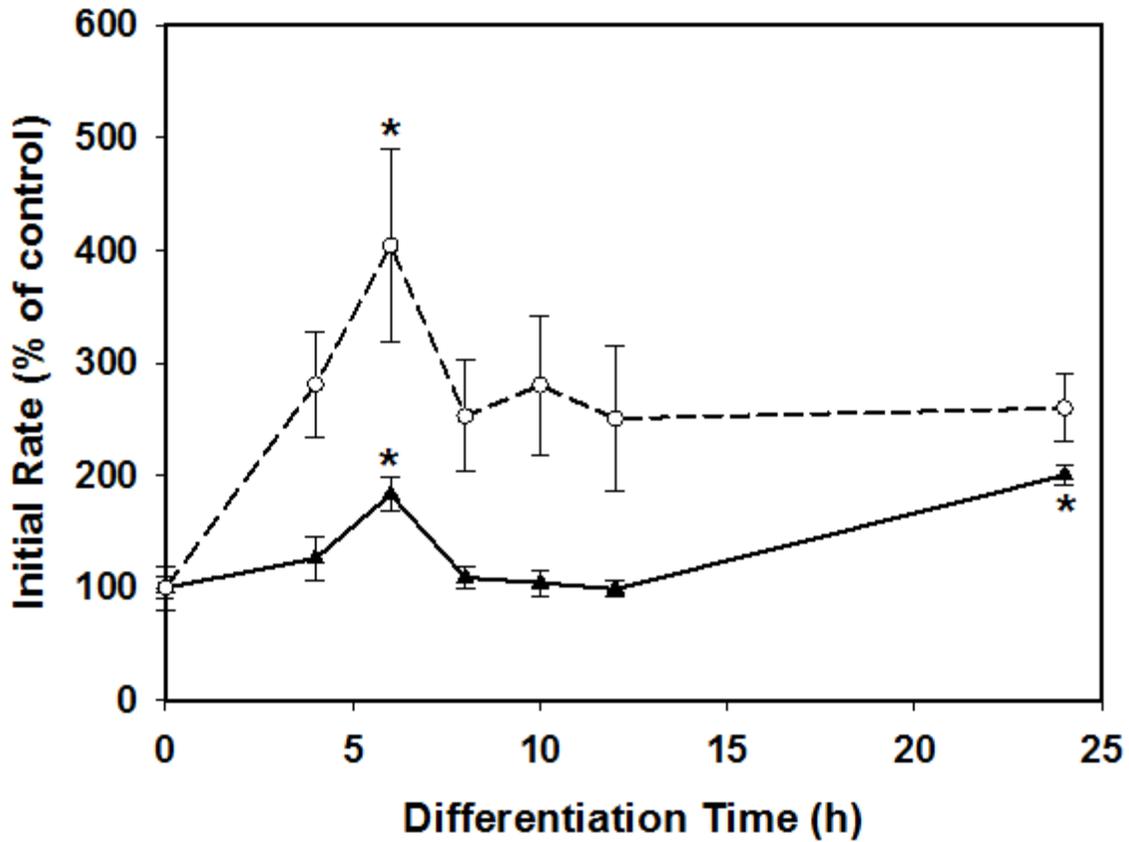


Figure 3.6 Time courses of measuring of CD38 cyclase activity in whole cell lysate (solid line) and in live cells (dashed line) in HL60 cells during differentiation using ATRA over 24 hours comparing to untreated control (100%). Data are means \pm SEM, $n = 3$ (1 measurement per replicate). * denotes significant difference from the untreated control (HL60), $P < 0.05$.

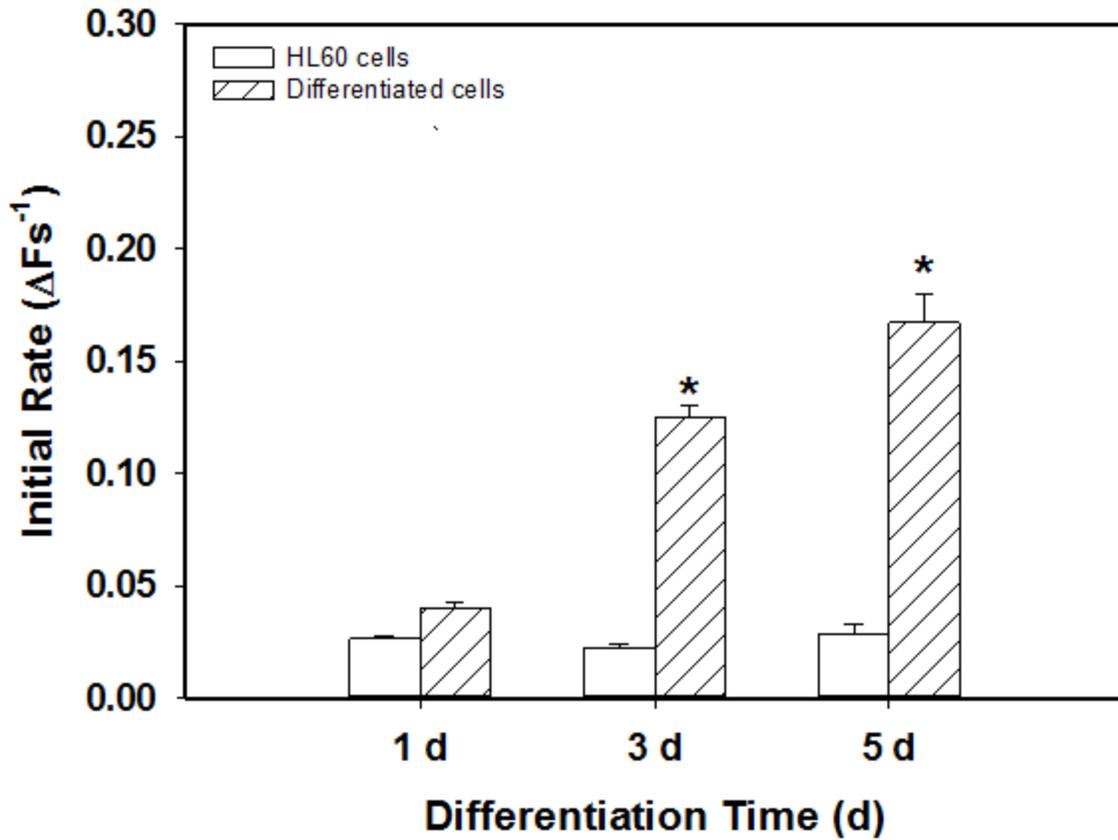


Figure 3.7 Time course of CD38 cyclase activity in HL60 cells treated with ATRA over 5 days comparing to each untreated control (HL60). Data are means \pm SEM, n = 3 (3 measurements per replicate). * denotes significant difference from the appropriate control (P < 0.05).

3.3.2.3 Analysis of intracellular and extracellular CD38 by FACS

As stated above, a comparatively rapid increase in CD38 expression occurs in response to ATRA in HL60 cells. This can be conveniently measured by using flowcytometry, in addition to the previously measured ADP-ribosyl cyclase activity of CD38, using the NGD technique, or its mRNA expression using qPCR. Thus, CD38 expression was analyzed before and after permeabilization using saponin, to distinguish between surface and internal CD38 expression. Saponin is a detergent which complexes with membrane cholesterol and thereby disrupts the lipid structure (Schroeder *et al.*, 1998).

In the current work, extracellular staining with a CD38-antibody in HL60 cells was determined after treatment with 1 μ M ATRA for 10 h, 18 h, 1 day, 3 days and 5 days as shown in Figure 3.8 A; 3.10 with significant differences in the CD38 positive cells being observed compared to the control. These results confirm that CD38 was significantly expressed at 10 h of differentiation, and up to 5 days. Parallel cultures of HL60 cells without the ATRA treatment and RAJI cells served as negative and positive controls, respectively (Figure 3.9).

Cell permeabilization with saponin, was also applied before staining with CD38 antibody in order to allow internal access which facilitates intracellular CD38 investigation in addition to measuring its surface localization. Unexpectedly, our findings (Fig. 3.8B) did not show an increase in the MFI from CD38 positive cells staining with a CD38-antibody compared to the extracellular staining. However, the results (Figure, 3.10) show more internal (total) CD38 expression at 10, 18, and 24 h differentiation compared to the undifferentiated HL60 cells.

The results suggest that, both in CD38 positive cells (RAJI) and during the differentiation, it seems likely that CD38 antibody was probably able to detect surface CD38 epitope better than the internal CD38 even under permeabilization circumstances. It might also suggest that CD38 is mostly expressed on the cell surface with less expressed intracellularly.

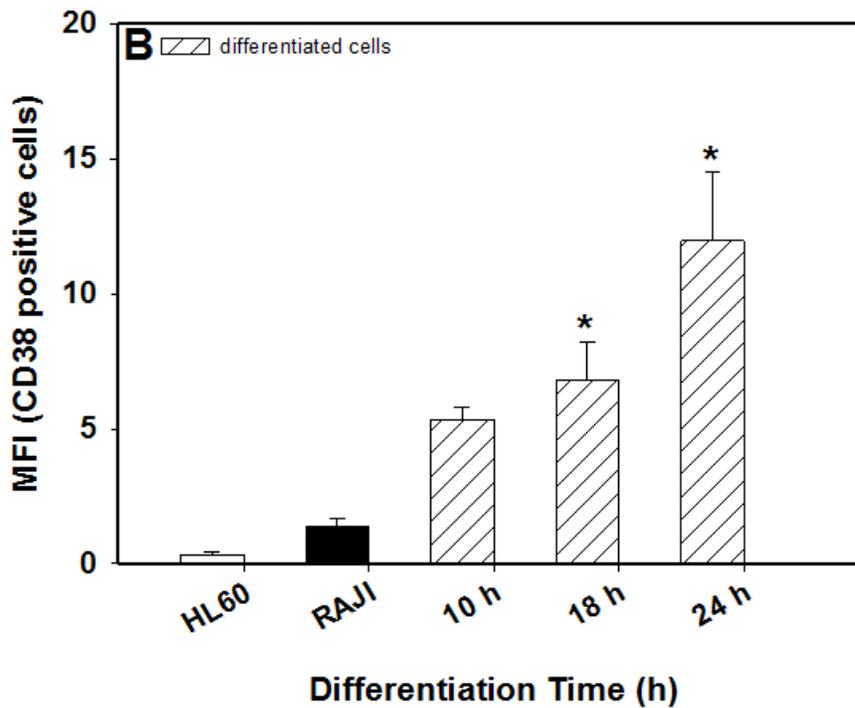
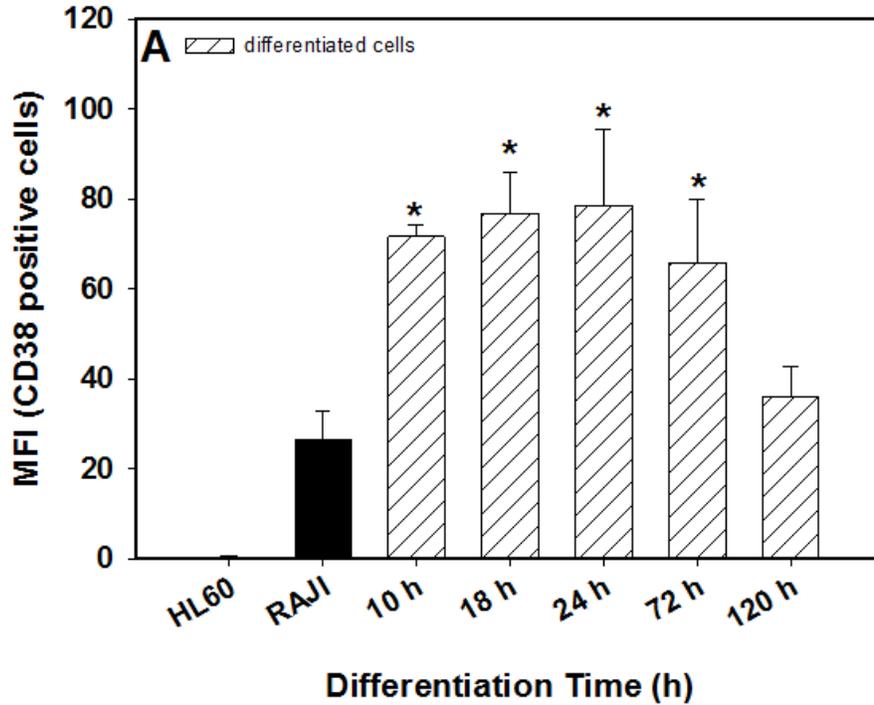


Figure 3.8 Expression of CD38 in HL60 cells treated with ATRA, analyzed by FACS after staining with CD38 antibody (HIT2-PE) and expressed as mean fluorescence index comparing to untreated HL60 cells (as control). (A) Extracellular CD38 expression from 10-120 hours of differentiation and (B) Total CD38 expression at 10, 18, and 24 h of differentiation. Data are means \pm SEM, $n = 3$ (1 measurement per replicate). * denotes significant difference from the control ($P < 0.05$).

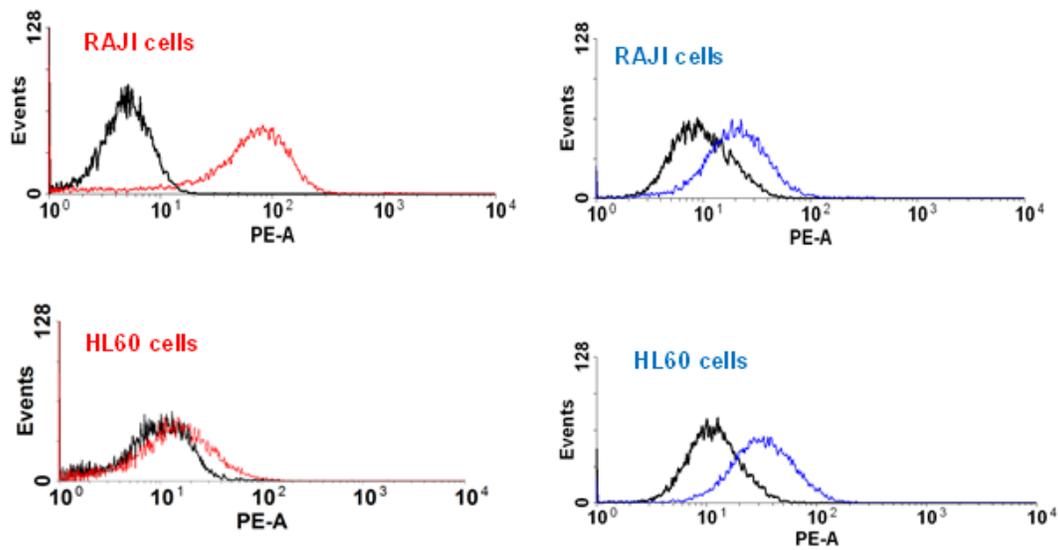


Figure 3.9 Expression of extracellular CD38 (red histograms) versus intracellular CD38 (blue histograms) in RAJI cells (positive control), and undifferentiated HL60 cells (negative control), in comparison with the Isotype control (IgG)-stained cells shown in the black histograms. Cells were stained with PE-labeled anti-CD38 mAb and analyzed by FACS. Data are representative of three independent experiments.

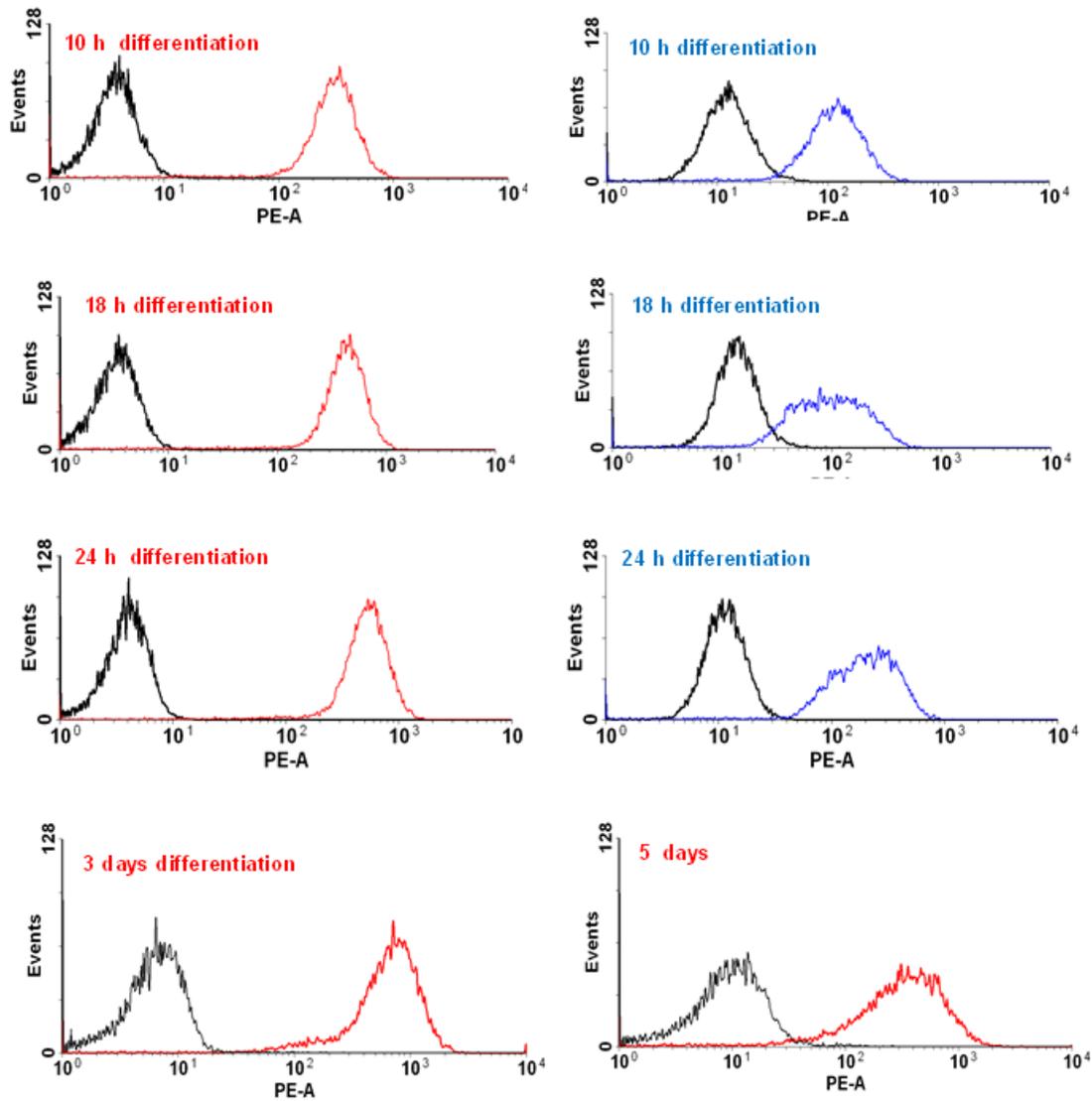


Figure 3.10 Expression of extracellular CD38 (red Histogram) versus intracellular CD38 (blue Histogram) in the time course of ATRA-induced HL60 differentiation, in comparison with the Isotype control (IgG) stained cells shown in the black histograms. Cells were stained with PE-labelled anti-CD38 mAb and analyzed by FACS. Data are representative of three independent experiments.

3.3.2.4 CD38 Western blots for whole cell lysate and nuclear extract

In this part of the work CD38 expression was investigated both in cell lysates from undifferentiated (control) and differentiating HL60 cells by Western blotting, in order to determine the time course of CD38 accumulation after ATRA treatment. An additional aim was to investigate the molecular forms of CD38 that are present in differentiating cells or the control on the plasma membrane and the subcellular location. Thus, Western blotting was used for all cell lysates under reducing and denaturing conditions by using a mouse monoclonal CD38 antibody. The results (Figure 3.11 A, B) showed that both HL60 cell lysate and differentiating HL60 cell lysate at 0-120 h (after ATRA treatment) possess a single 45 kDa monomer of CD38, but with different intensity. In all experiments, the positive control used, RAJI cell lysate always contained a single 45 kDa band form of CD38. A strong 45 kDa band corresponding to CD38 appeared after 10 h of incubation of HL60 cells with ATRA (Figure 3.11 A), with the maximum band intensity clearly shown on day 3 of differentiation. A weak 45 kDa band was observed in control cells as well as at 0, 3 and 6 h of differentiation. In addition, the results (Figure 3.11 A) confirmed that lysate from both differentiating and undifferentiated HL60 cells contain high molecular weight (HMW) forms of CD38 together with 60 kDa and 190 kDa molecular forms. A HMW form, 190 kDa has been observed clearly after 6 h of ATRA incubation with HL60 leukemic cells.

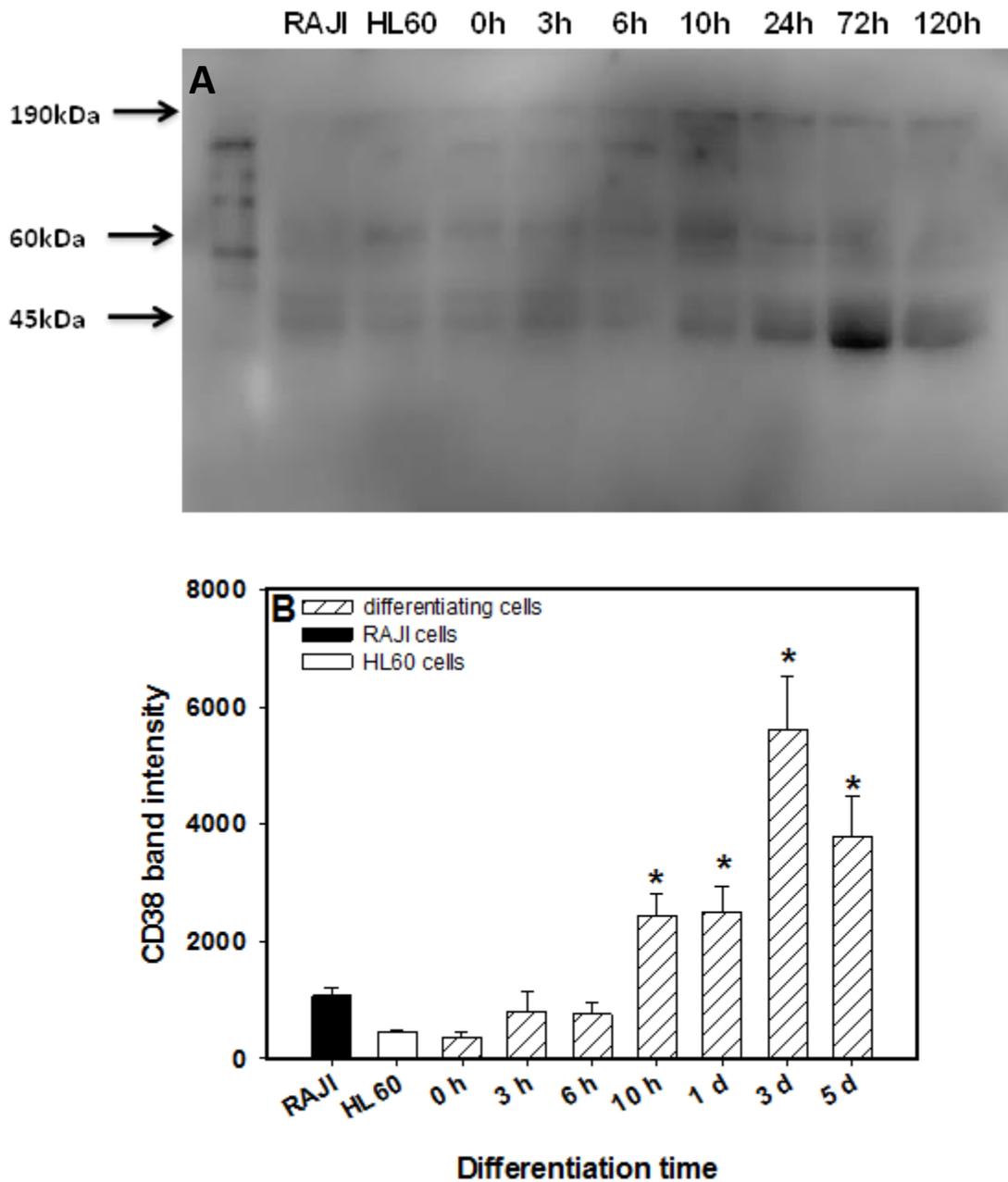


Figure 3.11 Time-course of ATRA treatment of HL60 cells over 5 days showing (A) Western blot of differentiating cells for CD38 showing the 45 kDa band corresponding to membrane CD38 under reducing, denaturing conditions and 12% SDS-PAGE. 100 μ g of protein/ well were used each experiment with 1:500 primary antibody dilution (data represent 1 of the 3 separated experiments) (B) The luminescence intensity of CD38 single band 45 kDa. Data are means \pm SEM, n = 3 (1 measurements per replicate). * denotes significant difference from the untreated control (HL60), $P < 0.05$.

In summary, the Western blotting results support FACS data, since the extracellular CD38 clearly appeared within 10 h of differentiation compared to undifferentiated HL60 cells. Therefore, as CD38 was expressed on the plasma membrane from early in the differentiation process, it seemed important to determine whether CD38 was also expressed intracellularly in the nuclei. Thus, to address this issue, the nuclei of ATRA-treated HL60 cells were extracted and the molecular forms of CD38 were investigated in both HL60 cells and HL60 cell lysate after 0, 10, 24 and 72 h of incubation with ATRA (Figure 3.12A). A weak 45 kDa band appeared at 24 h of differentiation and increased after 3 days of differentiation (Figure 3.12A). The same 45 kDa band, the monomeric form of CD38, was also seen in the RAJI cell nuclear fraction but was absent both in the undifferentiated HL60 cell lysate and in the cell lysate at 0 h and 10 h of differentiation. A high molecular weight (80 kDa) form of CD38 also appeared in nuclear fractions and was clearly visible in both RAJI cell lysate and after one day of HL60 differentiation.

It is important to mention that reducing conditions with mercaptoethanol were used in both the plasma membrane and nuclear fractions. Furthermore, ATRA-induced expression of CD38 on nuclei from HL60 cells was also investigated using the NGD assay (Figure 3.12B) at 10, 24 and 72 h after treatment with ATRA, and also using undifferentiated HL60 cells as a control. The results revealed NGD cyclization by CD38 activity which is clearly observed on the surface of nuclei after treatment with ATRA at 1 and 3 days. These and previous observations indicate that the majority of the CD38 cyclase activity occurred in the plasma membrane fraction and, to a lesser extent, in the nuclei, indicating that CD38 enzymatic activity might have an important role in the nucleus in addition to its extracellular activity.

It is important to note that the nuclei used in this investigation were isolated by a conventional method (Whiteside *et al.*, 1992). The purity of a nuclear preparation can be characterized by either measuring the activity of an endoplasmic reticulum marker; glucose-6-phosphatase or a plasma membrane marker; 5-nucleotidase. (Colowick and Kaplan, in: Fleischer and Packer, 1974). However, this approach was not carried out because contamination of the nuclear extract could be excluded on the basis of the absence of CD38 protein in the extract; in HL60 cells, CD38 is localised in the plasma membrane and not in the nuclear membrane. Importantly, the respective findings of this investigation provide further evidence for ATRA-promoted nuclear and plasma membrane CD38 activation. CD38 was previously detected in nuclear membrane of differentiating cells (Yalcintepe *et al.*, 2005). Further reports have also revealed that CD38 enzymatic activity is present not only in the plasma membrane, but also in intracellular membranes of organelles such as mitochondria and nuclei (Yamada *et al.*, 1997; Liang *et al.*, 1999; Khoo *et al.*, 2000; Iqbal and Zaidi, 2006). Interestingly, in all of the work described in this Chapter, HL60 differentiation was accompanied by a large increase in CD38 expression and cyclase activity (both extracellular and intracellular) from early in the differentiation process. Thus, CD38 expression might not only serve as a marker of HL60 maturation to neutrophil-like cells, but the enzyme might also catalyse the degradation of NAD during ATRA-induced HL60 differentiation. This expression might have important consequences on cell metabolism.

3.3.3 Effect of CD38 expression on NAD levels during HL60 differentiation

High levels of CD38 expression and cyclase activity were observed during ATRA-induced HL60 differentiation. Therefore, it was of importance to investigate the effect of this increased expression on the levels of the substrate of CD38, NAD, during ATRA-induced HL60 differentiation. However, in order to evaluate NAD levels during differentiation, it was important to first examine the effect of ATRA on the NAD assay. Therefore, to address this issue, two concentrations of ATRA (10 nM and 1 μ M) were analyzed along with a range of NAD concentrations (0.975 μ M, 1.95 μ M, 19.5 μ M and 195 μ M).

The results (Fig. 3.13) show that both 10 nM and 1 μ M ATRA had no apparent effects on the NAD assay, even though 10 nM ATRA, at an NAD concentration of 19.5 μ M, was the only concentration that exerted a significant effect on the NAD assay when compared to other NAD concentrations and the control (not treated with ATRA). Importantly, with 1 μ M ATRA, the concentration which was used to induce HL60 differentiation, the results confirmed that there was no interference with the NAD assay.

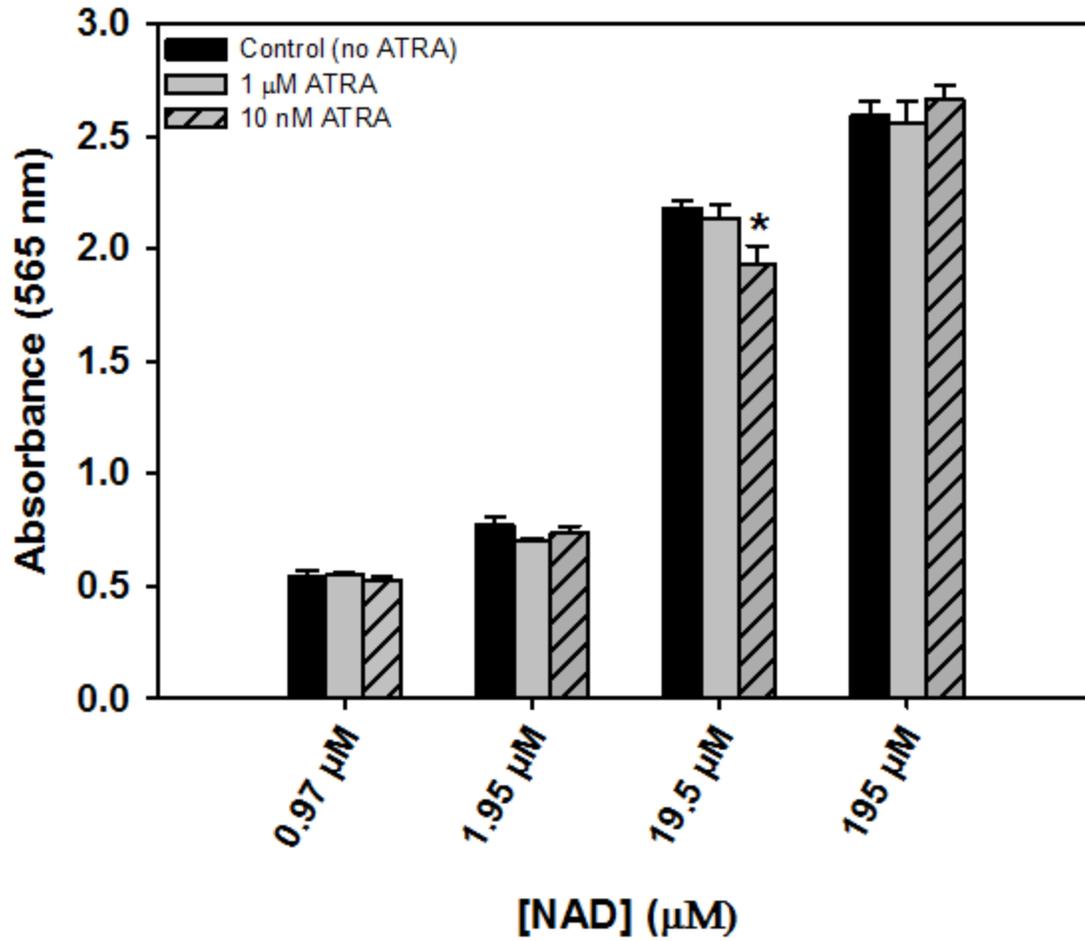


Figure 3.13 The effect of different ATRA concentrations (0, 10 nM and 1 μM) on the NAD assay, at a range of NAD concentrations (0.97, 1.95, 19.5 and 195 μM). Data are means ± SEM, n = 3 (3 measurements per replicate). * denotes significant difference from the appropriate untreated control (P < 0.05).

Thus, NAD levels were determined at 4 - 120 h of differentiation compared to the control (cells not treated with ATRA). Surprisingly, a substantial time-dependent decline in intracellular NAD levels was clearly detected in response to ATRA treatment in HL60 cells (Figure 3.14). There was a significant drop in NAD levels as differentiation occurred to $64.6 \pm 8.9\%$ on day 1, $47.3 \pm 7.0\%$ on day 3 and $40.5 \pm 8.7\%$ on day 5 compared to the control.

A significant decrease in the intracellular NAD levels was seen from early in the differentiation (4 h), and levels continued to drop up to 5 days. This rapid decline in NAD levels was concomitant with the rise of CD38 mRNA expression as seen in Figure 3.15. Interestingly, the latter was seen after 3 h, while NAD degradation started at 4 h differentiation time. These novel data might support a major role for CD38 as a regulator of intracellular NAD.

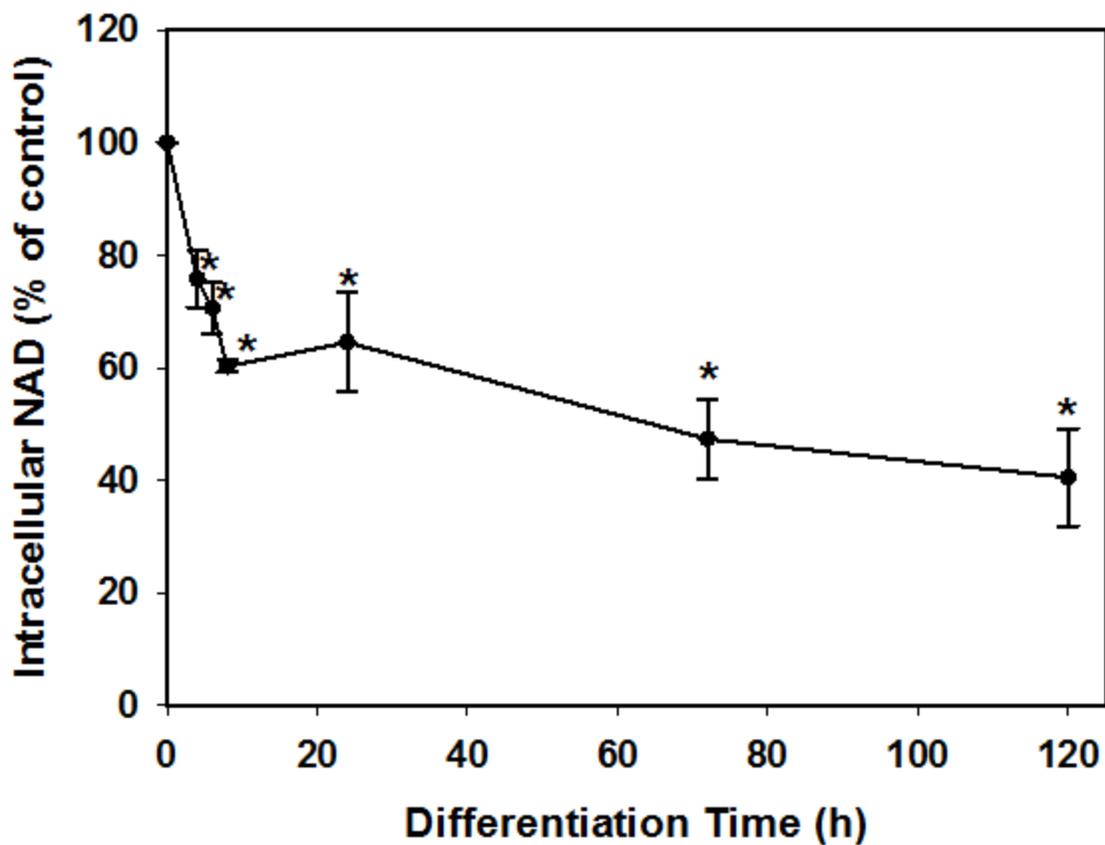


Figure 3.14 The decline in intracellular NAD levels during HL60 differentiation estimated over 5 days of differentiation and compared to untreated control (HL60). Data are means \pm SEM, n = 3 (3 - 7 measurements per replicate). * denotes significant difference from the control (100% HL60), P < 0.05.

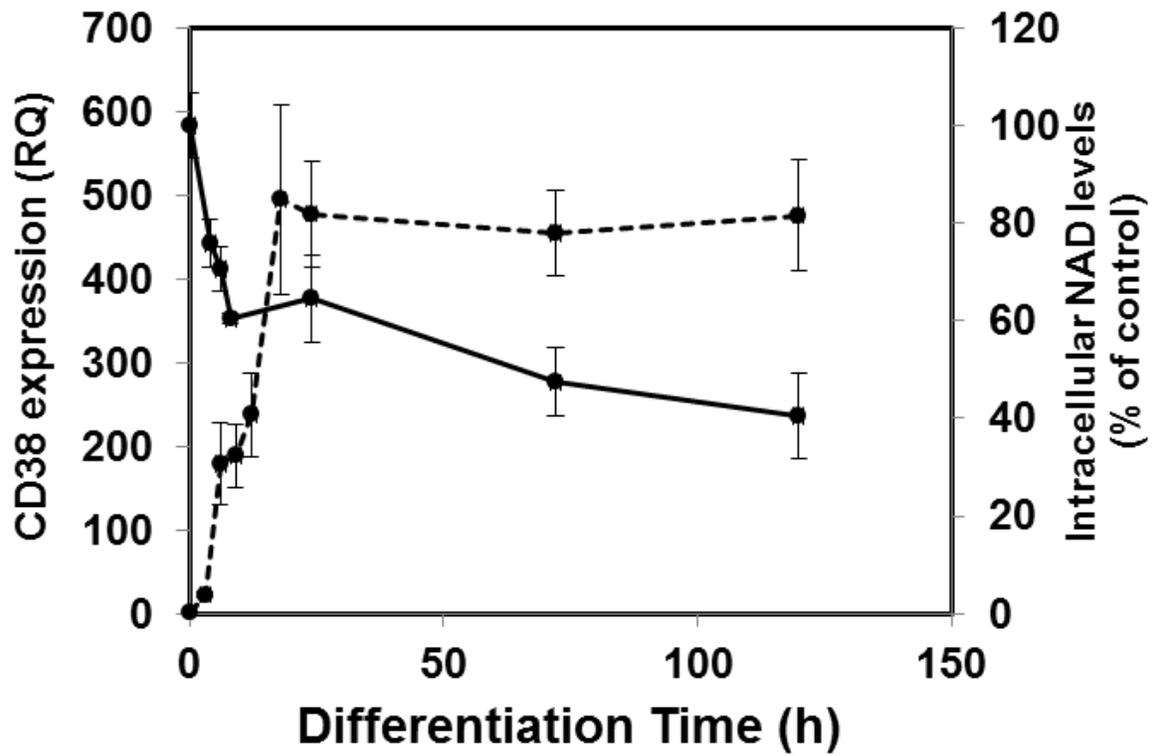


Figure 3.15 The decline in intracellular NAD levels (solid line), concomitant with CD38 mRNA induction (dashed line) during HL60 differentiation estimated over 5 days of differentiation and compared to untreated control (HL60). Data are means \pm SEM, n = 3 (3 - 7 measurements per replicate).

3.3.4 Kuromanin inhibited NAD-cyclization activity of CD38 and elevated NAD levels, but PARP and sirtuin inhibitors had no effect on NAD levels during the differentiation

To establish whether the novel finding of low NAD levels during HL60 differentiation was due to upregulation of CD38 and its enzymatic activity as evaluated in the current study, it was hypothesized that inhibition of CD38 activity might lead to elevation of intracellular NAD. Therefore, a novel inhibitor of the NAD cyclization activity of CD38, kuromanin, was tested. It has recently reported that flavonoids such as kuromanin and luteolin act as inhibitors of human CD38 at low micromolar concentrations (Kellenberger *et al.*, 2011). Thus, the effect of the inhibition of the enzymatic activity of CD38 by kuromanin was investigated in both RAJI cells and the differentiating HL60 cells on intracellular NAD levels (Fig. 3.17). It is worth noting that RAJI cells show high CD38 activity compared to HL60 cells, but they have low intracellular NAD compared to HL60 cells (Fig. 3.16).

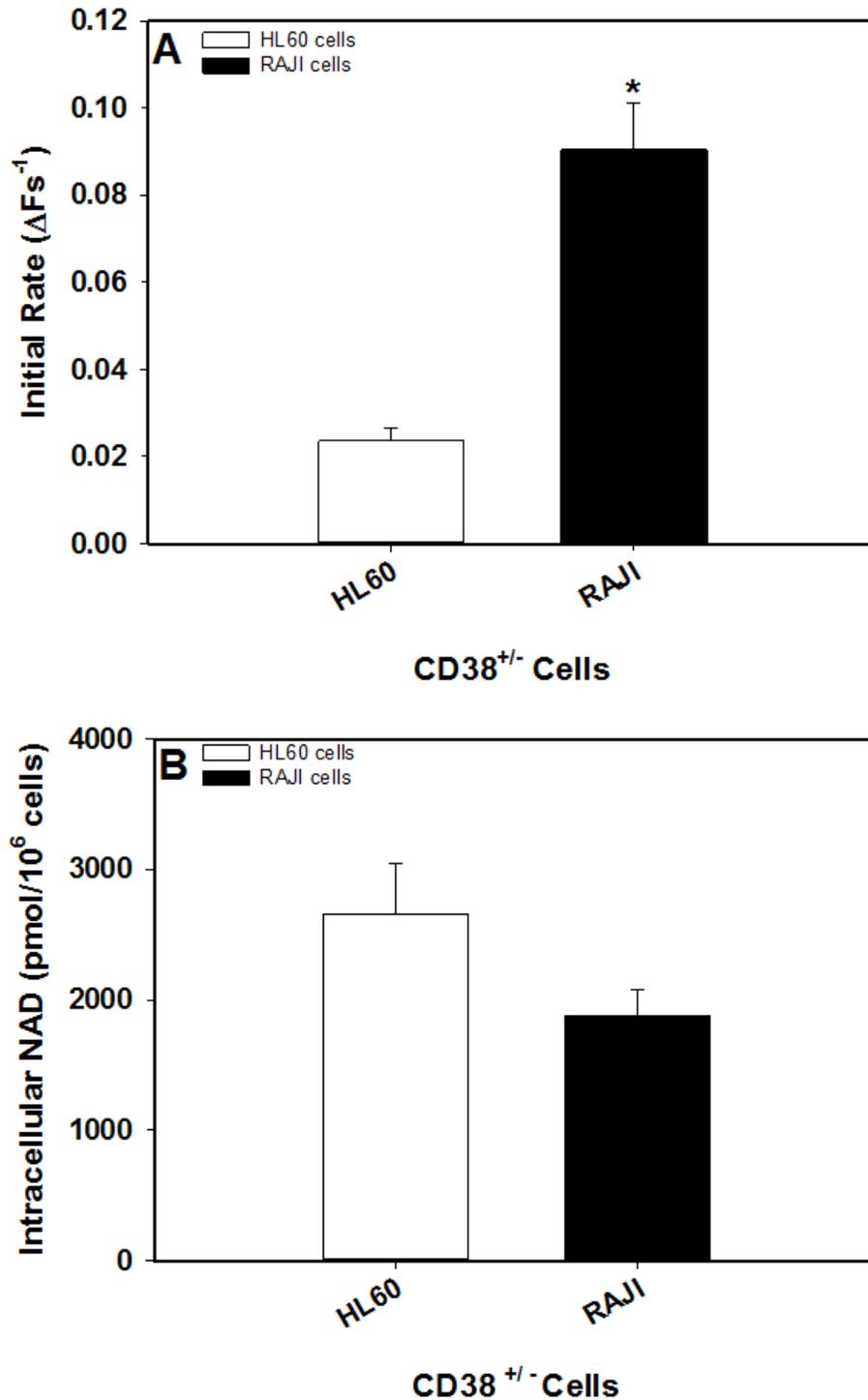


Figure 3.16 (A) CD38 cyclase activity in HL60 and RAJI cells as expressed as initial rate. (B) Intracellular NAD levels in HL60 and RAJI cells as expressed as pmol/10⁶ cells. Data are means \pm SEM, n = 2-3 (3-5 measurements per replicate). * denotes significant difference between group (Student's t test, P < 0.05).

In the current study, the effect of inhibition using 8 μM kuromanin on NAD levels was first investigated in RAJI and HL60 cells up to 2 h of incubation. The results (Fig. 3.17) show that RAJI cells have lower NAD levels than HL60 before kuromanin treatment, but they have higher NAD levels after kuromanin treatment, which might suggest that CD38 activity was inhibited by kuromanin.

Interestingly, Figure 3.18 A shows that inhibition of CD38 cyclase activity in RAJI cells with up to 30 μM kuromanin resulted in significantly elevated intracellular NAD levels after 6 h of treatment. As kuromanin leads to elevated intracellular NAD levels, the MTT assay was used to monitor cell vitality during kuromanin treatment. Cell vitality was not changed after 6 h incubation with kuromanin (Fig. 3.18 B), which might suggest that kuromanin has no effect on growth of RAJI cells after 6 h incubation, but nevertheless it significantly affects cell proliferation after 48 h incubation (Fig. 3.18 B).

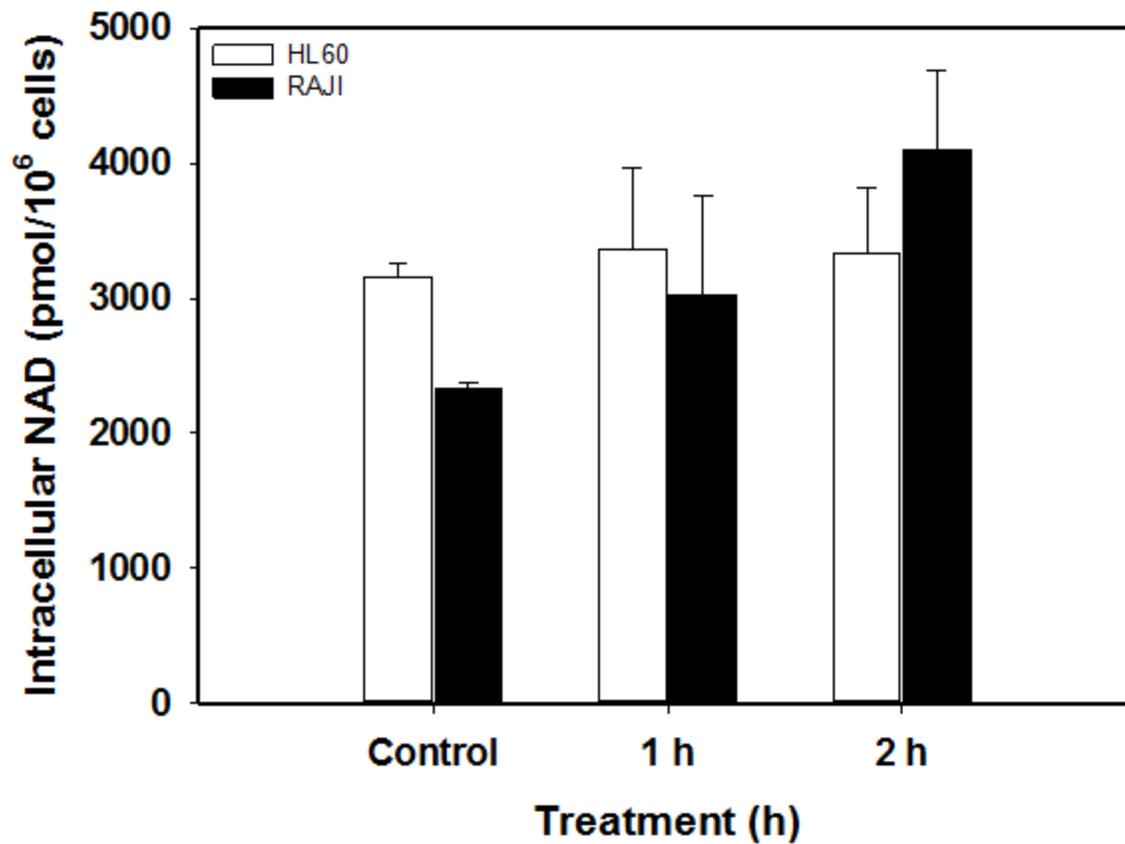


Figure 3.17 Intracellular NAD levels in RAJI and HL60 cells treated with kuromanin (8 μ M) for up to 2 h comparing to appropriate untreated control (RAJI or HL60 cells). Data are means \pm SEM, n = 3 (4-5 measurements per replicate), P > 0.05.

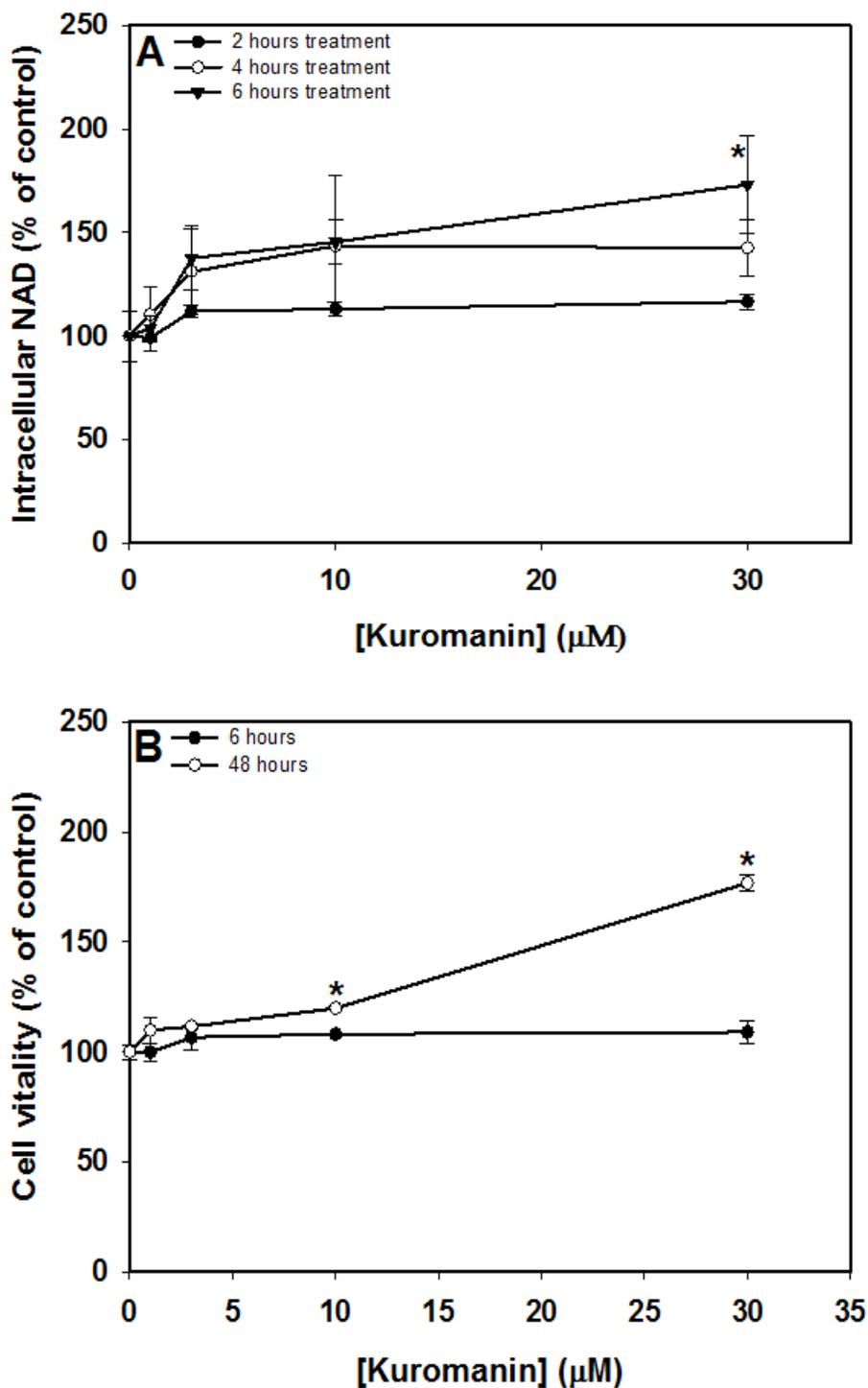


Figure 3.18 Effect of treatment with kuromanin up to 30 μM on (A) intracellular NAD levels in RAJI cells over 6 h comparing to untreated control (100% RAJI cells), and (B) the vitality (MTT assay) of RAJI cells when incubated for up to 48 h with kuromanin comparing to untreated control (100% RAJI cells). Data are means \pm SEM, $n = 3$ (3-6 measurements per replicate). * denotes significant difference from the untreated RAJI cells ($P < 0.05$).

The effect of kuromanin on differentiating HL60 cells was also evaluated. Firstly, the results of kuromanin exposure on NBT reduction showed that it might inhibit the differentiation of HL60 in a concentration-dependent manner (Fig. 3.19). NBT reduction levels also decreased as the incubation with kuromanin was prolonged to 4 days, compared to 4 days differentiation without kuromanin. However, the mechanism of this effect was not really clear, and it might be due to an additional, unknown factor.

Secondly, treatment of the differentiating cells with kuromanin also affected NAD levels. The results showed significantly increased NAD levels in differentiating cells treated with 10 μ M kuromanin after 6 h (Fig. 3.20). This increase in NAD levels was time-dependent, apparently concomitant with inhibition of CD38 activity.

Upregulation of CD38 expression during ATRA treatment was associated with a significant decrease in NAD levels to $60.41 \pm 0.92\%$ by 6 h of differentiation. However, inhibition of CD38 activity by kuromanin (Fig 3.20) was seen to stop the decrease in intracellular NAD and led to an increase in NAD levels to $120.71 \pm 14.81\%$ after 6 h differentiation with ATRA. The strong relationship between CD38 and NAD levels shown in several experiments may confirm a major role of CD38 as the main enzyme involved in the regulation of NAD levels. The findings with kuromanin are supported by CD38 knockout studies (Aksoy *et al.*, 2006 b; Barbosa *et al.*, 2007), and findings in macrophages where CD38 has been genetically deleted (Iqbal and Zaidi, 2006). Overall, whether CD38 removed or inhibited, intracellular NAD levels are significantly elevated.

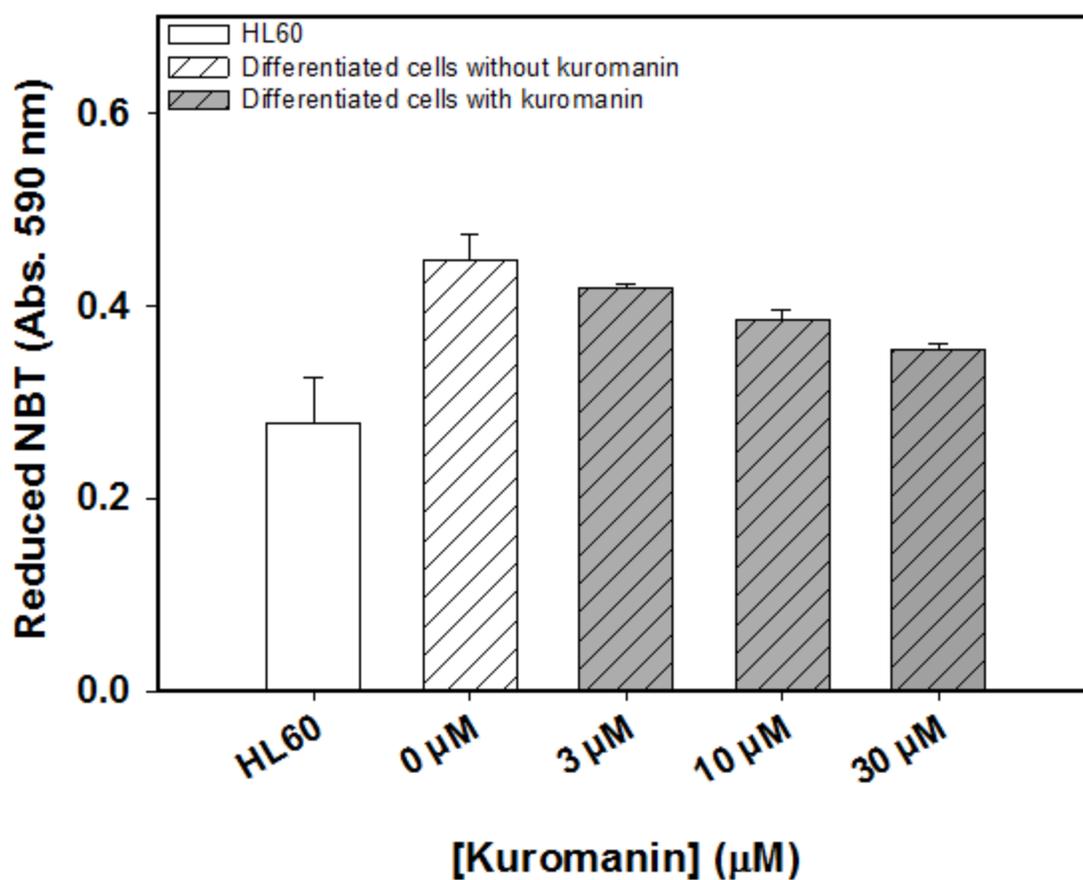


Figure 3.19 The effect of treatment with kuromanin up to 30 μM on NBT reduction by ATRA treated HL60 cells for 4 days comparing to untreated HL60 cells (control). Data are means ± SEM, n = 3 (4-6 measurements per replicate). * denotes significant difference from the control (P < 0.05).

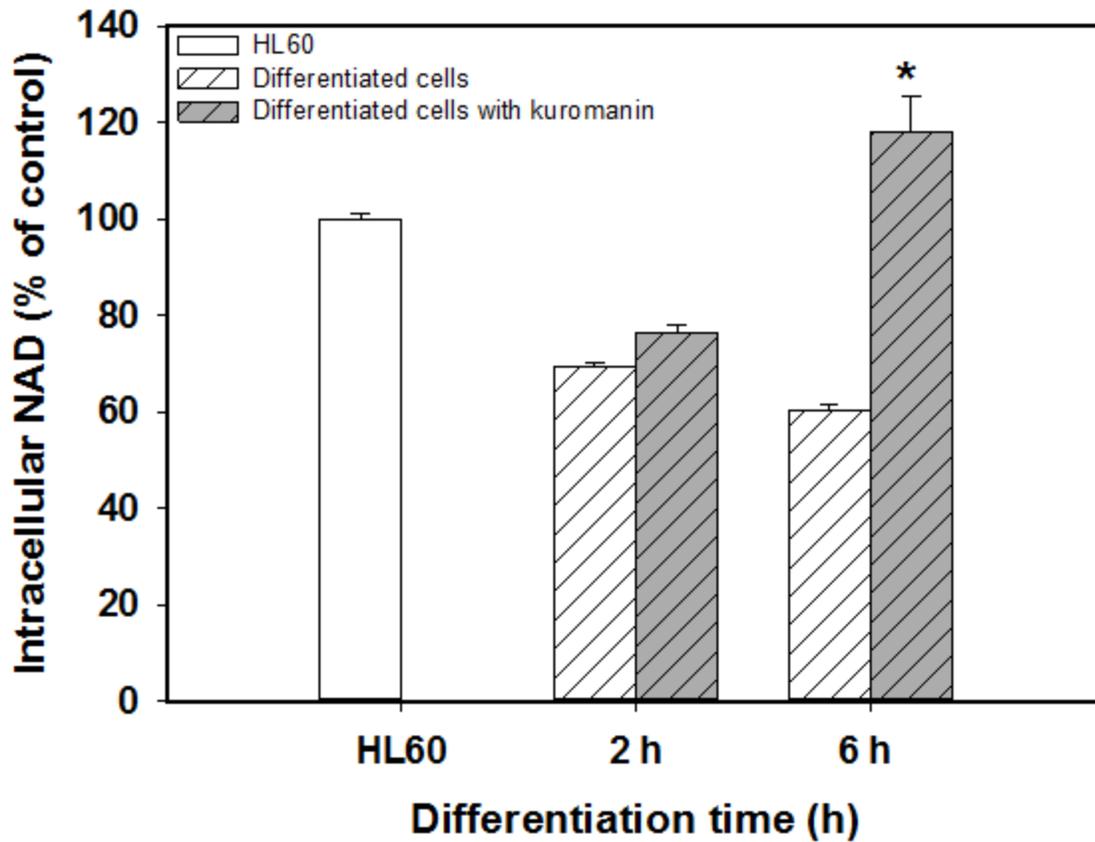


Figure 3.20 Effect of treatment with 10 μ M kuromanin on intracellular NAD levels of differentiated cell up to 6 h comparing to differentiated cells without kuromanin treatment (as control). Data are means \pm SEM, n = 3 (4 measurements per replicate). * denotes significant difference from the control (differentiated cells), P < 0.05.

To avoid the possibility of other known NAD-consuming enzymes (for example; PARP1, SIRT1) participating in the decline in NAD, in addition to the degradative role of CD38, during the differentiation process, other experiments were carried out, including treatment with SIRT1 and PARP1 inhibitors during ATRA-induced HL60 differentiation. The PARP1 inhibitor; 4-amino-1, 8-naphthalimide, has previously been shown to have a potent inhibitory effect on PARP activity in tumour cells (Schlicker *et al.*, 1999). PARP is also known as a major cellular NAD⁺ consumer, in addition to CD38 (Sims *et al.*, 1981). Thus, inhibition of PARP activity is reported to increase NAD levels in brown adipose tissue and muscle (Bai *et al.*, 2011). PARP inhibitors are currently in clinical development as antitumour drugs (Fong *et al.*, 2009).

On the other hand, NAD works as a substrate and regulator of NAD-dependent deacetylases such as SIRT1 which are located in the nuclei, and modulate ageing and energy metabolism in mammalian cells (Grubisha *et al.*, 2005; Guarente and Picard, 2005; Pillai *et al.*, 2005). Indeed, seven sirtuins (SIRT1-7) have been identified, which target histone and various nonhistone proteins in distinct subcellular locations. Both SIRT1 and SIRT2 may have a role in the development of cancer (Peck *et al.*, 2010). In addition, it has also been confirmed that Sirtinol, a SIRT1 inhibitor, can effectively induce significant growth inhibition or apoptosis *in vitro* studies (Peck *et al.*, 2010), or in *in vivo* studies such as with adult T-cell leukemia-lymphoma (ATL) patients (Kozako *et al.*, 2012). Thus, SIRT1 inhibitors have been suggested to be therapeutic agents for leukemia (Kozako *et al.*, 2012).

The results (Fig. 3.21 A, B) show that neither 4-amino-1,8-naphthalimide (PARP inhibitor), nor sirtinol (SIRT1 inhibitor) changed the intracellular levels of NAD during the differentiation compared to the control (the differentiating cells without the inhibitors). The results suggest that

there was not sufficient activity of either enzyme to impact on the intracellular levels of NAD. Interestingly, PARP activity has previously been reported to be decreased during neutrophilic differentiation of HL60 cells (Kanai *et al.*, 1982). This decline is suggested to be achieved through changes in the specific activity of PARP and increases in the NAD glycohydrolase activity (Kirsten *et al.*, 1991) and these findings strongly support the results obtained (Fig. 3.21 A). Moreover, the data (Fig. 3.21 B) on NAD levels during the differentiation and in combination with sirtinol, might suggest that sirtuin activity is not significant during the differentiation or that NAD levels might be mostly controlled by other NAD consuming enzymes, mainly CD38.

In conclusion, the decrease in NAD levels appears to be controlled by the main degrading enzyme CD38, and it is clearly independent of the actions of other NAD consuming enzymes (PARP and SIRT1) during HL60 differentiation. Moreover, the results of this part of the work have further confirmed that the endogenous activities of SIRT1 and PARP might be regulated via CD38 enzymatic activities by controlling the availability of their substrate, NAD.

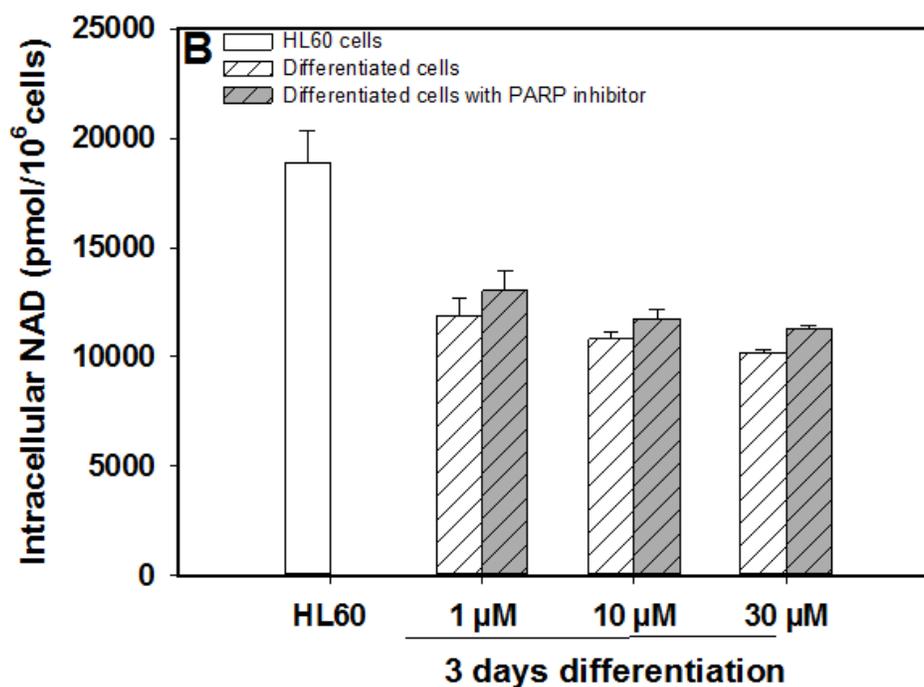
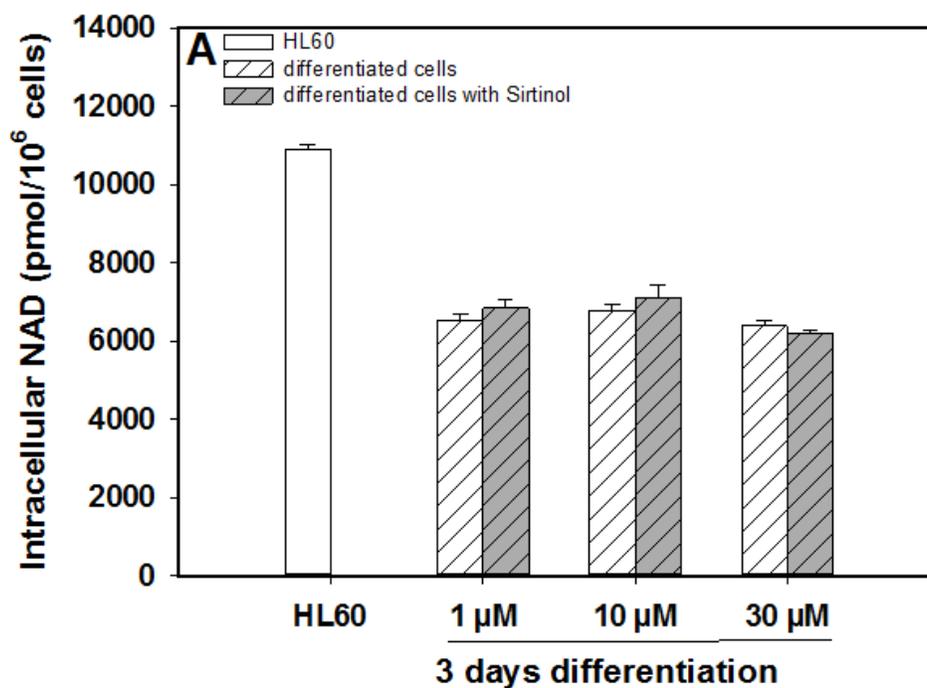


Figure 3.21 Intracellular NAD levels were investigated in differentiated cells for 3 days with ATRA after treatment with (A) PARP inhibitor (4-amino-1,8-naphthalimide) up to 30 μM or (B) sirtuin inhibitor (sirtinol) up to 30 μM. Data are means ± SEM, n = 3 (3 measurements per replicate). No significant differences in NAD levels were found between differentiated cells with or without inhibitor, P > 0.05.

3.3.5 Evaluation of the NAD biosynthesis enzymes during ATRA-induced HL60 differentiation

A considerable decline in NAD levels was clearly indicated in the time course of HL60 differentiation, which might be mediated mainly by the activity of CD38 and not by CD157, PARP or sirtuin. As it has been shown here that CD157 has negligible gene expression, it appears that it cannot account for the decline in NAD levels. Also inhibition of both PARP and sirtuin activities did not have any significant effect on intracellular NAD levels. Overall, the above data suggests that these enzymes might not participate in the consumption of NAD. Hence, having investigated the NAD consuming pathways, it was important to look for other mechanisms that might be involved in the decline of intracellular NAD. Thus, NAD biosynthesis enzymes were investigated in this study. The hypothesis was that changes in the level of expression of NAD biosynthesis enzymes might affect NAD levels.

It is well known that cellular NAD is synthesized either via the *de novo* pathway from tryptophan or via one of two possible recycling pathways: from nicotinic acid or nicotinamide; vitamin PP, or niacin (Magni *et al.*, 2004), and via the nicotinamide riboside pathway (Bieganowski and Brenner, 2004). Thus, mRNA levels of some NAD-biosynthesis enzymes were investigated from both the *de novo* (Fig. 3.22) and salvage pathways (Fig. 3.23 A, B).

Expression of IDO (a *de novo* pathway enzyme) was found to be upregulated early, at 12 h of differentiation ($p > 0.05$), with a clear decline later on. An increase in IDO mRNA levels then was observed at 72 h of differentiation with a continuous increase ($P < 0.05$) up to 120 h (Fig. 3.22). It has been demonstrated that the expression of the tryptophan-catabolizing enzyme (IDO) in neutrophils (as occurs during influenza infection), in addition to impairing host defense

against secondary bacterial infections, also enhances neutrophil apoptosis *in vivo* (Van der Sluijs *et al.*, 2011). This might suggest further functions for IDO in addition to its role in NAD biosynthesis.

The expression of the salvage pathway enzymes NMNAT and NAMPT was also investigated during the differentiation. Significantly increased NMNAT mRNA was observed (Fig. 3.23 A) at 120 h of differentiation, in addition to increases at 18 h and 72 h. NAMPT expression was also investigated during the time course; there was no significant change over time (Figure 3.23 B).

The results indicate an increase in NAD-biosynthesis enzymes, especially IDO, during differentiation. Taken together, the data suggest that differentiating HL60 strongly depend on the NAD *de novo* pathway to resynthesize intracellular NAD and to maintain the NAD pool.

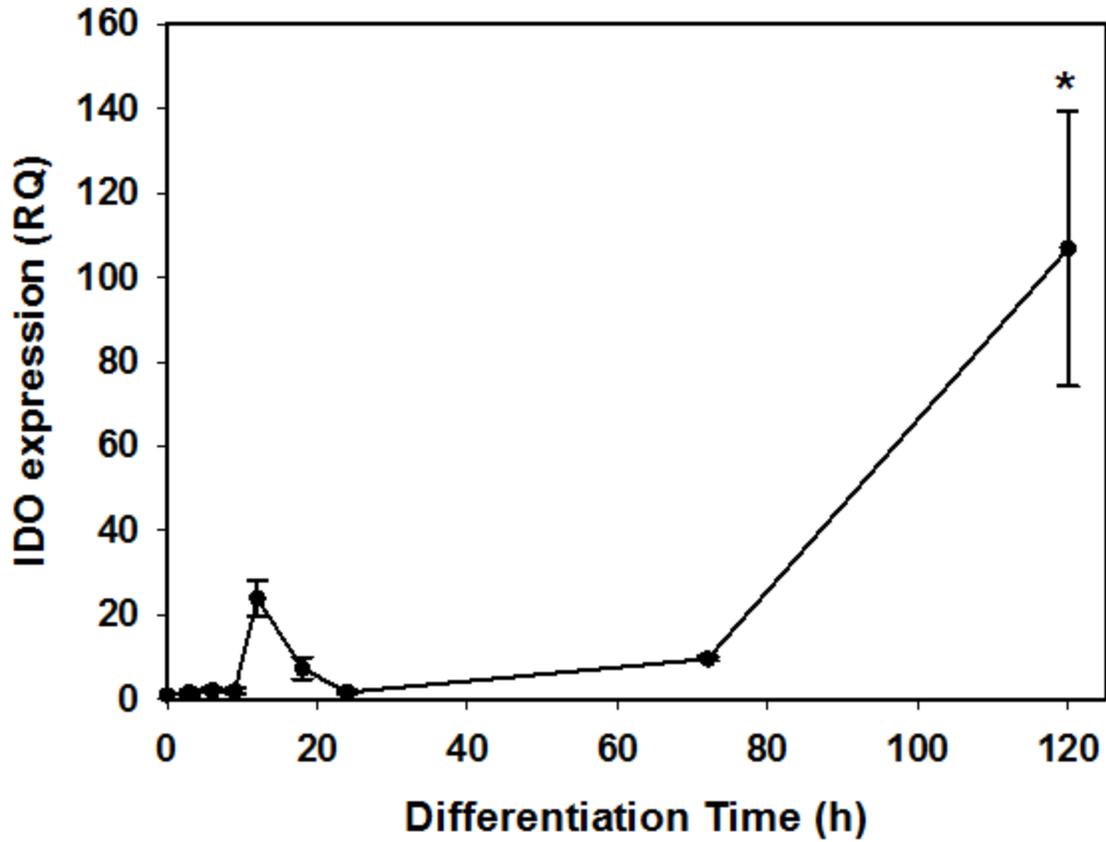


Figure 3.22 Time course of ATRA-induced differentiation of HL60 cells over 5 days showing the increase in IDO expression comparing to untreated HL60 cells (as control). Data are means \pm SEM, $n = 3$ (3-6 measurements per replicate). * denotes significant difference from the control ($P < 0.05$).

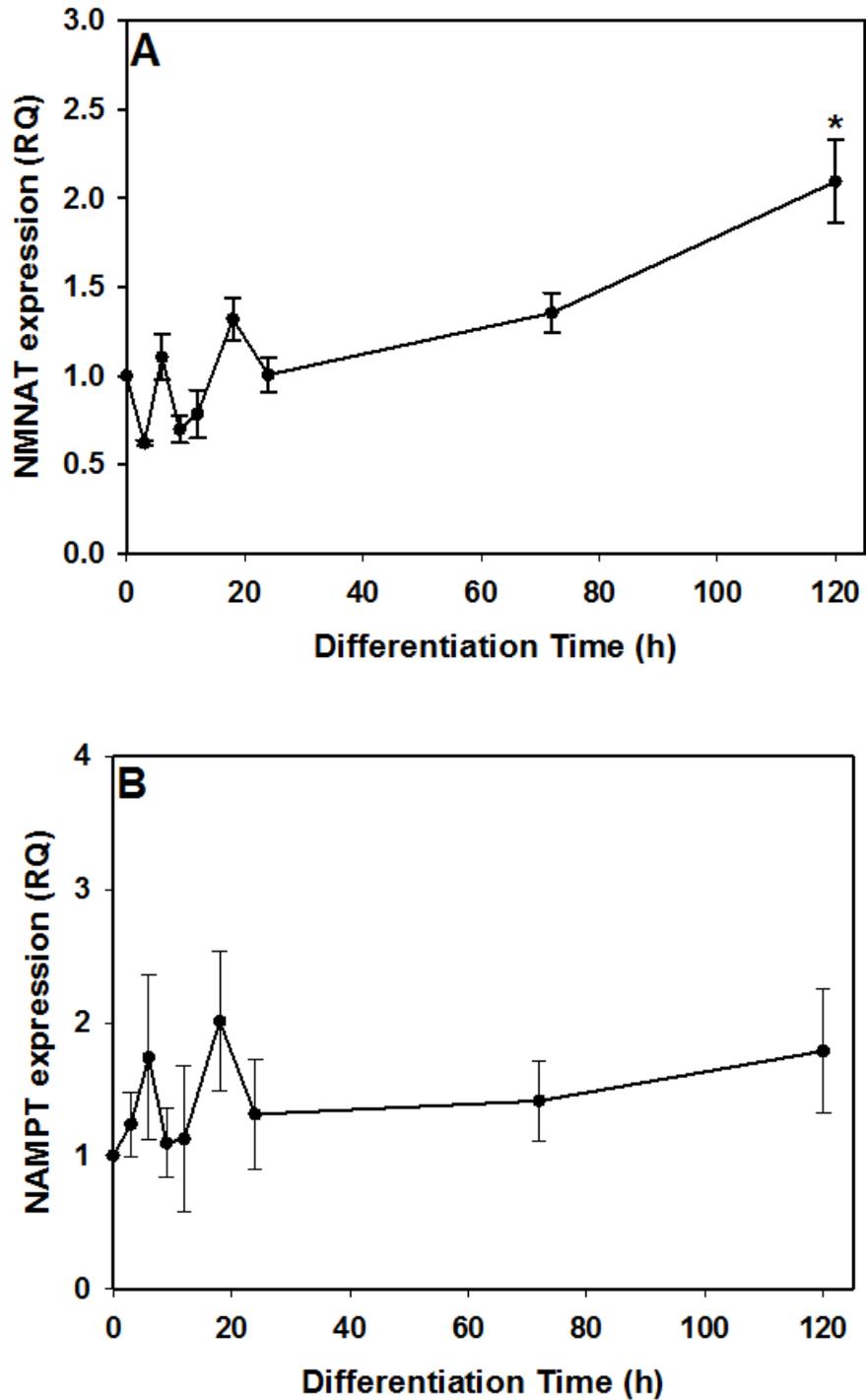


Figure 3.23 Time courses of ATRA-induced differentiation of HL60 cells over 5 days showing (A) NMNAT expression (B) NAMPT expression and were compared to untreated HL60 cells (as control). Data are means \pm SEM, n = 3 (3-4 measurements per replicate). * denotes significant difference from the control ($P < 0.05$).

3.3.6 CD38 and cell proliferation

It is well known that induction of granulocytic differentiation in HL60 cells by ATRA is followed by cell death via apoptosis (Mehta *et al.*, 1996). Hence, a reduction in cell proliferation was evident after 24 h of culture with ATRA and was most pronounced after 3 and 5 days of differentiation (Fig. 3.4). However, the finding of less cell proliferation was not expected in cells expressing CD38, since, as previously mentioned (Chapter 1), CD38⁺ CLL cells proliferate more in comparison to CD38⁻ CLL cells. However, one possible explanation was the presence of CD31, as an effective proliferation factor, known as a CD38 non- substrate ligand. The CD38/CD31 interaction has a role in CLL progression via the induction of a proliferation effect (Deaglio *et al.*, 1998; 2000; 2005). Therefore, the hypothesis was to test whether creating environments similar to those of leukemia (CLL), by culturing CD38⁺ cells (differentiated cells) with human solid tumour cell lines expressing CD31 such as MCF-7 (breast carcinoma; Tang *et al.*, 1993), would induce a proliferation in differentiating cells that are expressing CD38, but not CD31.

There was a significant decrease in cell vitality in the 3 day- differentiated cells as assayed using MTT (Fig. 3.24). However, a reversed effect on cell proliferation was interestingly shown after co-culturing the differentiated cells (CD38⁺) with MCF-7 cells (CD31⁺) for 1 day. This suggests that an interaction between CD38 and CD31 signalling might have occurred. CD38/ CD31 interactions and their effects have been previously reported; Gao and colleagues (2007) stated that CD38 expression induced by ATRA increases adhesion of differentiated HL60 cells to vascular endothelial cells (CD31⁺), that results from a protein-protein interaction between CD31 and CD38 molecules.

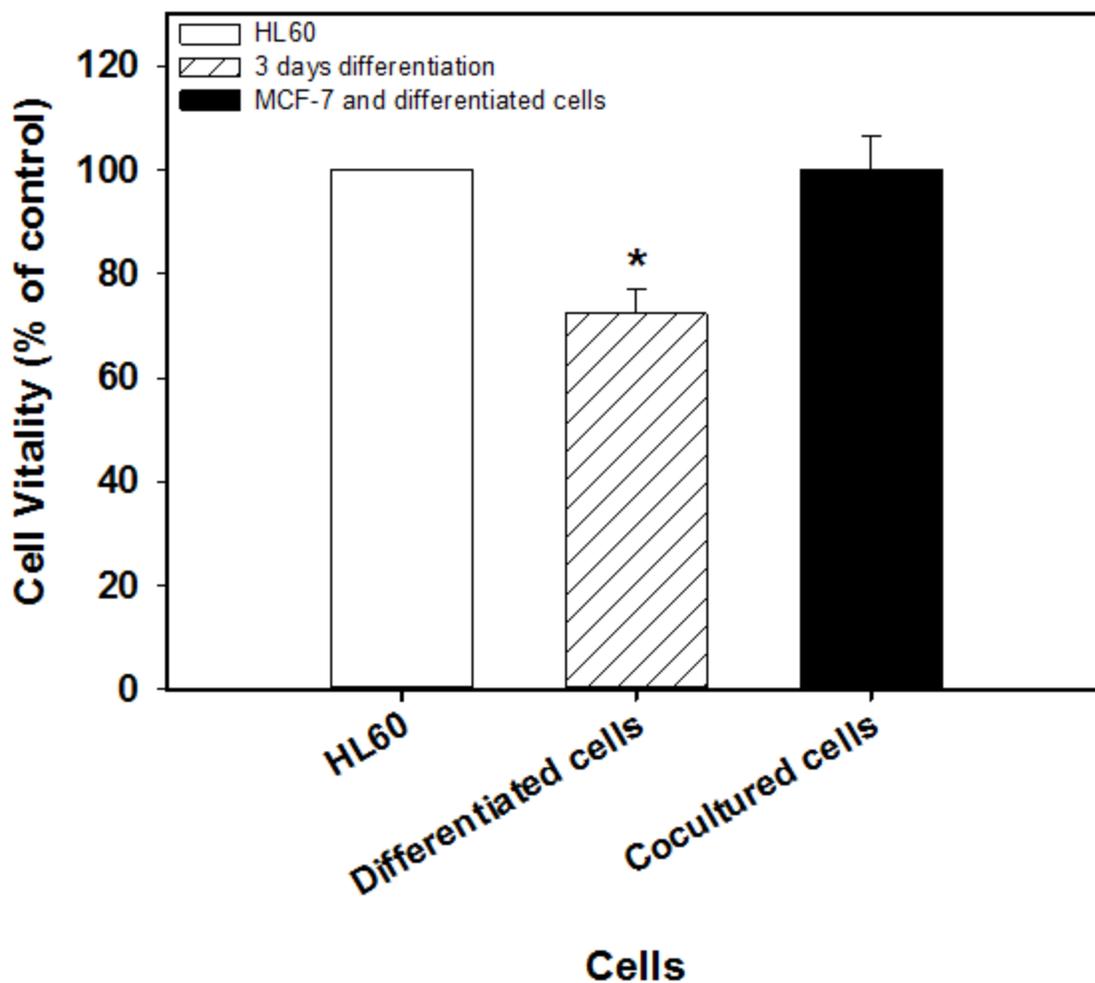


Figure 3.24 The effects of 1 day culture of differentiated cells (3 days) with MCF-7 cells on cell proliferation (MTT assay) as compared to the differentiating cells for 3 days (as control). Data are means \pm SEM, n = 3 (8 measurements per replicate). * denotes significant difference from the control ($P < 0.05$).

It is worth mentioning that important evidence for the effect of CD38/CD31 interaction on cell proliferation can also be confirmed in HL60 cells. The undifferentiated HL60 cells have a high proliferation capacity and low CD38 levels, but express significant levels of CD31 (Gallay *et al.*, 2007). Moreover, no observed regulation of CD31 antigen was reported when HL60 cells were stimulated to granulocytes by ATRA (Trayner *et al.*, 1998). That explains the low proliferation capacity of the CD38⁺ cells (the differentiated cells) compared to the leukemia cell line (HL60). Thus, cell proliferation increased especially when CD38⁺ cells interacted with CD31. This also suggests the effective role of CD38/CD31 interaction on cell proliferation in CD38⁺ leukemia patients.

3.4 Discussion

The role of CD38 as a modulator of NAD levels has not been completely elucidated. Therefore, in the present work, the effect of CD38 expression on NAD levels was investigated in the human leukaemia cell line (HL60) as a relevant model which can differentiate to neutrophil-like cells. A novel key finding of the present study is that HL60 cells are CD38⁻ and have high levels of NAD, whereas the differentiating cells were CD38⁺ and have a low content of NAD, which correlates with CD38 expression. These results suggest that CD38 may be a main NAD degrading enzyme that is expressed during HL60 differentiation. The expression of CD38 in the cells was demonstrated using real time PCR coupled with reverse transcription, western blotting and flow cytometer. These findings might help with the understanding of the mechanisms that regulates NAD levels, and the consequences of this degradation on different cell functions in health and disease. This is because NAD has important roles in energy homeostasis, signal transduction and ageing by serving as a substrate for a network of enzymes. Based on the current

results, it was further hypothesized that in CD38⁺ leukemia cells NAD levels might also be decreased compared to CD38⁻ leukemia cells. In reviewing the literature, no data was found on the association between CD38 and NAD levels in leukemia. Thus, CD38 enzymatic function speculated to have an important role, in addition to its receptor function, in leukemia. It was hypothesized that CD38 behaviour as a receptor is independent of its enzymatic function (Lund, 2006; Congleton *et al.*, 2011). However, there might be a connection between CD38 as a receptor and as an enzyme to achieve its functions in processes such as cell proliferation, apoptosis, differentiation and activation in disease as in leukemia patients, where CD38 is known to be a distinct prognostic marker (Malavasi *et al.*, 2008). The upregulation of CD38 expression might affect intracellular NAD levels and several consequences on cell physiology might occur. Hence, poor prognosis might be a result of a complex mechanism derived from the effect of CD38 enzymatic function, in addition to its receptor functions.

The present studies, employing a range of techniques, show that differentiating HL60 cells possess CD38 which is located extracellularly in the plasma membrane as well as intracellularly in the nucleus. Interestingly, CD38 expression can significantly degrade intracellular NAD during HL60 differentiation, since the results confirmed that CD38 was not just expressed on the plasma membrane. The findings of this study, as well as those of previous reports, have further confirmed the presence of intracellular CD38 expression where intracellular NAD, its main substrate, is present (Trubiani *et al.*, 2008; Zhao *et al.*, 2012). The presence of intracellular CD38 was demonstrated by western blotting (a weak 45 kDa band for CD38 at 24 h; Fig. 3.12 A) and cyclase activity associated with the nuclear extract (activity shown on day 1; Fig. 3.12 B). Also, FACS data for intracellular CD38 shows unexpected, high protein formation levels starting at least by 10 h of differentiation. Indeed, CD38 antibody showed high reactivity with extracellular

CD38 positive cells before permeabilization with less reactivity to detect the intracellular CD38 after permeabilization. This might be due to the presence of CD38 as type II and type III (opposite orientations) in the cell membrane. These two types were confirmed to be present in differentiating HL60 cells (Zhao *et al.*, 2012), which might explain the high levels of extracellular CD38 detected, since this antibody might also detect the intracellular CD38 at the time of its expression from the cytosol to the cell surface.

Furthermore, the other NAD-consuming enzymes (CD157, PARP, and SIRT) showed a negative contribution to NAD degradation during the differentiation. Since there was a virtually undetectable level of CD157 mRNA expression, this suggests that this enzyme cannot account for the large decline in NAD levels. Moreover CD157 cyclase activity has been reported to be one hundred-fold lower than that of CD38 when murine BST-1 has been expressed in yeast (Hussain *et al.*, 1998). Additionally, low activities of PARP (Kanai *et al.*, 1982) and SIRT have also been suggested during HL60 differentiation. This was confirmed by the lack of change in intracellular NAD levels following the addition of inhibitors of PARP and SIRT. Interestingly, sirtuin activity is strongly controlled by NAD availability that is, in turn, regulated by the main consuming enzyme; CD38 (Aksoy *et al.*, 2006b). Importantly, for enzyme inhibition, concentrations of 1-30 μM of the sirtuin inhibitor (sirtinol) and PARP inhibitor (4-amino-, 1, 8-naphthalimide) were applied during HL60 differentiation. It is worth noting, that this range of concentrations has previously been shown to inhibit both enzymes (Hegan *et al.*, 2010; Fernandes *et al.*, 2012). The current results during HL60 differentiation, also suggest that CD38 might be limiting the availability of NAD to other NAD-consuming enzymes. Furthermore, they reflect the restricted role of other NAD-consuming enzymes in the degradation of NAD during the differentiation.

The strongest evidence that clearly confirms the essential role of CD38 in degrading NAD levels during the differentiation comes from the observed effects of kuromanin. The effect of inhibition by kuromanin on CD38 cyclase activity occurred at micromolar concentrations. Kuromanin efficiently elevated intracellular NAD levels compared to those in untreated cells. The mechanism of this inhibition is suggested to be through interaction of the inhibitor with the active site of CD38, which affects the binding of CD38 with NAD⁺ (Kellenberger *et al.*, 2011). In addition to increasing NAD levels, treatment with kuromanin also suppressed the differentiation of HL60 to neutrophil-like cells as assessed by the NBT assay. This might be through the inhibition of CD38 activity, which is involved in the mechanism of HL60 differentiation. The recent data strongly confirm the major CD38 role in degrading NAD, because CD38, and no other NAD-consuming enzymes (PARP, sirtuin and CD157), is mainly expressed over time during the differentiation. Inhibition of CD38 activity might serve as a pharmacological target for multiple disease conditions, especially in CLL. Indeed, in CLL, studies have developed from CD38 as a marker to CD38 as a disease modifier and a therapeutic target (Deaglio *et al.*, 2008). The effects of kuromanin might also need to be investigated in other leukaemia cells expressing CD38 *in vivo* and *in vitro*. Following these investigations, kuromanin may represent a possible therapeutic agent to target CD38 in leukaemia.

As it was confirmed that NAD appeared to be consumed via the activity of CD38 during the differentiation, resynthesis of NAD would be necessary to maintain the functions of a wide variety of NAD-dependent enzymes in cells. It was found that during HL60 differentiation NMNAT expression showed a significant increase, but the rate-limiting enzyme (NAMPT) showed no significant change in expression. Hence, this pathway is unlikely to be able to compensate for the decrease in NAD levels through CD38 activity. An apparent elevation in IDO

expression was also recorded. However, IDO activity might also not be able to compensate for the decline in NAD levels, since it has been previously estimated that only 1/60 of NAD synthesis comes from tryptophan degradation via IDO (Bender, 1992). Thus, IDO expression might be linked to other functions; for instance, IDO serves more than one role in the immune system (Mellor and Munn, 2004). Furthermore, it has been documented that overexpression of the NAD biosynthesis enzymes might not necessarily affect NAD levels as the pyridine nucleotides can be turned over at a considerable rate (Mack *et al.*, 2001; Anderson *et al.*, 2002). Thus, the change in the expression of NAD biosynthesis enzymes might have other functions rather than maintaining NAD levels. For instance, It has been mentioned that NAMPT and NMNAT have important roles in regulating the functions of NAD-dependent enzymes such as the protein deacetylase, SIRT1, and PARP1 (Zhang *et al.* 2009). It has also been found that NMNAT activity correlates with DNA synthesis during the cell cycle (Solao and Shall 1971). Moreover, it has been suggested that IDO expression has a role in controlling autoimmune diseases (Opitz *et al.*, 2007) and chronic infection (Zelante *et al.*, 2009). Importantly, it is chronically activated in many cancer patients (Schroecksnadel *et al.*, 2007). Thus, IDO expression or enzymatic activity correlates with a poor prognosis in patients with various cancers (Ino *et al.*, 2008; Pan *et al.*, 2008). The role of IDO in the poor prognosis in cancer is therefore an interesting area and is yet to be determined. This could be achieved by exploring whether a link exists between CD38 expression, IDO expression, low intracellular NAD levels and poor prognosis. Hence, IDO might also serve as a target in patients with various cancers, such as CD38⁺ leukemia subset patients. Moreover, further investigation is needed to confirm whether NAMPT or NMNAT expression are associated with CD38 expression and low levels of NAD which are also expected to be as potential targets for therapeutic applications in leukemia.

Furthermore, in view of the results obtained in this study, it would be interesting to investigate the effect of low intracellular NAD levels on cADPR production. cADPR is a key messenger in the mobilization of intracellular Ca^{2+} stores, and is involved in a variety of cellular processes, including fertilization, cell proliferation, and differentiation (Lee, 2004; Guse, 2005). Thus, the observed decline in intracellular NAD levels might either suggest a high turnover of intracellular NAD levels to produce high levels of this secondary messenger, or alternatively that low levels of the messenger might be formed because of a low availability of its precursor, NAD. However, it has been found that CD38, in addition to inducing cell proliferation, also increases intracellular Ca^{2+} levels (Zocchi *et al.*, 1998), so, when CD38 is expressed, a consequential accumulation of cADPR might occur. Importantly, the ability of cADPR to increase cell proliferation has been observed in several human cell lines (Bruzzone *et al.*, 2003; Kim *et al.*, 2008; Yue *et al.*, 2009). Moreover, CD38-mediated cADPR production has been implicated in several diseases (Chapter 1), and the current finding may have attractive functional implications in CD38^+ leukemia patients. One of the possible implications is that the decrease in NAD levels concomitant with CD38 expression might be accompanied by a peak in cADPR production that might play a causal role in mediating leukemia proliferation and poor prognosis. However, the effect of CD38 expression in degrading NAD levels suggests that there is still much work to be done to understand this interesting relationship.

It is worth noting that the extracellular location of CD38 and the intracellular location of the substrate NAD and its product cADPR have raised an unresolved issue known as the ‘topological paradox’, since it was hard to understand how the product, cADPR, could exert its calcium-mobilizing activity intracellularly if it were produced extracellularly (De Flora *et al.*, 2000). However, there are two mechanisms that have been suggested to resolve the CD38 topological

paradox, depending on the membrane orientation of CD38. The first mechanism for NAD and CD38 product trafficking has been suggested by De Flora's group (De Flora *et al.*, 2004). It is based on the observation that CD38 is expressed as a type II protein on the cell surface. These findings suggest that a connexin-43 (CX43) channel is present in the plasma membrane to transport the cytosolic substrates, NAD and NADP (Bilington *et al.*, 2008a), and to make them available to the extracellular CD38 (Zocchi *et al.*, 1999). Ultimately, both the products, cADPR and NAADP, are transported back into the cytosol via a nucleoside transporter (NuT) to act on their targets by affecting Ca^{2+} release from the intracellular stores (Bruzzzone *et al.*, 2001; Lee, 2012). It has also been suggested that cADPR is transported through CD38 itself by a channel mechanism (Franco *et al.*, 1998). Importantly, type III CD38 serves as a simple solution to the topological paradox (De Flora *et al.*, 2000), and represents the second proposed mechanism. Indeed, CD38 with type III orientation should be more suitable than the type II isoform for performing intracellular signalling functions, since its substrate NAD location and the sites of CD38 action mediated by cADPR and NAADP, are all cytosolic. Altogether, these two signalling mechanisms are consistent with the wide range of functions that are regulated by this enzyme activity (Zhao *et al.*, 2012). Interestingly, it has been suggested that both type II and type III orientations may possibly be in the same cell (Lee, 2012). For instance, both types of CD38 are found on the cell surface of HL60 on the first day of ATRA-induced differentiation as well as in other cells, such as human primary monocytes and the U937 monocytic cell line after activation by IFN- γ (Zhao *et al.*, 2012). In view of the results of this study, type III CD38, which has been shown in differentiating HL60 cells, supports the main role of CD38 in degrading intracellular NAD. Moreover, the presence of two signalling mechanisms in the differentiating cells might require a rapid NAD degradation by CD38 both extracellularly and intracellularly. In

summary, these findings further support the current investigations which confirmed a high drop in intracellular NAD levels in cells expressing high levels of CD38. In addition, in the context of leukaemia conditions, the presence of CD38 in two orientations might suggest a complex mechanism associated with CD38 signalling that is involved in cell proliferation and poor prognosis.

In conclusion, the main aim in this particular study was to provide new evidence for the main role of CD38 as the major NAD regulatory enzyme in the cells. An elevated level of this efficient enzyme on the surface or in the cytosol of some cells might have an impact on different NAD-dependent pathways. However, the three main processes which might be affected are (a) the NAD-dependent glycolysis pathway, which directly affects cellular energy since the $\text{NAD}^+:\text{NADH}$ ratio is a direct measure of the energy status of a cell, and (b) the formation of cyclic ADP-ribose, a Ca^{2+} -mobilizing messenger, which is known to play a role in the control of gene expression and apoptotic cell death (Zupo *et al.*, 1994; Hardingham *et al.*, 1997). In this context, Yalcintepe *et al.*, (2005) postulated that NAD may function as a signal that regulates nuclear calcium homeostasis and gene expression. Finally, (c) increasing CD38 cyclase activity not only decreases the intracellular NAD levels, but it also limits the substrate availability for other ectoenzymes such as ADP-ribosyl transferases and the intracellular enzymes such as PARP and sirtuin. These enzymes mediate important roles in modified cellular functions such as genomic stability, apoptosis, cell signalling and stress tolerance (Malavasi *et al.*, 2010). Finally, further studies are needed to explore whether CD38-mediated NAD degradation might provide solutions that increase understanding of the reasons as to why patients with CLL and high CD38 expression have a progressive stage of this disease and a lower survival rate (Deaglio *et al.*,

2008). CD38 enzymatic function might also serve as a possible target in leukemia therapy, in addition to its receptor function.

CHAPTER 4

**EFFECT OF LOWERED NAD LEVELS ON
CELL PHYSIOLOGY**

4.1 Introduction

NAD(H) and its phosphorylated form, NADP(H), play key roles in major aspects of energy metabolism (Berger *et al.*, 2004; Ying, 2006). NAD mediates glycolysis by acting as a coenzyme for some key glycolytic enzymes (such as GAPDH). It also modulates other important energy metabolism-related reactions in cytosol, such as the lactate dehydrogenase catalyzed lactate-pyruvate conversions. Furthermore, NAD(P)(H) is an essential co-enzyme in some of the most fundamental reaction pathways, such as the TCA cycle and the pentose phosphate pathway (Ziegler, 2000). In addition to NAD having major roles in energy metabolism, it can also affect cellular antioxidant capacity through its phosphorylated form, NADP, the precursor for synthesizing the major reducing molecule NADPH (Stryer, 1995). The latter carries out several cell protective functions (Pollak *et al.*, 2007). Importantly, the role of NAD has been extended from simply being an oxidoreductase coenzyme to acting as a precursor for a wide range of products produced by other enzymes. These include ADP-ribosyl cyclase/NAD glycohydrolase (CD38), NAD-dependent protein deacetylases (sirtuins), poly (ADP-ribose) polymerases (PARP), and ADP-ribosyl transferases (ARTs). Altogether, NAD provides a direct link between the cellular redox status and the control of DNA repair (via PARP; Kim *et al.*, 2005), post-translational protein modification (via ARTs; Koch-Nolte *et al.*, 2008), gene expression (via sirtuins; Michan and Sinclair, 2007) and Ca²⁺-signalling (via CD38/CD157; Malavasi *et al.*, 2008). Several studies have also confirmed that NAD works as a modulator of protein activities due to nucleotide availability (Ying, 2006; 2008). The NAD⁺:NADH ratio is an important regulator of mitochondrial permeability transition (MPT; Zoratti and Szabo, 1995), and may indirectly affect mitochondrial function by modulating calcium homeostasis, which is known to profoundly affect mitochondrial activities (Nicholls *et al.*, 1999). NAD regulates calcium

homeostasis through the formation of Ca^{2+} -mobilizing messengers, for example cADPR, which is known to play a role in the control of gene expression and also apoptosis (Zupo *et al.*, 1994; Hardingham *et al.*, 1997).

As such, changes in NAD levels or the $\text{NAD}^+:\text{NADH}$ ratio, which lead to changes in metabolism, have been implicated directly and indirectly in the mechanisms of several age-associated diseases such as diabetes, cancers and neurodegenerative diseases e.g. Parkinson's disease (Soriano *et al.*, 2001; Zhang *et al.*, 2002; Greenamyre *et al.*, 2001; Lin and Guarente 2003). Thus, NAD has major roles in multiple physiological processes via a number of pathways, and there has been much interest in the NAD homeostasis pathways as potential pharmacological targets for a wide variety of diseases. However, studies have not fully examined the effect of low NAD levels on cell physiology, particularly in HL60 cells, during treatment with ATRA and under conditions of upregulation of CD38 expression. Therefore, the aim of this study was to extend the studies of Chapter 3, and to examine the effect of low NAD levels on the $\text{NAD}^+:\text{NADH}$ ratio and the levels of major antioxidants such as glutathione. In addition to examine the effect of low intracellular NAD in differentiated cells on lipid peroxidation status and glycolysis. From this study it might be possible to understand the reason for metabolic dysfunction and a resistance to apoptosis cell death or find a mechanism that explains the reason for the poor prognosis in CD38^+ leukemia subset patients.

4.2 Materials and methods

4.2.1 Materials

Reduced glutathione (GSH), glutathione reductase, dithionitrobenzoate (DTNB), thiobarbituric acid (TBA), 1,1,3,3-tetraethoxypropane, lactate dehydrogenase (LDH), glycine, glucose, and PBS were all purchased from Sigma (Poole, UK). NAD, NADH, and NADPH were all from Melford Laboratories (Ipswich, UK). Hydrazine hydrate liquid and lactate were a kind gift from Mr. Nick Crocker (University of Plymouth, UK) and came from Sigma (Poole, UK).

4.2.2 Measurement of the NAD⁺: NADH ratio

The NAD⁺: NADH ratio was estimated by measuring both the NAD⁺ and the NADH concentration for each sample by using the NAD cycling assay as described in Chapter 2, Section 2.9.2.1. Briefly, the control cells and HL60 treated with ATRA for 1, 3 and 5 days were harvested and both NAD⁺ and NADH were extracted from each sample as detailed in Chapter 2. After the extraction, NAD⁺ and NADH levels were estimated by comparison with NAD⁺ and NADH standards. Also nucleotide levels were normalized to the cell concentration for each sample. The NAD⁺:NADH ratio was calculated by dividing intracellular NAD⁺ levels by the NADH levels in the same sample.

4.2.3 Determination of total glutathione by the enzymatic recycling assay

This assay was used to measure total intracellular glutathione levels (GSH and GSSG). In this assay, GSH reacts with the DTNB to produce 5-thio-2-nitrobenzoate (TNB) and a mixed disulphide (GSSTNB). The latter produce GSH again in the presence of glutathione reductase

(GR) and NADPH. A similar reaction may form two molecules of GSH by reducing GSSG in the presence of both GR and NADPH (Jones, 2002), as shown in Figure 4.1.

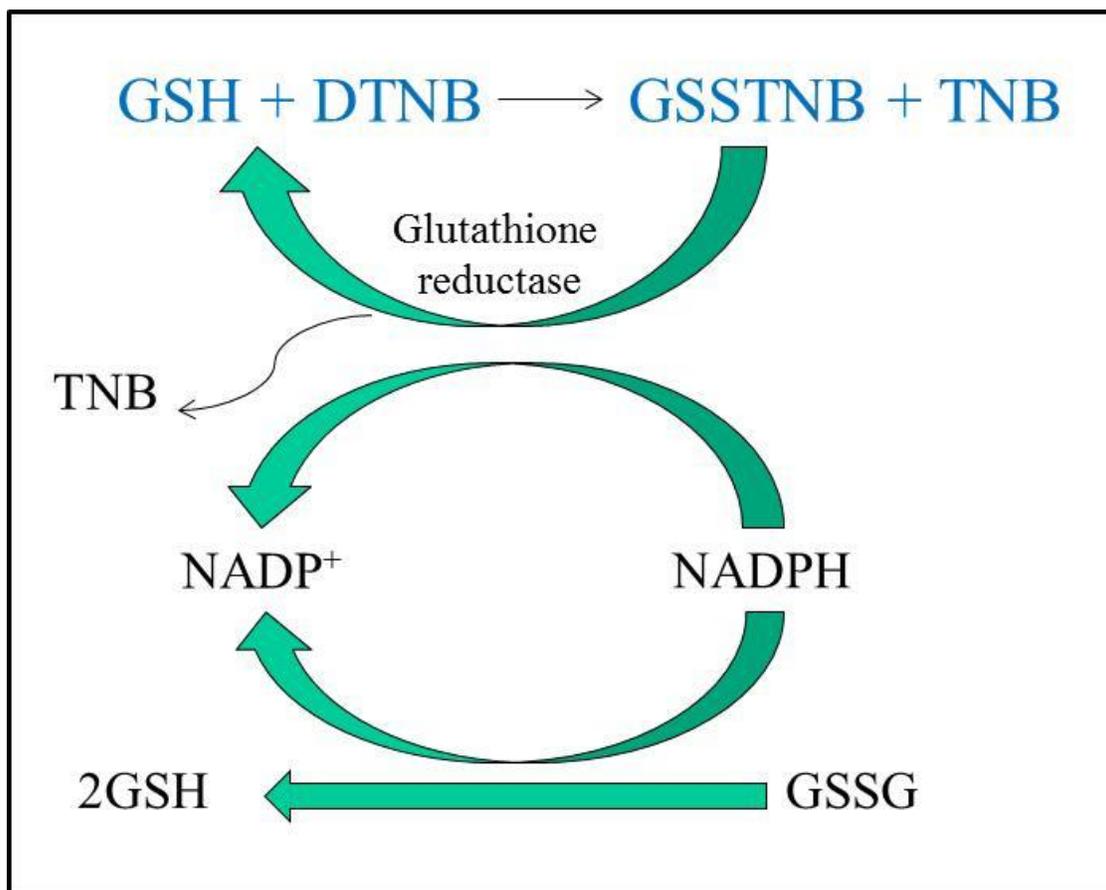


Figure 4.1 Principle of the total glutathione assay. GSH produce GSSTNB in the presence of DTNB. GSSG or the mix (GSSTNB) converted again to GSH in the presence of glutathione reductase (GR) and NADPH.

The total glutathione (GSH and GSSG) assay was performed as described by Adams *et al.* (1983). The control or ATRA-treated HL60 cells (1×10^6 cells ml^{-1}) were collected and washed twice with PBS. After collection, cells were lysed in the assay buffer (100 mM potassium

phosphate, pH 7.5, containing 5 mM potassium EDTA) by three cycles of freeze-thawing followed by centrifugation at $7000 \times g$ for 5 min. Sample lysate (40 μ l) or GSH standard (after being mixed with an equal volume from fresh buffered DTNB (10 mM in assay buffer)) were added to 210 μ l of assay buffer containing 0.15 U glutathione reductase. The reaction was started by adding 60 μ l of freshly prepared 1 mM NADPH, and the absorbance at 412 nm was read at room temperature for 10 min. Total glutathione results are expressed as nmol per 10^6 cells.

4.2.4 Thiobarbituric Acid Reactive Substance assay

Lipid peroxidation is used as an indicator of oxidative stress in cells and tissues. Lipid peroxides are unstable and decompose to form a complex series of compounds including reactive carbonyl compounds. Polyunsaturated fatty acid peroxides generate malondialdehyde (MDA) and 4-hydroxyalkenals (HAE) (Esterbaue *et al.*, 1991). The thiobarbituric acid reactive substances (TBARS) assay measures lipid hydroperoxides and aldehydes, such as MDA, in the cell culture medium and cell lysate. MDA combines with thiobarbituric acid (TBA) in a 1:2 ratio to form a coloured complex that is measured at 532 nm. TBARS are expressed as MDA equivalents (Dubuisson *et al.*, 2000).

The measurement of MDA was performed according to the protocol reported by Ohkawa *et al.* (1979). Briefly, untreated HL60 cells (the control) and cells treated with ATRA ($5-10 \times 10^6$ cells ml^{-1}) were collected in 15 ml tubes, followed by low-speed centrifugation ($200 \times g$) for 5 min. The cell pellets were re-suspended in 0.2 ml ice-cold PBS and sonicated for 15 s at low power sonication (4 W output, Microson TM Ultrasonic Cell Disruptor, USA) on ice. Aliquots (100 μ l) of the cell lysate were assayed for MDA according to the following protocol: Ice-cold 10% TCA (200 μ l) was added to 100 μ l of each sonicated sample to precipitate proteins and the sample

centrifuged at $7000 \times g$ for 5 minutes at $4\text{ }^{\circ}\text{C}$, followed by addition of $200\text{ }\mu\text{l}$ of 4.6 mM (0.67%) thiobarbituric acid (TBA) to an equal volume of each supernatant. The color was developed by incubating at $100\text{ }^{\circ}\text{C}$ for 30 min and the reaction was stopped by cooling on ice for 5 min. Three hundred microlitres from each sample was transferred to a 96-well plate and the absorbance at 532 nm was measured with reference to a reagent blank. The lipid peroxide levels were expressed in terms of pmol of malondialdehyde per 10^6 cells of each sample and calculated from a standard curve (Fig. 4.2) made with various concentrations of 1,1,3,3-tetraethoxypropane ($0\text{--}100\text{ }\mu\text{M}$).

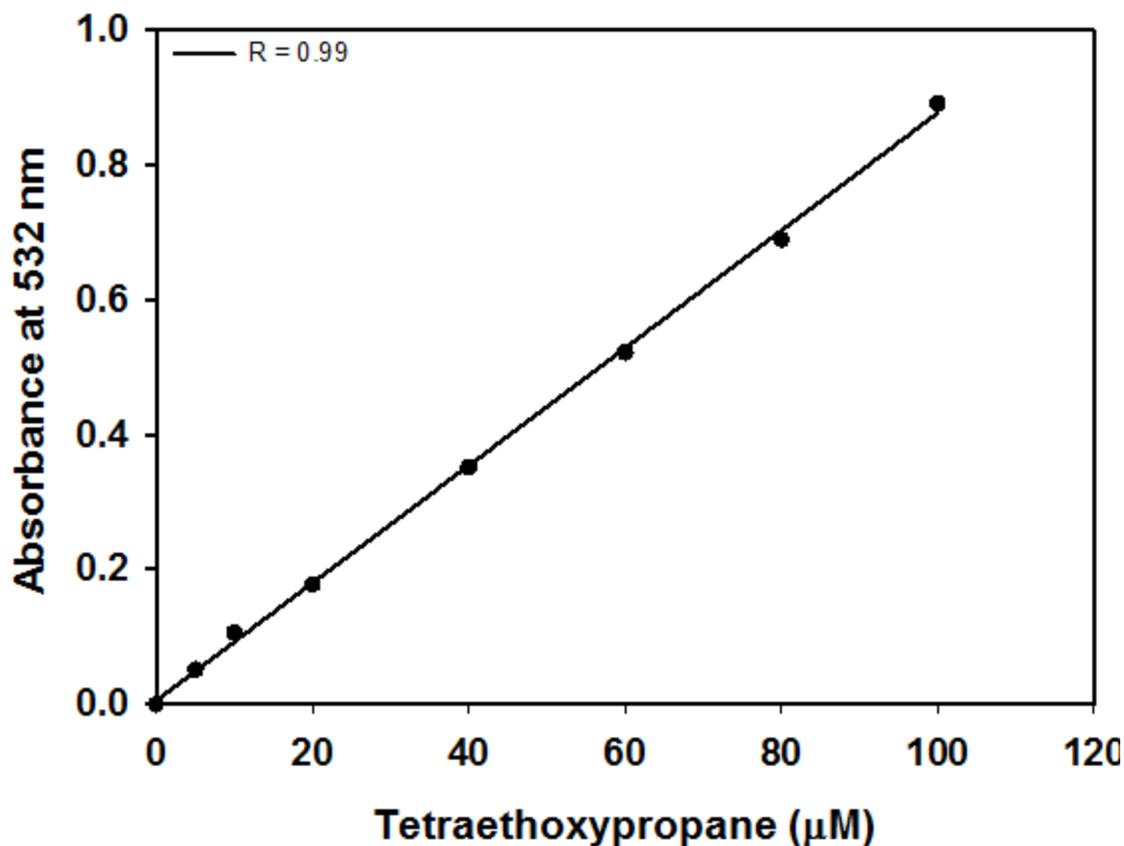


Figure 4.2 Standard curve of ($0\text{--}100\mu\text{M}$) 1,1,3,3-tetraethoxypropane, was used to estimate of TBARS levels for each sample. Change in absorbance is recorded at 532 nm .

4.2.5 Lactate assay

Lactate accumulation in the medium was used to assess the rate of glycolysis during HL60 cell differentiation with ATRA for 1-5 days (Fig. 4.3). Two hundred and fifty microlitres of the assay mixture (containing 500 mM glycine, 400 mM hydrazine, 20 mM NAD^+ and 16.6 U/ml of lactate dehydrogenase) was mixed with 50 μl from the sample (medium) or lactate standard solution (0.1-1 mM) and incubated at 37 °C for 30 min to complete the reaction. The absorbance at 340 nm was measured in a plate reader (VersaMax, Molecular Devices, Sunny Vale, CA).

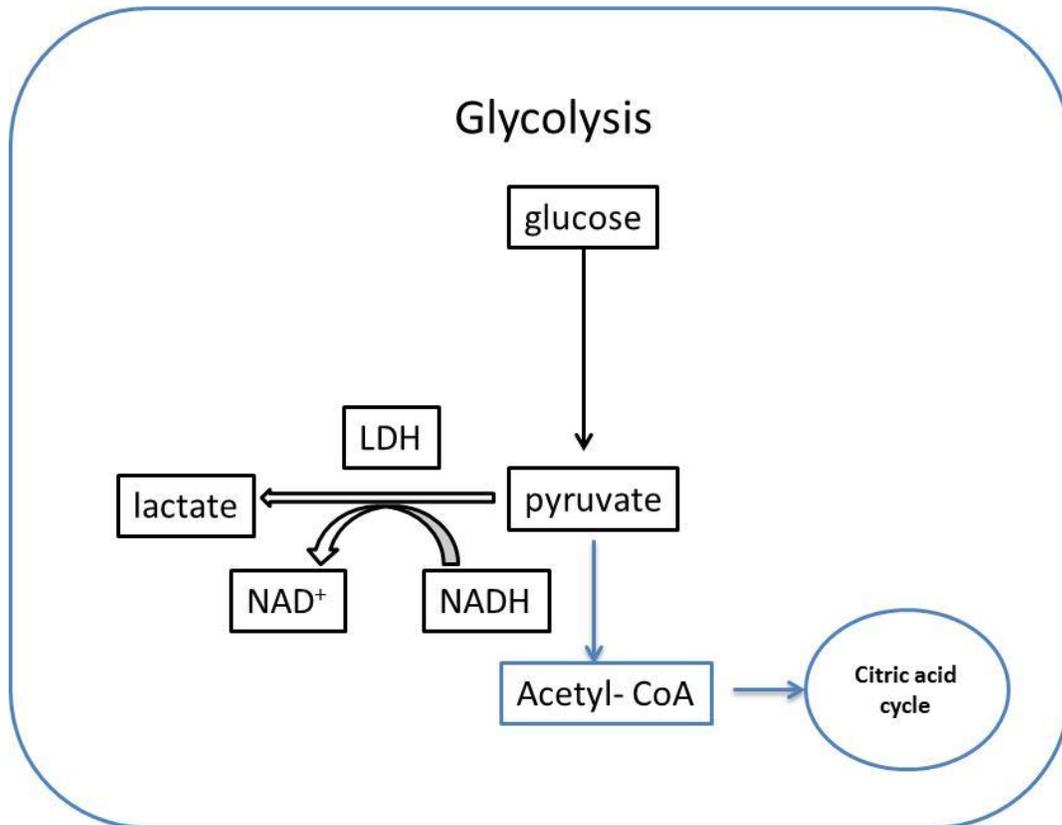


Figure 4.3 Simple diagram showing lactate production from glycolysis as product of lactic fermentation.

4.2.6 Glucose challenge

Cells treated with either 1 μ M ATRA, 100 μ M NAD for 1 day, or untreated cells (control) were harvested by centrifugation ($200 \times g$) for 5 min, resuspended in fresh medium and treated with 25 mM glucose for 1 h at 37 °C. Incubated cell cultures catabolized glucose through glycolysis converting it into products including lactate. Following incubation, cells were separated as pellets, and the supernatant (containing the generated lactate) was removed for the analysis of lactate content using a previously described lactate assay (Section 4.2.5).

4.2.7 Statistical analysis

Statistical analysis of the data was assessed using Fisher's one way analysis of variance (Statview 5.0.1; Abacus concepts, USA) or Student's t-test as appropriate. Data are expressed as means \pm SEM for three separate experiments in triplicate. A difference of $P < 0.05$ was considered statistically significant.

4.3 Results

4.3.1 NAD^+ :NADH ratio during HL60 differentiation

As has been previously shown (Chapter 3), CD38 expression during HL60 differentiation leads to a decrease in intracellular NAD^+ levels in a time dependent manner. So, in this Chapter, it was questioned whether this NAD degradation could cause a further effect on cell metabolism, as NAD(H) is a major coenzyme in glycolysis.

Firstly, both oxidized and reduced nucleotides, NAD^+ (Fig. 4.4 A) and NADH (Fig. 4.4 B) were investigated during the time course of HL60 differentiation. NAD^+ levels significantly decreased throughout differentiation and a similar decline in NADH levels could be seen on the 3rd and 5th days of differentiation compared to each appropriate control.

As the results showed an apparent drop both in the oxidized and reduced forms, the NAD^+ :NADH ratio, as one of the important metabolic indicators, was therefore assessed during ATRA-induced HL60 differentiation (Fig. 4.4 C), to further investigate the consequences of CD38 expression on the nucleotide levels and on their dependent processes. Notably, there was no marked change in the NAD^+ :NADH ratio after 1 and 3 days of differentiation, i.e. the ratio remained relatively stable during early differentiation.

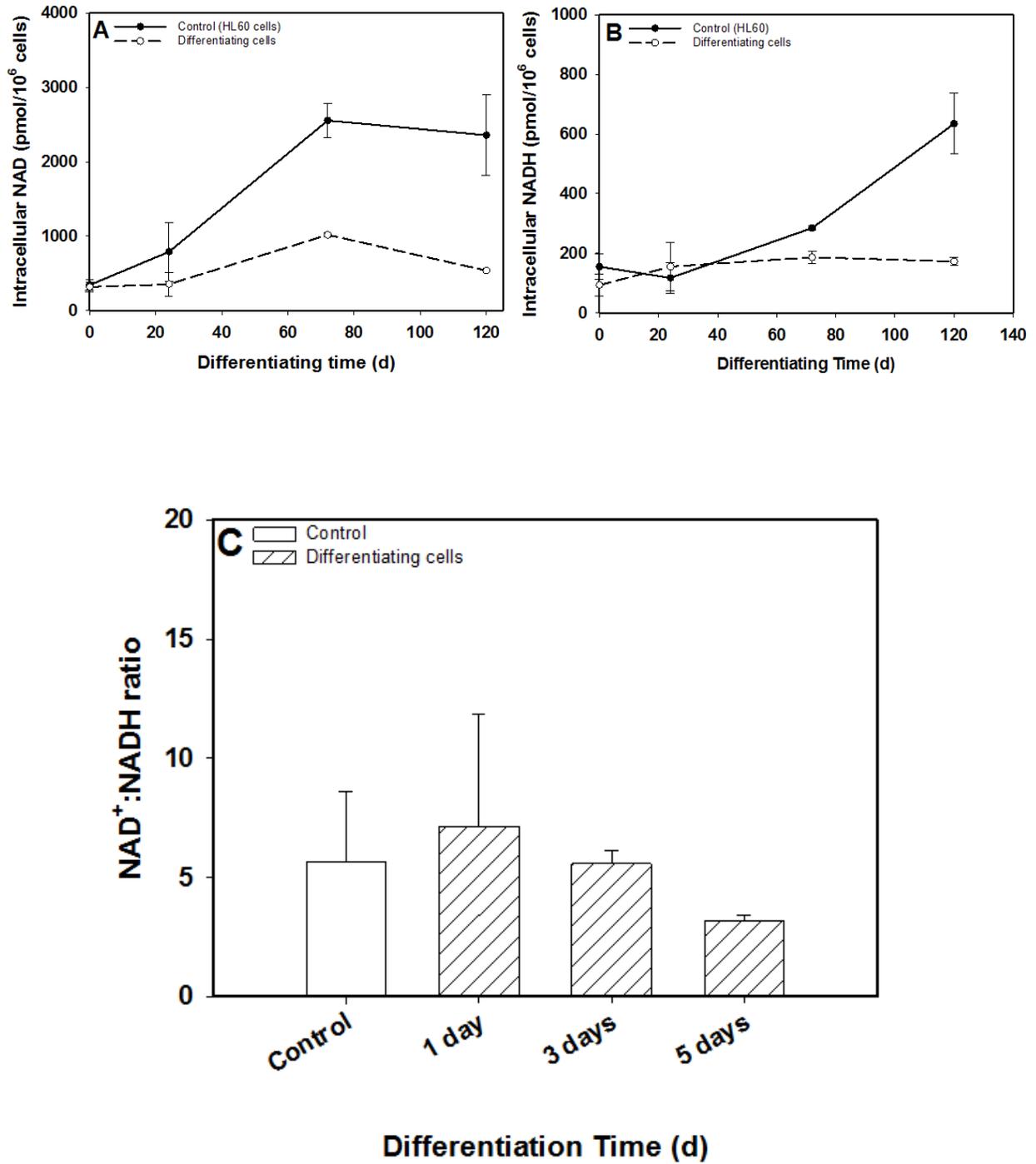


Figure 4.4 Time course of ATRA induced differentiation of HL60 cells over 5 days comparing to HL60 (as control), showing (A) intracellular NAD levels (B) intracellular NADH levels (C) the NAD⁺:NADH ratio. Data are means ± SEM, n = 2 (3-6 measurements per replicate).

4.3.2 Effect of low intracellular NAD levels on lactate levels before and after glucose application and during cell differentiation

To assess the effect of lowered NAD levels on cell physiology lactate production (the product of lactic fermentation) levels in the medium was measured, as it was expected that lactate levels might be reduced when NAD levels dropped due to the effect of lower levels of NAD on glycolysis. The data revealed that HL60 cells treated with ATRA showed a negligible, but significant decrease in lactate accumulation on days 1-3 after induction of HL60 differentiation compared to the control. However, the lactate levels after the 4th day of differentiation were not different from the control (HL60), whereas they increased at day 5 of differentiation in comparison to the control as shown in Figure 4.5. These results suggest that lowered NAD levels might have an effect on glycolysis activity.

The lactate production during cell differentiation was further investigated after supplying the glucose (25 mM) to the cells. In this test and after 1 day of HL60 differentiation, cells were treated for 1 h with 25 mM glucose. Glucose was used to assess the glycolytic activity and to investigate whether glycolysis can potentially use the glucose to produce lactate even at the lowered NAD levels.

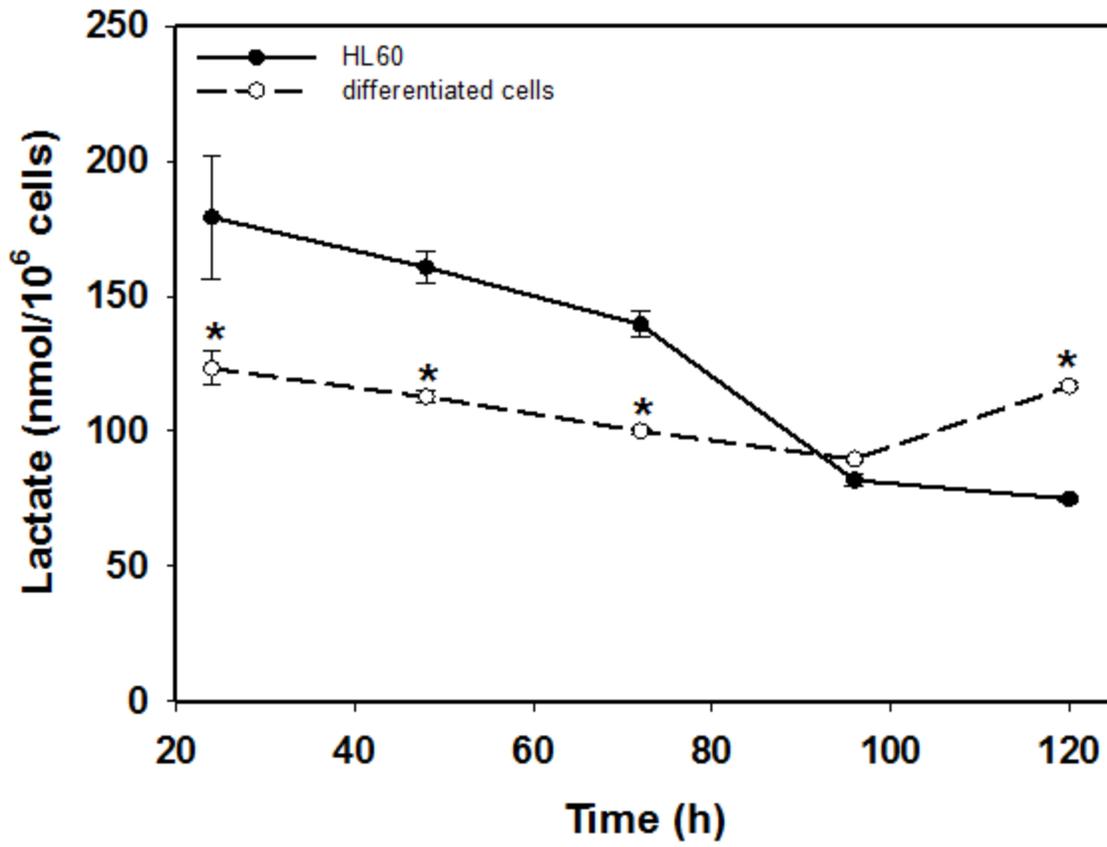


Figure 4.5 Lactate production expressed as nmol/10⁶ cells during the time course of ATRA-induced differentiation of HL60 cells over 5 days compared to untreated HL60 cells (control). Data are means \pm SEM, n = 4 (3 measurements per replicate). * denotes a significant difference from the appropriate control, P < 0.05.

The results (Fig. 4.6) show that the production of lactate was not increased in spite of the presence of 25 mM glucose when compared to the control incubated without glucose (differentiated cells). Treatment with glucose was also performed in HL60 cells with no significant change being recorded. However, this is not the case when the differentiating cells were treated with 100 μ M NAD⁺ for 1 day (to replenish the intracellular NAD, during the differentiation with ATRA; see Chapter 5), before they were treated with or without 25 mM glucose. The results (Fig. 4.6) show that lactate levels in the medium were relatively high after NAD⁺ application compared to the untreated differentiated HL60 cells and were similar to lactate levels in undifferentiated HL60 cells. A similar elevation in lactate levels was also seen in differentiated cells that treated with glucose following the incubation with NAD⁺ for 1 day (Fig. 4.6). However, after treatment with glucose and/or NAD⁺ no changes in lactate levels were seen in HL60 cells, possibly because these cells already had high NAD levels compared to the differentiated cells. These data reveal the effect of low NAD levels on cell metabolism particularly glycolysis, as reflected by lactate levels.

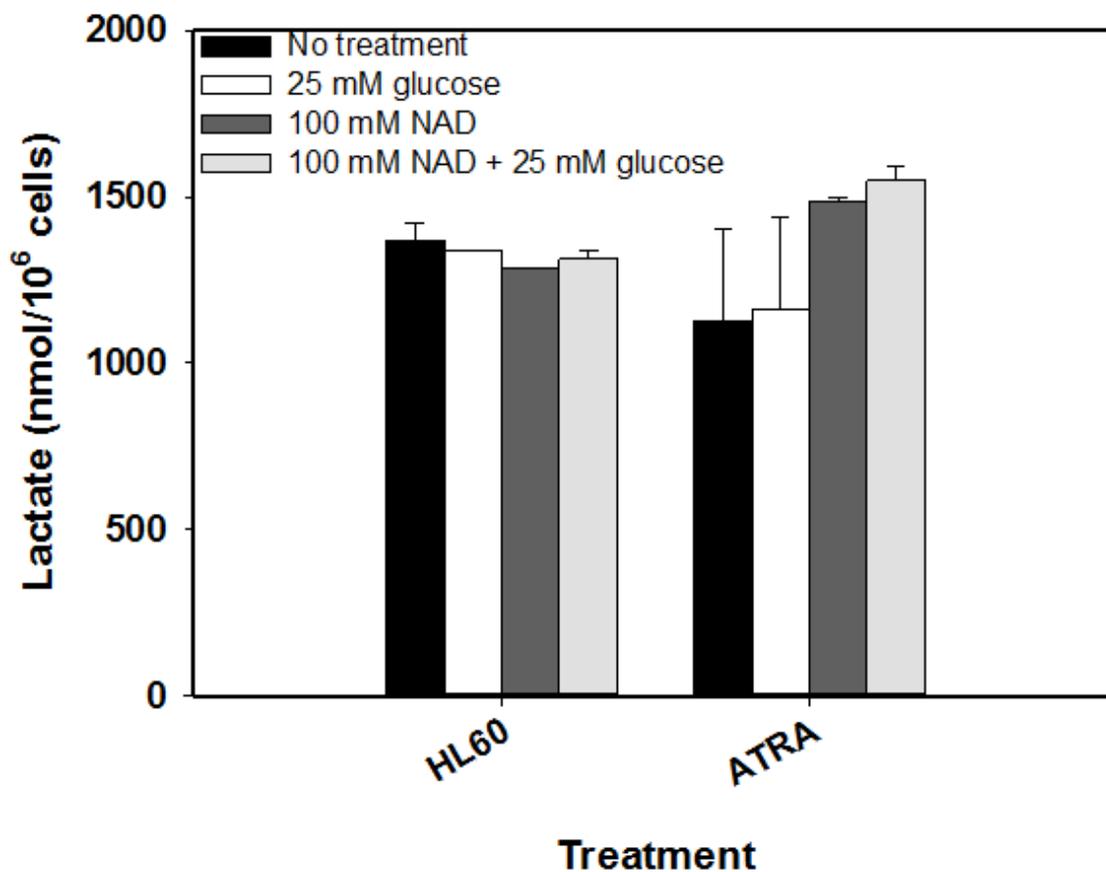


Figure 4.6 Lactate production expressed as nmol/ 10^6 cells after incubation of HL60 cells or 1 day-differentiated cells (either treated or not treated with 100 μ M NAD) for 1 h with 25 mM glucose and compared to appropriate untreated control. Data are means \pm SEM, n = 3 (5 measurements per replicate), p > 0.05.

4.3.3 TBARS production during ATRA-induced HL60 differentiation

To further determine the consequences of the decline in intracellular NAD levels on cell physiology, intracellular reactive oxygen species (ROS) were assessed during ATRA-induced HL60 differentiation. Lipid peroxidation was evaluated by measuring TBARS production (Fig. 4.2). Lipid peroxidation in ATRA-treated HL60 cells, as well as untreated cells, was evaluated after 1, 3 and 5 days incubation. TBARS levels increased significantly in differentiating cells in a time-dependent manner (Fig. 4.7) compared to the appropriate control, reaching highest levels on day 5.

Taken together, these data suggest that an imbalance in the oxidant/antioxidant status might have occurred, as high lipid peroxidation levels might reflect low antioxidant levels which might be a consequence of NAD depletion.

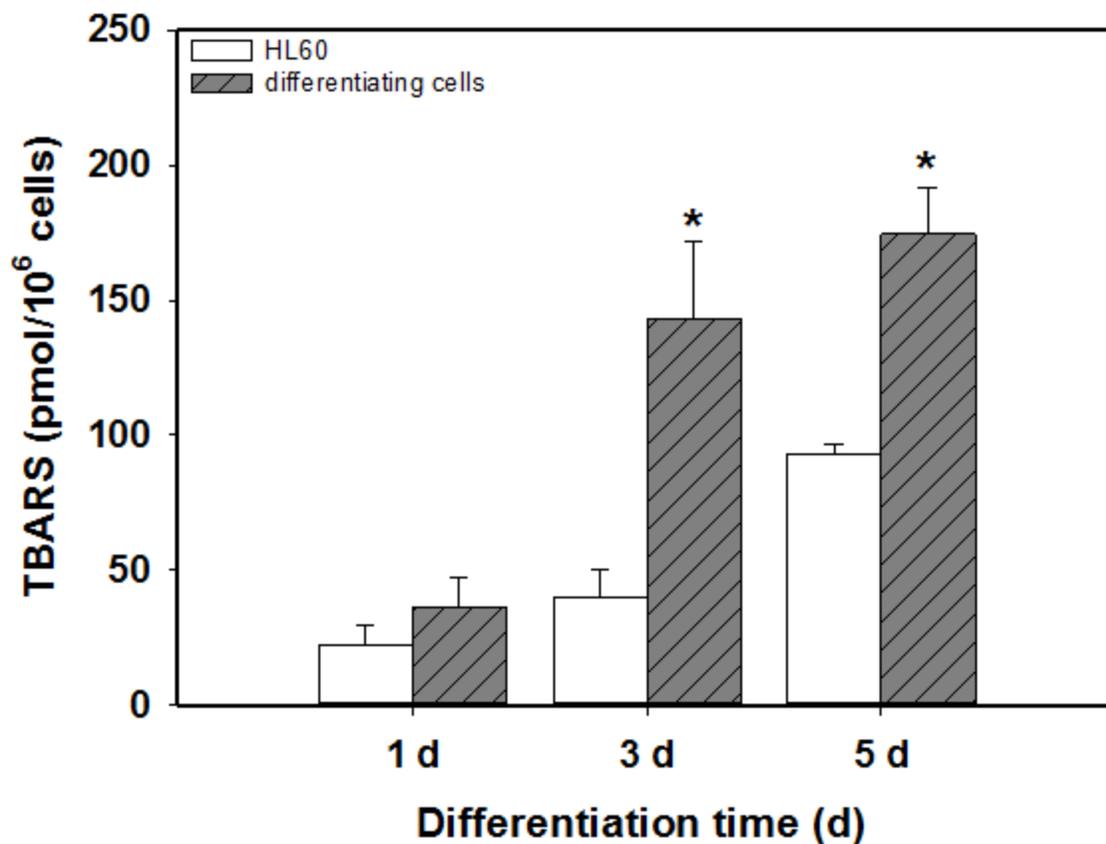


Figure 4.7 Lipid peroxidation as evaluated by TBARS levels during the time course of HL60 differentiation over 5 days comparing to untreated HL60 cells (control). Data are means \pm SEM, $n = 3$ (3 measurements per replicate). * denotes a significant difference from each appropriate control, $P < 0.05$.

4.3.4 Total glutathione levels

ATRA-induced HL60 differentiation seems to be accompanied by an increase in oxidative stress (as measured by TBARS levels) that may be due to the effect of CD38 expression and the significant drop in NAD levels. To further investigate this, a key cellular antioxidant system was also investigated by measuring total glutathione (GSH) levels during cell differentiation (Fig. 4.8).

A significant elevation in glutathione levels (oxidized GSSG and reduced GSH) after one day of differentiation (Figure 4.8) was observed, with less increase after three days of differentiation compared to the control. However, glutathione levels returned to control levels by the 5th day of differentiation.

The significant increase in glutathione levels after one day of differentiation suggests the involvement of glutathione during the differentiation as an antioxidant. However, glutathione levels were not further increased during the 3rd and 5th days of differentiation. These observations suggest a link between NAD depletion and glutathione levels; they also suggest that NAD depletion-mediated by CD38 might disturb the balance in the oxidant/antioxidant state during the differentiation.

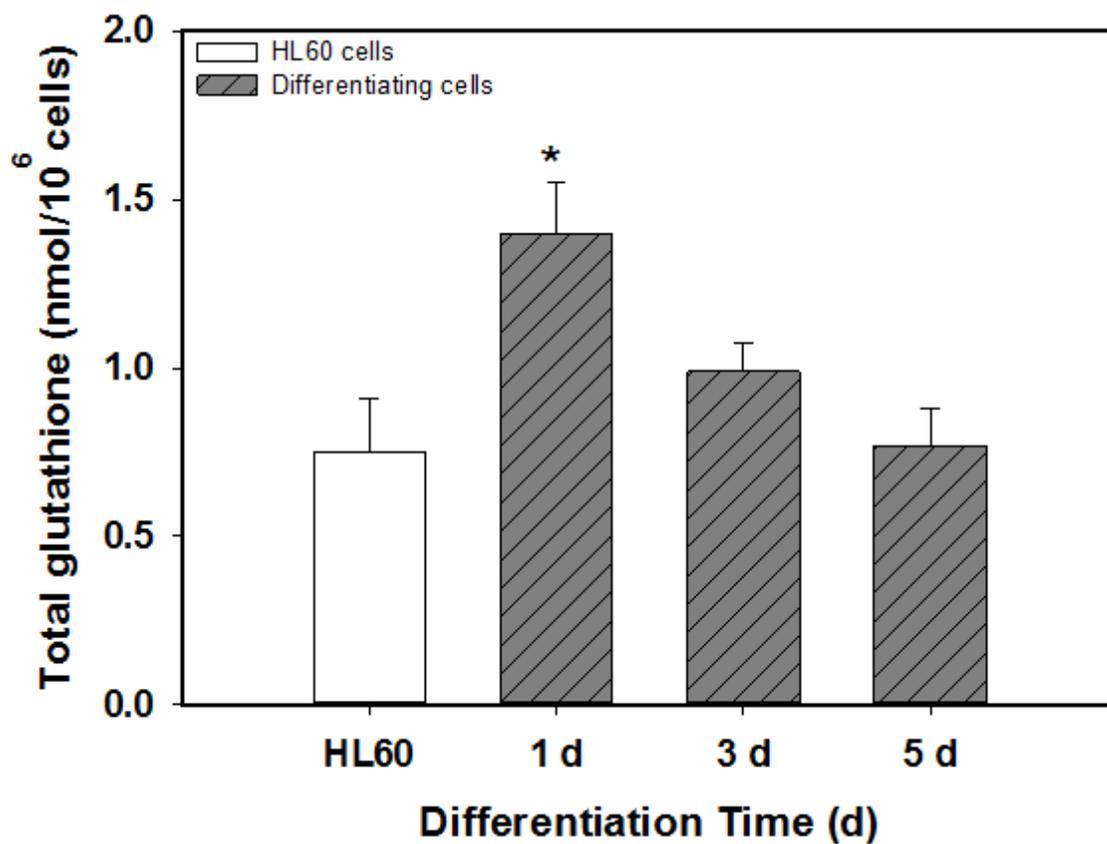


Figure 4.8 Time course of ATRA-induced HL60 differentiation over 5 days showing the increase in total glutathione levels after day 1 of differentiation but not after 3 and 5 days comparing to untreated HL60 cells (control). Data are means \pm SEM, $n = 4$ (4 measurements per replicate). * denotes a significant difference from the control (HL60), $P < 0.05$.

4.4 Discussion

As mentioned in Chapter 1, one of the interesting events during HL60 differentiation is the regulation of CD38 activity which could affect NAD levels over time. Although the pyridine nucleotides, NAD^+ and NADH, have been shown to be important for glycolysis and its regulation (Tilton *et al.*, 1991) and as vital cofactors for numerous enzymes, no previous studies or explanations are available for the effects of the apparent depletion of NAD levels on the cell metabolism, including lactate accumulation, NAD^+ :NADH ratio, antioxidant status represented by glutathione levels and TBARS levels (as a lipid peroxidation marker) during HL60 differentiation. Low NAD levels might affect cell physiology particularly in cells expressing CD38 (for instance in leukemia).

In this Chapter, cell metabolism was first investigated by measuring the NAD^+ :NADH ratio during HL60 differentiation using ATRA. In this study, levels of both nucleotides (NAD^+ , NADH) were significantly decreased. Surprisingly, despite the significant decreases in NAD^+ and NADH levels during the differentiation process, there were limited changes in the NAD^+ :NADH ratio during early differentiation. The NAD^+ :NADH ratio has been suggested to be relatively constant in order for normal physiological processes to proceed (Barron *et al.*, 2000); NAD is a coenzyme for over 700 oxidoreductases, such as glyceraldehyde-3-phosphate dehydrogenase and the pyruvate dehydrogenase complex that catalyze numerous biochemical reactions in cells (Matthew *et al.*, 2000). For instance, in cancer cells the NAD^+ :NADH ratio is suggested to be constant, because the high glycolytic rate generates excessive pyruvate and NADH, which are converted to lactate and NAD^+ by the action of lactate dehydrogenase (LDH), thereby maintaining the stability of the NAD^+ :NADH ratio (Sun *et al.*, 2012). Ultimately, the

NAD⁺:NADH ratio plays an important role in regulating the intracellular redox state (Droge, 2002). The NAD⁺/NADH redox state also influences the production of ROS, since ROS production by the respiratory chain increases as the NAD⁺/NADH redox pair becomes more reduced (Starkov and Fiskum, 2003). Thus, in the current study, the negligible change in the ratio might also be linked with ROS generation during cell differentiation. Interestingly, in the current study, the data for NAD⁺:NADH ratio, is within the range of previously reported ratios: 3-10 in mammals (Swierczynski *et al.*, 2001) and 0.03-4 in several cell lines derived from mice (Gaikwad *et al.*, 2001; Sanni *et al.*, 2001).

The second factor related to the effects of lowered NAD levels during HL60 differentiation on glycolysis is lactate accumulation. Studies on HL60 differentiation using ATRA, in this Chapter, indicated that there was a relative decrease in lactate production during the early days of differentiation compared to undifferentiated HL60 cells and that this was correlated with the drop in NAD levels which might suggest a small effect on glycolysis at this stage. This decrease in lactate accumulation was also previously shown during HL60 differentiation with DMSO (Wu *et al.*, 1991). Interestingly the presence of additional glucose failed to increase the glycolysis rate as shown by low lactate production. However, the same results were not obtained with NAD⁺ application. These results suggest that the change in lactate accumulation might be linked to the change in NAD levels during the differentiation, but that it might be independent of changes in glucose levels. The lowered lactate production during early differentiation might be caused (a) by glycolysis dysfunction as a result of the lowered NAD levels, and (b) by ongoing metabolism of pyruvate via the Krebs' cycle and oxidative phosphorylation. However, the increase in lactate production during the last days of differentiation might be because when HL60 cells differentiate to neutrophil-like cells they lose mitochondrial function and hence rely on increased glycolysis

(lactic fermentation), like neutrophils, which rely mainly on glycolysis for the generation of ATP (van Raam *et al.*, 2008).

However, it is also worth mentioning that HL60 cells show relatively high lactate production compared to the differentiated cells. This might suggest that lactic fermentation is a dominant pathway for energy production in HL60 cells (Boyunaga *et al.*, 2011). It is well known that a variety of cancer cells show high rates of lactate production from glucose, and an enhanced rate of lactic fermentation, despite the presence of oxygen and functional mitochondria; this is known as the Warburg effect (Warburg, 1956; Baggetto, 1992). This shift in cell metabolism ensures the propagation and survival of cancer cells, and allows them to obtain ATP at a faster rate through a simpler process (Tennant *et al.*, 2009), without requiring oxidative metabolism (Boyunaga *et al.*, 2011). The enhancement of glycolytic activity is also thought to provide sufficient pyruvate, which might work as an antioxidant in cancer cells (Brand and Hermfisse, 1997). Lactic fermentation might also be preferred in leukemia cells. If so, one might expect that in CD38⁺ leukemia, in addition to a high demand for NAD as the substrate for CD38, there will be a requirement for high levels of NAD to maintain the high rate of lactic fermentation. Low NAD levels might cause poor physiological consequences (such as a resistance to apoptotic cell death) and that might explain the reason for poor consequences in CD38⁺ leukemia patients.

The remaining metabolic indicators used to evaluate the consequences of low NAD levels on redox state and cell physiology in cells expressing CD38, were TBARS (an indicator of lipid peroxidation) and total glutathione (as a key antioxidant). The results confirmed that when CD38 expression was increased following ATRA treatment, lipid peroxidation was also enhanced, suggesting a link between CD38 expression mediating a lowering in NAD levels and the increase

in lipid peroxidation. One possible explanation for this is that CD38 might mediate intracellular $O_2^{\bullet-}$ production via cADPR/ Ca^{2+} -mediated activation of NAD(P)H oxidase (NOX4). The latter has been reported to be a major source of ROS in the vasculature (Mohazzab *et al.*, 1994; Xu *et al.*, 2012). Interestingly, the production of ROS was markedly reduced in embryonic fibroblasts from CD38^{-/-} mice (Ge *et al.*, 2010). This strongly suggests a connection between CD38 and ROS production; undifferentiated HL60 cells, which are CD38⁻, have lower TBARS levels than the differentiated (CD38⁺) cells. Hence, in common with differentiated HL60 cells, high ROS levels might be also expected in CD38⁺ leukemia compared to CD38⁻ leukemia. Interestingly, a relative increase in the oxidative stress state has been observed in CD38 positive CLL patients compared to CD38 negative patients (Ortin *et al.*, 2012). These data suggest a possible reason for the observed resistance to apoptotic cell death and the induction of cell proliferation in cells expressing CD38, since high ROS might contribute to a resistance to apoptotic cell death and consequently poor prognosis in leukemia.

In addition to evaluating the oxidative state, the antioxidant level was also evaluated by measuring glutathione, which is the major non-enzymatic component of intracellular antioxidant defenses, and is present both in a reduced, biologically active form (GSH), and in an oxidized form, namely glutathione disulphide; GSSG (Circu and Aw, 2010). During HL60 differentiation, the results showed a negligible increase in total glutathione levels in the first 24 h with decreased levels in the periods afterwards. Decreased glutathione levels might reflect depletion of the non-enzymatic antioxidant reserve, due to overproduction of ROS (consistent with the TBARS results). GSH works as a vital intracellular scavenger of ROS, protecting the cells against toxic free radicals (Wu *et al.*, 2004). Another possible explanation is that a decline in NAD levels might affect glutathione levels, i.e. that glutathione might be NAD-dependent. However, the

early increase in glutathione levels might suggest low ROS production. Interestingly, it has been demonstrated that GSH levels are dynamic during HL60 differentiation when stimulated by several inducing agents (Krance *et al.*, 2010). Finally, a measurable change in the redox status during ATRA-induced HL60 differentiation was seen. These changes might be linked to the elevation in CD38 activity and a reduction in NAD levels.

The indicated declines in NAD⁺ levels that are mediated by CD38 activities might have a further consequence on NADP⁺ levels, since the biosynthesis of NADP⁺ requires the phosphorylation of NAD⁺ in a reaction catalysed by NADK (ATP:NAD 2-phosphotransferase) as shown in Figure 4.9 (Pollak *et al.*, 2007). Hence, a decline in NADP⁺ might be occurring due to the drop in NAD⁺ levels. If so, one might expect further consequences on NADP-dependent processes, for instance NADPH synthesis. The latter is synthesised through NADP⁺-specific dehydrogenases, including glucose-6-phosphate dehydrogenase (G-6-P), isocitrate dehydrogenase (IDP), malic enzyme (ME) and aldehyde dehydrogenase (ALDH), (Fig. 4.9). Alternatively, NADPH can also be generated through phosphorylation of NADH via NAD kinase (Pollak *et al.*, 2007). It is worth noting that the phosphorylated nucleotide, NADPH, has been shown to be crucial in maintaining an effective defense against oxidant-mediated damage. It has been shown to be essential in the function of catalase and the maintenance of reduced glutathione, both of which have important roles in the antioxidant defense as previously confirmed in the erythrocytes (Gaetani *et al.*, 1989). NADP⁺ is also involved in signal transduction as a precursor of the messenger molecule, NAADP. Hence, a decline in NAD might have an effect on NADP⁺ levels and cause a disturbance in the antioxidant defense system, or it might also affect other NADP-dependent processes.

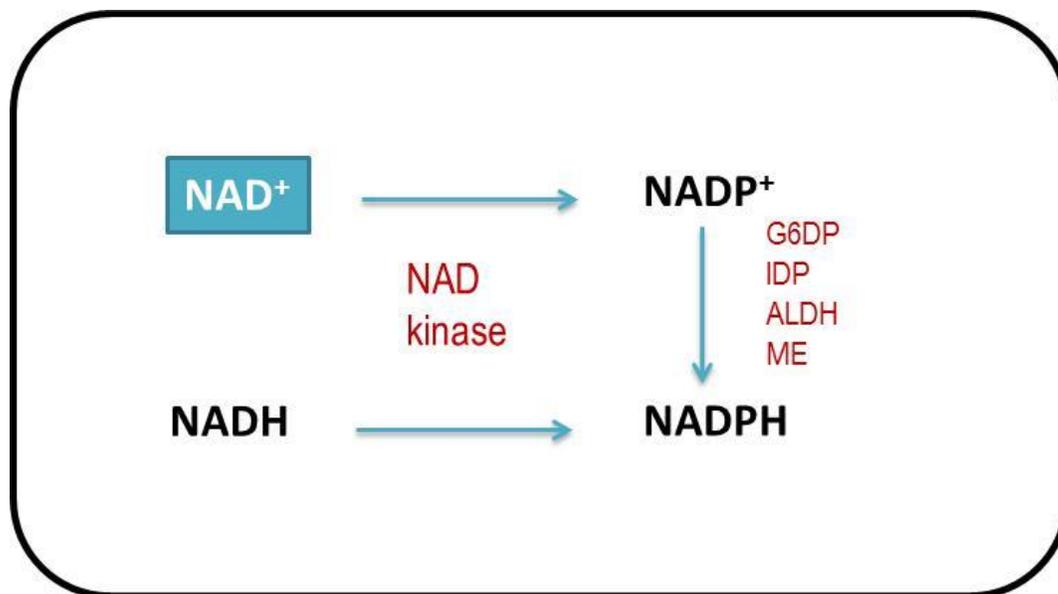


Figure 4.9 Simple diagram representing generation of NADP⁺ from NAD and NADPH from NADP⁺. Adapted from Pollak *et al.* (2007).

Studies on glutathione levels in leukemia are generally partial and contradictory. An elevation of glutathione levels in CLL patients was reported to cause cell survival and also to protect the cells from drug-induced cytotoxicity (Zhang *et al.*, 2012). However, a decrease in cellular glutathione was also indicated in CLL patients along with an increase in TBARS levels (Trachootham *et al.*, 2008; Ortin *et al.*, 2012). Interestingly, disabling this protective mechanism significantly sensitizes CLL cells to drug treatment (Zhang *et al.*, 2012). This seems to be because under mild oxidative stress, protein glutathionylation was shown to regulate the functions of multiple proteins (Ghezzi, 2005). For instance, it has been found that glutathionylation of the antiapoptotic protein MCL1, a novel substrate of glutathionylation, regulates its stability and protects it from being cleaved by caspase-3, and thus promotes cell survival (Trachootham *et al.*, 2008). However, removal of glutathionylation by a glutathione-depleting agent, such as PEITC, rendered MCL1 susceptible to rapid proteolytic cleavage, leading to leukemia cell death

(Trachootham *et al.*, 2008). It is worth noting that recent studies are targeting the molecular mechanisms that control the redox environment in leukemia cells, made up from the production of ROS and the expression and activity of antioxidant enzymes. It has been demonstrated that leukemia cells gain proliferative and survival advantages by manipulating this system. Therefore, ROS production by the mitochondrial electron transport chain, NADPH oxidase, xanthine oxidoreductase, and cytochrome P450, have all been targeted to promote leukemia cell death (Irwin *et al.*, 2013). In this Chapter, the results suggest that CD38 might also serve as a possible target to regulate the redox system specifically in CD38⁺ leukemia cells through controlling its role in ROS production.

The data presented in this Chapter reveal novel findings concerning the effects of NAD depletion on cell physiology. As discussed above, NAD depletion during HL60 differentiation caused an enhancement of lipid peroxidation, and relative depletion of released lactate and total glutathione levels, while the NAD⁺:NADH ratio remained relatively constant. These data raise the possibility that lowered NAD levels might have effects on NAD-dependent processes such as glycolysis, depending on the availability of NAD⁺ (Kristian *et al.*, 2011). An insufficient supply of NAD⁺ limits cellular energy production (Wilhelm and Hirrlinger, 2012), and it might also affect cell survival and cause cell death (as in differentiated HL60 cells). However, the consequences of lowered NAD levels via CD38 expression in leukemia cells might promote anti-apoptotic effects, as shown in Figure 4.10.

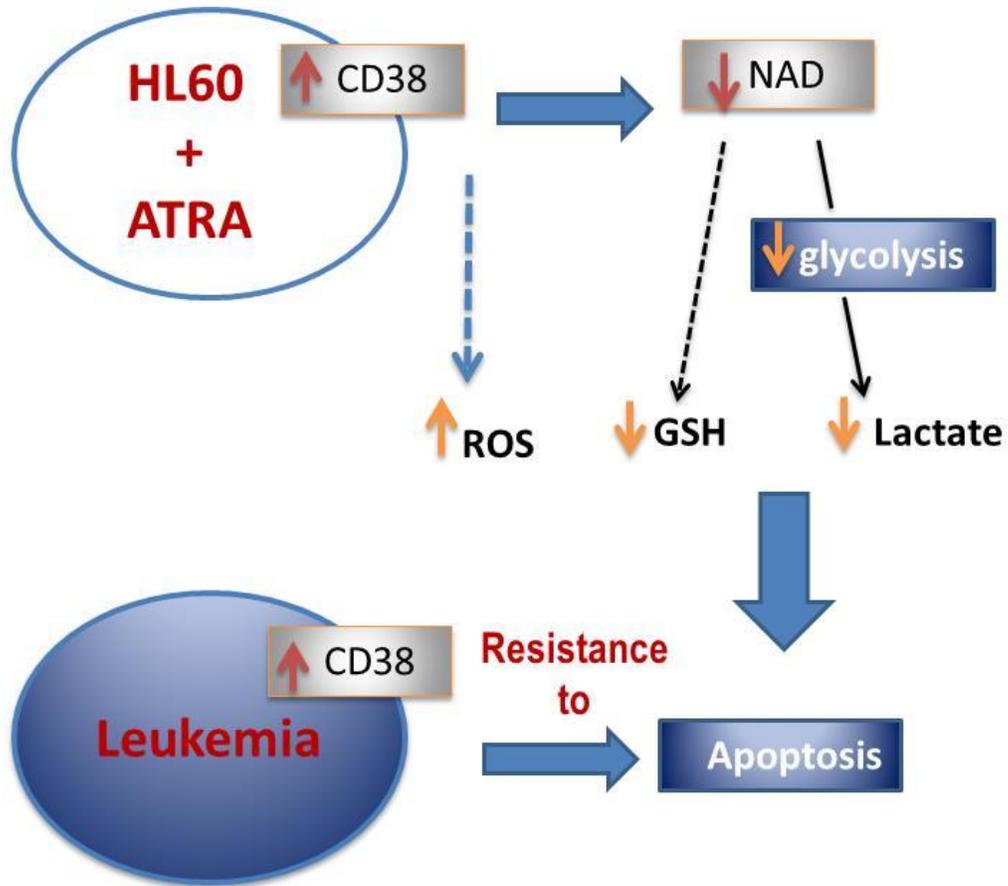


Figure 4.10 The consequences of lowered intracellular NAD levels on cell metabolism. This diagram describes the role of CD38 expression as a determinant of NAD- mediated cell survival, leading to either apoptosis in differentiated HL60 cells or anti-apoptotic effects in CD38⁺ leukemia cells.

CHAPTER 5

REGULATION OF CD38 EXPRESSION

5.1 Introduction

The involvement of CD38 expression in various types of cells and in several diseases makes it a possible therapeutic target, especially in leukaemia. Thus, transcriptional regulation of CD38 has been extensively studied. Cytokines and hormones are two major groups of signalling molecules implicated in the regulation of CD38 expression. In CLL, studies have shown that interferons (IFN- α , - β and - γ), IL-2 and IL-4 increase CD38 mRNA expression (Bauvois *et al.*, 1999; Deaglio *et al.*, 2003; Levesque *et al.*, 2006). Furthermore, the effects of tumour necrosis factor- α (TNF- α), IFN- γ , IL-1 β and the Th2 cytokine, IL-13, on the increase of CD38 mRNA have also been studied in human airway smooth muscle (HASM) cells (Deshpande *et al.*, 2004). Further studies suggest a transcriptional upregulation of CD38 by TNF- α in myometrial cells (Barata *et al.*, 2004) and macrophages (Iqbal, and Zaidi, 2007). Moreover, in human monocytes and the derived lines U937 and THP-1, the study of Musso *et al.* (2001) found that IFN- γ and IL-2 increased CD38 expression but that lipopolysaccharide (LPS), TNF- α and GM-CSF had no detectable effects. However, further studies showed that LPS increased CD38 mRNA expression in J774 macrophage cells (Lee *et al.*, 2012a).

The effects of hormones on CD38 expression have been studied in myometrial tissue (Dogan *et al.*, 2002; 2006). In ovariectomized rats, administration of estradiol-17 β caused a significant induction of CD38 expression in the myometrium (Dogan *et al.*, 2004). However, glucocorticoids (a class of steroid hormones) have been found to inhibit CD38 expression as shown in HASM cells (Kang *et al.*, 2006; 2008).

Transcriptional regulation of CD38 has been also investigated in the HL60 cell line during differentiation with various agents. It was observed that differentiation of HL60 to granulocytes induced by isonicotinic acid, led to CD38 expression (Iwata *et al.*, 2003). Moreover, $1\alpha,25$ -dihydroxy vitamin D₃, which is an inducer of differentiation of HL60 towards monocyte-like cells, has also been shown to induce CD38 expression (Stoekler *et al.*, 1996). Importantly, the differentiation of HL60 into granulocytic cells using ATRA is accompanied by the induction of CD38 expression (Drach *et al.*, 1993), while DMSO has no effect on CD38 expression (Iwata *et al.*, 2003; Guida *et al.*, 2004). It was suggested that ATRA-induced CD38 expression is mediated by direct transcriptional regulation via activation of a RAR/RXR heterodimer interacting with a retinoic acid response element located in the first intron of the CD38 gene (Mehta *et al.*, 1997). In undifferentiated-HL60 cells, a mitochondrial NADH dehydrogenase inhibitor, rotenone, was also shown to induce CD38 expression (Matsunaga *et al.*, 1996). Importantly, the finding of appropriate regulators that inhibit CD38 mRNA expression might be a useful approach, especially in CD38⁺ subset patients. Compared to CD38⁻ leukemia subset patients, inhibition of CD38 mRNA production in CD38⁺ leukemia might successfully inhibit cell proliferation and reduce resistance to apoptosis, and hence improve the prognosis.

Collectively, several regulators of CD38 expression have been suggested that mostly regulate CD38 mRNA, such as ATRA, cytokines and hormones. However, regulation of CD38 expression by its substrate, NAD, has not been studied. The novel work in this chapter suggested firstly that CD38 expression might be regulated by manipulating NAD levels, either by inhibiting a key enzyme in NAD biosynthesis, NAMPT, by using FK866 in order to decrease NAD levels or by supplementing cells with NAD to elevate the intracellular levels. Manipulation of NAD levels might be involved in CD38 regulation indirectly through the effect of NAD availability on

sirtuin and PARP, as NAD-consuming enzymes. Alternatively, NAD might be involved in CD38 transcriptional regulation via a protein such as C-terminal binding protein (CtBP). This study has provided the first evidence indicating that controlling NAD levels can attenuate CD38 mRNA expression.

5.2 Materials and methods

5.2.1 Materials

Kuromanin was purchased from Sigma (Poole, UK), NAD was from Melford (Ipswich, UK) and FK866 (APO866, (E)-N-[4-(1-benzoylpiperidin-4-yl) butyl]-3-(pyridin-3yl) acrylamide was from Axon Medchem (Groningen, The Netherlands). Plastic boxes for oxygen exposures and cylinders containing custom mixtures of O₂, CO₂ and N₂ were all obtained from the Diving Diseases Research Centre (DDRC, Plymouth, UK).

5.2.2 Evaluation of CD38 expression in differentiating cells after treatment with kuromanin

Differentiated cells treated with 30 µM kuromanin for 6, 18 and 24 hours were subjected to qPCR analysis for CD38 expression as previously described in Chapter 2, Section 2.7.

5.2.3 Determination of the effects of addition of FK866 or NAD on intracellular NAD levels, cell proliferation and CD38 expression in cell lines

HL60 and RAJI cells (5×10^5 cells ml⁻¹) were incubated in 24-well plates at 37 °C in RPMI-1640 culture media in the presence or absence of 1-100 µM NAD⁺ or 1-1000 nM FK866. After 24 hours cells were removed from each well and used for analysis of intracellular NAD levels and MTT assay (Sections 2.9.2.1 and 2.6 respectively).

CD38 expression in RAJI, HL60 and differentiating HL60 cells were determined in the presence or absence of 100 μM NAD⁺ or 100 nM FK866 for 6, 12 and 24 hours incubation at 37 °C, by quantitative real-time qPCR (see Chapter 2, section 2.7). The $\Delta\Delta\text{C}_T$ method was used to determine the relative quantity of CD38 mRNA in samples.

5.2.4 Oxygen exposure protocol

HL60 or RAJI cells ($1-2 \times 10^6 \text{ ml}^{-1}$) were placed in 6-well plates in air tight plastic boxes (21.5 cm \times 21.5 cm \times 11 cm; total volume five litres) prepared at the DDRC (Fig. 5.1). Boxes were flushed for 5 min with gas mixtures either giving a hypoxic environment (2% O₂, 5% CO₂, 93% N₂ or 5% O₂, 5% CO₂ and 90% N₂) or a hyperoxic environment (95% O₂, 5% CO₂) at a rate of 4 l min⁻¹. The boxes were then sealed and placed at 37 °C in a conventional cell incubator for 30, 60 and 90 min. In each experiment the normoxic controls were incubated under conditions of atmospheric oxygen concentration (21% O₂, 5% CO₂ and 74% N₂). All the cells were grown in RPMI-1640 medium supplemented with 10% FCS.

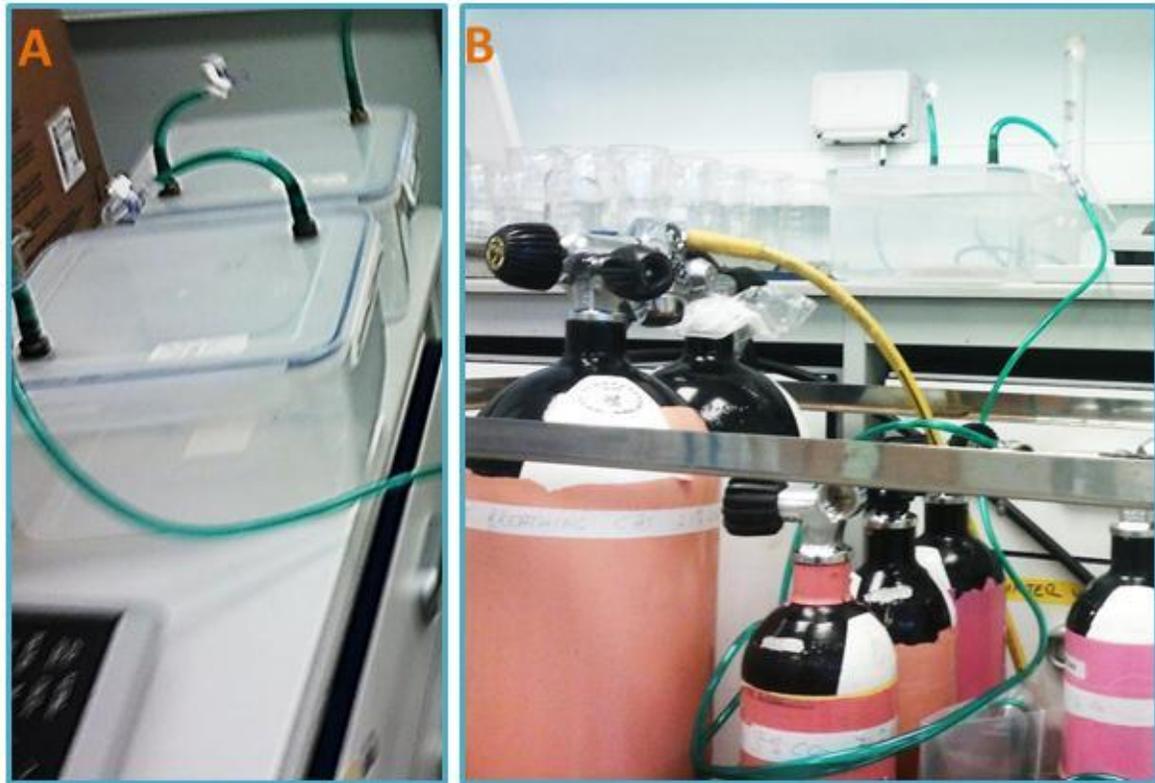


Figure 5.1 (A) boxes and (B) Oxygen cylinders used in normoxia, hypoxia and hyperoxia experiments.

5.2.5 Statistical analysis

Statistical analysis of the data was assessed using Fisher's one way analysis of variance (Statview 5.0.1; Abacus concepts, USA) or Student's t-test as appropriate. Data are expressed as means \pm SEM for three separate experiments in triplicate, unless otherwise stated. A difference of $P < 0.05$ was considered statistically significant.

5.3 Results

5.3.1 Effect of elevated NAD⁺ levels on CD38 expression after kuromanin treatment

It was found previously (Chapter 3) that kuromanin, the novel human CD38 inhibitor, caused an elevation in intracellular NAD⁺ levels. In this Chapter the aim was to establish whether this elevation in intracellular NAD⁺ might regulate CD38 mRNA expression. Interestingly, qPCR results revealed that treatment with kuromanin leads to attenuation of CD38 expression.

The results showed significant inhibition of CD38 mRNA expression in differentiating cells with 30 µM kuromanin and started from as early as 6 h differentiation in the presence of kuromanin (Fig. 5.2). A significant drop in mRNA levels was also shown at 18 h and 24 h incubation compared to each control (differentiating cells without kuromanin). In this respect, low CD38 mRNA expression during kuromanin treatment suggested that it might be regulated by intracellular NAD⁺.

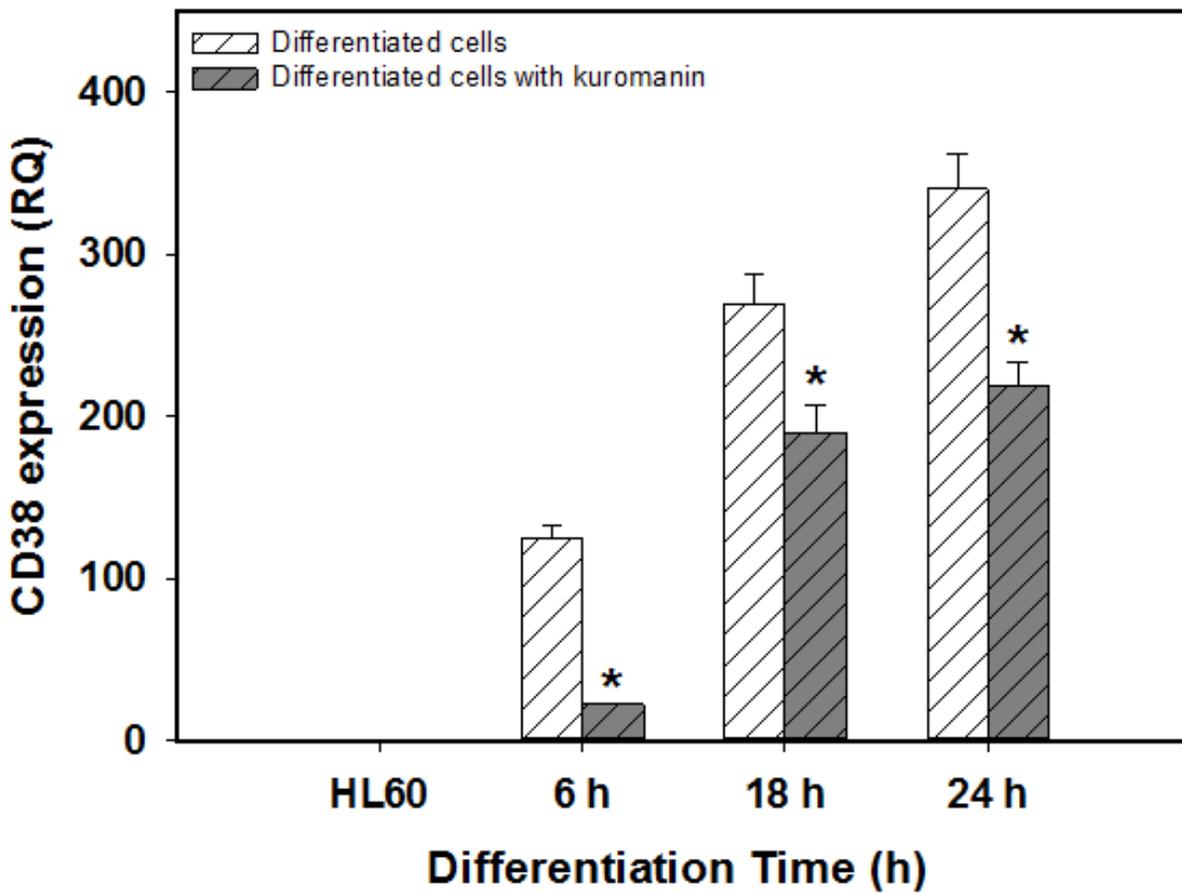


Figure 5.2 Effect of kuromanin (30 μ M) on CD38 expression during the time course of differentiation of HL60 cells with 1 μ M ATRA up to 24 h comparing to differentiated cells without treatment (as control). Data are means \pm SEM, n = 3 (3 measurements per replicate), * denotes a significant difference from each control, P < 0.05.

5.3.2 Manipulation of intracellular NAD⁺ levels by NAD application or using FK866

To further investigate the kuromanin results, the NAD levels in the cells were manipulated by either elevating NAD⁺ levels by NAD⁺ application or decreasing the intracellular NAD⁺ levels after treatment with FK866, based on previously published reports by Billington *et al.* (2008a; 2008b). In this part of the work, firstly it was tested whether NAD⁺ application could be used as a tool to elevate intracellular NAD⁺ levels. Hence, HL60 cells and RAJI cells were incubated separately for 24 hours with 0-100 μM extracellular NAD⁺ at 37 °C. The results showed an elevation in intracellular NAD⁺ levels that was significant in RAJI cells after 24 h incubation with 30 μM and 100 μM NAD⁺, and in HL60 cells with only 100 μM NAD⁺ (Fig. 5.3A).

As intracellular NAD⁺ levels were elevated, the MTT assay was performed to monitor cell vitality during treatment. The results show that treatment with NAD⁺ had an apparent effect on vitality of RAJI cells that was significant with 10 and 100 μM NAD⁺ (Fig. 5.3B). In HL60 cells, a similar effect was seen, but it was not statistically significant (Fig. 5.3B). Collectively, an increase in intracellular NAD⁺ levels was confirmed both in HL60 and RAJI cells with the extracellular NAD⁺ application.

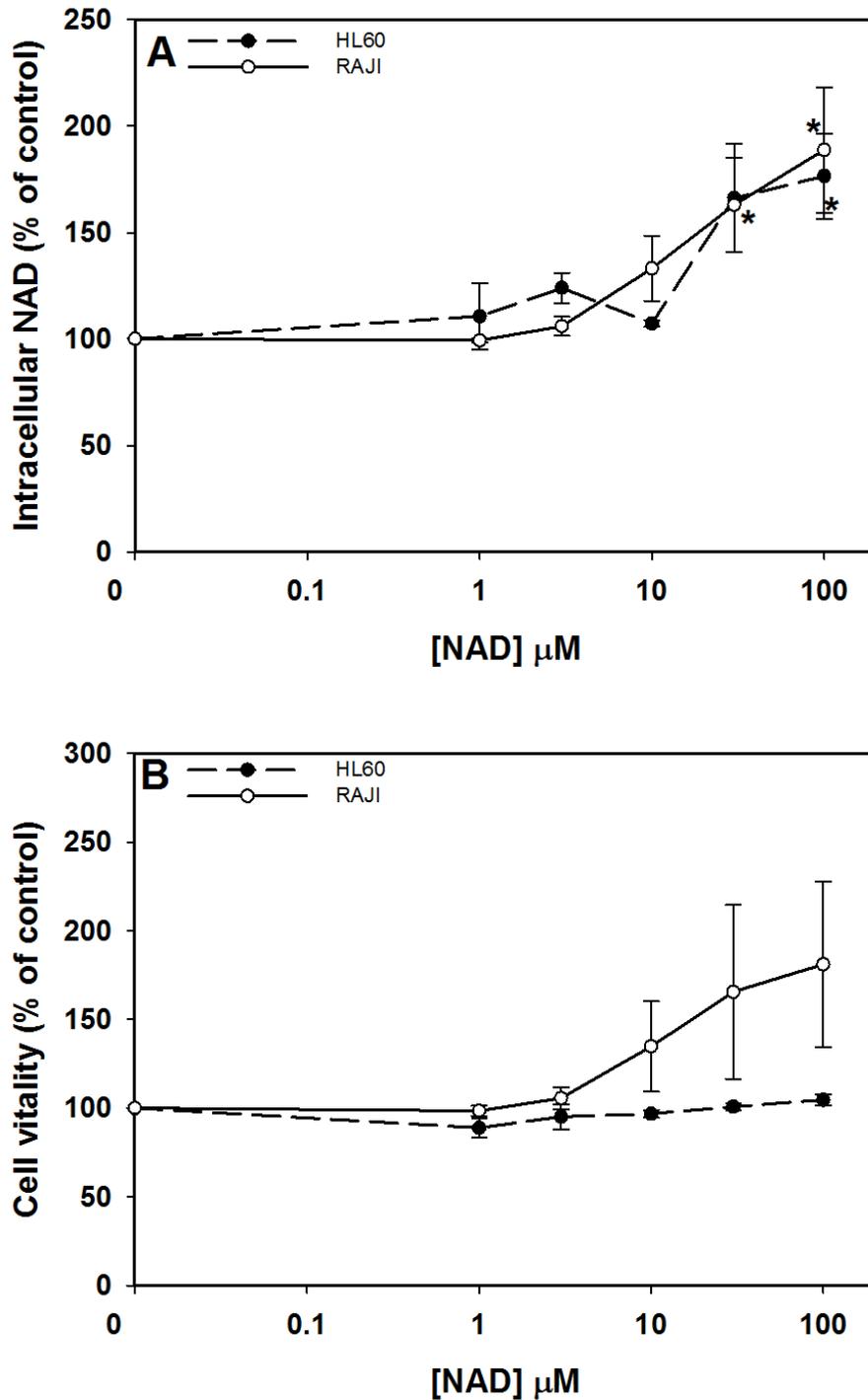


Figure 5.3 Effect of treatment with NAD^+ (0-100 μM) for 1 day on RAJI and HL60 cells comparing to untreated control (100%). (A) Intracellular NAD^+ levels and (B) cell vitality (as determined by MTT assay). Data are means \pm SEM, $n = 3$ (3-4 measurements per replicate). * denotes a significant difference from the control (HL60 or RAJI cells without treatments), $P < 0.05$.

Several FK866 concentrations (0-1000 nM) were also incubated for up to 24 h with HL60 and RAJI cells, and intracellular NAD⁺ levels were determined. A significant reduction in intracellular NAD⁺ levels in RAJI and HL60 cells was evident after 24 h incubation with all FK866 concentrations (Fig. 5.4 A). Thus, FK866 caused a concentration-dependent decrease in intracellular NAD⁺ levels.

Interestingly, intracellular NAD⁺ levels in RAJI cells after treatment with FK866 were lower than in HL60 cells; this may be because RAJI cells already showed lower NAD⁺ levels compared to HL60 cells accompanied by significantly higher CD38 activity. Furthermore, the MTT results have shown that cell vitality was rapidly depleted after 24 h treatment with FK866 (Fig. 5.4 B). A significant drop in cell vitality was evident both in HL60 and RAJI cells and with 1-1000 nM FK866. Moreover, cell vitality in RAJI cells was lower than that in HL60 cells when assayed using MTT reduction. Altogether, the cell vitality and NAD⁺ data in the present study and the effect of treatment with FK866 suggests a high turnover of intracellular NAD⁺, and after treatment with extracellular NAD⁺ suggests the cell's ability to uptake the extracellular NAD⁺.

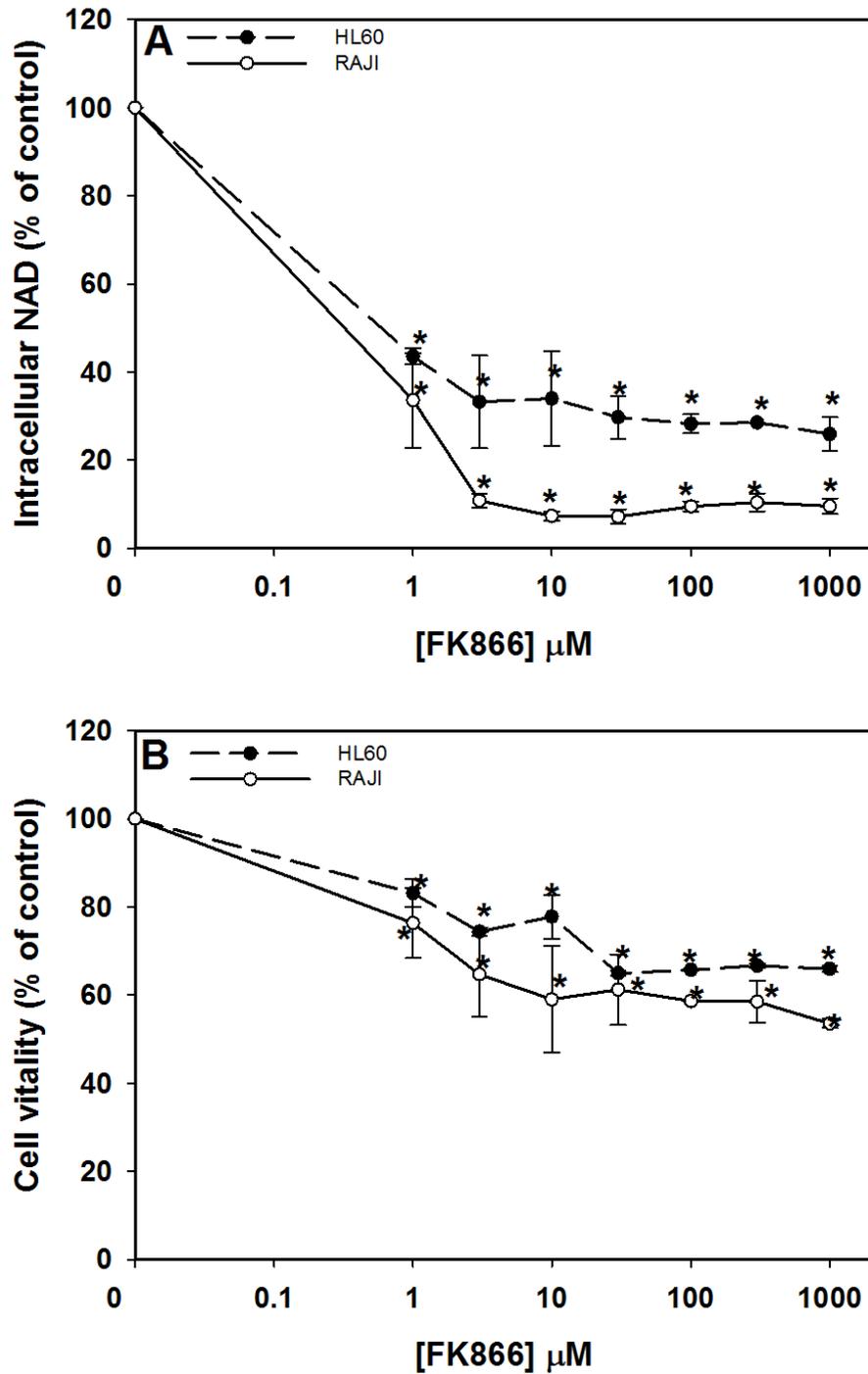


Figure 5.4 Effect of treatment with FK866 for 1 day on RAJI and HL60 cells comparing to untreated control (100%).. (A) Intracellular NAD levels and (B) cell vitality (as determined by MTT assay). Data are means \pm SEM, n = 3 (3-4 measurements per replicate). * denotes a significant difference from the control (HL60 or RAJI cells without treatments), $P < 0.05$.

5.3.3 Effect of intracellular NAD⁺ levels on CD38 expression

In the above section it was confirmed that intracellular NAD⁺ levels in HL60 and RAJI cells were significantly depleted after treatment with FK866 and elevated after extracellular NAD⁺ application. It was of interest to test whether decreasing or elevating intracellular NAD⁺ levels after treatment with FK866 and NAD⁺, respectively, would also participate in the regulation of CD38 expression, in the same way as the effect of intracellular NAD⁺ elevation by kuromanin. Therefore, analysis of CD38 gene expression profiles was performed using qPCR in HL60 and RAJI cells (Fig 5.5A and B, respectively), and during the time course of HL60 differentiation (Fig 5.6).

qPCR analysis of HL60 cells (Fig. 5.5 A) demonstrated that the effect of NAD⁺ (100 μM) or FK866 (100 nM) was not the same at each time point, since an apparent decrease in CD38 expression at 24 h ($P > 0.05$) was found with all treatments, compared to the control (untreated HL60 cells). Also, there was a moderate, but not significant, increase in CD38 expression at 6 h and 12 h incubation with FK866 and NAD⁺. However, FK866 or NAD⁺ application had a similar effect on CD38 expression in HL60 cells.

This experiment was also performed with RAJI cells with comparable results to those with HL60 cells (Fig. 5.5 B). A visible attenuation in CD38 expression was shown at 12 h ($P > 0.05$) and at 24 h ($P < 0.05$) after treatment with FK866 and NAD⁺. However, at 6 h, a notable rise in CD38 expression after treatment with NAD⁺ was observed (but not with FK866) compared to the control. Overall, an apparent decline in CD38 mRNA expression was shown in both HL60 and RAJI cells, particularly after 24 h incubation with FK866 or NAD⁺ application.

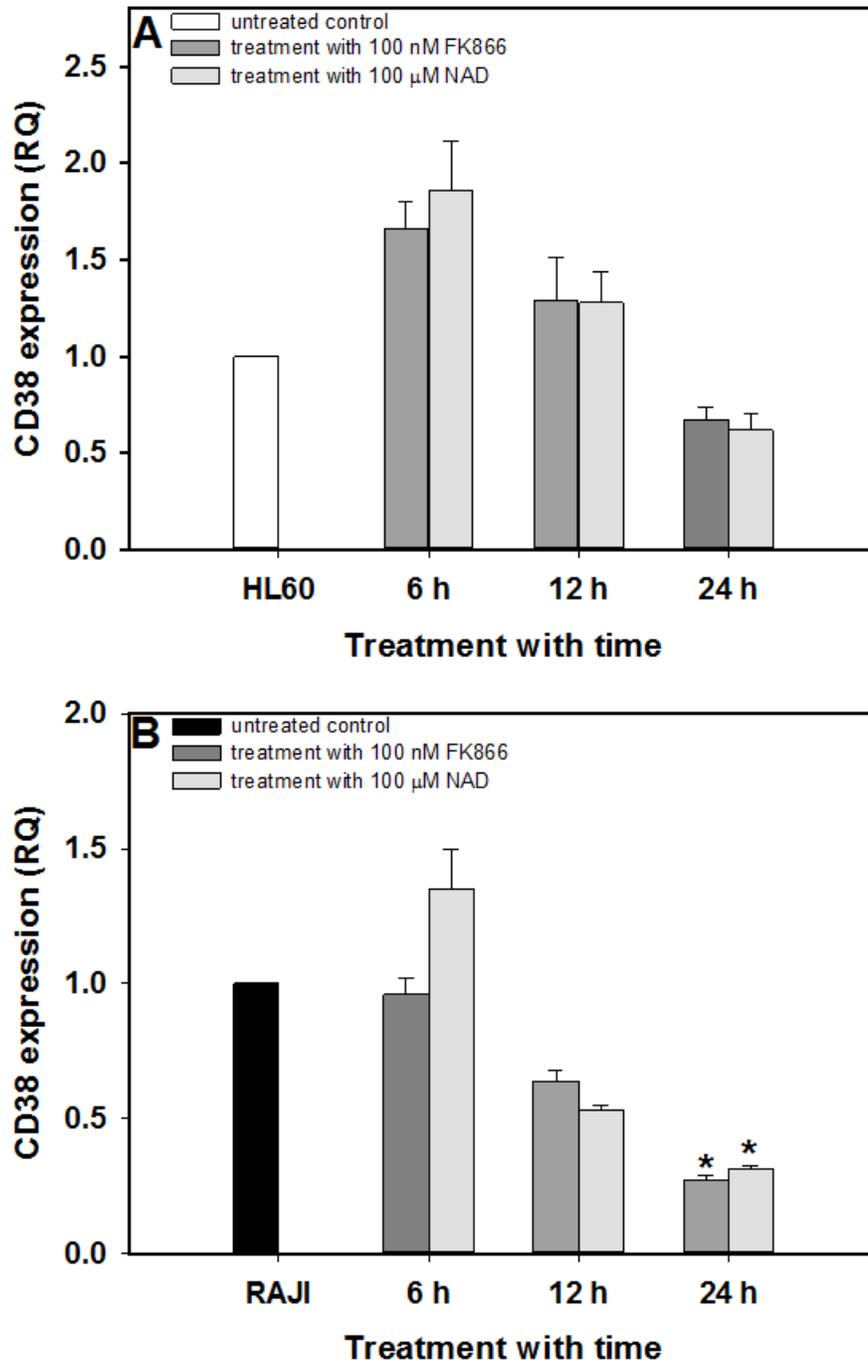


Figure 5.5 Effect of treatment with 100 nM FK866 and 100 μ M NAD⁺ on CD38 expression after 1 day incubation comparing to the control (untreated HL60 and RAJI cells) in (A) HL60 cells, and (B) RAJI cells. Data are means \pm SEM, n = 3 (3 measurements per replicate). * denotes a significant difference from the control (RAJI cells without treatments), P < 0.05.

To further investigate the effect of manipulating NAD⁺ levels on the transcriptional regulation of CD38 expression, a similar experiment was also performed in differentiating HL60 cells by incubating the cells with FK866 or NAD⁺ up to 24 h. The data demonstrated a significant attenuation in CD38 expression at 6, 12 and 24 h of treatment with FK866 or NAD⁺ compared to untreated controls (differentiating cells, Fig. 5.6). A similar effect was observed with both treatments. Overall, attenuation in CD38 expression was clearly shown in cells treated with FK866. However, unexpectedly, the results showed that CD38 expression dropped rapidly even with increasing intracellular NAD⁺. The results of NAD⁺ application are consistent with the kuromanin results, showing an inhibition of CD38 expression when intracellular NAD⁺ levels were elevated.

Hence, whether NAD⁺ is elevated or increased, attenuation in CD38 expression may have been occurring. This strongly confirmed a possible role of NAD⁺ levels in the regulation of CD38 expression. These observations suggested that NAD⁺ metabolism might be considered as a novel target for regulating CD38 expression.

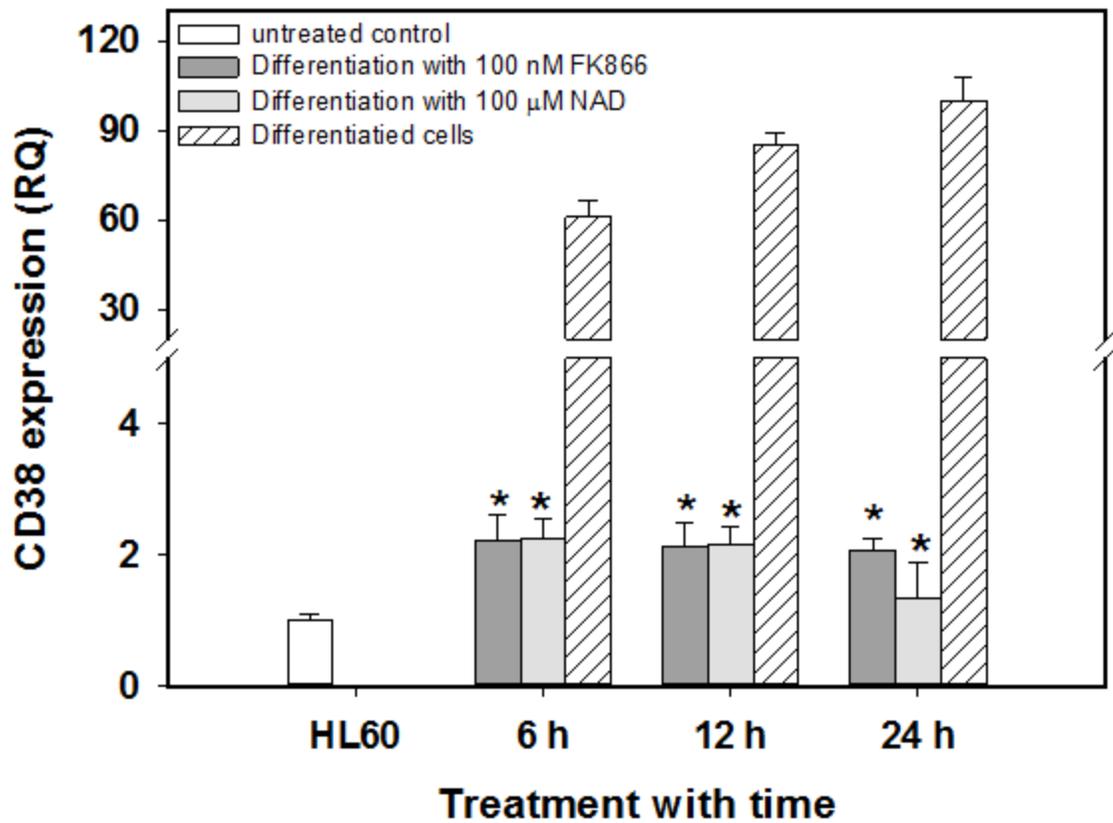


Figure 5.6 Effect of treatment with 100 nM FK866 and 100 μM NAD⁺ on CD38 expression after 1 day incubation in differentiating cells (ATRA treated cells) up to 24 h comparing to HL60 and ATRA treated cells without FK866 or NAD. Data are means ± SEM, n = 3 (3 measurements per replicate). * denotes a significant difference from the appropriate control (differentiated cells without treatments), P < 0.05.

5.3.4 Effects of hypoxia and hyperoxia conditions on CD38 expression in leukaemia cell lines

Hypoxia, a decrease in oxygen levels, is a hallmark of human cancer cells *in vivo* (Harris, 2002). For instance, leukaemia cells in bone marrow are considered physiologically hypoxic (Harrison *et al.*, 2002). In the current study, the malignant cells, HL60 and RAJI cells, which are derived from human leukaemia cells and lymphoma cells respectively, might also be adapted to proliferate in a low-O₂ environment. However, these cells were cultured *in vitro* under 21% O₂ (normoxia). This study aimed to culture these cells under conditions that mimic the *in vivo* environment in order to determine the effect of this environment on CD38 expression. As shown in Figure 5.7, RAJI cells were cultured under hypoxia (2% O₂) and incubated for 30 and 90 min and CD38 expression was determined compared to normoxia conditions (21% O₂). CD38 expression, as measured by qPCR analysis, was slightly increased under hypoxia 2% O₂ at 30 min and 90 min incubation times compared with normoxia, but this was not significant ($P > 0.05$). It is important to note that the level of O₂ (2% hypoxia) used was based on previous reports indicating that most cells can be maintained when cultured under these conditions (Han *et al.*, 2006). These data might suggest a link between hypoxia and CD38 expression in the leukaemia cell line. However, the vitality results (Fig. 5.9B) showed no changes in cell vitality as assessed by MTT assay at 30 min under 2% O₂ hypoxia in RAJI cells compared to normoxia.

CD38 expression was also determined in HL60 cells under 2% O₂ and 5% O₂ (simulating hypoxia), and for 30 min, 90 min and 6 h incubation times. Interestingly, a significant effect at 2% O₂ compared to 5% O₂ was observed on CD38 expression (Fig. 5.8). Furthermore, the data showed a strong and significant effect of 2% O₂ hypoxia at 30 min on regulation of CD38 expression in HL60 cells compared to 90 min and 6 h with both 2% O₂ or 5% O₂ ($P < 0.05$). An

apparent decrease in cell vitality was detected under hypoxia (2% O₂) at 30 min incubation time (P < 0.05; Fig. 5.9 B).

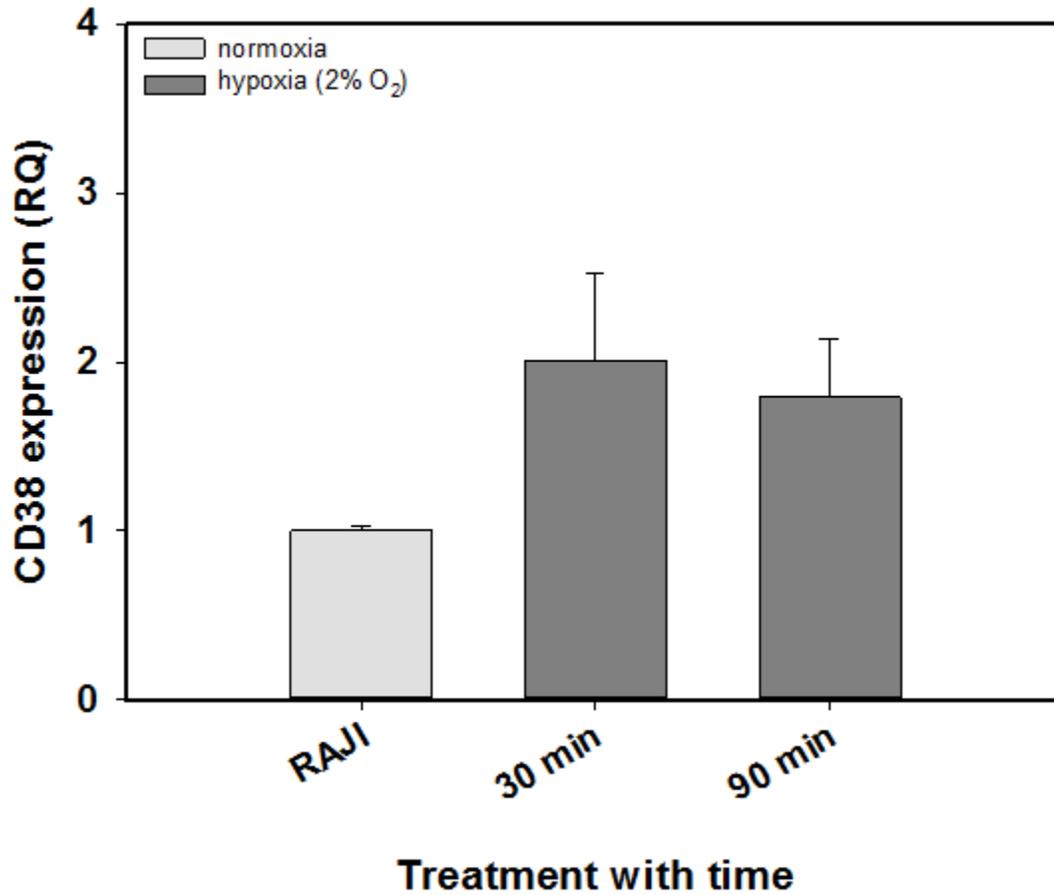


Figure 5.7 CD38 expression in RAJI cells exposed to hypoxia (2% O₂) and incubated for 30 min and 90 min compared to the untreated control (normoxia). Data are means ± SEM, n = 3 (3 measurements per replicate), no significant differences between groups were found (P > 0.05).

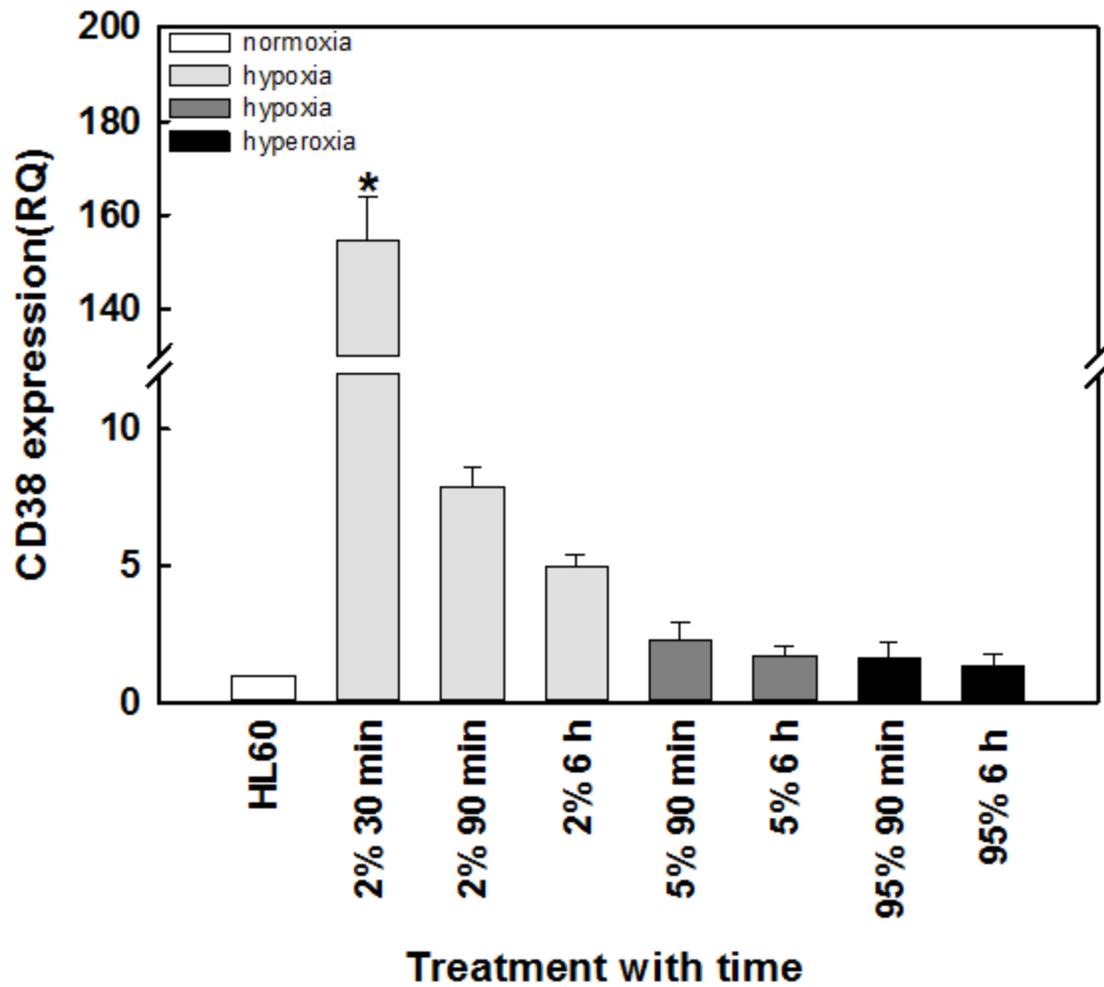


Figure 5.8 CD38 expression in HL60 cells exposed to hypoxia (2% O₂) and incubated for 30 min, 90 min and 6 h compared to the control (normoxia), hypoxia (5% O₂), and hyperoxia (95% O₂). Data are means ± SEM, n = 3 (3 measurements per replicate). * denotes a significant difference from the control (HL60 cells without treatments), P < 0.05.

It is thought that the cell vitality assay measures mitochondrial dehydrogenase activity (Mosmann, 1983). However, under hypoxia the metabolism of normal or cancerous cells shifts from the aerobic pathway to lactic fermentation (Warburg, 1956) rather than oxidative phosphorylation. Therefore, one might expect that dehydrogenase activity may be affected under these conditions, so that under hypoxia (2% O₂), the measured cell vitality is decreased. In addition to investigating CD38 expression under hypoxia, it was also investigated under 95% O₂ (hyperoxia) at 90 min and 6 h incubation (Fig. 5.8). As expected, there was no effect of hyperoxia on CD38 expression. Collectively, these novel data strongly confirmed the effect of low oxygen tension on CD38 expression in leukaemia cells.

The effect of hypoxia on glycolysis activity was evaluated by measuring lactate production in both leukaemia cell lines. Figure 5.9 A clearly illustrates that under hypoxia (2% O₂, 30 min incubation), HL60 cells significantly increased lactate levels compared to RAJI cells or to normoxia. These data might suggest a link between hypoxia, CD38 expression and glycolysis activity.

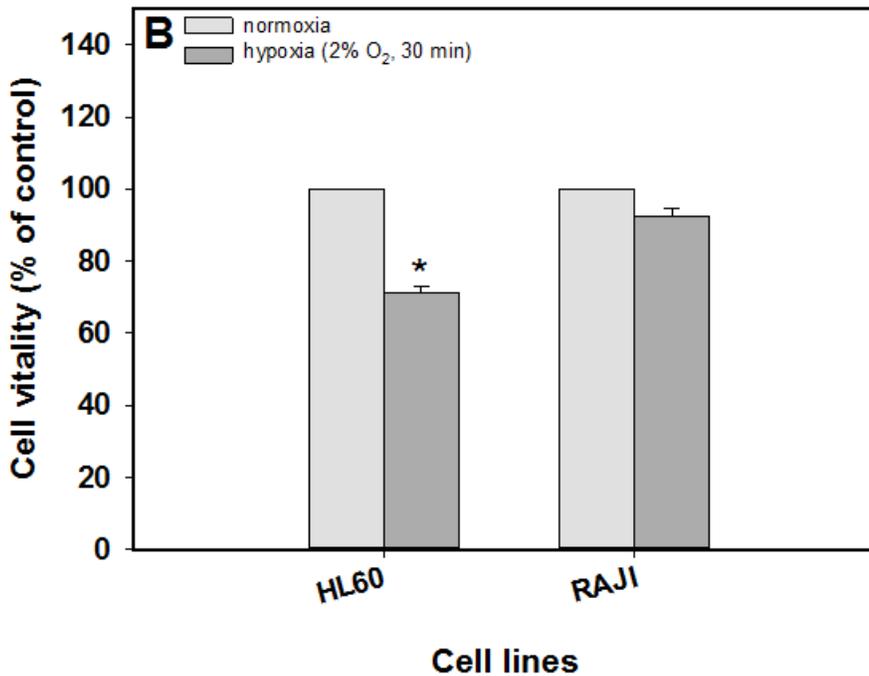
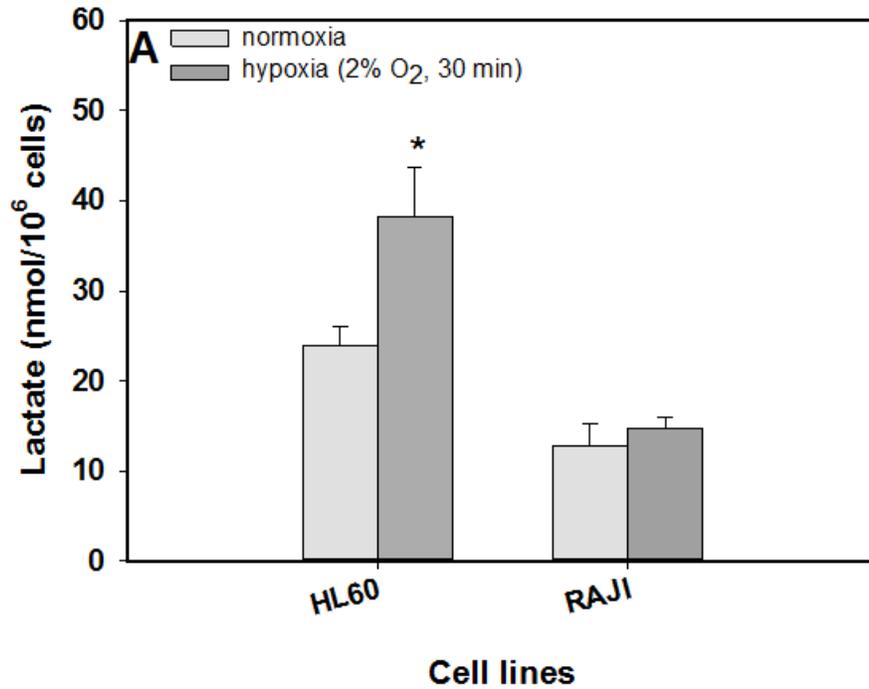


Figure 5.9 Effect of hypoxia (2% O₂) after 30 min incubation in both HL60 and RAJI cells on (A) lactate production, n = 3 (2 measurements per replicate), and (B) cell vitality (MTT assay) comparing to each untreated control (normoxia), n=2 (3 measurements per replicate). Data are means ± SEM.* denotes a significant difference from the related control (HL60 or RAJI cells without treatment), P < 0.05.

To further characterize the hypoxic response in the cells, it seemed important to evaluate intracellular NAD⁺ levels in addition to evaluating the effects of low O₂ tension on cell vitality and lactate levels *in vitro*. Therefore, and also to determine whether NAD⁺ levels might be playing a role in the upregulation of CD38 under the hypoxic conditions, the same experiment was repeated and NAD⁺ levels were assayed by the routine NAD cycling assay.

The results show that lower NAD⁺ levels were observed under hypoxic conditions (2% O₂) at 30 min incubation time in HL60 cells compared to the normoxia, while RAJI cells did not show any change in NAD⁺ levels (Fig 5.10). The drop in NAD⁺ levels (in HL60) might be mediated by CD38 upregulation as confirmed under the same conditions in HL60 cells. However, CD38 activity might not be regulated at 30 min under hypoxia; there might be other mechanisms responsible for the decline in NAD⁺ levels, such as a high glycolysis activity. Interestingly, the decrease in NAD⁺ levels was concomitant with the decrease in the cell vitality (MTT) in HL60 cells and under hypoxic conditions (Fig. 5.9 B).

Altogether, the results indicate that the hypoxic response of human leukaemia cells is characterized by a rapid but transient increase in CD38 expression and lactate production, but with a significant decrease in intracellular NAD⁺ levels and not with a significant decrease in cell vitality. Interestingly, the expression of CD38 in CD38⁻ cells (HL60) under hypoxia (2% O₂) was greater than that of CD38⁺ cells (RAJI) at 30 min incubation time.

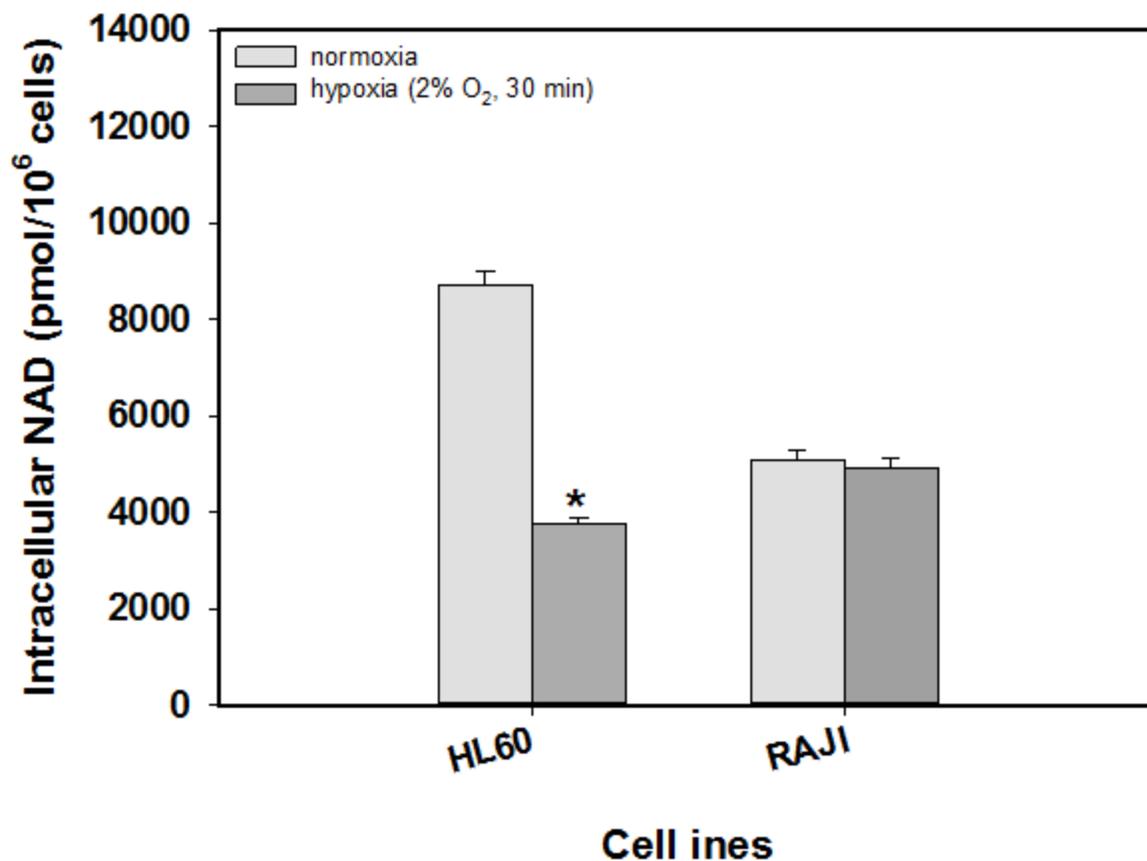


Figure 5.10 Effect of hypoxia (2% O₂) after 30 min incubation both in HL60 and RAJI cells on intracellular NAD⁺ levels comparable to the untreated control (normoxia). Data are means ± SEM, n = 3 (2 measurements per replicate). * denotes a significant difference from the control (HL60 cells without treatments), P < 0.05.

5.4 Discussion

Several mechanisms of regulation of CD38 expression that involve transcriptional and post-transcriptional levels of gene expression have been previously reported. Interestingly, the analysis of the human CD38 gene has revealed the presence of a number of response elements, for example, the retinoic acid response element (RARE; Tirumurugaan *et al.*, 2008). These make this gene responsive to a variety of physiological stimuli, suggesting the complex nature of CD38 expression in various types of mammalian cells. For instance, a comparatively rapid increase in CD38 expression occurs in response to ATRA in HL60 cells, and the mechanism that mediates this regulation has been previously studied (Munshi *et al.*, 2002). Transcriptional regulation of CD38 expression was also studied during ATRA-induced HL60 differentiation in the work described in this Chapter, but after incubation with kuromanin. It was seen that treating the differentiating cells with kuromanin inhibits CD38 mRNA expression compared to the untreated control. There are two suggested mechanisms that might explain this attenuation in CD38 expression. Firstly, kuromanin inhibition of CD38 cyclase activity might have consequences on the inhibition of CD38 expression. Secondly, the elevation in intracellular NAD^+ following inhibition of CD38 cyclase activity might have an impact on CD38 expression, since NAD^+ may affect gene expression through two pathways: (1) through the NAD^+ -consuming enzymes, PARP-1 and sirtuins, that can affect several transcriptional factors (D'Amours *et al.*, 1999; Ford *et al.*, 2006) and (2) through the alterations in NAD levels that might modulate an important NAD(H)-dependent transcription co-repressor, the C-terminal binding protein (CtBP). The change in NAD levels may regulate the dehydrogenase activity of CtBP as well as affect the binding of CtBP to specific repressor complexes (Kumar *et al.*, 2002). It is important to note that repressors require an association with corepressors to mediate

inhibition of gene transcription (Tyler and Kadonaga, 1999). Hence, the elevation of NAD^+ levels might mediate CD38 mRNA inhibition through regulation of CtBP.

In addition to the kuromanin results, it was investigated whether CD38 expression is regulated by NAD^+ levels by using NAD^+ application and FK866. It was hypothesized that the elevation in intracellular NAD^+ levels following NAD^+ application might induce CD38 expression, in order to degrade the high NAD^+ levels and vice versa with FK866. However, the results unexpectedly showed that elevation of intracellular NAD^+ by extracellular NAD^+ application or inhibition intracellular NAD^+ in all cell lines resulted in attenuation of CD38 expression. One explanation is that CD38 might be regulated by specific concentrations of NAD^+ , but not by 100 μM extracellular NAD^+ or by using 100 nM FK866 to diminish NAD^+ levels. These concentrations might be completely different from the normal levels in cells, which are suggested to be around the high micromolar range (Yang *et al.*, 2007). Therefore, investigations of CD38 expression in cells incubated with a range of concentrations of NAD^+ are suggested for further studies. It is worth mentioning that initial studies found that treatment of the CD38^+ cells with NAD^+ was shown to induce inactivation of CD38 activities; cyclase, hydrolase (Han *et al.*, 2000) or CD38 might undergo extensive self-oligomerization in the presence of NAD^+ (Guida *et al.*, 1995). Hence, NAD^+ application inhibited CD38 activities in previous studies, but the effect of NAD^+ application on CD38 mRNA was not investigated. Furthermore, CD38 expression was also investigated, in this study, after inhibition of intracellular NAD^+ . NAD^+ levels were inhibited by FK866 through its impact on the NAD biosynthesis enzyme (NAMPT). Interestingly, low intracellular NAD^+ was accompanied by an inhibition of CD38 expression. This downregulation of CD38 expression might also be NAD-dependent. One of the possible explanations is that limited availability of the substrate NAD for the CD38 enzymatic activities might result in

reduction in both NAD-hydrolase and cyclase activities, which further leads to the control of CD38 expression. It is important to note that FK866 causes depletion of NAD⁺ levels which results in cell death by autophagy as confirmed by Billington *et al.* (2008b). Thus, cells incubated for 24 h with this agent, to ensure that NAD⁺ levels dropped first, and to keep the cells viable in order to investigate the effect of inhibiting the NAD recycling pathway on CD38 expression.

Previous results (Chapter 3) suggested that NAD levels are CD38-dependent. Intriguingly, this study suggests that CD38 expression might also be NAD-dependent. The current findings have provided the first *in vitro* evidence that NAD⁺ metabolism might be a novel target for controlling CD38 expression by using FK866 and extracellular NAD⁺ application strategies in addition to using kuromanin. Targeting NAD metabolism by using NAD⁺ application might serve as a treatment strategy in cancer, Huntington's disease, multiple sclerosis, and neurodegenerative diseases (Khan *et al.*, 2007). Targeting NAD metabolism by using FK866 might also be implicated in cancer therapy (Hasmann and Schemainda, 2003; Hølen *et al.*, 2008). Indeed, regulation of CD38 expression via manipulation of NAD levels might serve as a treatment strategy for leukemia patients, since CD38 works as a dependable marker of unfavourable prognosis and as an indicator of cell proliferation and activation (Malavasi *et al.*, 2011). Moreover, inhibition of CD38 expression might reduce the consequences of the CD38-CD31 interaction, and supramolecular complex signalling that mediated CLL homing processes and survival. Hence, controlling CD38 expression in leukemia patients might affect the unfavourable prognosis and consequently inflict on patient survival.

Regulation of CD38 expression in leukaemia cells was further investigated under hypoxia (similar to *in vivo* conditions). Hypoxia, a decrease in oxygen levels, plays a major role in many pathological processes such as ischemic stroke and tumour progression (Harris, 2002). Under hypoxia, cells may survive and adapt to the hypoxic environment. These adaptive responses of cells to hypoxia may involve the induction of specific gene expression which may help to suppress or limit the effects of hypoxia on these cells (Yun *et al.*, 1997). Several studies have showed a significant association between hypoxia and CD38 activity in disease states, in several types of cells. For instance, a change in CD38 activity that is associated with hypoxic pulmonary vasoconstriction (HPV) has been indicated (Wilson *et al.*, 2001). It was suggested that hypoxia-mediated vasoconstriction is cADPR dependent and the mechanism was attributed to increase an NADH:NAD⁺ ratio (due to increased NADH formation via glycolysis) that appears to favour the net production of cADPR probably because of the inhibition of cADPR hydrolase activity of CD38 (Wilson *et al.*, 2001; Kotlikoff *et al.*, 2004). cADPR accumulation might also suggest activation of ADP-ribosyl cyclase activity. CD38 expression was also found to be changed under hypoxia in brain cells from rats (Salmina *et al.*, 2008). It is important to mention that regulation of CD38 activities might reflect regulation of its mRNA expression. In addition to that, hypoxia attenuated CD38 expression in pancreatic β -cells from HIT-T15 hamsters (Ota *et al.*, 2012). Recently, an association between CD38 and activation of hypoxia inducible factor (HIF), a family of transcription factors extensively involved in the response of mammalian cells to low oxygen tension, was shown in allergic airway disease (So Ri *et al.*, 2011). However, regulation of CD38 expression under hypoxia and in leukaemia cells is still poorly studied. The current novel results successfully demonstrate that hypoxia induces the expression of CD38 in leukaemia cells. The data has shown that different leukaemia cells exhibit different levels of sensitivity to

hypoxia (2% O₂); there was more regulation of CD38 mRNA in HL60 cells in response to hypoxia compared to RAJI cells, although CD38 expression in untreated RAJI cells was higher than in HL60 cells. Indeed, leukaemia cells in bone marrow are considered physiologically hypoxic, with oxygen levels approximately three times lower than that usually applied during *in vitro* cell culture (Harrison *et al.*, 2002). Therefore, the hypoxic condition in a current study was within the range for these environments. The reason for using hypoxic conditions was that under hypoxia a drop in NAD levels might occur. Hence, and in line with the FK866 results, it was hypothesized that the decline in NAD levels (as a consequence of lactic fermentation) might also mediate CD38 mRNA downregulation. However, the results unexpectedly showed upregulation of CD38 mRNA expression. This might raise the possibility that NAD levels might also be involved in this interesting regulation. Another possibility is that tumour cells may require increased expression of CD38 to maintain cell survival and resistance to apoptosis under hypoxic conditions, and targeting this molecule may be useful for cancer prevention and treatments. Other suggested mechanisms might be associated with hypoxia-induced cytokines. For instance, the release of TNF- α , expected to have occurred under hypoxia as previously shown in retinal ganglion cells (Hong *et al.*, 2008), might be linked to CD38 overexpression, since TNF- α has been shown to induce CD38 expression (Barata *et al.*, 2004). However, further studies are needed to clarify the mechanism of the hypoxia induced upregulation of CD38 in leukaemia cells. The consequences of a hypoxic environment on cell physiology, that is reflected by more lactate production (from lactic fermentation) with lowered intracellular NAD levels, might cause metabolic dysfunction. Thus, the possible reason that CD38 protein is frequently overexpressed in a leukemia might be because leukaemia cells, *in vivo*, exist under constant hypoxic conditions

and that this might be participating in the development of poor prognosis and metabolic dysfunction in leukaemia cells.

It is worth noting that under hypoxia (2% O₂) for 30 min, CD38 expression levels were greater than under all other conditions. Hence, the glycolysis state was investigated by measuring both lactate and NAD⁺ levels, and cell vitality only under these particular conditions. Furthermore, lactate levels were measured as an indicator of glycolytic activity under hypoxia, thus, there was no need to reconfirm the hypoxic conditions by measuring HIF, as most studies do. Ultimately, although the mechanism of hypoxia-induced CD38 regulation was not investigated, but it seems that NAD levels might be involved in this process (Fig. 5.11).

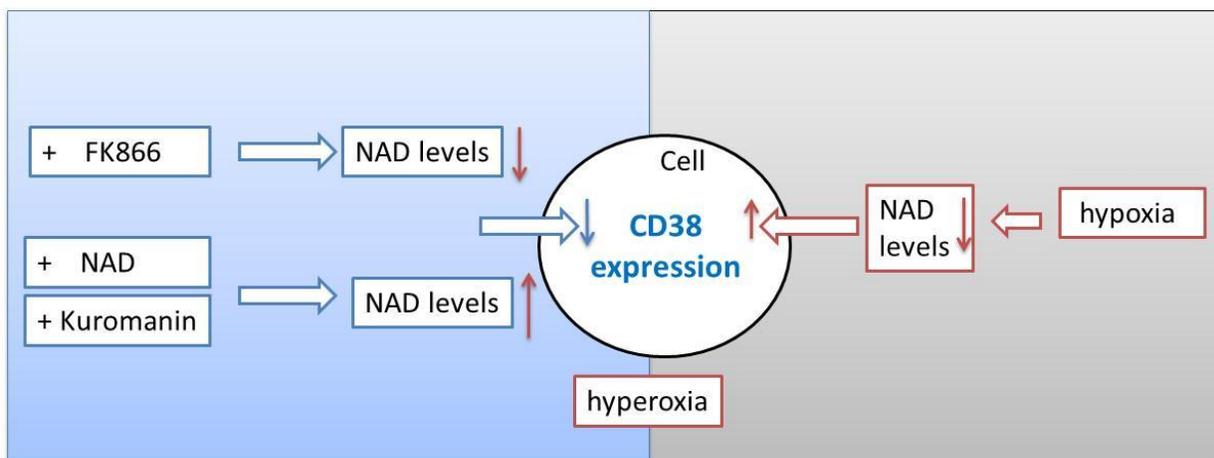


Figure 5.11 Schematic diagram showing how NAD levels might regulate CD38 expression through multiple suggested mechanisms. For instance, elevated NAD levels following kuromanin and NAD⁺ application might inhibit CD38 mRNA expression. Alternatively, depletion of NAD by using FK866 might also inhibit CD38 mRNA expression, while decreased NAD levels under hypoxia might upregulate CD38 expression.

Interestingly, under 95% hyperoxia the results did not show any effect on CD38 regulation unlike those seen with hypoxia in leukaemia cells, since it reversed the action of hypoxia on CD38 expression. One of the possible explanations of these results is that the leukaemia cell lines are adapted to function in hypoxic environments, rather than under hyperoxic conditions, and that therefore a hyperoxic environment might not regulate CD38 expression. Indeed, limited studies have investigated the effect of hyperoxia in HL60 cells; an earlier report confirmed that hyperbaric oxygen induces spontaneous and chemotherapy-induced apoptosis in Jurkat and HL60 cells (Ganguly *et al.*, 2002). Other studies have documented the use of hyperoxia as a potential anticancer therapeutic (Henk *et al.*, 1977; Watson *et al.*, 1978), while there are no studies of the effect of hyperoxia on CD38 expression in human cell lines.

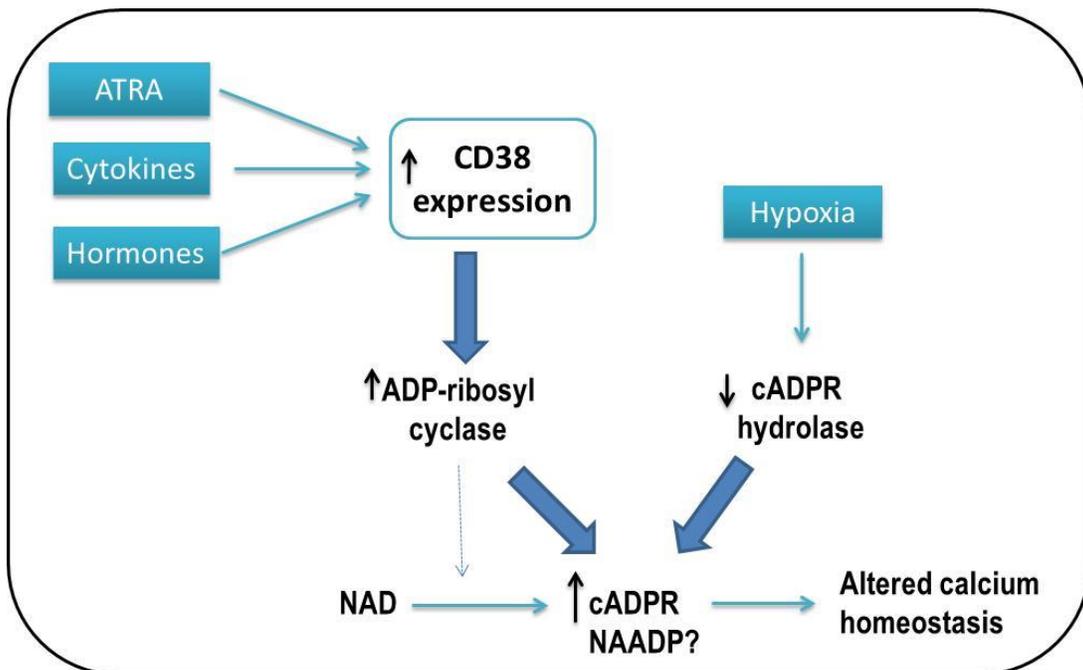


Figure 5.12 CD38 regulations in different cell types by hormones, cytokines, and retinoic acid and the associated increase in ADP ribosyl cyclase activity. In addition to decreasing cADPR hydrolase activity under hypoxia and the consequences of cADPR accumulation, adapted from Kotlikoff *et al.* (2004).

Collectively, regulation of CD38 expression under different stimuli, such as hormones, cytokines, ATRA, hypoxia (Fig. 5.12) or by manipulating NAD levels (Fig. 5.11) are key points for investigation. This might lead to regulation of CD38 activities, or its products, cADPR and NAADP, and their related functions, since the role of CD38 or CD38/cADPR signalling in regulating different cellular functions in humans and animal models has been well investigated. For instance, cADPR plays an important role in hypoxic pulmonary vasoconstriction; HPV (Dipp and Evans, 2001). In diabetes, CD38 plays a distinct regulatory role in the murine model with regards to insulin secretion via calcium mobilization of cADPR-sensitive stores (Kato *et al.*, 1995). The crucial role of CD38 deficiency on prevention of the development of obesity through activation of SIRT/PGC1 α has also been documented (Baur *et al.*, 2006). Finally, in CLL high levels of CD38 expression correlate with both disease stage and poor prognosis (Morabito *et al.*, 2002). Studies have also confirmed that CD38 is a master regulator of CLL cell homing (Vaisitti *et al.*, 2011). Indeed, therapeutic applications that target CD38 have been more explored in leukemia.

Thus, the current study might prove useful to future researchers especially when they are investigating mechanisms that regulate CD38 expression as a target in leukemia therapy or in other CD38-related diseases.

CHAPTER 6

EFFECT OF LOW NAD LEVELS ON THE DNA DAMAGE AND CELL DEATH

6.1 Introduction

In addition to the well-known functions of NAD in metabolism or as a substrate for CD38, it also participates in DNA repair and cell death via PARP, a family of enzymes with 17 members of which PARP-1 is the founding member (Ying *et al.*, 2005; Hassa and Hottiger 2008). These enzymes catalyze the covalent attachment of poly ADP-ribose (PAR) polymers either to themselves or to other acceptor proteins, using NAD^+ as a donor of ADP-ribose units, in addition to the release of nicotinamide (Hassa and Hottiger 2008). The poly ADP-ribosylation of specific target proteins is crucial for genome stability, DNA repair, telomere maintenance and cell death (Khan *et al.*, 2007). PARP-1 activation is critical in determining cellular fate after DNA damage has occurred (Pieper *et al.* 1999) since, through its role in DNA repair, PARP-1 activation may serve to rescue damaged cells, preventing them from death (Chatterjee *et al.*, 1999). However, extensive DNA damage results in PARP hyperactivation, leading to a rapid depletion of cellular NAD^+ and lowered ATP production, ultimately leading to cell death (Alano *et al.*, 2004; 2010). Cell death by autophagy has also been observed when intracellular NAD levels are decreased by using FK866, a NAD-depleting drug (Billington *et al.*, 2008b).

Thus, researchers have shown an increased interest in the area of influence of NAD^+ status on genomic stability, DNA repair and apoptotic cell death, specifically in cancer (Schwartz *et al.*, 1974). The reason for this interest is that cancer cells, which mostly depend on lactic fermentation for ATP production, exhibit a particularly high sensitivity to DNA damage and PARP-1 activation (Zong *et al.*, 2004). For this, an adequate level of cellular NAD in cancer cells is necessary because of a high rate of NAD^+ turnover due to elevated ADP-ribosylation activity (Burkle, 2005). Several studies have drawn attention to the effects of decreases or

increases in NAD levels on PARP activity and cell death (Ying *et al.*, 2003; Benavente *et al.*, 2012). Other cancer therapy studies combined NAD-depleting drugs with chemotherapy and radiotherapy (Ekelund *et al.*, 2002; Progrebniak *et al.*, 2006), or combined PARP inhibitors with DNA-binding antitumour drugs as a suitable strategy in cancer therapy (Cepeda *et al.*, 2006). However, to this author's knowledge, no research to elucidate the consequences of low NAD levels on DNA repair, PARP activity and apoptotic cell death in CD38- expressing leukaemia cells, has been carried out to date. Therefore, according to the hypothesis that hyperactivation of PARP requires a certain level of cellular NAD to induce cell apoptosis and to decrease cell proliferation, it was postulated that in CD38⁺ cells such as leukemia there will be a high demand for NAD that might render these cells more resistant to apoptosis.

The aim of the work described in this chapter was therefore to use a comet assay approach to investigate the response to DNA damage induced by UVB in cells expressing CD38 with low cellular NAD levels. In addition, the consequences of UVB on PAR production (confirmed by western blotting) and finally apoptotic cell death were examined. Whilst the data in this Chapter are preliminary, the results showed a significant level of UVB-induced DNA damage in cells with low NAD levels, in addition to cell resistance to apoptosis. Finally, these preliminary results may help to increase future understanding of the nature of cell resistance to apoptotic death in CD38⁺ subsets of leukemia patients, even during chemotherapy or radiotherapy.

6.2 Material and methods

6.2.1 Materials

Low melting point agarose, normal melting point agarose, EDTA, Tris base, Triton X-100, DMSO, and Wright-Giemsa stain were all purchased from Sigma (Poole, UK). The PAR antibody was purchased from Abcam (Cambridge, UK).

6.2.2 Comet assay and quantification of DNA damage

Single-cell gel electrophoresis (the comet assay) is a microelectrophoretic technique for the direct visualization of DNA damage in individual cells. The comet assay (outlined in Fig. 6.1) was performed as described by Singh *et al* (1988) on HL60, RAJI and differentiated HL60 cells. Cell suspension (100 μ l of 1×10^5 cells ml^{-1}) were transferred to individual 1.5 ml microcentrifuge tubes and centrifuged at $200 \times g$ for 5 min. The supernatants were discarded and the pellets were each mixed with 85 μ l of low melting-point agarose (0.5% in PBS), which was then pipetted onto agarose-coated microscope slides (pre-coated with normal melting-point agarose (1% in PBS) and dried at 37 °C). After the cell/ agarose mixture had solidified (4 °C for 15 min), the slides were then immersed vertically in lysis solution (2.5 M NaCl, 100 mM Na₂EDTA, 10 mM Tris-base, pH 10, containing freshly added 1% Triton X-100 and 10% DMSO) for 24 h at 4 °C. The slides were then washed three times vertically with neutralization buffer containing 0.4 M Tris-base, pH 7.5, and then placed into a horizontal electrophoresis apparatus (tank) filled with fresh, pre-cooled electrophoresis buffer (1 mM EDTA, 300 mM NaOH, pH 13.3). After 20 min of pre-incubation (unwinding of DNA), the electrophoresis was run for 20 min at a fixed voltage of 25 V and 300-400 mA, after which the slides were put in a tray and washed by adding neutralisation buffer in a drop-wise manner; this process was repeated

ten times. The slides were then left to dry at room temperature for 60 min. After drying, the slides were kept in a chamber in the dark at room temperature until analysis.

After 24 h, cells were stained with 20 μl ethidium bromide solution ($2 \mu\text{g ml}^{-1}$), and analysed at $200\times$ magnification with a Leica EL6000 fluorescence microscope (Bradford, UK). Assessment of DNA damage was based on the analysis of 100 randomly selected comets from each slide which were analysed by the comet IV imaging system (Perceptive Instruments, Suffolk, UK). In this system, tail DNA is considered to be the parameter most directly related to DNA damage. Each experiment was repeated three times with different cell preparations, and statistical analysis was carried out using a one-way ANOVA.

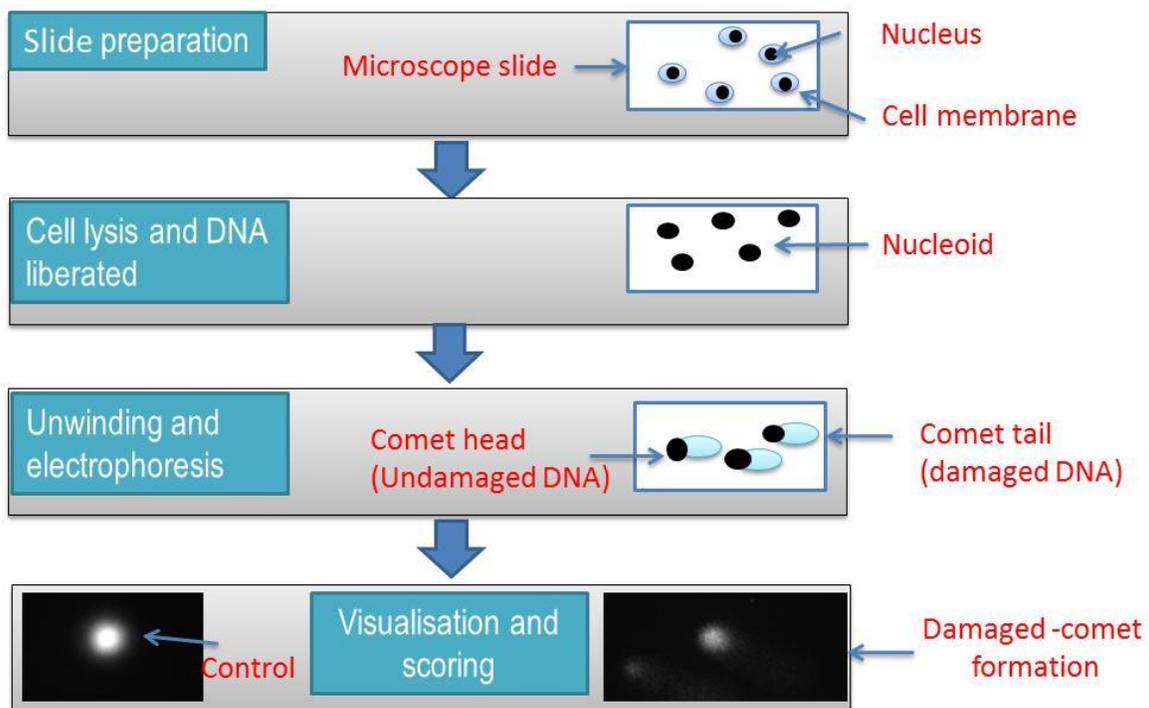


Figure 6.1 Schematic representation of the comet assay describing slide preparation, cell lysis, electrophoresis, visualisation and scoring steps (adapted from Tice *et al.*, 2000).

6.2.3 Validation of the comet assay under in vitro conditions using hydrogen peroxide

The comet assay was validated using hydrogen peroxide H₂O₂, as a reference genotoxic agent to determine oxidative DNA damage (Tice *et al.*, 2000). This was conducted by *in vitro* exposure of HL60 and differentiated HL60 cells to a range of H₂O₂ concentrations. The cell pellet was incubated with 100 µl of 0-300 µM concentrations of H₂O₂ for 10 min at 4 °C in the dark. Following the incubation, cells were washed with PBS to remove any remaining H₂O₂, and cell viability was determined using trypan blue. Slides were then prepared as described in Section 6.2.2 and processed for the comet assay.

6.2.4 UVB radiation of differentiated cells and induction of apoptosis

HL60, RAJI and 3 day differentiated HL60 cells were irradiated as freshly harvested suspensions. The cells were resuspended in PBS after two washes at the desired density (0.2 - 3 × 10⁶ cells ml⁻¹). UVB irradiation was performed using a twin-tube lamp (TL-20W/12RS; Philips, Guildford, UK). UVB irradiation was calculated by using a Macam spectroradiometer (Macam SR9910, Livingston, UK) using integrated intensity between 280 - 340 nm (peak intensity of 310 nm). Irradiation was performed in 24-well plates. The UVB source was positioned directly above the cell suspension covered with a filter lid. The dose of UVB was 1.6 kJ m⁻² for 560.8 s. In all experiments after exposure to UVB was completed, cells were immediately processed for the comet assay, MTT assay, Halo assay, Geimsa staining and western blotting (poly ADP-ribose modified protein production). In other samples measuring post-irradiation effects on DNA (DNA repair), cell suspensions were maintained at 37 °C for 45 min, 90 min and 6 h after exposure before processing using the comet assay etc. Cells used as

controls were similarly washed, centrifuged, counted, and placed in the 24 well plate, but were not exposed to UVB irradiation.

6.2.5 Halo-Comet assay

This technique was first described by Vinograd *et al.* (1965) and it was improved as the alkaline-halo assay by Sestili *et al.* (2006). In the normal comet assay, and in response to the electric current, charged DNA migrates away from the nucleus. The halo assay, in contrast, does not include an electrophoresis step. Also, the intact DNA remains within a residual nucleus-like structure called a nucleoid. If the nucleoid DNA contains strand breaks, a halo of DNA extends around the original form of the nucleus and may be visualized by fluorescence microscopy.

In this assay, following cell irradiation, the DNA damage was assessed as described in the Section on the comet assay (Section 6.2.2, except for omission of the electrophoresis step), and halo cells were visualized using a fluorescence microscope (Nikon Eclipse 80i, Surrey, UK), with image analysis software (NIS-Elements BR, Nikon, Surrey, UK).

6.2.6 Wright-Giemsa staining method

For morphological assessments of apoptosis, the UVB-exposed cells were stained using the Wright-Giemsa staining method. Cells were centrifuged and the pellets were resuspended in PBS. Cell suspension (100 μl of 1×10^6 cells ml^{-1}) were prepared on slides using a cytospin centrifuge (Shandon, Leicester, UK) and fixed with 5 μl methanol before staining with Wright-Giemsa stain. After 4 min, slides were rinsed in water and air-dried. The morphology of cells was examined under a light microscope ($\times 100$; Olympus, Japan).

6.2.7 Statistical analysis

Statistical analysis of the data was assessed using Fisher's one way analysis of variance (Statview 5.0.1; Abacus concepts, USA) or Student's t-test as appropriate. Data are expressed as means \pm SEM for three separate experiments in triplicate, unless otherwise stated. A difference of $P < 0.05$ was considered statistically significant.

6.3 Results

6.3.1 Effect of cellular NAD levels on UVB-induced DNA damage

The induction and repair of UV-induced DNA damage has been previously studied *in vitro* and in several cell lines (Cadet *et al.*, 1997; Ravanat *et al.*, 2001). However, the study in this Chapter aimed to induce DNA damage *in vitro* by using UVB irradiation, and also to investigate DNA repair in RAJI, HL60 and differentiated HL60 cells. The alkaline comet assay was used to detect the damaged DNA due to its high sensitivity (Collins, 2009). Among all the parameters provided by the comet software, the percentage of DNA in the tail (% tail DNA), is considered to be the most reliable parameter (Kumaravel and Jha, 2006), and was used in this work to represent cellular DNA damage.

To validate the comet assay, an experiment was conducted with H₂O₂ exposure to HL60 and 1 day ATRA-treated cells. DNA damage was clearly seen in the both groups of cells, and was similar in cases (Fig. 6.2). The percentage tail DNA data showed an increase in DNA damage with concentration in the range 30 to 300 μ M H₂O₂. There was a \approx 2.3 fold increase in percentage tail DNA with 300 μ M H₂O₂ in HL60 and differentiated HL60 cells, compared to the untreated control. Thus, the comet assay proved to be a sensitive technique for the detection of DNA damage, and showed that DNA damage by H₂O₂ was concentration-dependent.

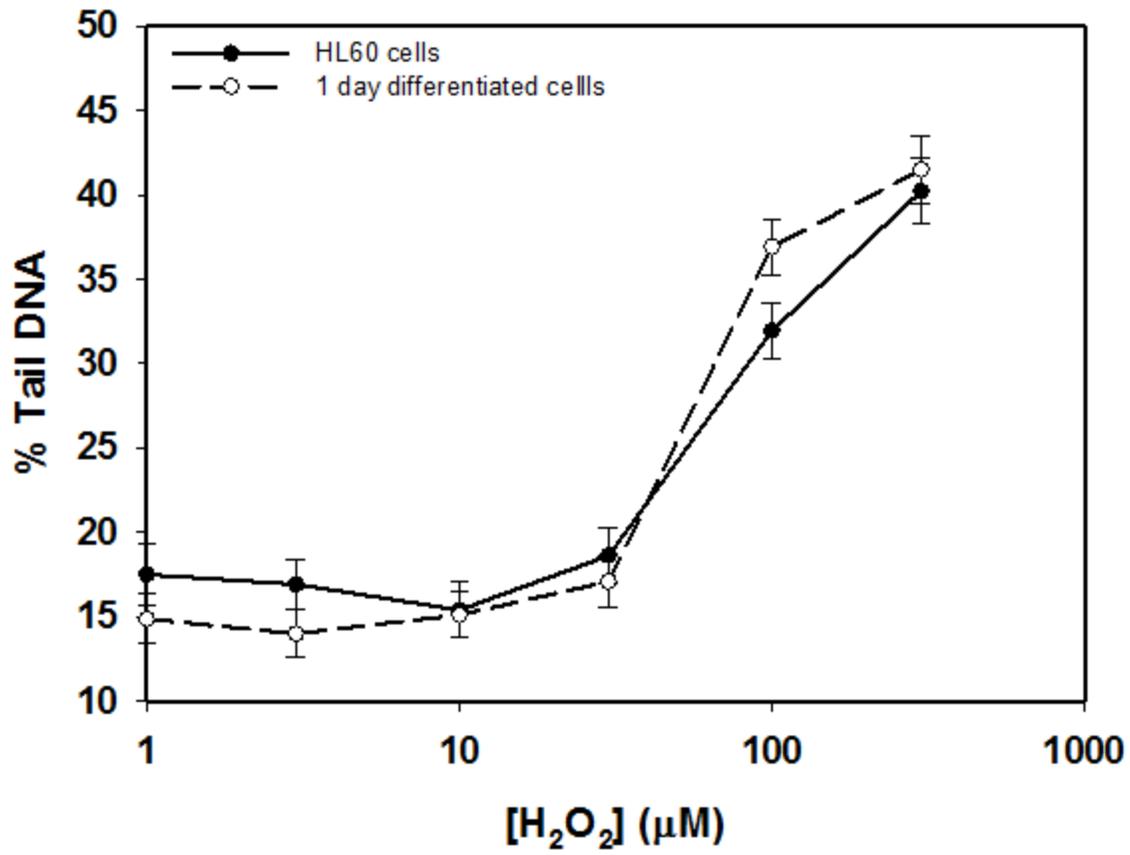


Figure 6.2 DNA damage expressed as percentage tail DNA in HL60 (solid line) and 1 day differentiated HL60 cells (dashed line) following 10 min *in vitro* incubation with different concentrations of H_2O_2 (1-300 μM). Data are means \pm SEM, n = 1 (100 measurements).

In order to induce DNA damage, a UVB-irradiation system was used. A UVB meter was used to control the irradiation dose and to calculate the irradiation time. The emission spectrum from 280-340 nm of the lamp is shown in Figure 6.3 with a peak at 310 nm. Thus, to irradiate the cells with the desired dosage (1.6 kJ m^{-2}); the cells were irradiated for 560.8 s by using a twin-tube lamp (TL-20W/12RS; Philips). The irradiation time (t) was measured in seconds and was calculated using the formula: $D = I \times t$, where I is the UV radiation density ($2.853 \text{ W m}^{-2} \{ \text{J s}^{-1} \text{ m}^{-2} \}$ at 310 nm and D is dose of irradiation (1600 J m^{-2}).

In the current study, the induction of the DNA damage by exposure to 1.6 kJ m^{-2} UVB dosages was performed on the undifferentiated, 3 day-differentiated HL60 cells and RAJI cells. The results (Figure 6.4) showed that the UVB irradiation induced DNA damage in all cell lines, as estimated by percentage tail DNA. The DNA damage was more striking in differentiated HL60 cells and RAJI cells, in comparison to cells not expressing CD38 (undifferentiated HL60 cells), which showed relatively low levels of DNA damage. The same results were also confirmed in the comet images (Fig. 6.5). There was also no significant loss of cell viability (Figure 6.7) in any of the cell lines (cell viability using trypan blue exclusion was 70-80% in all cases). These results suggest that the maximum induced DNA damage can be clearly seen in cells that have low intracellular NAD levels (CD38^+ cells) than cells that have a high level of NAD.

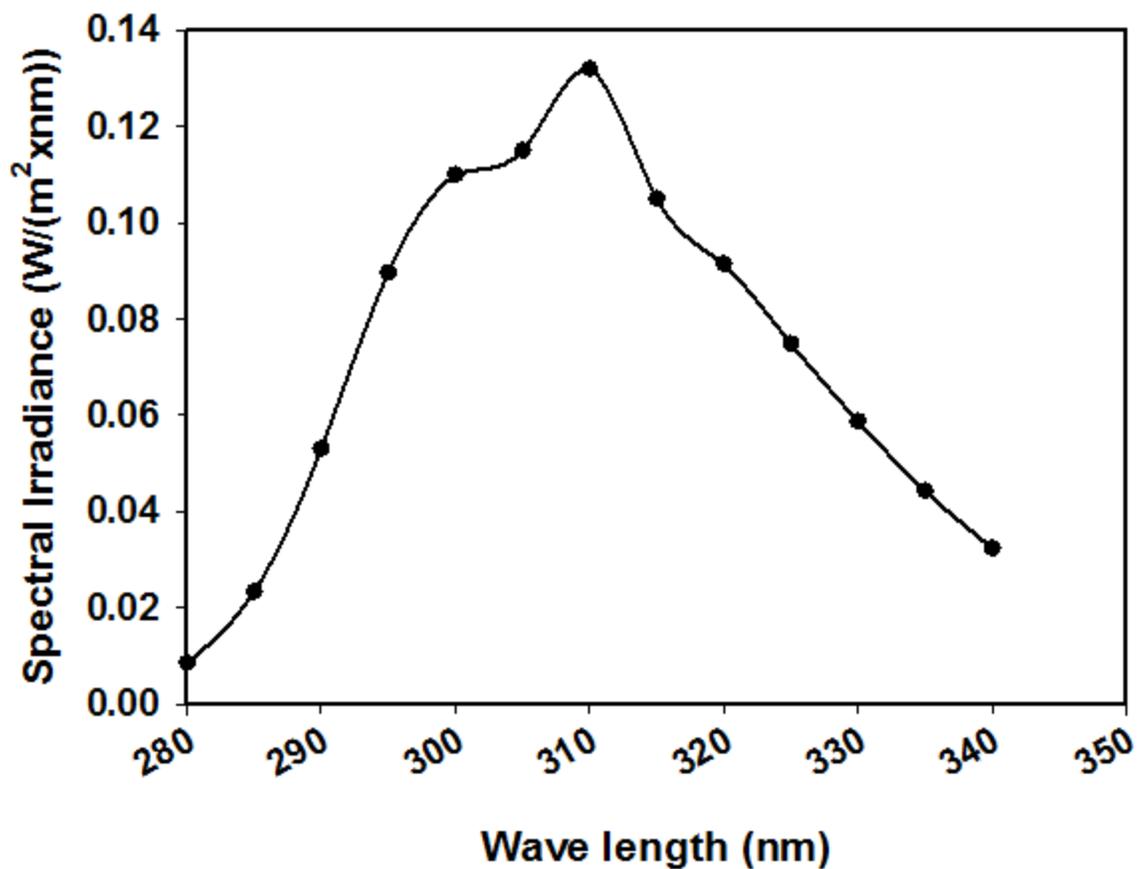


Figure 6.3 Spectrum of the twin-tube UV lamp with a maximum emission in the UVB region (310 nm). The lamp was used to irradiate the cells to induce DNA damage. The data represent a single measurement.

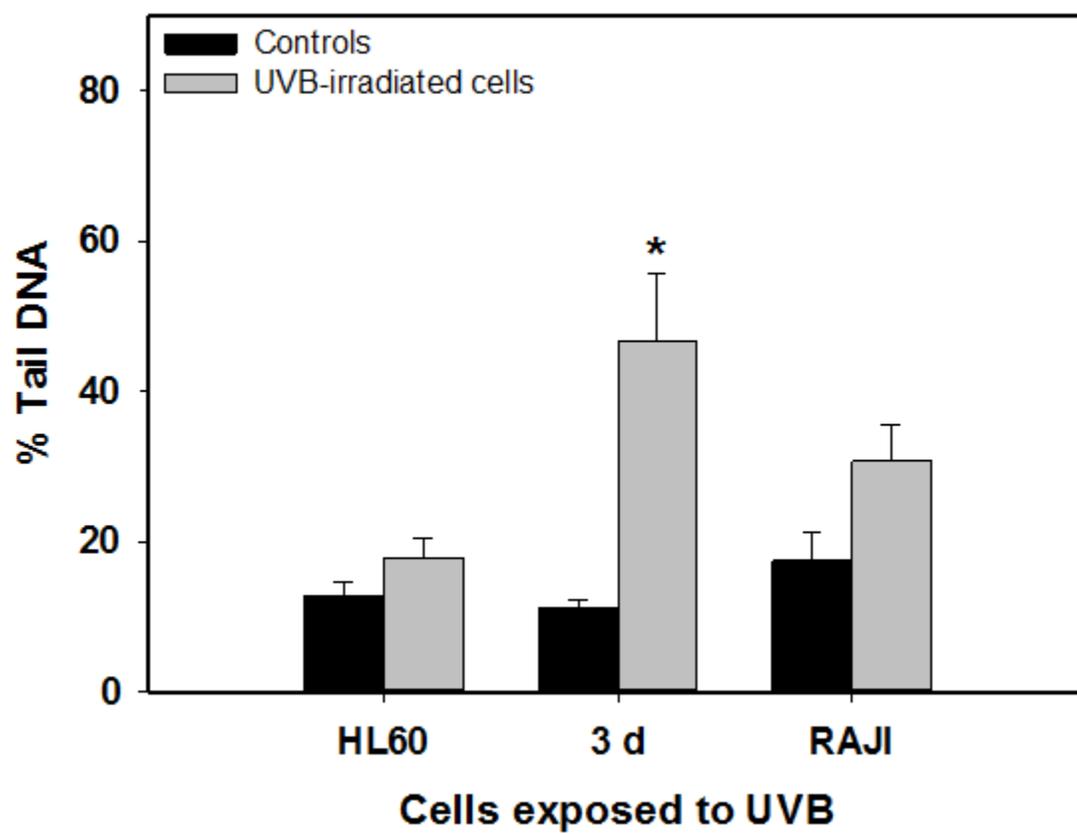


Figure 6.4 DNA damage expressed as percentage tail DNA in undifferentiated HL60 cells, differentiated HL60 cells (3 days) and RAJI cells following the irradiation with 1.6 kJ m^{-2} UVB. Data are means \pm SEM, $n = 3$ (100 measurements per replicate). * denotes significant difference from the appropriate untreated control ($P < 0.05$).

The DNA damage was also assessed in undifferentiated HL60, RAJI and differentiated HL60 cells after recovery times of 45 min, 90 min and 6 hours after UVB-irradiation, to evaluate the DNA repair process (Fig. 6.6). There was an apparent drop in DNA damage in the all cell lines between 45-90 min after irradiation. This might suggest that DNA repair processes were more evident in HL60 and RAJI cells than in the differentiating HL60 cells. Interestingly, there was no decrease in cell viability at 45 min and 90 min in all cells after irradiation (Figure 6.7). Surprisingly, after a clear decline in the DNA damage at 45 and 90 min there was an increase in percentage tail DNA in all cells at 6 h post irradiation. No significant difference was observed between the different cell types at that time, which might suggest impairment in the DNA repair process. Moreover, cell viability results after 6 h recovery time showed a significant loss of viability (Figure 6.7) as determined by trypan blue exclusion in all of the cell lines.

Thus, the above results confirm that a decline in intracellular NAD in CD38 positive cells (3 days differentiated HL60 cells and RAJI cells) might increase the cell response to UVB-induced DNA damage as shown in Figure 6.4. However, these cells showed relatively recovered DNA after a short time of irradiation which might be related to PAR accumulation, which initiates the repair process in the case of moderate DNA damage (1.6 kJ m^{-2} dosages).

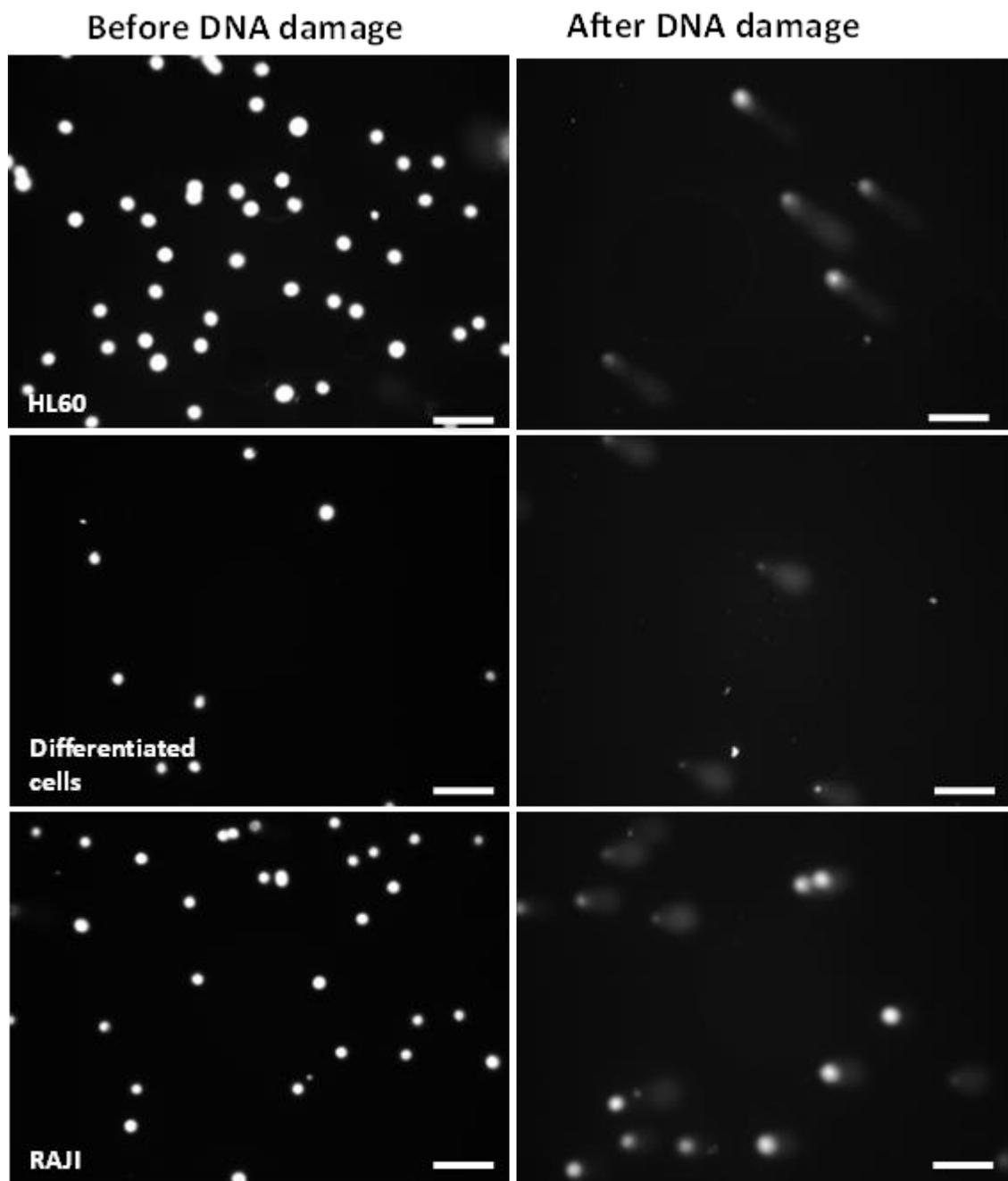


Figure 6.5 Representative comet images of undifferentiated HL60, 3 days differentiated HL60 cells and RAJI cells, which were exposed to UVB-induced DNA damage (1.6 kJ m^{-2}). Cells were stained with ethidium bromide before visualization. Magnification = $\times 200$. Scale bars: $50 \mu\text{m}$.

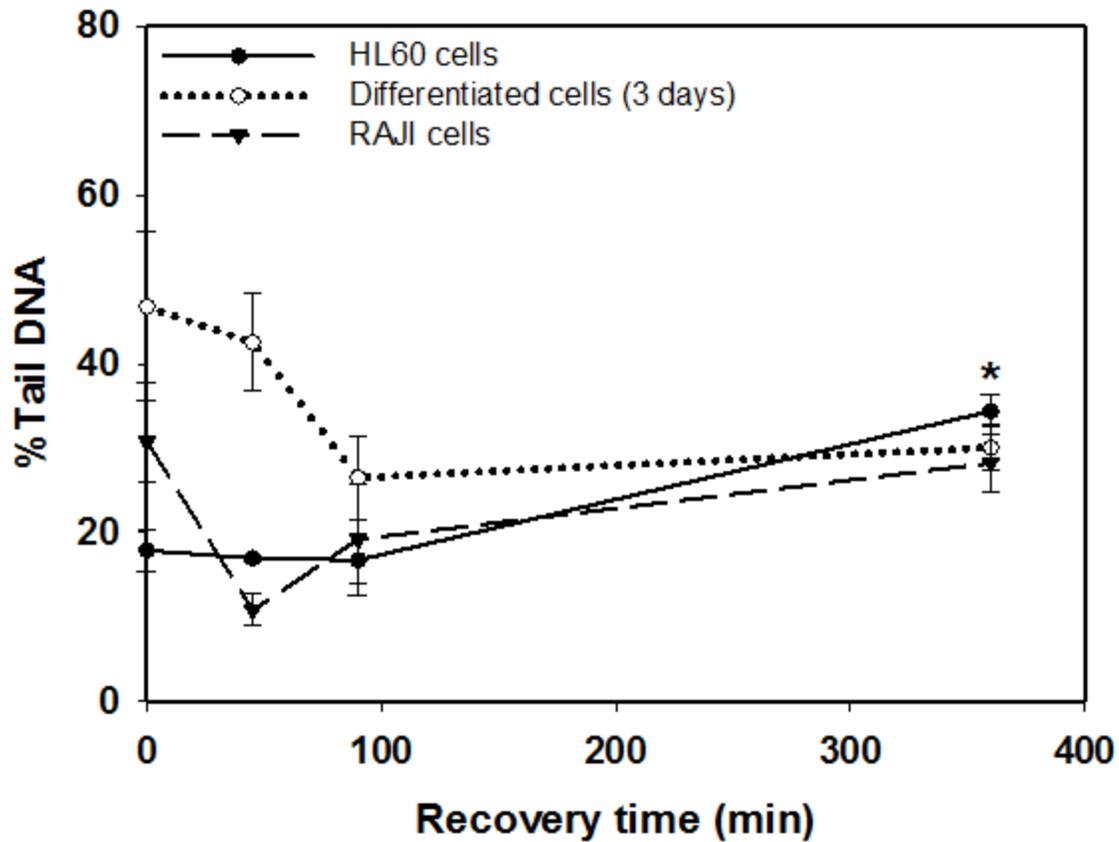


Figure 6.6 DNA repair of UVB-induced DNA damage (1.6 kJ m^{-2}). Following HL60, ATRA-induced HL60 differentiation (3 days) and RAJI cell irradiation, the percentage of DNA damage was assessed after recovery times of 45 min, 90 min and 6 hours. Data are means \pm SEM, $n = 3$ (100 measurements per replicate). * denotes significant difference from the appropriate control ($P < 0.05$).

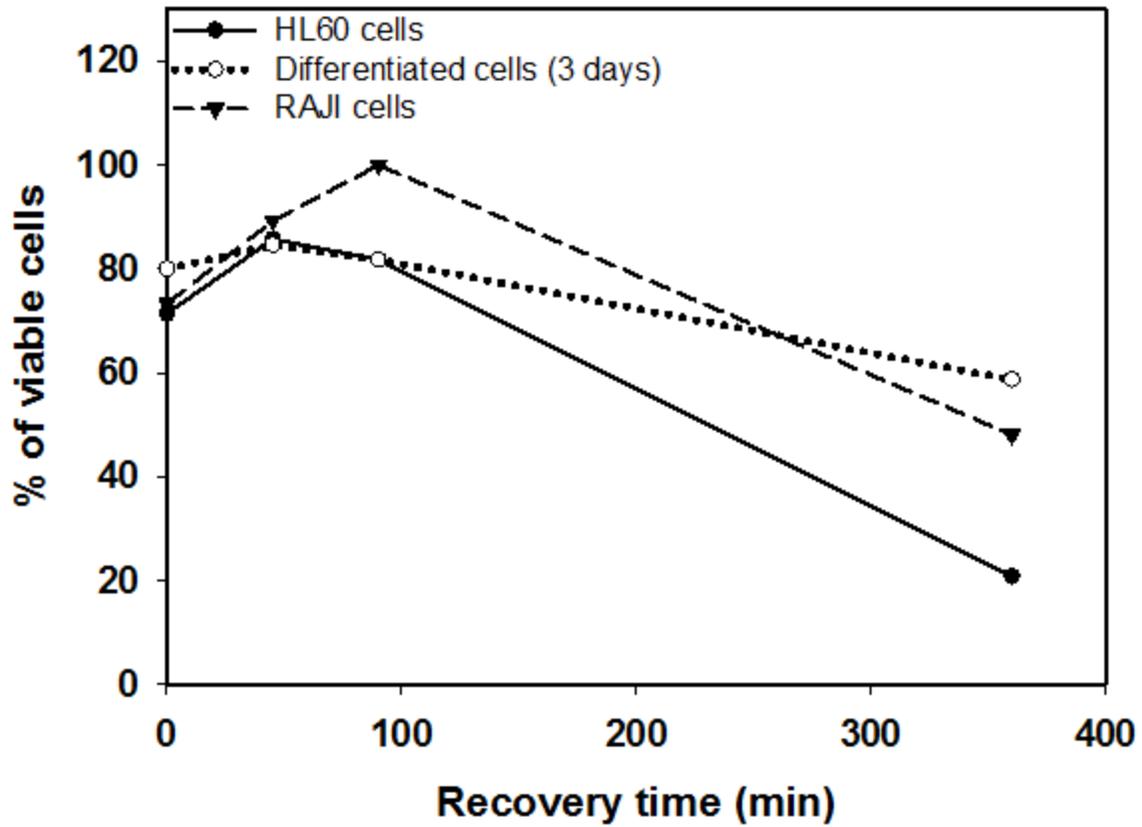


Figure 6.7 Cell viability following UVB-induced DNA damaged (1.6 kJ m^{-2}) in HL60, ATRA-induced differentiated HL60 and RAJI cells as assessed by trypan blue exclusion over a recovery time of 45 min, 90 min and 6 h, $n = 1$ (4 measurements).

6.3.2 Effect of UVB on PAR production in CD38^{+/} cells

Next, the effect of UVB on PAR accumulation in cells expressing CD38 was examined. It is well known that PARP-1 is activated upon binding to damaged or abnormal DNA (Durkacz *et al.*, 1980) and catalyzes the formation of poly(ADP-ribose) polymers (PAR) onto different acceptor proteins, including PARP-1 itself (auto PARsylation), using NAD⁺ as substrate. PAR accumulation is an immediate response following UV exposure. PARP catalytic activation was assessed by detection of its product, PAR-modified proteins, in CD38 negative cells (HL60) and CD38 expressing-cells (RAJI, 3 day differentiated HL60 cells) up to 6 h after UVB treatment (Fig. 6.8 A).

Western blotting (Fig. 6.8 A) showed that UVB exposure resulted in an observed decrease in PAR hypermodified proteins in HL60 cells, RAJI, and differentiated cells from 0-90 min post irradiation compared to the basal levels in each corresponding non-exposed control (Fig. 6.8 B), including PARP-1, whose modifications appear clearly between 100-200 kDa (Yu *et al.*, 2002). Interestingly, PAR production increases significantly at 6 h post-UVB treatment in all samples compared to immediately after treatment (Fig. 6.8 A); this was clearly shown in HL60 cells compared to the NAD-restricted cells (RAJI and differentiated HL60 cells) which showed less detectable PAR-hypermodified proteins (Fig. 6.8 A). The low PAR levels might reflect low availability of the substrate for PARP (NAD), probably restricted by CD38 activity.

Collectively, Western blotting results for poly ADP-ribose polymer expression might not show clear variations in cell response to DNA damage or PAR production which was based on whether or not the cells expressed CD38.

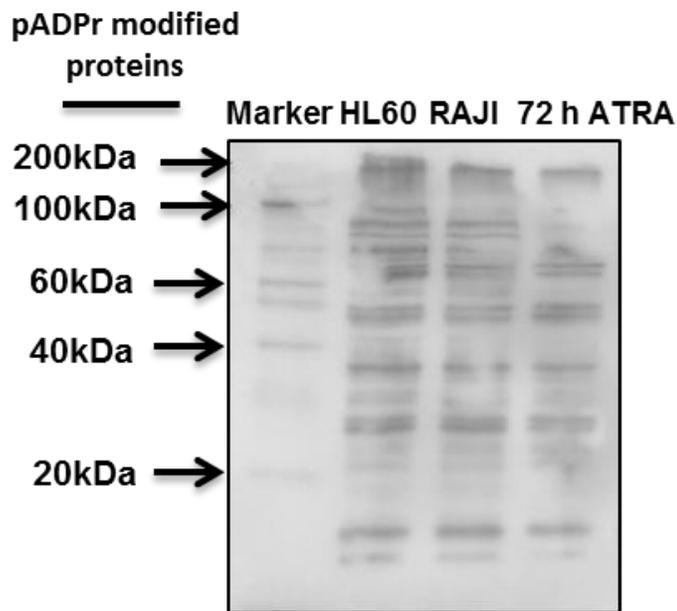
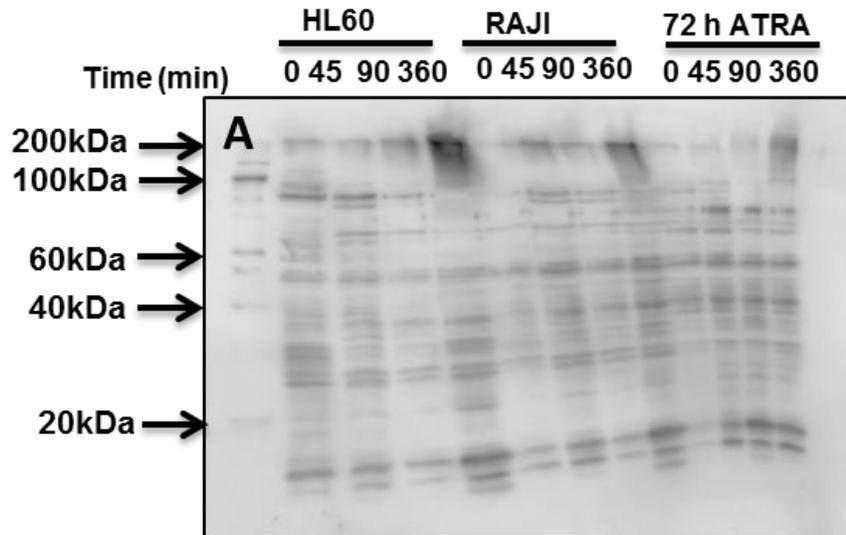


Figure 6.8 Western blotting analysis for poly ADP-ribose polymer expression under (A) normal conditions, represented by HL60 cells treated for 3 days with ATRA compared to the controls (RAJI and undifferentiated HL60 cells), and (B) PAR production after UVB exposure from 0-6 h for 50 μ g cell lysate under reducing conditions and 12% SDS PAGE (Chapter 2, section 2.8.4). The figure represents one of two separate cultures.

6.3.3 Effect of UVB-induced DNA damage on apoptotic cell death in CD38⁺ and CD38⁻ cells

In this Section of the work, an attempt was made to examine a possible relationship between NAD levels, and effects on DNA-damage and cell death. In previous Sections, a different cell response to UVB-induced damage DNA was found. Therefore, it seemed important to further confirm these findings by using another method of assessing cell damage or death. Thus, two different morphological determination methods- the halo assay and Wright-Giemsa staining- were performed to compliment the data already obtained and to further investigate the effect of cellular NAD content on either DNA repair or apoptotic cell death. It is worth mentioning that radiation therapy is used in cancer treatment via the induction of DNA damage to kill cancer cells or to keep them from growing (Lawrence *et al.*, in: DeVita *et al.*, 2008).

Morphological observation of cell death was performed by two simple, sensitive, and reliable assays, the halo assay and Wright-Giemsa staining. These assays were used for the quantification of apoptosis in HL60, 3 day differentiated HL60 cells and RAJI cells that had been exposed to UVB as a DNA damaging source. Giemsa-stained cells (Fig. 6.9), and cells that were assayed by the halo assay (Fig. 6.10) showed morphological changes after UVB irradiation for up to 6 h. Typical apoptotic changes, including chromatin condensation, nuclear fragmentation and formation of apoptotic bodies, were clearly observed in Giemsa stained cells (Fig. 6.9). Those cells exhibiting morphological changes can be easily differentiated from normal cells which, under a light microscope, show normal morphology with no apoptotic bodies (Searle *et al.*, 1982). This was found in the controls for all cell lines. Furthermore, apoptotic cells assayed by the halo assay (Fig. 6.10) showed a halo of DNA with a hazy outer boundary that extends around the original form of the nucleus.

There was variation in cell responses to UVB-induced DNA damage that depended on the cell line and the time after irradiation. Thus, apoptosis appeared immediately after irradiation in all cell types as detected by Giemsa stain (Fig. 6.9) and halo assays (Fig. 6.10). Interestingly, HL60 cells showed a greater response to UVB-induced DNA damage with both assays at 0 h, compared to the other cells. Also, repair following irradiation was seen at 45 min and 90 min in HL60, 3 day differentiated HL60 cells and RAJI cells, respectively, and this observation might confirm initiation of the DNA repair process. No characteristics of apoptosis were seen for each non-irradiated control, HL60, differentiated HL60 cells and RAJI cells (Fig. 6.9, 6.10). Finally, after the recovery time, 6 h, apoptosis was observed in the differentiated HL60 cells and control HL60 cells to a greater degree than was observed in RAJI cells (Fig. 6.9, 6.10). These data appear to confirm that NAD is a key determinant of apoptotic cell death. Therefore, as NAD levels in HL60 cells are higher than those in RAJI cells, these cells were more responsive to UVB-induced DNA damage as confirmed by more apoptotic cell death. Importantly, similar results were obtained using the two assays (Fig 6.9; 6.10) and these morphological data are concomitant with DNA damage results (Fig. 6.6) for the same cells.

In summary, irradiation of HL60, differentiated HL60 cells and RAJI cells with UVB light caused the cells to undergo morphological changes characteristic of apoptosis, and the level of apoptosis differed between cells depending on the levels of CD38 expression, intracellular NAD content, PAR production and the time after irradiation. Collectively, these data supported the comet results and suggest that leukaemia cells that express CD38 might exhibit a resistance to apoptotic cell death that is induced under UVB radiation.

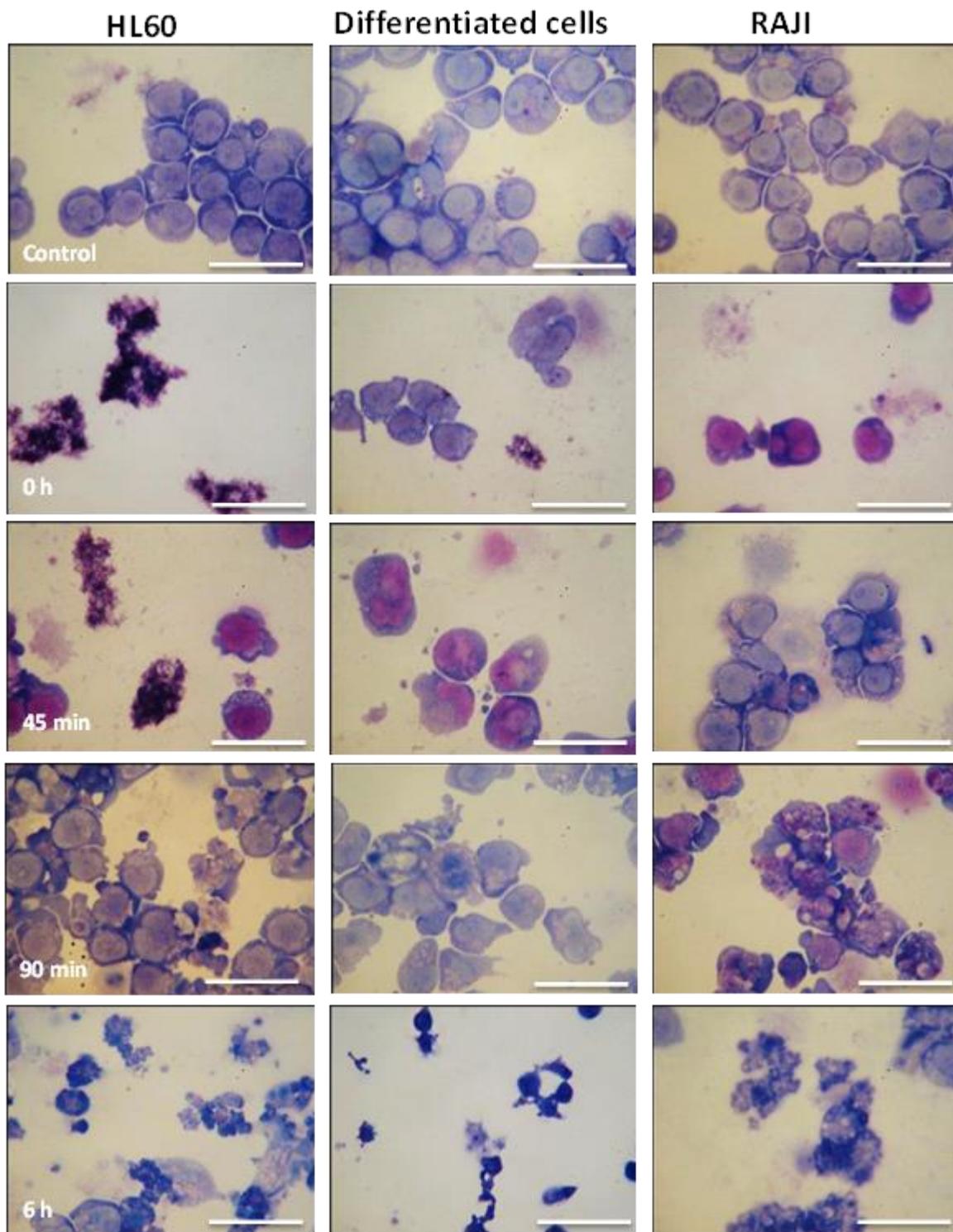


Figure 6.9 Photomicrographs showing HL60, 3 day- differentiated HL60 cells and RAJI cells stained with Wright-Giemsa stain before, and after irradiation (0-6 h). Cells exhibit features typical of apoptosis after UVB-irradiation. Original magnification x100. Scale bars: 50 μ m.

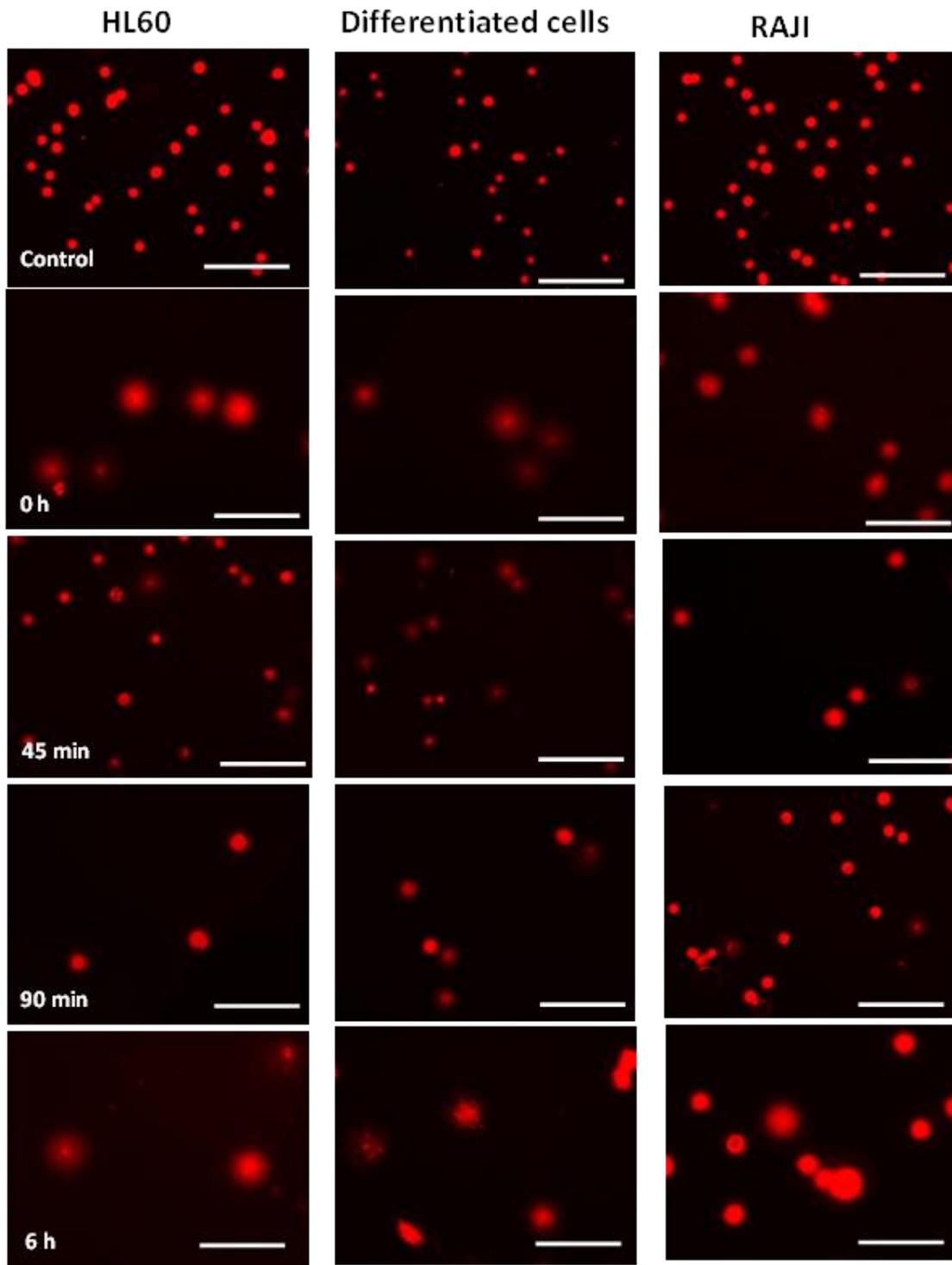


Figure 6.10 Photomicrographs processed during the halo assay showing HL60, 3 day differentiated HL60 cells and RAJI cells stained with ethidium bromide as controls or after UVB irradiation (0-6 h). Original magnification x 400. Scale bars: 50 μ m.

6.4 Discussion

The aim of this study was to evaluate the effect of a CD38-mediated decrease in NAD levels on the cellular response to DNA damage (after UVB exposure), both in cells expressing CD38 (RAJI and 3 day differentiated HL60 cells), compared to undifferentiated HL60 cells, which do not express CD38. In the current study, the halo and comet assays were used to assess the DNA damage following UVB-induced DNA damage. Ultraviolet B (UVB) causes either direct DNA damage, forming cyclobutane pyrimidine dimers (CPD) and 6,4-photoproducts which are removed by nucleotide excision repair (NER), or oxidative DNA damage (for example single strand breaks), which are removed by base excision repair (BER), and single strand break repair (SSBR) (Caldecott, 2003). Interestingly, in order to repair the DNA damage, PARP is known to be activated, and it is implicated in both SSBR (Caldecott, 2003) and BER (Le Page *et al.*, 2003) of UV-induced oxidative DNA damage (Caldecott, 2003).

The UVB-induced DNA damage results shown in Fig. 6.4 clearly showed that CD38 negative cells (with lower intracellular NAD levels) showed less DNA damage compared to CD38 positive cells (RAJI and differentiated HL60 cells). Ultimately, these data confirm that the decline in NAD levels strongly enhances DNA damage. Furthermore, an important finding is that DNA repair was seen from the earliest times after irradiation as confirmed by the less DNA damage in HL60 and RAJI cells at 45 min and 90 min compared to differentiated HL60 cells. The results suggest that the cellular response to DNA damage is based on the variation in NAD levels. Although the differentiated cells expressed high levels of CD38 with lower NAD content, they also showed low DNA damage at 90 min which might relate to the initiation of repair processes. A possible explanation for this repair is that the levels of NAD⁺ were suitable to

initiate the repair process, and that NAD^+ might not drop to lower levels after PARP-1 activation. Also, PARP-1 activation may lead to rapid depletion of the cytosolic pool, but not of the mitochondrial pool, of NAD^+ (Ying *et al.*, 2005). These reasons might contribute to a relative DNA repair in the differentiated HL60 cells. Altogether, these results suggest that a repair process through PARP activation might occur in response to UVB-induced DNA damage, since at low or mild levels of DNA damage, PARP initiates DNA repair processes (for instance, recombination, remodelling of chromatin, transcriptional changes at the damaged site, and DNA base excision repair, Virag and Szabo, 2002). It is worth noting that an early PARP activation (represented by PAR accumulation) has been observed previously at 1 to 2 h after irradiation with UVB in mouse fibroblasts (Vodenicharov *et al.*, 2005). However, in the current study, early PAR production was observed in HL60 at 90 min after UVB-irradiation, increasing in all cell lines after 6 h. Surprisingly, at 6 h, a detectable level of DNA damage was also evident ($\approx 30\%$ tail DNA), and it was relatively similar in all cell lines. One possible explanation for these data is that PARP activation and PAR production might not be able to participate in the repair of UV-induced DNA damage, which might reflect the key role of NAD levels in the repair process. In addition to the effect of UVB irradiation in inducing DNA damage (Zong *et al.*, 2004), the decline in intracellular NAD, probably via CD38, might also participate in increasing this damage. CD38 might affect PARP activity by limiting the availability of NAD, ultimately mediating DNA damage and some of its consequences (collectively known as genomic instability, e.g. chromosomal aberrations, DNA translocations, deletions, and amplifications). In the absence of a repair system, probably PARP, genomic instability would rapidly accumulate and disturb DNA replication, gene expression and ultimately cellular and tissue homeostasis (Burkle, 2001).

NAD levels are an important factor in deciding cell fate. In general, two controversial hypotheses have been suggested involving NAD as a determinant of cell fate. It was firstly hypothesized that NAD depletion increased DNA damage (Winter and Boyer, 1973) and that PARP activation causes cell death via apoptosis (Yu *et al.*, 2002), necrosis (Ha and Snyder, 1999) or autophagy (Munoz-Gamez *et al.*, 2009). A second hypothesis proposed that NAD-depleted cells are resistant to apoptotic cell death, as demonstrated by a study of Wright *et al.* (1996). This study indicated that NAD-deficient cells are resistant to UV light-induced apoptotic cell death. Collectively, these two controversial hypotheses might explain that there are two mechanisms by which NAD-deficient cells respond when death appears imminent, these being either resistance or induced cell death. Importantly, the second hypothesis is strongly confirmed by the results of this Chapter. In the current study, it was hypothesized that the decrease in NAD levels might increase DNA damage and hence inhibits apoptotic cell death, as it was shown that cells with adequate levels of NAD undergo apoptosis, but that cells with restricted or lowered NAD levels show a relative resistance to apoptotic cell death. For example, apoptosis was more evident in HL60 cells than RAJI cells. It has been shown previously that UVB induced apoptotic cell death in HL60 (Lu *et al.*, 1996). The differentiated HL60 cells, unexpectedly, were also found to undergo apoptosis, which might be one of the consequences of ATRA-induced terminal differentiation of HL60 cells (James *et al.*, 1999). Thus, apoptotic cell death was NAD-independent in differentiated HL60 cells and NAD-dependent in both HL60 cells and RAJI cells. Altogether, cells that are expressing CD38 are expected to have an impaired repair system and accumulate DNA damage along with a characteristic resistance to cell death.

Several approaches have been developed to target NAD⁺ metabolism for both the prevention and treatment of cancer (Jacobson *et al.*, 1999). For instance, pharmacological inhibition of PARP-1

activity worked as a suitable target to enhance the activity of antitumour drugs through inhibition of necrosis and activation of apoptosis (Southan and Szabo, 2003). Furthermore, researchers have developed drugs targeting the inhibition of NAMPT (the crucial enzyme in NAD synthesis that is overexpressed in human malignancies), that have anticancer properties through depletion of cellular NAD⁺ (Van Beijnum *et al.*, 2002), such as using FK866 (Hasmann and Schemainda, 2003) and CHS828 (now under development as the prodrug GMX1777) either alone (Hjarnaa *et al.*, 1999) or in combination with cancer therapy producing DNA damage, the alkylating drugs and radiotherapy. For instance, FK866 has been combined with ionizing radiation in a mouse tumour model, which shows a delay in tumour growth, with no effect on normal tissues (Muruganandham *et al.*, 2005; Kato *et al.*, 2010). Importantly, the results of the current study might also be taken into account in cancer therapy while using chemotherapy or radiotherapy in combination with inhibitors of NAD biosynthesis, especially in CD38⁺ leukemia subset patients.

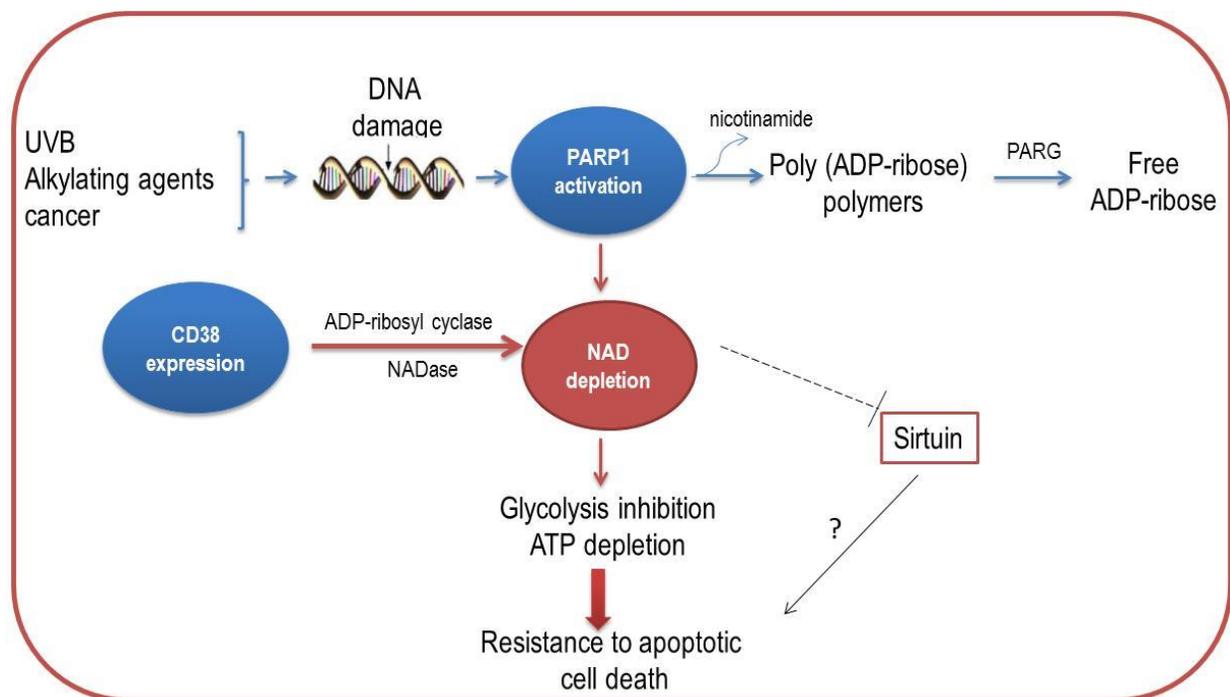


Figure 6.11 The effects of CD38 expression on NAD depletion and the role of NAD as a metabolic link between DNA damage induced by different stimuli or in cancer, and the resistance to cell death via a reduction in ATP levels.

In conclusion, NAD depletion in cells expressing CD38 might induce a resistance to apoptotic cell death and promote cell survival in leukaemia cell lines, which might have important implications for the pathogenesis and progression of cancer. In terms of leukemia patients, cells that are expressing high levels of CD38 (in patients with poor prognosis) would also be expected to show a similar relationship. Firstly, according to the results (Chapter 3), the increase in CD38 expression, concomitant with a decrease in NAD levels, will be linked with reduced glycolytic activity which may in turn affect ATP levels, since cells consume ATP to replenish NAD^+ (Virag and Szabo, 2002). Thus, a depletion of ATP might lead to increased resistance to cell death, since apoptosis is an energy-dependent process (Kass *et al.*, 1996), Secondly, as suggested by the

results presented in this Chapter, low intracellular NAD content may be as a result of CD38 activities, in addition to PARP activation (following DNA damage under UVB irradiation). CD38 activity and low NAD levels might further lead to restricted PARP activity, lowered PAR levels, reduction in the repair process and defective induction of apoptosis, since PAR is known as an inducer of apoptosis. This may lead to impairment of the repair system and failure to control the carcinogenesis.

Finally, the information presented in this chapter raises the possibility that in leukemia patients the combinations of chemotherapy or radiotherapy with CD38 expression might lead to poor responsiveness, drug resistance and a worsening of the disease stage. For this reason, DNA-damaging therapy that uses irradiation or drugs to destroy cancer cells is often accompanied by the development of drug resistance and severe side effects (Libura *et al.*, 2005; Mistry *et al.*, 2005). One possible explanation for this is that CD38 expression is an important regulator of intracellular NAD⁺ pools and therefore of metabolic pathways that are related to the availability of NAD⁺ rather than glycolysis, such as PARP reactions. This might reduce PAR production leading to a delay in apoptotic cell death in preference to cell resistance and survival. Altogether, combined CD38 expression with cancer therapy agents or radiotherapy may promote cell proliferation (Fig. 6.11), and drug resistance. For these reasons, CD38⁺ patients at a more advanced stage of disease show poor responsiveness to chemotherapy and a shorter survival state in comparison to CD38⁻ CLL patients (Morabito *et al.*, 2002). Thus, to improve patient therapy, one possible suggestion is to avoid the use of DNA-damaging therapy (chemotherapy or radiotherapy) in CD38⁺ CLL patients, in order to reduce cell resistance to such treatment.

CHAPTER 7

GENERAL DISCUSSION

7.1 Discussion

Leukaemia is one of the common haematological malignant diseases, and CLL is the most frequent leukaemia in Europe and North America. It is a highly heterogeneous, incurable disease that ranges from a stable condition, not requiring treatment, to a rapidly progressive disease unresponsive to therapy (Hallek *et al.*, 2008). The presence of CD38 on the CLL cell surface has prognostic relevance, with high levels being associated with an unfavourable outcome (Damle *et al.*, 1999). For these two reasons, CLL was selected as a disease model in the current study to investigate the underlying hypothesis. Generally, most studies to date have focused on the role of receptor function of CD38 in poor CLL prognosis. This study is the first to describe an important role of CD38 enzymatic function in altering NAD levels and of their contribution to leukaemia development and progression, in addition to its receptor function. The human leukaemia cell line HL60, was predominantly used as an alternative model for leukemia in the current study as a model expressing CD38 when differentiated to neutrophil-like cells using ATRA. The current findings suggest that CD38 expression plays a key role as a determinant of cell survival, which is mediated through consumption of NAD, as a redox cofactor and the substrate for a network of NAD-consuming enzymes. Overall, these findings, combined with previous findings, lead to three hypotheses describing the synergistic connection between the receptor and enzymatic functions of CD38, which might help to explain the poor prognosis in CD38⁺ leukemia subset patients.

Initially, Vaisitti *et al.* (2011) described two hypotheses in terms of the mechanism by which CD38 regulates the homing process and therefore why patients with CD38⁺ CLL clones experience a generally more aggressive disease and a worse prognosis. In the first hypothesis, it

was suggested that CD38 could transmit its own indirect signals through the generation of Ca^{2+} active messengers (Vaisitti *et al.*, 2010). Extracellular CD38 catalyses NAD^+ hydrolysis, generating ADPR and, at lower levels, cADPR. These two messengers are transported inside the cell by CD38 itself or by active channels, where they could then trigger Ca^{2+} influx from the binding to TRPM2 or RyR (Perraud *et al.*, 2001). An increase in Ca^{2+} concentrations may lead to direct activation of Ca^{2+} -sensitive tyrosine kinases (Schaller, 2010), in addition to direct nuclear translocation of Ca^{2+} -sensitive transcription factors (Graef *et al.*, 1999). Ultimately, this leads to the initiation of a transcriptional program regulating proliferation.

The second hypothesis suggests that CD38 induces the formation of highly stable supramolecular complexes that include surface molecules as well as intracellular signalling adaptors (Deaglio *et al.*, 2007). CD38 plays direct role as a molecular amplifier that activates the polymerization of actin and nuclear events, specifically in the presence of its non-substrate ligand CD31. In addition, the presence of other possible molecules as previously described (Chapter 1) together creates a suitable environment for CD38 to work as a master regulator of the CLL cell homing process in patients with CD38^+ CLL clones.

The current study explores a third hypothesis (Fig. 7.1), which postulates that, in addition to the aforementioned role of CD38 as a receptor, CD38 enzymatic functions are also involved in CD38-mediated poor prognosis in leukemia patients. Tests of the current hypothesis had two major aims, the first was to provide solid confirmation that CD38 is the main NAD consuming enzyme, but not its analogue (CD157), nor other NAD consumers (PARP or sirtuin). The findings (Chapter 3) supported the hypothesis, confirming the major role of CD38 in altering NAD levels to the lower levels concomitant with its expression; this relationship was reversed by

the impact of kuromanin in inhibiting CD38 cyclase activity. This study produced results which corroborate the findings of Barbosa *et al.* (2007), who demonstrated that loss of CD38 in CD38 KO mice had a major effect on NAD homeostasis, since a significant boost in NAD levels were shown.

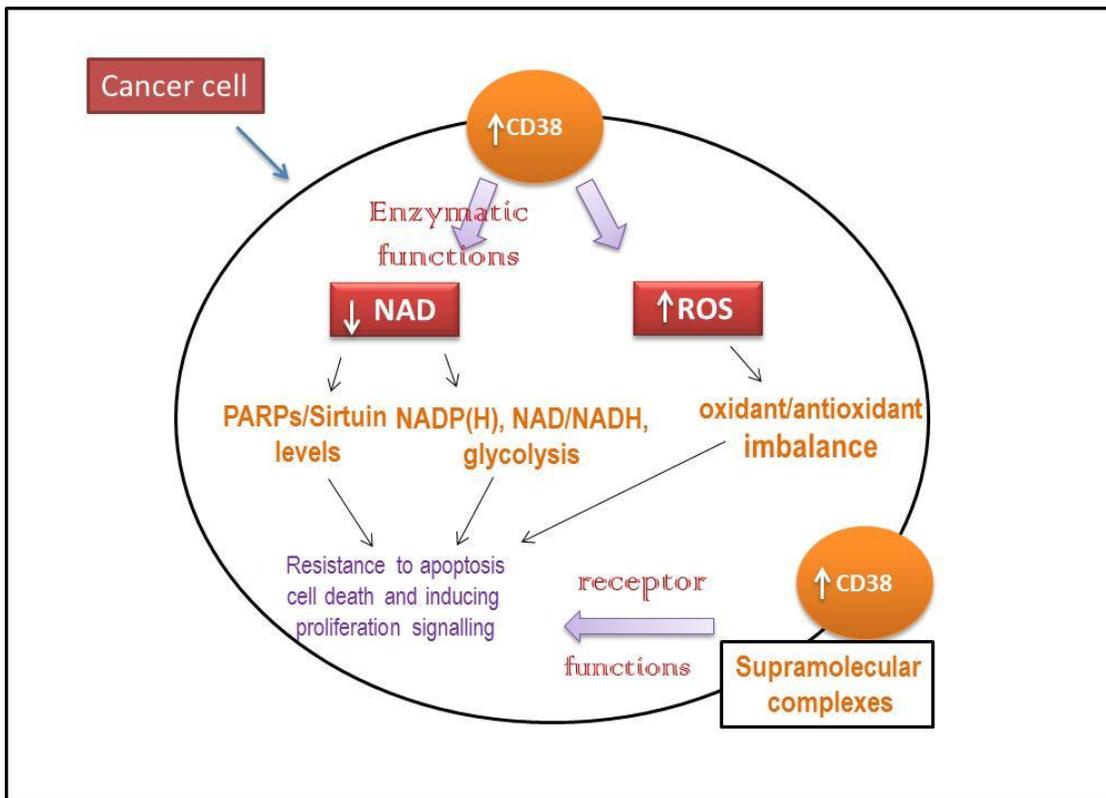


Figure 7.1 Schematic diagram representing the third hypothesis for the functional role of CD38 enzymatic functions mediated by NAD, combining with its receptor functions in inducing cell proliferation and poor prognosis in CD38⁺ leukemia patients.

The second aim in testing the current hypothesis was to investigate the consequences of CD38 enzymatic function (since it has a major role in NAD consumption) on NAD-dependent processes, cell physiology and induction of cell proliferation in leukaemia, specifically in chronic lymphocytic leukaemia. The results in Chapters 4 and 6 provide positive data that support this hypothesis. The results confirmed that many processes were affected by CD38-mediated lowering of NAD levels. For example, glycolytic activity, which was reflected by reduced lactate production and a relatively constant $\text{NAD}^+ : \text{NADH}$ ratio. This might directly affect cellular energy as the $\text{NAD}^+ : \text{NADH}$ ratio is a measure of the energy status of a cell (Ying, 2006). Moreover, CD38 activity might also restrict NAD-dependent enzyme activities (PARP, sirtuin) and their dependent processes in the cells by limiting the substrate availability (NAD). These enzymes mediate important roles in modifying cellular functions such as genomic stability, apoptosis, cell signalling and stress tolerance (Malavasi *et al.*, 2010). CD38 expression was accompanied by elevated lipid peroxidation (as assessed by TBARS) and low total glutathione levels, which represents the antioxidant status in the cells, suggesting that an imbalance between oxidant/antioxidant status was concomitant with CD38 expression. Collectively, these two results using differentiated HL60 cells support the third hypothesis.

It is worth noting that ATRA-induced CD38 expression in HL60 cells has been shown to induce cell apoptosis (Mehta *et al.*, 1996), despite a large decrease in intracellular NAD levels. One of the possible explanations for this is that ADP ribosylation of nuclear CD38 may trigger an induction of apoptosis in ATRA-treated HL60 cells (Yalcintepe *et al.*, 2005). Similar results have been obtained *in vivo* to the effect of ATRA, in patients with acute promyelocytic leukaemia, but with a side effect known as an APL differentiation syndrome (Sanz *et al.*, 2009). In other cells, however, CD38 has been attributed to different effects on cell growth; its cellular

effects have shown to be ambiguous, since CD38 expression was either a positive or negative regulator of induced cell differentiation and growth arrest, depending on the expression level per cell (Lamkin *et al.*, 2006). For example, in 3T3 or HeLa cells, it promotes cell cycle progression (Zocchi *et al.*, 1998), in B lymphocytes or T lymphocytes it can cause apoptosis (Kumagai *et al.*, 1995; Tenca *et al.*, 2003), but in CLL, a B cell leukaemia, CD38 is an indicator of poor prognosis (Ghia *et al.*, 2003). According to previous studies, CD38⁺ CLL clones show a resistance to apoptosis; this might be due to a decline in NAD levels that occur while CD38 expression is upregulated. Hence, from the current data in differentiated HL60 cells, it is possible to suggest that leukemia cell survival might not be affected by NAD-depletion. Instead, cancer cells with low cellular ATP levels may show higher resistance to programmed cell death due to the high energetic requirements of apoptosis. The findings relating to the current hypothesis along with the previous hypotheses may provide a better understanding of the mechanism of resistance of leukemic cells to apoptosis.

In cancer cells, the same basic metabolic pathways are utilized to generate energy as in normal cells, but some changes in a tumour microenvironment lead to protective metabolic adaptation (DeBerardinis, 2008; Semenza, 2008). For example, the cells in such an environment tend to use lactic fermentation in the absence of oxygen, which is a faster way to generate metabolic energy (Jones and Thompson, 2009). The main advantage of lactic fermentation is that ATP can be obtained at a faster rate through a simpler process (DeBerardini, 2008). Hence, cancer cells exhibit a high rate of NAD turnover due to a high glycolytic activity in addition to high levels of ADP-ribosylation activity (Gagne *et al.*, 2006), resulting from PARP activation (required for DNA repair and genome stability). Thus, in cancer cells, low intracellular NAD levels may lead to a resistance to apoptosis and induce cell proliferation. Interestingly, in CD38 negative

leukaemia cells one might expect that the replenishment of NAD levels might relatively enhance the DNA repair process and control disease progression. However, the same effect might not be seen in leukaemia cells that express CD38, since NAD-depletion would have more impact on NAD-dependent process and cell survival. Thus, low NAD levels lead to a drop in ATP, the level of which is an important factor in the process of apoptosis. Moreover, the metabolic pathways that depend on NAD availability such as sirtuin and PARP would also be affected. Low intracellular NAD might lead to accumulation of damaged DNA that would further decrease NAD levels due to PARP hyperactivation. Altogether, a severe drop in NAD levels leads to a similar drop in the determinant factor of apoptotic cell death, ATP. Ultimately, these environments create cellular resistance to apoptosis, and also facilitate the cell proliferation process. It is worth noting that drug resistance in tumour cells is a common obstacle in cancer chemotherapy. Resistance includes decreased drug accumulation, intracellular drug detoxification, enhanced DNA repair/ tolerance and failure of apoptotic pathways (Fuentes *et al.*, 2003). Beyond NAD depletion, it has been suggested that highly resistant tumour cells may express different versions of caspases or they may contain endogenous caspase inhibitors that limit apoptotic cell death pathways (Schimmer *et al.*, 2003).

In conclusion, targeting CD38 enzymatic functions in leukemia therapy along with its receptor function might serve as a possible solution to apoptotic cell resistance or poor cell metabolism in leukemia patients, and that future studies should pay attention to the evaluation of intracellular NAD levels as well as CD38 expression levels as a marker for poor prognosis in leukemia patients.

7.2 Future studies

One of the current treatments for leukaemia is a drug-based chemotherapy that uses one or more drugs to destroy cancer cells and induce apoptosis. However, this may be accompanied by the development of drug resistance and severe side effects (Libura *et al.*, 2005; Mistry *et al.*, 2005). Chemotherapeutic alkylating agents have been shown to cause miscoding lesions, chromosomal aberrations (Veld *et al.*, 1997) and secondary cancer, particularly leukaemia. They may also depress NAD⁺ levels (Dreizen *et al.*, 1990). For instance, the chemotherapeutic agents (e.g., 5-fluorouracil, 6-mercaptopurine) interfere with the conversion of tryptophan to niacin (Stevens *et al.*, 1993). Moreover, rat studies have shown that niacin deficiency significantly increases the risk of chemotherapeutic induced secondary leukaemia (Kirkland, 2003). Therefore, it is imperative to develop other potential therapeutic agents for the treatment of this disease. Thus, NAD metabolism has an important position in total cellular metabolism, because it has multifunctional roles as a cofactor for individual enzymes and as a substrate for NAD⁺-consuming enzymes. It could pose an attractive target for the treatment of various pathologies, especially in the fields of CD38 biology, linked to the prevention of aging and its related diseases like obesity and cancer. The results obtained in the current study might successfully be applied in the field of cancer therapy and also open the door for future studies to further characterize the functional role of CD38-mediated NAD depletion in the development of leukaemia, for example if the observations obtained from a current study using the human leukaemia model (HL60) are confirmed in the context of leukaemia cells. If so, therapeutic strategies which target this CD38/NAD relationship, such as investigating the effect of manipulating NAD levels on prognosis in CD38⁺ leukemia patients, might be effective in fighting leukemia. However, several areas still need further investigation to clarify the precise effect of CD38 expression on the

nucleotide levels or on other NAD-dependent reactions. One of the important questions to be addressed is the levels of NADP in this situation; cADPR levels also need to be measured while NAD is consumed. If levels of this messenger decrease concomitantly with NAD levels, this raises further questions as to how CD38 induces proliferation signalling since, as previously mentioned, cADPR plays a role in the control of cell proliferation via Ca^{2+} signalling (Zupo *et al.*, 1994; Hardingham *et al.*, 1997). Similar investigations need to be focus on NAADP as a second messenger produced from its precursor, NADP.

Moreover, according to the results obtained in Chapter 5, CD38 expression can be downregulated by adding NAD^+ to the medium, or using FK866. It would therefore be tempting to investigate the mechanism of this inhibitory effect as a future study. It has previously been observed that in cancer cells DNA damage can stimulate NAD^+ biosynthesis (Jacobson *et al.*, 1999), through upregulation of the expression of NAMPT (Van Beijnum *et al.*, 2002), which is the rate-limiting enzyme in the salvage pathway from the breakdown product nicotinamide (Revollo *et al.*, 2004). That suggests that NAMPT may be crucial in maintaining cellular NAD^+ levels in tumours. For that reason FK866, a potent inhibitor of human NAMPT, is used, and the consequent reduction in NAD^+ levels has been seen to induce apoptosis of tumour cells (Hasmann, and Schemainda, 2003; Muruganandham *et al.*, 2005). If a similar mechanism applies to the primary leukaemia cells (CD38^+ cells), and according to the results in Chapter 5, then FK866 might serve as a useful therapeutic agent target for leukemia patients. This suggested study might succeed in the case of moderate DNA damage in cancer cells, since depletion of NAD levels and also CD38 expression by using FK866 might be a useful tool to induce apoptotic cell death. Interestingly, downregulation of CD38 expression might reduce its signalling effect on proliferation. Furthermore, it would be interesting to determine whether the

same process could apply to leukaemia patients by using NAD⁺ supplementation, since applying NAD⁺ has also been shown to downregulate CD38 expression (Chapter 5). An elevation of intracellular NAD levels through control of NAD homeostasis pathways, either via consuming enzyme pathways, or recycling pathways could heavily impact on metabolism, cellular viability and signalling pathways. In this situation, repletion of cellular NAD levels by adding NAD⁺ directly to the culture medium with concomitant inhibition of CD38 expression might also lead to apoptotic cell death, since NAD levels are a determinant of cell survival.

CD38, as a major NAD consumer enzyme in the cells, has developed from a mere marker to a disease modifier in leukemia. Thus, it is important to determine the role of other NAD consumers in modifying the environment or inducing proliferation signalling in cancer cells. Previously published studies observed that inhibition of PARP-1 in cancer cells exposed to DNA-damaging drugs would decrease DNA repair and would induce apoptotic cell death, and may also increase the sensitivity of tumour cells to DNA damaging antitumour drugs (Munoz-Gamez *et al.*, 2005). Interestingly, this was more effective against tumour cells than against normal cells. However, in cancer cells that express CD38 the mechanism may be different, since NAD would be consumed by CD38 as the main NAD-degrading enzyme rather than PARP, and this might delay apoptotic cell death according to the results Chapter 6. Thus, utilizing CD38 inhibitors along with PARP inhibitors might elevate intracellular NAD levels and hence might also target apoptotic cell death. Furthermore, in the case of severe DNA damage combining intracellular NAD-elevating compounds (e.g. nicotinamide or NAD⁺) along with CD38 inhibitors and PARP inhibitors might serve as an excellent therapeutic approach for CD38⁺ leukaemia patients, since elevation of intracellular NAD levels might help to induce apoptotic cell death. Indeed, the fact that NAD⁺ levels could be elevated by selective inhibition of NAD⁺ consumers, PARPs or CD38 might lead

to the activation of other NAD⁺ consumers, such as sirtuin. The latter enzyme has important functions such as gene silencing, longevity and genome stability (Zhang, 2003; Pillai *et al.*, 2005). Nevertheless, blockage or inhibition of one pathway of NAD⁺ consumption might cause potential side effects, as, for example, it has been suggested that SIRT1 and 2 are crucial antiapoptotic molecules in leukaemia cells and have a role in the development of cancer; thus, the SIRT inhibitor, sirtinol, effectively induced cell death and that may be a useful therapeutic agent for leukaemia (Peck *et al.*, 2010). Therefore, further studies are still required to evaluate whether such a strategy may be of therapeutic value, or whether utilizing inhibitors of DNA repair pathways concomitant with the above suggestions could be an efficient strategy for cancer therapy.

One of the fundamental problems of tumour cells is the phenomenon of lactic fermentation; the metabolic adaptation of cancer cells in response to hypoxia has been shown to be associated with reduced sensitivity to common anti-cancer agents (Xu *et al.*, 2005). Thus, it has previously been suggested that targeting the glycolytic pathway might preferentially sensitize cancer cells to chemotherapeutic agents without significant toxicity to normal cells (Xu *et al.*, 2005). Hence, in combination with the results in Chapter 5, CD38 expression has been seen to be upregulated under hypoxic conditions (specifically 2% O₂). Therefore, it is worth investigating the role of CD38 in inducing cell proliferation under the same *in vivo* conditions by exposing the cells to a range of oxygen levels in order to characterize the enzymatic and receptor functions of CD38 in a hypoxic environment similar to that of cancer cells.

Moreover, it is interesting to note that recently published studies by Vaisitti *et al.* (2011) found that CLL cells taken from patients died easily in culture and appeared to have severe

impairments in vital signalling pathways. One possible explanation is that CLL cells from patients are more dependent on the external environment and supporting signals from other cells *in vivo* (Vaisitti *et al.*, 2010). This reflects a key role of the host environment in CLL progression and suggests that targeting the host might be a valuable therapeutic target. For instance, In addition to targeting CD38-mediated NAD depletion and its related processes, it would be interesting to target the non-substrate ligand for CD38, CD31. leukemia cells' resistance to apoptosis is probably due to CD38/CD31 interaction-mediated anti-apoptotic signals. Thus, targeting CD31/CD38 interaction and their proliferation signalling might also be a potential target in leukaemia, since CD38 receptor functions have a large signalling effect on proliferation in addition to its enzymatic functions.

Finally, it would be interesting to investigate the role of CD38 expression leading to depletion of intracellular NAD and the consequences of this relationship in the development of other diseases beyond leukaemia such as obesity. CD38 expression is linked to obesity and it has been suggested CD38 deficiency has a key role in preventing the development of obesity following NAD elevation (Baur *et al.*, 2006). Thus, future studies might target NAD levels through regulation of CD38 expression, such as combining CD38 inhibitors with NAD-elevation compounds which is also found to down regulate CD38 expression, as shown in the current study.

REFERENCES

- Aarhus, R., Graeff, R. M., Dickey, D. M., Walseth, T. F. and Lee, H. C. 1995. ADP-ribosyl cyclase and CD38 catalyze the synthesis of a calcium-mobilizing metabolite from NADP. *J Biol Chem*, 270, 30327-33.
- Adams, J. D., Jr., Lauterburg, B. H. and Mitchell, J. R. 1983. Plasma glutathione and glutathione disulfide in the rat: regulation and response to oxidative stress. *J Pharmacol Exp Ther*, 227, 749-54.
- Adebanjo, O. A., Anandatheerthavarada, H. K., Koval, A. P., Moonga, B. S., Biswas, G., Sun, L., Sodam, B. R., Bevis, P. J., Huang, C. L., Epstein, S., Lai, F. A., Avadhani, N. G. and Zaidi, M. 1999. A new function for CD38/ADP-ribosyl cyclase in nuclear Ca²⁺ homeostasis. *Nat Cell Biol*, 1, 409-14.
- Adriouch, S., Ohlrogge, W., Haag, F., Koch-Nolte, F. and Seman, M. 2001. Rapid induction of naive T cell apoptosis by ecto-nicotinamide adenine dinucleotide: requirement for mono(ADP-ribosyl)transferase 2 and a downstream effector. *J Immunol*, 167, 196-203.
- Ahmed, N., Williams, J. F. and Weidemann, M. J. 1991. The human promyelocytic HL60 cell line: a model of myeloid cell differentiation using dimethylsulphoxide, phorbol ester and butyrate. *Biochem Int*, 23, 591-602.
- Aksoy, P., Escande, C., White, T. A., Thompson, M., Soares, S., Benech, J. C. and Chini, E. N. 2006b. Regulation of SIRT 1 mediated NAD dependent deacetylation: a novel role for the multifunctional enzyme CD38. *Biochem Biophys Res Commun*, 349, 353-9.
- Aksoy, P., White, T. A., Thompson, M. and Chini, E. N. 2006a. Regulation of intracellular levels of NAD: a novel role for CD38. *Biochem Biophys Res Commun*, 345, 1386-92.
- Alano, C. C., Garnier, P., Ying, W., Higashi, Y., Kauppinen, T. M. and Swanson, R. A. 2010. NAD⁺ depletion is necessary and sufficient for poly(ADP-ribose) polymerase-1-mediated neuronal death. *J Neurosci*, 30, 2967-78.
- Alano, C. C., Ying, W. and Swanson, R. A. 2004. Poly(ADP-ribose) polymerase-1-mediated cell death in astrocytes requires NAD⁺ depletion and mitochondrial permeability transition. *J Biol Chem*, 279, 18895-902.
- Anderson, R. M., Bitterman, K. J., Wood, J. G., Medvedik, O., Cohen, H., Lin, S. S., Manchester, J. K., Gordon, J. I. and Sinclair, D. A. 2002. Manipulation of a nuclear NAD⁺ salvage pathway delays aging without altering steady-state NAD⁺ levels. *J Biol Chem*, 277, 18881-90.
- Atkinson, M. A. and Maclaren, N. K. 1994. The pathogenesis of insulin-dependent diabetes mellitus. *N Engl J Med*, 331, 1428-36.
- Audrito, V., Vaisitti, T., Serra, S., Rossi, D., D'arena, G., Laurenti, L., Gaidano, G., Malavasi, F. and Deaglio, S. 2012. Metabolism and cancer: The CD38-NAMPT connection in chronic lymphocytic leukemia In: Proceedings of the 103rd Annual Meeting of the American Association for Cancer Research, Chicago, IL. Philadelphia (PA): AACR *Cancer Res* Abstract nr 5170. doi:1538-7445.
- Baehner, R. L., Boxer, L. A. and Davis, J. 1976. The biochemical basis of nitroblue tetrazolium reduction in normal human and chronic granulomatous disease polymorphonuclear leukocytes. *Blood*, 48, 309-13.
- Baggetto, L. G. 1992. Deviant energetic metabolism of glycolytic cancer cells. *Biochimie*, 74, 959-74.
- Bai, P., Canto, C., Oudart, H., Brunyanszki, A., Cen, Y., Thomas, C., Yamamoto, H., Huber, A., Kiss, B., Houtkooper, R. H., Schoonjans, K., Schreiber, V., Sauve, A. A., Menissier-De Murcia, J. and Auwerx, J. 2011. PARP-1 inhibition increases mitochondrial metabolism through SIRT1 activation. *Cell Metab*, 13, 461-8.
- Ball, H. J., Yuasa, H. J., Austin, C. J., Weiser, S. and Hunt, N. H. 2009. Indoleamine 2,3-dioxygenase-2; a new enzyme in the kynurenine pathway. *Int J Biochem Cell Biol*, 41, 467-71.

- Barata, H., Thompson, M., Zielinska, W., Han, Y. S., Mantilla, C. B., Prakash, Y. S., Feitoza, S., Sieck, G. and Chini, E. N. 2004. The role of cyclic-ADP-ribose-signaling pathway in oxytocin-induced Ca^{2+} transients in human myometrium cells. *Endocrinology*, 145, 881-9.
- Barber, N., Belov, L. and Christopherson, R. I. 2008. All-trans retinoic acid induces different immunophenotypic changes on human HL60 and NB4 myeloid leukaemias. *Leuk Res*, 32, 315-22.
- Barbosa, M. T., Soares, S. M., Novak, C. M., Sinclair, D., Levine, J. A., Aksoy, P. and Chini, E. N. 2007. The enzyme CD38 (a NAD glycohydrolase, EC 3.2.2.5) is necessary for the development of diet-induced obesity. *FASEB J*, 21, 3629-39.
- Barron, J. T., Gu, L. and Parrillo, J. E. 2000. NADH/NAD redox state of cytoplasmic glycolytic compartments in vascular smooth muscle. *Am J Physiol Heart Circ Physiol*, 279, H2872-8.
- Baur, J. A., Pearson, K. J., Price, N. L., Jamieson, H. A., Lerin, C., Kalra, A., Prabhu, V. V., Allard, J. S., Lopez-Lluch, G., Lewis, K., Pistell, P. J., Poosala, S., Becker, K. G., Boss, O., Gwinn, D., Wang, M., Ramaswamy, S., Fishbein, K. W., Spencer, R. G., Lakatta, E. G., Le Couteur, D., Shaw, R. J., Navas, P., Puigserver, P., Ingram, D. K., De Cabo, R. and Sinclair, D. A. 2006. Resveratrol improves health and survival of mice on a high-calorie diet. *Nature*, 444, 337-42.
- Bauvois, B., Durant, L., Laboureau, J., Barthelemy, E., Rouillard, D., Boulla, G. and Deterre, P. 1999. Upregulation of CD38 gene expression in leukemic B cells by interferon types I and II. *J Interferon Cytokine Res*, 19, 1059-66.
- Benavente, C. A., Schnell, S. A. and Jacobson, E. L. 2012. Effects of niacin restriction on sirtuin and PARP responses to photodamage in human skin. *PLoS One*, 7, e42276.
- Bender, D. 1992. Nutritional biochemistry of the vitamins, Cambridge university press, P 190-200.
- Berger, F., Ramirez-Hernandez, M. H. and Ziegler, M. 2004. The new life of a centenarian: signalling functions of NAD(P). *Trends Biochem Sci*, 29, 111-8.
- Bernofsky, C. and Swan, M. 1973. An improved cycling assay for nicotinamide adenine dinucleotide. *Anal Biochem*, 53, 452-8.
- Berridge, M. J. 1993. Cell signalling. A tale of two messengers. *Nature*, 365, 388-9.
- Bieganowski, P. and Brenner, C. 2004. Discoveries of nicotinamide riboside as a nutrient and conserved NRK genes establish a Preiss-Handler independent route to NAD⁺ in fungi and humans. *Cell*, 117, 495-502.
- Billington, R. A., Bellomo, E. A., Floriddia, E. M., Erriquez, J., Distasi, C. and Genazzani, A. A. 2006. A transport mechanism for NAADP in a rat basophilic cell line. *FASEB J*, 20, 521-3.
- Billington, R. A., Genazzani, A. A., Travelli, C. and Condorelli, F. 2008b. NAD depletion by FK866 induces autophagy. *Autophagy*, 4, 385-7.
- Billington, R. A., Ho, A. and Genazzani, A. A. 2002. Nicotinic acid adenine dinucleotide phosphate (NAADP) is present at micromolar concentrations in sea urchin spermatozoa. *J Physiol*, 544, 107-12.
- Billington, R. A., Travelli, C., Ercolano, E., Galli, U., Roman, C. B., Grolla, A. A., Canonico, P. L., Condorelli, F. and Genazzani, A. A. 2008a. Characterization of NAD uptake in mammalian cells. *J Biol Chem*, 283, 6367-74.
- Bofill, M., Akbar, A. N., Salmon, M., Robinson, M., Burford, G. and Janossy, G. 1994. Immature CD45RA(low)RO(low) T cells in the human cord blood. I. Antecedents of CD45RA⁺ unprimed T cells. *J Immunol*, 152, 5613-23.

- Bolognesi, A., Polito, L., Farini, V., Bortolotti, M., Tazzari, P. L., Ratta, M., Ravaioli, A., Horenstein, A. L., Stirpe, F., Battelli, M. G. and Malavasi, F. 2005. CD38 as a target of IB4 mAb carrying saporin-S6: design of an immunotoxin for ex vivo depletion of hematological CD38⁺ neoplasia. *J Biol Regul Homeost Agents*, 19, 145-52.
- Bonner-Weir, S. 2000. Islet growth and development in the adult. *J Mol Endocrinol*, 24, 297-302.
- Boyunaga, H., Dikmen, G., Ugur Ural, A. and Melekoglu, A. 2011. Effects of Thalidomide and rhGM-CSF on Carbohydrate Metabolism in HL-60 Acute Promyelocytic Leukemia Cell Line. *International Journal of Hematology and Oncology*, (3) 21, 170-175.
- Bradford, M. M. 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal Biochem*, 72, 248-54.
- Brailoiu, E., Churamani, D., Cai, X., Schrlau, M. G., Brailoiu, G. C., Gao, X., Hooper, R., Boulware, M. J., Dun, N. J., Marchant, J. S. and Patel, S. 2009. Essential requirement for two-pore channel 1 in NAADP-mediated calcium signaling. *J Cell Biol*, 186, 201-9.
- Brand, K. A. and Hermfisse, U. 1997. Aerobic glycolysis by proliferating cells: a protective strategy against reactive oxygen species. *FASEB J*, 11, 388-95.
- Breitman, T. R., Collins, S. J. and Keene, B. R. 1981. Terminal differentiation of human promyelocytic leukemic cells in primary culture in response to retinoic acid. *Blood*, 57, 1000-4.
- Breitman, T. R., Selonick, S. E. and Collins, S. J. 1980. Induction of differentiation of the human promyelocytic leukemia cell line (HL-60) by retinoic acid. *Proc Natl Acad Sci U S A*, 77, 2936-40.
- Bruzzone, S., De Flora, A., Usai, C., Graeff, R. and Lee, H. C. 2003. Cyclic ADP-ribose is a second messenger in the lipopolysaccharide-stimulated proliferation of human peripheral blood mononuclear cells. *Biochem J*, 375, 395-403.
- Bruzzone, S., Guida, L., Zocchi, E., Franco, L. and De Flora, A. 2001. Connexin 43 hemi channels mediate Ca²⁺-regulated transmembrane NAD⁺ fluxes in intact cells. *FASEB J*, 15, 10-12.
- Burger, J. A., Ghia, P., Rosenwald, A. and Caligaris-Cappio, F. 2009. The microenvironment in mature B-cell malignancies: a target for new treatment strategies. *Blood*, 114, 3367-75.
- Burkle, A. 2001. PARP-1: a regulator of genomic stability linked with mammalian longevity. *ChemBiochem*, 2, 725-8.
- Burkle, A. 2005. Poly(ADP-ribose). The most elaborate metabolite of NAD⁺. *FEBS J*, 272, 4576-89.
- Byk, T., Kahn, J., Kollet, O., Petit, I., Samira, S., Shvitiel, S., Ben-Hur, H., Peled, A., Piacibello, W. and Lapidot, T. 2005. Cycling G1 CD34⁺/CD38⁺ cells potentiate the motility and engraftment of quiescent G0 CD34⁺/CD38⁻/low severe combined immunodeficiency repopulating cells. *Stem Cells*, 23, 561-74.
- Cadet, J., Berger, M., Douki, T., Morin, B., Raoul, S., Ravanat, J. L. and Spinelli, S. 1997. Effects of UV and visible radiation on DNA-final base damage. *Biol Chem*, 378, 1275-86.
- Cai, Y. D. and Chou, K. C. 2006. Predicting membrane protein type by functional domain composition and pseudo-amino acid composition. *J Theor Biol*, 238, 395-400.
- Calcraft, P. J., Ruas, M., Pan, Z., Cheng, X., Arredouani, A., Hao, X., Tang, J., Rietdorf, K., Teboul, L., Chuang, K. T., Lin, P., Xiao, R., Wang, C., Zhu, Y., Lin, Y., Wyatt, C. N., Parrington, J., Ma, J., Evans, A. M., Galione, A. and Zhu, M. X. 2009. NAADP mobilizes calcium from acidic organelles through two-pore channels. *Nature*, 459, 596-600.
- Caldecott, K. W. 2003. DNA single-strand break repair and spinocerebellar ataxia. *Cell*, 112, 7-10.

- Caligaris-Cappio, F. and Hamblin, T. J. 1999. B-cell chronic lymphocytic leukemia: a bird of a different feather. *J Clin Oncol*, 17, 399-408.
- Calissano, C., Damle, R. N. and Yan, X. J. 2009. Multi-parameter phenotypic analysis of members of chronic lymphocytic leukemia clones identifies distinct proliferative and resting/re-entry compartments with discrete gene expression profiles. *Blood*, 114(22), 279.
- Cepeda, V., Fuertes, M. A., Castilla, J., Alonso, C., Quevedo, C., Soto, M. and Perez, J. M. 2006. Poly(ADP-ribose) polymerase-1 (PARP-1) inhibitors in cancer chemotherapy. *Recent Pat Anticancer Drug Discov*, 1, 39-53.
- Chatterjee, S., Berger, S. J. and Berger, N. A. 1999. Poly(ADP-ribose) polymerase: a guardian of the genome that facilitates DNA repair by protecting against DNA recombination. *Mol Cell Biochem*, 193, 23-30.
- Chen, J., Chen, Y. G., Reifsnnyder, P. C., Schott, W. H., Lee, C. H., Osborne, M., Scheuplein, F., Haag, F., Koch-Nolte, F., Serreze, D. V. and Leiter, E. H. 2006. Targeted disruption of CD38 accelerates autoimmune diabetes in NOD/Lt mice by enhancing autoimmunity in an ADP-ribosyltransferase 2-dependent fashion. *J Immunol*, 176, 4590-9.
- Chen, L., Widhopf, G., Huynh, L., Rassenti, L., Rai, K. R., Weiss, A. and Kipps, T. J. 2002. Expression of ZAP-70 is associated with increased B-cell receptor signaling in chronic lymphocytic leukemia. *Blood*, 100, 4609-14.
- Chiorazzi, N. and Ferrarini, M. 2011. Cellular origin(s) of chronic lymphocytic leukemia: cautionary notes and additional considerations and possibilities. *Blood*, 117, 1781-91.
- Choe, C. U., Lardong, K., Gelderblom, M., Ludewig, P., Leyboldt, F., Koch-Nolte, F., Gerloff, C. and Magnus, T. 2011. CD38 exacerbates focal cytokine production, postischemic inflammation and brain injury after focal cerebral ischemia. *PLoS One*, 6, e19046.
- Churchill, G. C., Okada, Y., Thomas, J. M., Genazzani, A. A., Patel, S. and Galione, A. 2002. NAADP mobilizes Ca⁽²⁺⁾ from reserve granules, lysosome-related organelles, in sea urchin eggs. *Cell*, 111, 703-8.
- Circu, M. L. and Aw, T. Y. 2010. Reactive oxygen species, cellular redox systems, and apoptosis. *Free Radic Biol Med*, 48, 749-62.
- Clapper, D. L., Walseth, T. F., Dargie, P. J. and Lee, H. C. 1987. Pyridine nucleotide metabolites stimulate calcium release from sea urchin egg microsomes desensitized to inositol trisphosphate. *J Biol Chem*, 262, 9561-8.
- Collins, A. R. 2009. Investigating oxidative DNA damage and its repair using the comet assay. *Mutat Res*, 681, 24-32.
- Collins, S. J., Gallo, R. C. and Gallagher, R. E. 1977. Continuous growth and differentiation of human myeloid leukaemic cells in suspension culture. *Nature*, 270, 347-9.
- Collins, S. J., Ruscetti, F. W., Gallagher, R. E. and Gallo, R. C. 1978. Terminal differentiation of human promyelocytic leukemia cells induced by dimethyl sulfoxide and other polar compounds. *Proc Natl Acad Sci U S A*, 75, 2458-62.
- Colowick, S. P. and Kaplan, N. O. 1974. In: Fleischer, S., Packer, L.(Eds.), *Methods in Enzymology*. Academic Press, London.
- Congleton, J., Jiang, H., Malavasi, F., Lin, H. and Yen, A. 2011. ATRA-induced HL-60 myeloid leukemia cell differentiation depends on the CD38 cytosolic tail needed for membrane localization, but CD38 enzymatic activity is unnecessary. *Exp Cell Res*, 317, 910-9.

- D'amours, D., Desnoyers, S., D'silva, I. and Poirier, G. G. 1999. Poly(ADP-ribosyl)ation reactions in the regulation of nuclear functions. *Biochem J*, 342 (Pt 2), 249-68.
- Damle, R. N., Batliwalla, F. M., Ghiotto, F., Valetto, A., Albesiano, E., Sison, C., Allen, S. L., Kolitz, J., Vinciguerra, V. P., Kudalkar, P., Wasil, T., Rai, K. R., Ferrarini, M., Gregersen, P. K. and Chiorazzi, N. 2004. Telomere length and telomerase activity delineate distinctive replicative features of the B-CLL subgroups defined by immunoglobulin V gene mutations. *Blood*, 103, 375-82.
- Damle, R. N., Ghiotto, F., Valetto, A., Albesiano, E., Fais, F., Yan, X. J., Sison, C. P., Allen, S. L., Kolitz, J., Schulman, P., Vinciguerra, V. P., Budde, P., Frey, J., Rai, K. R., Ferrarini, M. and Chiorazzi, N. 2002. B-cell chronic lymphocytic leukemia cells express a surface membrane phenotype of activated, antigen-experienced B lymphocytes. *Blood*, 99, 4087-93.
- Damle, R. N., Temburni, S., Calissano, C., Yancopoulos, S., Banapour, T., Sison, C., Allen, S. L., Rai, K. R. and Chiorazzi, N. 2007. CD38 expression labels an activated subset within chronic lymphocytic leukemia clones enriched in proliferating B cells. *Blood*, 110, 3352-9.
- Damle, R. N., Wasil, T., Fais, F., Ghiotto, F., Valetto, A., Allen, S. L., Buchbinder, A., Budman, D., Dittmar, K., Kolitz, J., Lichtman, S. M., Schulman, P., Vinciguerra, V. P., Rai, K. R., Ferrarini, M. and Chiorazzi, N. 1999. Ig V gene mutation status and CD38 expression as novel prognostic indicators in chronic lymphocytic leukemia. *Blood*, 94, 1840-7.
- Dargie, P. J., Agre, M. C. and Lee, H. C. 1990. Comparison of Ca²⁺ mobilizing activities of cyclic ADP-ribose and inositol trisphosphate. *Cell Regul*, 1, 279-90.
- De Flora, A., Franco, L., Guida, L., Bruzzone, S., Usai, C. and Zocchi, E. 2000. Topology of CD38. *Chem Immunol*, 75, 79-98.
- De Flora, A., Zocchi, E., Guida, L., Franco, L. and Bruzzone, S. 2004. Autocrine and paracrine calcium signaling by the CD38/NAD⁺/cyclic ADP-ribose system. *Ann N Y Acad Sci*, 1028, 176-91.
- De Weers, M., Tai, Y. T., Van Der Veer, M. S., Bakker, J. M., Vink, T., Jacobs, D. C., Oomen, L. A., Peipp, M., Valerius, T., Slootstra, J. W., Mutis, T., Bleeker, W. K., Anderson, K. C., Lokhorst, H. M., Van De Winkel, J. G. and Parren, P. W. 2011. Daratumumab, a novel therapeutic human CD38 monoclonal antibody, induces killing of multiple myeloma and other hematological tumors. *J Immunol*, 186, 1840-8.
- Deaglio, S., Aydin, S., Vaisitti, T., Bergui, L. and Malavasi, F. 2008. CD38 at the junction between prognostic marker and therapeutic target. *Trends Mol Med*, 14, 210-8.
- Deaglio, S., Capobianco, A., Bergui, L., Durig, J., Morabito, F., Duhrsen, U. and Malavasi, F. 2003. CD38 is a signaling molecule in B-cell chronic lymphocytic leukemia cells. *Blood*, 102, 2146-55.
- Deaglio, S., Dianzani, U., Horenstein, A. L., Fernandez, J. E., Van Kooten, C., Bragardo, M., Funaro, A., Garbarino, G., Di Virgilio, F., Banchereau, J. and Malavasi, F. 1996. Human CD38 ligand. A 120-KDA protein predominantly expressed on endothelial cells. *J Immunol*, 156, 727-34.
- Deaglio, S. and Malavasi, F. 2006. The CD38/CD157 mammalian gene family: An evolutionary paradigm for other leukocyte surface enzymes. *Purinergic Signal*, 2, 431-41.
- Deaglio, S., Mallone, R., Baj, G., Arnulfo, A., Surico, N., Dianzani, U., Mehta, K. and Malavasi, F. 2000. CD38/CD31, a receptor/ligand system ruling adhesion and signaling in human leukocytes. *Chem Immunol*, 75, 99-120.
- Deaglio, S., Mallone, R., Baj, G., Donati, D., Giraud, G., Corno, F., Bruzzone, S., Geuna, M., Ausiello, C. and Malavasi, F. 2001. Human CD38 and its ligand CD31 define a unique lamina propria T lymphocyte signaling pathway. *FASEB J*, 15, 580-2.

- Deaglio, S., Morra, M., Mallone, R., Ausiello, C. M., Prager, E., Garbarino, G., Dianzani, U., Stockinger, H. and Malavasi, F. 1998. Human CD38 (ADP-ribosyl cyclase) is a counter-receptor of CD31, an Ig superfamily member. *J Immunol*, 160, 395-402.
- Deaglio, S., Vaisitti, T., Aydin, S., Bergui, L., D'arena, G., Bonello, L., Omede, P., Scatolini, M., Jaksic, O., Chiorino, G., Efremov, D. and Malavasi, F. 2007a. CD38 and ZAP-70 are functionally linked and mark CLL cells with high migratory potential. *Blood*, 110, 4012-21.
- Deaglio, S., Vaisitti, T., Bergui, L., Bonello, L., Horenstein, A. L., Tamagnone, L., Boumsell, L. and Malavasi, F. 2005. CD38 and CD100 lead a network of surface receptors relaying positive signals for B-CLL growth and survival. *Blood*, 105, 3042-50.
- Deaglio, S., Vaisitti, T., Billington, R., Bergui, L., Omede, P., Genazzani, A. A. and Malavasi, F. 2007. CD38/CD19: a lipid raft-dependent signaling complex in human B cells. *Blood*, 109, 5390-8.
- Deaglio, S., Vaisitti, T., Billington, R., Bergui, L., Omede, P., Genazzani, A. A. and Malavasi, F. 2007b. CD38/CD19: a lipid raft-dependent signaling complex in human B cells. *Blood*, 109, 5390-8.
- Deaglio, S., Vaisitti, T., Zucchetto, A., Gattei, V. and Malavasi, F. 2010. CD38 as a molecular compass guiding topographical decisions of chronic lymphocytic leukemia cells. *Seminars in cancer biology*, 20, 416-423.
- Deberardinis, R. J. 2008. Is cancer a disease of abnormal cellular metabolism? New angles on an old idea. *Genet Med*, 10, 767-77.
- Del Poeta, G., Maurillo, L., Venditti, A., Buccisano, F., Epiceno, A. M., Capelli, G., Tamburini, A., Suppo, G., Battaglia, A., Del Principe, M. I., Del Moro, B., Masi, M. and Amadori, S. 2001. Clinical significance of CD38 expression in chronic lymphocytic leukemia. *Blood*, 98, 2633-9.
- Deshpande, D. A., Dogan, S., Walseth, T. F., Miller, S. M., Amrani, Y., Panettieri, R. A. and Kannan, M. S. 2004. Modulation of calcium signaling by interleukin-13 in human airway smooth muscle: role of CD38/cyclic adenosine diphosphate ribose pathway. *Am J Respir Cell Mol Biol*, 31, 36-42.
- Deshpande, D. A., White, T. A., Guedes, A. G., Milla, C., Walseth, T. F., Lund, F. E. and Kannan, M. S. 2005. Altered airway responsiveness in CD38-deficient mice. *Am J Respir Cell Mol Biol*, 32, 149-56.
- Dipp, M. and Evans, A. M. 2001. Cyclic ADP-ribose is the primary trigger for hypoxic pulmonary vasoconstriction in the rat lung in situ. *Circ Res*, 89, 77-83.
- Dogan, S., Deshpande, D. A., Kannan, M. S. and Walseth, T. F. 2004. Changes in CD38 expression and ADP-ribosyl cyclase activity in rat myometrium during pregnancy: influence of sex steroid hormones. *Biol Reprod*, 71, 97-103.
- Dogan, S., Deshpande, D. A., White, T. A., Walseth, T. F. and Kannan, M. S. 2006. Regulation of CD 38 expression and function by steroid hormones in myometrium. *Mol Cell Endocrinol*, 246, 101-6.
- Dogan, S., White, T. A., Deshpande, D. A., Murtaugh, M. P., Walseth, T. F. and Kannan, M. S. 2002. Estrogen increases CD38 gene expression and leads to differential regulation of adenosine diphosphate (ADP)-ribosyl cyclase and cyclic ADP-ribose hydrolase activities in rat myometrium. *Biol Reprod*, 66, 596-602.
- Domingo-Domenech, E., Domingo-Claros, A., Gonzalez-Barca, E., Beneitez, D., Alonso, E., Romagosa, V., De Sanjos, S., Petit, J., Granena, A. and Fernandez De Sevilla, A. 2002. CD38 expression in B-chronic lymphocytic leukemia: association with clinical presentation and outcome in 155 patients. *Haematologica*, 87, 1021-7.
- Drach, J., Mcqueen, T., Engel, H., Andreeff, M., Robertson, K. A., Collins, S. J., Malavasi, F. and Mehta, K. 1994. Retinoic acid-induced expression of CD38 antigen in myeloid cells is mediated through retinoic acid receptor-alpha. *Cancer Res*, 54, 1746-52.

- Drach, J., Zhao, S., Malavasi, F. and Mehta, K. 1993. Rapid induction of CD38 antigen on myeloid leukemia cells by all trans-retinoic acid. *Biochem Biophys Res Commun*, 195, 545-50.
- Dreizen, S., Mccredie, K. B., Keating, M. J. and Andersson, B. S. 1990. Nutritional deficiencies in patients receiving cancer chemotherapy. *Postgrad Med*, 87, 163-7, 170.
- Droge, W. 2002. Free radicals in the physiological control of cell function. *Physiol Rev*, 82, 47-95.
- Dubuisson, M. L., De Wergifosse, B., Trouet, A., Baguet, F., Marchand-Brynaert, J. and Rees, J. F. 2000. Antioxidative properties of natural coelenterazine and synthetic methyl coelenterazine in rat hepatocytes subjected to tert-butyl hydroperoxide-induced oxidative stress. *Biochem Pharmacol*, 60, 471-8.
- Durkacz, B. W., Omidiji, O., Gray, D. A. and Shall, S. 1980. (ADP-ribose)_n participates in DNA excision repair. *Nature*, 283, 593-6.
- Ekelund, S., Persson, I., Larsson, R. and Nygren, P. 2002. Interactions between the new cytotoxic drug CHS 828 and amiloride and mitomycin C in a human tumour cell line and in tumour cells from patients. *Chemotherapy*, 48, 196-204.
- Escande, C., Nin, V., Price, N. L., Capellini, V., Gomes, A. P., Barbosa, M. T., O'neil, L., White, T. A., Sinclair, D. A. and Chini, E. N. 2013. Flavonoid apigenin is an inhibitor of the NAD⁺ ase CD38: implications for cellular NAD⁺ metabolism, protein acetylation, and treatment of metabolic syndrome. *Diabetes*, 62, 1084-93.
- Esterbauer, H., Schaur, R. J. and Zollner, H. 1991. Chemistry and biochemistry of 4-hydroxynonenal, malonaldehyde and related aldehydes. *Free Radic Biol Med*, 11, 81-128.
- Fedele, G., Frasca, L., Palazzo, R., Ferrero, E., Malavasi, F. and Ausiello, C. M. 2004. CD38 is expressed on human mature monocyte-derived dendritic cells and is functionally involved in CD83 expression and IL-12 induction. *Eur J Immunol*, 34, 1342-50.
- Fernandes, C. A., Fievez, L., Neyrinck, A. M., Delzenne, N. M., Bureau, F. and Vanbever, R. 2012. Sirtuin inhibition attenuates the production of inflammatory cytokines in lipopolysaccharide-stimulated macrophages. *Biochem Biophys Res Commun*, 420, 857-61.
- Fernandez, J. E., Deaglio, S., Donati, D., Beusan, I. S., Corno, F., Aranega, A., Forni, M., Falini, B. and Malavasi, F. 1998. Analysis of the distribution of human CD38 and of its ligand CD31 in normal tissues. *J Biol Regul Homeost Agents*, 12, 81-91.
- Ferrero, E. and Malavasi, F. 1997. Human CD38, a leukocyte receptor and ectoenzyme, is a member of a novel eukaryotic gene family of nicotinamide adenine dinucleotide⁺-converting enzymes: extensive structural homology with the genes for murine bone marrow stromal cell antigen 1 and aplysian ADP-ribosyl cyclase. *J Immunol*, 159, 3858-65.
- Ferrero, E. and Malavasi, F. 1999. The metamorphosis of a molecule: from soluble enzyme to the leukocyte receptor CD38. *J Leukoc Biol*, 65, 151-61.
- Fischkoff, S. A. 1988. Graded increase in probability of eosinophilic differentiation of HL-60 promyelocytic leukemia cells induced by culture under alkaline conditions. *Leuk Res*, 12, 679-86.
- Fischkoff, S. A., Pollak, A., Gleich, G. J., Testa, J. R., Misawa, S. and Reber, T. J. 1984. Eosinophilic differentiation of the human promyelocytic leukemia cell line, HL-60. *J Exp Med*, 160, 179-96.
- Fong, P. C., Boss, D. S., Yap, T. A., Tutt, A., Wu, P., Mergui-Roelvink, M., Mortimer, P., Swaisland, H., Lau, A., O'connor, M. J., Ashworth, A., Carmichael, J., Kaye, S. B., Schellens, J. H. and De Bono, J. S. 2009. Inhibition of poly(ADP-ribose) polymerase in tumors from BRCA mutation carriers. *N Engl J Med*, 361, 123-34.

- Ford, E., Voit, R., Liszt, G., Magin, C., Grummt, I. and Guarente, L. 2006. Mammalian Sir2 homolog SIRT7 is an activator of RNA polymerase I transcription. *Genes Dev*, 20, 1075-80.
- Franco, L., Guida, L., Bruzzone, S., Zocchi, E., Usai, C. and De Flora, A. 1998. The transmembrane glycoprotein CD38 is a catalytically active transporter responsible for generation and influx of the second messenger cyclic ADP-ribose across membranes. *FASEB J*, 12, 1507-20.
- Fruscione, F., Scarfi, S., Ferraris, C., Bruzzone, S., Benvenuto, F., Guida, L., Uccelli, A., Salis, A., Usai, C., Jacchetti, E., Ilengo, C., Scaglione, S., Quarto, R., Zocchi, E. and De Flora, A. 2011. Regulation of human mesenchymal stem cell functions by an autocrine loop involving NAD⁺ release and P2Y₁₁-mediated signaling. *Stem Cells Dev*, 20, 1183-98.
- Fuertes, M. A., Alonso, C. and Perez, J. M. 2003. Biochemical modulation of Cisplatin mechanisms of action: enhancement of antitumor activity and circumvention of drug resistance. *Chem Rev*, 103, 645-62.
- Fujita, T., Kantarci, A., Warbington, M. L., Zawawi, K. H., Hasturk, H., Kurihara, H. and Van Dyke, T. E. 2005. CD38 expression in neutrophils from patients with localized aggressive periodontitis. *J Periodontol*, 76, 1960-5.
- Funaro, A., De Monte, L. B., Dianzani, U., Forni, M. and Malavasi, F. 1993. Human CD38 is associated to distinct molecules which mediate transmembrane signaling in different lineages. *Eur J Immunol*, 23, 2407-11.
- Funaro, A., Morra, M., Calosso, L., Zini, M. G., Ausiello, C. M. and Malavasi, F. 1997. Role of the human CD38 molecule in B cell activation and proliferation. *Tissue Antigens*, 49, 7-15.
- Funaro, A., Spagnoli, G. C., Ausiello, C. M., Alessio, M., Roggero, S., Delia, D., Zaccolo, M. and Malavasi, F. 1990. Involvement of the multilineage CD38 molecule in a unique pathway of cell activation and proliferation. *J Immunol*, 145, 2390-6.
- Gaetani, G. F., Galiano, S., Canepa, L., Ferraris, A. M. and Kirkman, H. N. 1989. Catalase and glutathione peroxidase are equally active in detoxification of hydrogen peroxide in human erythrocytes. *Blood*, 73, 334-9.
- Gagne, J. P., Hendzel, M. J., Droit, A. and Poirier, G. G. 2006. The expanding role of poly(ADP-ribose) metabolism: current challenges and new perspectives. *Curr Opin Cell Biol*, 18, 145-51.
- Gaikwad, A., Long, D. J., Stringer, J. L. and Jaiswal, A. K. 2001. In vivo role of NAD(P)H:quinone oxidoreductase 1 (NQO1) in the regulation of intracellular redox state and accumulation of abdominal adipose tissue. *J Biol Chem*, 276, 22559-64.
- Galione, A. and Churchill, G. C. 2000. Cyclic ADP ribose as a calcium-mobilizing messenger. *Sci STKE*, 18.
- Galione, A., Parrington, J. and Funnell, T. 2011. Physiological roles of NAADP-mediated Ca²⁺ signaling. *Sci China Life Sci*, 54, 725-32.
- Gallay, N., Anani, L., Lopez, A., Colombat, P., Binet, C., Domenech, J., Weksler, B. B., Malavasi, F. and Herault, O. 2007. The role of platelet/endothelial cell adhesion molecule 1 (CD31) and CD38 antigens in marrow microenvironmental retention of acute myelogenous leukemia cells. *Cancer Res*, 67, 8624-32.
- Ganguly, B. J., Tonomura, N., Benson, R. M., Osborne, B. A. and Granowitz, E. V. 2002. Hyperbaric oxygen enhances apoptosis in hematopoietic cells. *Apoptosis*, 7, 499-510.
- Gao, Y., Camacho, L. H. and Mehta, K. 2007. Retinoic acid-induced CD38 antigen promotes leukemia cells attachment and interferon-gamma/interleukin-1beta-dependent apoptosis of endothelial cells: implications in the etiology of retinoic acid syndrome. *Leuk Res*, 31, 455-63.

- Ge, Y., Jiang, W., Gan, L., Wang, L., Sun, C., Ni, P., Liu, Y., Wu, S., Gu, L., Zheng, W., Lund, F. E. and Xin, H. B. 2010. Mouse embryonic fibroblasts from CD38 knockout mice are resistant to oxidative stresses through inhibition of reactive oxygen species production and Ca⁽²⁺⁾ overload. *Biochem Biophys Res Commun*, 399, 167-72.
- Genazzani, A., Thomas, J., Patel, S., Galione, A., Ruas, M., Billington, R., Churchill, G., Yamasaki, Y., Masgrau, R., Morgan, A. and Davis, L. 2005. Methods in Cyclic ADP-Ribose and NAADP Research. In: Putney, J. W. (ed.) *Calcium Signaling, Second Edition*. CRC Press: 265-334.
- Ghezzi, P. 2005. Regulation of protein function by glutathionylation. *Free Radic Res*, 39, 573-80.
- Ghia, P., Guida, G., Stella, S., Gottardi, D., Geuna, M., Strola, G., Scielzo, C. and Caligaris-Cappio, F. 2003. The pattern of CD38 expression defines a distinct subset of chronic lymphocytic leukemia (CLL) patients at risk of disease progression. *Blood*, 101, 1262-9.
- Graef, I. A., Mermelstein, P. G., Stankunas, K., Neilson, J. R., Deisseroth, K., Tsien, R. W. and Crabtree, G. R. 1999. L-type calcium channels and GSK-3 regulate the activity of NF-ATc4 in hippocampal neurons. *Nature*, 401, 703-8.
- Graeff, R., Liu, Q., Kriksunov, I. A., Hao, Q. and Lee, H. C. 2006. Acidic residues at the active sites of CD38 and ADP-ribosyl cyclase determine nicotinic acid adenine dinucleotide phosphate (NAADP) synthesis and hydrolysis activities. *J Biol Chem*, 281, 28951-7.
- Graeff, R. M., Mehta, K. and Lee, H. C. 1994. GDP-ribosyl cyclase activity as a measure of CD38 induction by retinoic acid in HL-60 cells. *Biochem Biophys Res Commun*, 205, 722-7.
- Graeff, R. M., Walseth, T. F., Fryxell, K., Branton, W. D. and Lee, H. C. 1994a. Enzymatic synthesis and characterizations of cyclic GDP-ribose. A procedure for distinguishing enzymes with ADP-ribosyl cyclase activity. *J Biol Chem*, 269, 30260-7.
- Greenamyre, J. T., Sherer, T. B., Betarbet, R. and Panov, A. V. 2001. Complex I and Parkinson's disease. *IUBMB Life*, 52, 135-41.
- Grubisha, O., Smith, B. C. and Denu, J. M. 2005. Small molecule regulation of Sir2 protein deacetylases. *FEBS J*, 272, 4607-16.
- Gruson, D., Hilbert, G., Boiron, J. M., Portel, L., Cony-Makoul, P., Reiffers, J., Gbikpi-Benissan, G. and Cardinaud, J. P. 1998. Acute respiratory distress syndrome due to all-trans retinoic acid. *Intensive Care Med*, 24, 642.
- Guarente, L. and Picard, F. 2005. Calorie restriction--the SIR2 connection. *Cell*, 120, 473-82.
- Guida, L., Franco, L., Bruzzone, S., Sturla, L., Zocchi, E., Basile, G., Usai, C. and De Flora, A. 2004. Concentrative influx of functionally active cyclic ADP-ribose in dimethyl sulfoxide-differentiated HL-60 cells. *J Biol Chem*, 279, 22066-75.
- Guida, L., Franco, L., Zocchi, E. and De Flora, A. 1995. Structural role of disulfide bridges in the cyclic ADP-ribose related bifunctional ectoenzyme CD38. *FEBS Lett*, 368, 481-4.
- Guse, A. H. 2005. Second messenger function and the structure-activity relationship of cyclic adenosine diphosphoribose (cADPR). *FEBS J*, 272, 4590-7.
- Guse, A. H. and Lee, H. C. 2008. NAADP: a universal Ca²⁺ trigger. *Sci Signal*, 1.
- Ha, H. C. and Snyder, S. H. 1999. Poly(ADP-ribose) polymerase is a mediator of necrotic cell death by ATP depletion. *Proc Natl Acad Sci U S A*, 96, 13978-82.
- Hallek, M., Cheson, B. D., Catovsky, D., Caligaris-Cappio, F., Dighiero, G., Dohner, H., Hillmen, P., Keating, M. J., Montserrat, E., Rai, K. R. and Kipps, T. J. 2008. Guidelines for the diagnosis and treatment of chronic lymphocytic leukemia: a report from the International Workshop on Chronic

- Lymphocytic Leukemia updating the National Cancer Institute-Working Group 1996 guidelines. *Blood*, 111, 5446-56.
- Han, M.-K., Cho, Y.-S., Kim, Y. S., Yim, C.-Y. and Kim, U.-H. 2000. Interaction of Two Classes of ADP-ribose Transfer Reactions in Immune Signaling. *Journal of Biological Chemistry*, 275, 20799-20805.
- Han, Y. H., Xia, L., Song, L. P., Zheng, Y., Chen, W. L., Zhang, L., Huang, Y., Chen, G. Q. and Wang, L. S. 2006. Comparative proteomic analysis of hypoxia-treated and untreated human leukemic U937 cells. *Proteomics*, 6, 3262-74.
- Harden, A. and Young, W. J. 1906. The Alcoholic Ferment of Yeast-Juice. Part II. The Conferment of Yeast-Juice. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*, 78, 369-375.
- Hardingham, G. E., Chawla, S., Johnson, C. M. and Bading, H. 1997. Distinct functions of nuclear and cytoplasmic calcium in the control of gene expression. *Nature*, 385, 260-5.
- Harris, A. L. 2002. Hypoxia--a key regulatory factor in tumour growth. *Nat Rev Cancer*, 2, 38-47.
- Harris, M. I. 1989. Impaired glucose tolerance in the U.S. population. *Diabetes Care*, 12, 464-74.
- Harrison, J. S., Rameshwar, P., Chang, V. and Bandari, P. 2002. Oxygen saturation in the bone marrow of healthy volunteers. *Blood*, 99, 394.
- Hasmann, M. and Schemainda, I. 2003. FK866, a highly specific noncompetitive inhibitor of nicotinamide phosphoribosyltransferase, represents a novel mechanism for induction of tumor cell apoptosis. *Cancer Res*, 63, 7436-42.
- Hassa, P. O. and Hottiger, M. O. 2008. The diverse biological roles of mammalian PARPS, a small but powerful family of poly-ADP-ribose polymerases. *Front Biosci*, 13, 3046-82.
- Hegan, D. C., Lu, Y., Stachelek, G. C., Crosby, M. E., Bindra, R. S. and Glazer, P. M. 2010. Inhibition of poly(ADP-ribose) polymerase down-regulates BRCA1 and RAD51 in a pathway mediated by E2F4 and p130. *Proc Natl Acad Sci U S A*, 107, 2201-6.
- Henk, J. M., Kunkler, P. B. and Smith, C. W. 1977. Radiotherapy and hyperbaric oxygen in head and neck cancer. Final report of first controlled clinical trial. *Lancet*, 2, 101-3.
- Heyman, R. A., Mangelsdorf, D. J., Dyck, J. A., Stein, R. B., Eichele, G., Evans, R. M. and Thaller, C. 1992. 9-cis retinoic acid is a high affinity ligand for the retinoid X receptor. *Cell*, 68, 397-406.
- Hjarnaa, P. J., Jonsson, E., Latini, S., Dhar, S., Larsson, R., Bramm, E., Skov, T. and Binderup, L. 1999. CHS 828, a novel pyridyl cyanoguanidine with potent antitumor activity in vitro and in vivo. *Cancer Res*, 59, 5751-7.
- Holen, K., Saltz, L. B., Hollywood, E., Burk, K. and Hanauske, A. R. 2008. The pharmacokinetics, toxicities, and biologic effects of FK866, a nicotinamide adenine dinucleotide biosynthesis inhibitor. *Invest New Drugs*, 26, 45-51.
- Hong, S., Park, K., Kim, C. Y. and Seong, G. J. 2008. Agmatine inhibits hypoxia-induced TNF-alpha release from cultured retinal ganglion cells. *Biocell*, 32, 201-5.
- Hoshino, S., Kukimoto, I., Kontani, K., Inoue, S., Kanda, Y., Malavasi, F. and Katada, T. 1997. Mapping of the catalytic and epitopic sites of human CD38/NAD⁺ glycohydrolase to a functional domain in the carboxyl terminus. *J Immunol*, 158, 741-7.
- Howard, M., Grimaldi, J. C., Bazan, J. F., Lund, F. E., Santos-Argumedo, L., Parkhouse, R. M., Walseth, T. F. and Lee, H. C. 1993. Formation and hydrolysis of cyclic ADP-ribose catalyzed by lymphocyte antigen CD38. *Science*, 262, 1056-9.

- Hussain, A. M., Lee, H. C. and Chang, C. F. 1998. Functional expression of secreted mouse BST-1 in yeast. *Protein Expr Purif*, 12, 133-7.
- Ibrahim, S., Keating, M., Do, K. A., O'Brien, S., Huh, Y. O., Jilani, I., Lerner, S., Kantarjian, H. M. and Albitar, M. 2001. CD38 expression as an important prognostic factor in B-cell chronic lymphocytic leukemia. *Blood*, 98, 181-6.
- Ikehata, F., Satoh, J., Nata, K., Tohgo, A., Nakazawa, T., Kato, I., Kobayashi, S., Akiyama, T., Takasawa, S., Toyota, T. and Okamoto, H. 1998. Autoantibodies against CD38 (ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase) that impair glucose-induced insulin secretion in noninsulin-dependent diabetes patients. *J Clin Invest*, 102, 395-401.
- Imaizumi, M. and Breitman, T. R. 1987. Retinoic acid-induced differentiation of the human promyelocytic leukemia cell line, HL-60, and fresh human leukemia cells in primary culture: a model for differentiation inducing therapy of leukemia. *Eur J Haematol*, 38, 289-302.
- Ino, K., Yamamoto, E., Shibata, K., Kajiyama, H., Yoshida, N., Terauchi, M., Nawa, A., Nagasaka, T., Takikawa, O. and Kikkawa, F. 2008. Inverse correlation between tumoral indoleamine 2,3-dioxygenase expression and tumor-infiltrating lymphocytes in endometrial cancer: its association with disease progression and survival. *Clin Cancer Res*, 14, 2310-7.
- Iqbal, J. and Zaidi, M. 2006. TNF regulates cellular NAD⁺ metabolism in primary macrophages. *Biochem Biophys Res Commun*, 342, 1312-8.
- Iqbal, J. and Zaidi, M. 2007. CD38 is required for priming by TNF-alpha: a mechanism for extracellular coordination of cell fate. *Am J Physiol Renal Physiol*, 292, F1283-90.
- Irwin, M. E., Rivera-Del Valle, N. and Chandra, J. 2013. Redox control of leukemia: from molecular mechanisms to therapeutic opportunities. *Antioxid Redox Signal*, 18, 1349-83.
- Iwata, K., Ogata, S., Okumura, K. and Taguchi, H. 2003. Expression of CD38 in human promyelocytic leukemia HL-60 cell line during differentiation by niacin-related compounds. *Biosci Biotechnol Biochem*, 67, 1836-9.
- Jackson, D. G. and Bell, J. I. 1990. Isolation of a cDNA encoding the human CD38 (T10) molecule, a cell surface glycoprotein with an unusual discontinuous pattern of expression during lymphocyte differentiation. *J Immunol*, 144, 2811-5.
- Jacob, M. C., Favre, M. and Bensa, J. C. 1991. Membrane cell permeabilization with saponin and multiparametric analysis by flow cytometry. *Cytometry*, 12, 550-8.
- Jacobson, E. L., Shieh, W. M. and Huang, A. C. 1999. Mapping the role of NAD metabolism in prevention and treatment of carcinogenesis. *Mol Cell Biochem*, 193, 69-74.
- Jaksic, O., Paro, M. M., Kardum Skelin, I., Kusec, R., Pejasa, V. and Jaksic, B. 2004. CD38 on B-cell chronic lymphocytic leukemia cells has higher expression in lymph nodes than in peripheral blood or bone marrow. *Blood*, 103, 1968-9.
- James, S. Y., Williams, M. A., Newland, A. C. and Colston, K. W. 1999. Leukemia cell differentiation: cellular and molecular interactions of retinoids and vitamin D. *Gen Pharmacol*, 32, 143-54.
- Jin, D., Liu, H. X., Hirai, H., Torashima, T., Nagai, T., Lopatina, O., Shnayder, N. A., Yamada, K., Noda, M., Seike, T., Fujita, K., Takasawa, S., Yokoyama, S., Koizumi, K., Shiraishi, Y., Tanaka, S., Hashii, M., Yoshihara, T., Higashida, K., Islam, M. S., Yamada, N., Hayashi, K., Noguchi, N., Kato, I., Okamoto, H., Matsushima, A., Salmina, A., Munesue, T., Shimizu, N., Mochida, S., Asano, M. and Higashida, H. 2007. CD38 is critical for social behaviour by regulating oxytocin secretion. *Nature*, 446, 41-5.

- Johnson, J. D., Ford, E. L., Bernal-Mizrachi, E., Kusser, K. L., Luciani, D. S., Han, Z., Tran, H., Randall, T. D., Lund, F. E. and Polonsky, K. S. 2006. Suppressed insulin signaling and increased apoptosis in CD38-null islets. *Diabetes*, 55, 2737-46.
- Jones, D. P. 2002. Redox potential of GSH/GSSG couple: assay and biological significance. *Methods Enzymol*, 348, 93-112.
- Jones, R. G. and Thompson, C. B. 2009. Tumor suppressors and cell metabolism: a recipe for cancer growth. *Genes Dev*, 23, 537-48.
- Kaisho, T., Ishikawa, J., Oritani, K., Inazawa, J., Tomizawa, H., Muraoka, O., Ochi, T. and Hirano, T. 1994. BST-1, a surface molecule of bone marrow stromal cell lines that facilitates pre-B-cell growth. *Proc Natl Acad Sci U S A*, 91, 5325-9.
- Kamiguti, A. S., Lee, E. S., Till, K. J., Harris, R. J., Glenn, M. A., Lin, K., Chen, H. J., Zuzel, M. and Cawley, J. C. 2004. The role of matrix metalloproteinase 9 in the pathogenesis of chronic lymphocytic leukaemia. *Br J Haematol*, 125, 128-40.
- Kanai, M., Miwa, M., Kondo, T., Tanaka, Y., Nakayasu, M. and Sugimura, T. 1982. Involvement of poly (ADP-ribose) metabolism in induction of differentiation of HL-60 promyelocytic leukemia cells. *Biochem Biophys Res Commun*, 105, 404-11.
- Kang, B. N., Jude, J. A., Panettieri, R. A., Jr., Walseth, T. F. and Kannan, M. S. 2008. Glucocorticoid regulation of CD38 expression in human airway smooth muscle cells: role of dual specificity phosphatase 1. *Am J Physiol Lung Cell Mol Physiol*, 295, L186-93.
- Kang, B. N., Tirumurugaan, K. G., Deshpande, D. A., Amrani, Y., Panettieri, R. A., Walseth, T. F. and Kannan, M. S. 2006. Transcriptional regulation of CD38 expression by tumor necrosis factor- α in human airway smooth muscle cells: role of NF- κ B and sensitivity to glucocorticoids. *FASEB J*, 20, 1000-2.
- Kang, J., Park, K. H., Kim, J. J., Jo, E. K., Han, M. K. and Kim, U. H. 2012. The role of CD38 in Fc γ receptor (Fc γ R)-mediated phagocytosis in murine macrophages. *J Biol Chem*, 287, 14502-14.
- Kass, G. E., Eriksson, J. E., Weis, M., Orrenius, S. and Chow, S. C. 1996. Chromatin condensation during apoptosis requires ATP. *Biochem J*, 318 (Pt 3), 749-52.
- Kato, H., Ito, E., Shi, W., Alajez, N. M., Yue, S., Lee, C., Chan, N., Bhogal, N., Coackley, C. L., Vines, D., Green, D., Waldron, J., Gullane, P., Bristow, R. and Liu, F. F. 2010. Efficacy of combining GMX1777 with radiation therapy for human head and neck carcinoma. *Clin Cancer Res*, 16, 898-911.
- Kato, I., Takasawa, S., Akabane, A., Tanaka, O., Abe, H., Takamura, T., Suzuki, Y., Nata, K., Yonekura, H., Yoshimoto, T. and *Et Al*. 1995. Regulatory role of CD38 (ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase) in insulin secretion by glucose in pancreatic beta cells. Enhanced insulin secretion in CD38-expressing transgenic mice. *J Biol Chem*, 270, 30045-50.
- Katz, F., Povey, S., Parkar, M., Schneider, C., Sutherland, R., Stanley, K., Solomon, E. and Greaves, M. 1983. Chromosome assignment of monoclonal antibody-defined determinants on human leukemic cells. *Eur J Immunol*, 13, 1008-13.
- Kellenberger, E., Kuhn, I., Schuber, F. and Muller-Steffner, H. 2011. Flavonoids as inhibitors of human CD38. *Bioorg Med Chem Lett*, 21, 3939-42.
- Khan, J. A., Forouhar, F., Tao, X. and Tong, L. 2007. Nicotinamide adenine dinucleotide metabolism as an attractive target for drug discovery. *Expert Opin Ther Targets*, 11, 695-705.
- Khoo, K. M. and Chang, C. F. 2000. Localization of plasma membrane CD38 is domain specific in rat hepatocyte. *Arch Biochem Biophys*, 373, 35-43.

- Khoo, K. M., Han, M. K., Park, J. B., Chae, S. W., Kim, U. H., Lee, H. C., Bay, B. H. and Chang, C. F. 2000. Localization of the cyclic ADP-ribose-dependent calcium signaling pathway in hepatocyte nucleus. *J Biol Chem*, 275, 24807-17.
- Kikutani, H. and Kumanogoh, A. 2003. Semaphorins in interactions between T cells and antigen-presenting cells. *Nat Rev Immunol*, 3, 159-67.
- Kim, M. Y., Zhang, T. and Kraus, W. L. 2005. Poly(ADP-ribosyl)ation by PARP-1: 'PAR-laying' NAD⁺ into a nuclear signal. *Genes Dev*, 19, 1951-67.
- Kim, S. Y., Cho, B. H. and Kim, U. H. 2010. CD38-mediated Ca²⁺ signaling contributes to angiotensin II-induced activation of hepatic stellate cells: attenuation of hepatic fibrosis by CD38 ablation. *J Biol Chem*, 285, 576-82.
- Kim, S. Y., Gul, R., Rah, S. Y., Kim, S. H., Park, S. K., Im, M. J., Kwon, H. J. and Kim, U. H. 2008. Molecular mechanism of ADP-ribosyl cyclase activation in angiotensin II signaling in murine mesangial cells. *Am J Physiol Renal Physiol*, 294, F982-9.
- Kirkland, J. B. 2003. Niacin and carcinogenesis. *Nutr Cancer*, 46, 110-8.
- Kirsten, E., Bauer, P. I. and Kun, E. 1991. Cellular regulation of ADP-ribosylation of proteins. IV. Conversion of poly(ADP-ribose) polymerase activity to NAD-glycohydrolase during retinoic acid-induced differentiation of HL60 cells. *Exp Cell Res*, 194, 1-8.
- Kishimoto, H., Hoshino, S., Ohori, M., Kontani, K., Nishina, H., Suzawa, M., Kato, S. and Katada, T. 1998. Molecular mechanism of human CD38 gene expression by retinoic acid. Identification of retinoic acid response element in the first intron. *J Biol Chem*, 273, 15429-34.
- Kitanaka, A., Ito, C., Coustan-Smith, E. and Campana, D. 1997. CD38 ligation in human B cell progenitors triggers tyrosine phosphorylation of CD19 and association of CD19 with lyn and phosphatidylinositol 3-kinase. *J Immunol*, 159, 184-92.
- Klein, C., Grahnert, A., Abdelrahman, A., Muller, C. E. and Hauschildt, S. 2009. Extracellular NAD⁽⁺⁾ induces a rise in [Ca⁽²⁺⁾]_i in activated human monocytes via engagement of P2Y(1) and P2Y(11) receptors. *Cell Calcium*, 46, 263-72.
- Knutti, D. and Kralli, A. 2001. PGC-1, a versatile coactivator. *Trends Endocrinol Metab*, 12, 360-5.
- Koch-Nolte, F., Kernstock, S., Mueller-Dieckmann, C., Weiss, M. S. and Haag, F. 2008. Mammalian ADP-ribosyltransferases and ADP-ribosylhydrolases. *Front Biosci*, 13, 6716-29.
- Koguma, T., Takasawa, S., Tohgo, A., Karasawa, T., Furuya, Y., Yonekura, H. and Okamoto, H. 1994. Cloning and characterization of cDNA encoding rat ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase (homologue to human CD38) from islets of Langerhans. *Biochim Biophys Acta*, 1223, 160-2.
- Kotaka, M., Graeff, R., Chen, Z., Zhang, L. H., Lee, H. C. and Hao, Q. 2012. Structural studies of intermediates along the cyclization pathway of Aplysia ADP-ribosyl cyclase. *J Mol Biol*, 415, 514-26.
- Kotlikoff, M. I., Kannan, M. S., Solway, J., Deng, K. Y., Deshpande, D. A., Dowell, M., Feldman, M., Green, K. S., Ji, G., Johnston, R., Lakser, O., Lee, J., Lund, F. E., Milla, C., Mitchell, R. W., Nakai, J., Rishniw, M., Walseth, T. F., White, T. A., Wilson, J., Xin, H. B. and Woodruff, P. G. 2004. Methodologic advancements in the study of airway smooth muscle. *J Allergy Clin Immunol*, 114, S18-31.
- Kozako, T., Aikawa, A., Shoji, T., Fujimoto, T., Yoshimitsu, M., Shirasawa, S., Tanaka, H., Honda, S., Shimeno, H., Arima, N. and Soeda, S. 2012. High expression of the longevity gene product SIRT1 and apoptosis induction by sirtinol in adult T-cell leukemia cells. *Int J Cancer*, 131, 2044-55.

- Kramer, G., Steiner, G., Fodinger, D., Fiebiger, E., Rappersberger, C., Binder, S., Hofbauer, J. and Marberger, M. 1995. High expression of a CD38-like molecule in normal prostatic epithelium and its differential loss in benign and malignant disease. *J Urol*, 154, 1636-41.
- Krance, S. M., Keng, P. C., Palis, J. and Ballatori, N. 2010. Transient glutathione depletion determines terminal differentiation in HL-60 cells. *Oxid Med Cell Longev*, 3, 53-60.
- Kristian, T., Balan, I., Schuh, R. and Onken, M. 2011. Mitochondrial dysfunction and nicotinamide dinucleotide catabolism as mechanisms of cell death and promising targets for neuroprotection. *J Neurosci Res*, 89, 1946-55.
- Krober, A., Seiler, T., Benner, A., Bullinger, L., Bruckle, E., Lichter, P., Dohner, H. and Stilgenbauer, S. 2002. V(H) mutation status, CD38 expression level, genomic aberrations, and survival in chronic lymphocytic leukemia. *Blood*, 100, 1410-6.
- Kuhn, I., Kellenberger, E., Rognan, D., Lund, F. E., Muller-Steffner, H. and Schuber, F. 2006. Redesign of *Schistosoma mansoni* NAD⁺ catabolizing enzyme: active site H103W mutation restores ADP-ribosyl cyclase activity. *Biochemistry*, 45, 11867-78.
- Kumagai, M., Coustan-Smith, E., Murray, D. J., Silvennoinen, O., Murti, K. G., Evans, W. E., Malavasi, F. and Campana, D. 1995. Ligation of CD38 suppresses human B lymphopoiesis. *J Exp Med*, 181, 1101-10.
- Kumar, V., Carlson, J. E., Ohgi, K. A., Edwards, T. A., Rose, D. W., Escalante, C. R., Rosenfeld, M. G. and Aggarwal, A. K. 2002. Transcription corepressor CtBP is an NAD⁽⁺⁾-regulated dehydrogenase. *Mol Cell*, 10, 857-69.
- Kumaravel, T. S. and Jha, A. N. 2006. Reliable Comet assay measurements for detecting DNA damage induced by ionising radiation and chemicals. *Mutat Res*, 605, 7-16.
- Lagouge, M., Argmann, C., Gerhart-Hines, Z., Meziane, H., Lerin, C., Daussin, F., Messadeq, N., Milne, J., Lambert, P., Elliott, P., Geny, B., Laakso, M., Puigserver, P. and Auwerx, J. 2006. Resveratrol improves mitochondrial function and protects against metabolic disease by activating SIRT1 and PGC-1alpha. *Cell*, 127, 1109-22.
- Lamkin, T. J., Chin, V., Varvayanis, S., Smith, J. L., Sramkoski, R. M., Jacobberger, J. W. and Yen, A. 2006. Retinoic acid-induced CD38 expression in HL-60 myeloblastic leukemia cells regulates cell differentiation or viability depending on expression levels. *J Cell Biochem*, 97, 1328-38.
- Lawrence, T. S., Ten Haken, R. K. and Giaccia, A. 2008. Principles of Radiation Oncology. In: DeVita VT Jr., Lawrence TS, Rosenberg SA (eds), Philadelphia: Lippincott Williams and Wilkins,
- Le Page, F., Schreiber, V., Dherin, C., De Murcia, G. and Boiteux, S. 2003. Poly(ADP-ribose) polymerase-1 (PARP-1) is required in murine cell lines for base excision repair of oxidative DNA damage in the absence of DNA polymerase beta. *J Biol Chem*, 278, 18471-7.
- Lee, C. U., Song, E. K., Yoo, C. H., Kwak, Y. K. and Han, M. K. 2012a. Lipopolysaccharide induces CD38 expression and solubilization in J774 macrophage cells. *Mol Cells*, 34, 573-6.
- Lee, H. C. 2002. Cyclic ADP-ribose and NAADP. Structures, Metabolism and Functions. *Dordrecht: Kluwer Academic Publishers*, pp. 1-21.
- Lee, H. C. 2004. Multiplicity of Ca²⁺ messengers and Ca²⁺ stores: a perspective from cyclic ADP-ribose and NAADP. *Curr Mol Med*, 4, 227-37.
- Lee, H. C. 2006. Structure and enzymatic functions of human CD38. *Mol Med*, 12, 317-23.
- Lee, H. C. 2012. The Cyclic ADP-Ribose/NAADP/CD38-signaling pathway: past and present. *MESSENGER*, 1, 16-33.

- Lee, H. C. and Aarhus, R. 1995. A derivative of NADP mobilizes calcium stores insensitive to inositol trisphosphate and cyclic ADP-ribose. *J Biol Chem*, 270, 2152-7.
- Lee, H. C., Aarhus, R. and Graeff, R. M. 1995a. Sensitization of calcium-induced calcium release by cyclic ADP-ribose and calmodulin. *J Biol Chem*, 270, 9060-6.
- Lee, H. C., Walseth, T. F., Bratt, G. T., Hayes, R. N. and Clapper, D. L. 1989. Structural determination of a cyclic metabolite of NAD⁺ with intracellular Ca²⁺-mobilizing activity. *J Biol Chem*, 264, 1608-15.
- Leonardo, M. R., Dailly, Y. and Clark, D. P. 1996. Role of NAD in regulating the adhE gene of Escherichia coli. *J Bacteriol*, 178, 6013-8.
- Levesque, M. C., Chen, Y., Beasley, B. E., O'loughlin, C. W., Gockerman, J. P., Moore, J. O. and Weinberg, J. B. 2006. Chronic lymphocytic leukemia cell CD38 expression and inducible nitric oxide synthase expression are associated with serum IL-4 levels. *Leuk Res*, 30, 24-8.
- Lewandowski, D., Linassier, C., Iochmann, S., Degenne, M., Domenech, J., Colombat, P., Binet, C. and Herault, O. 2002. Phosphatidylinositol 3-kinases are involved in the all-trans retinoic acid-induced upregulation of CD38 antigen on human haematopoietic cells. *Br J Haematol*, 118, 535-44.
- Li, N. and Chen, G. 2002. Flow injection analysis of trace amounts of NADH with inhibited chemiluminescent detection. *Talanta*, 57, 961-967.
- Liang, J., Wu, W. L., Liu, Z. H., Mei, Y. J., Cai, R. X. and Shen, P. 2007. Study the oxidative injury of yeast cells by NADH autofluorescence. *Spectrochim Acta A Mol Biomol Spectrosc*, 67, 355-9.
- Liang, M., Chini, E. N., Cheng, J. and Dousa, T. P. 1999. Synthesis of NAADP and cADPR in mitochondria. *Arch Biochem Biophys*, 371, 317-25.
- Libura, J., Slater, D. J., Felix, C. A. and Richardson, C. 2005. Therapy-related acute myeloid leukemia-like MLL rearrangements are induced by etoposide in primary human CD34⁺ cells and remain stable after clonal expansion. *Blood*, 105, 2124-31.
- Lin, J., Handschin, C. and Spiegelman, B. M. 2005. Metabolic control through the PGC-1 family of transcription coactivators. *Cell Metab*, 1, 361-70.
- Lin, S. J. and Guarente, L. 2003. Nicotinamide adenine dinucleotide, a metabolic regulator of transcription, longevity and disease. *Curr Opin Cell Biol*, 15, 241-6.
- Liu, Q., Kriksunov, I. A., Graeff, R., Munshi, C., Lee, H. C. and Hao, Q. 2005. Crystal structure of human CD38 extracellular domain. *Structure*, 13, 1331-9.
- Liu, Q., Kriksunov, I. A., Graeff, R., Munshi, C., Lee, H. C. and Hao, Q. 2006. Structural basis for the mechanistic understanding of human CD38-controlled multiple catalysis. *J Biol Chem*, 281, 32861-9.
- Liu, Q., Kriksunov, I. A., Jiang, H., Graeff, R., Lin, H., Lee, H. C. and Hao, Q. 2008. Covalent and noncovalent intermediates of an NAD utilizing enzyme, human CD38. *Chem Biol*, 15, 1068-78.
- Livak, K. J. and Schmittgen, T. D. 2001. Analysis of relative gene expression data using real-time quantitative PCR and the 2(-Delta Delta C(T)) Method. *Methods*, 25, 402-8.
- Lohmann, W., Mussmann, J. and Lohmann, C. 1989. Native fluorescence of the cervix uteri as a marker for dysplasia and invasive carcinoma. *European journal of obstetrics, gynecology, and reproductive biology*, 31(3), 249-53.
- Lopez-Giral, S., Quintana, N. E., Cabrerizo, M., Alfonso-Perez, M., Sala-Valdes, M., De Soria, V. G., Fernandez-Ranada, J. M., Fernandez-Ruiz, E. and Munoz, C. 2004. Chemokine receptors that mediate B cell homing to secondary lymphoid tissues are highly expressed in B cell chronic

- lymphocytic leukemia and non-Hodgkin lymphomas with widespread nodular dissemination. *J Leukoc Biol*, 76, 462-71.
- Lu, M. L., Sato, M., Cao, B. and Richie, J. P. 1996. UV irradiation-induced apoptosis leads to activation of a 36-kDa myelin basic protein kinase in HL-60 cells. *Proc Natl Acad Sci U S A*, 93, 8977-82.
- Lund, F. E. 2006. Signaling properties of CD38 in the mouse immune system: enzyme-dependent and -independent roles in immunity. *Mol Med*, 12, 328-33.
- Lund, F. E., Yu, N., Kim, K. M., Reth, M. and Howard, M. C. 1996. Signaling through CD38 augments B cell antigen receptor (BCR) responses and is dependent on BCR expression. *J Immunol*, 157, 1455-67.
- Mack, T. G., Reiner, M., Beirowski, B., Mi, W., Emanuelli, M., Wagner, D., Thomson, D., Gillingwater, T., Court, F., Conforti, L., Fernando, F. S., Tarlton, A., Andressen, C., Addicks, K., Magni, G., Ribchester, R. R., Perry, V. H. and Coleman, M. P. 2001. Wallerian degeneration of injured axons and synapses is delayed by a Ube4b/Nmnat chimeric gene. *Nat Neurosci*, 4, 1199-206.
- Magni, G., Amici, A., Emanuelli, M., Orsomando, G., Raffaelli, N. and Ruggieri, S. 2004. Enzymology of NAD⁺ homeostasis in man. *Cell Mol Life Sci*, 61, 19-34.
- Malavasi, F., Caligaris-Cappio, F., Milanese, C., Dellabona, P., Richiardi, P. and Carbonara, A. O. 1984. Characterization of a murine monoclonal antibody specific for human early lymphohemopoietic cells. *Hum Immunol*, 9, 9-20.
- Malavasi, F., Deaglio, S., Damle, R., Cutrona, G., Ferrarini, M. and Chiorazzi, N. 2011. CD38 and chronic lymphocytic leukemia: a decade later. *Blood*, 118, 3470-8.
- Malavasi, F., Deaglio, S., Ferrero, E., Funaro, A., Sancho, J., Ausiello, C. M., Ortolan, E., Vaisitti, T., Zubiaur, M., Fedele, G., Aydin, S., Tibaldi, E. V., Durelli, I., Lusso, R., Cozno, F. and Horenstein, A. L. 2006. CD38 and CD157 as receptors of the immune system: a bridge between innate and adaptive immunity. *Mol Med*, 12, 334-41.
- Malavasi, F., Deaglio, S., Funaro, A., Ferrero, E., Horenstein, A. L., Ortolan, E., Vaisitti, T. and Aydin, S. 2008. Evolution and function of the ADP ribosyl cyclase/CD38 gene family in physiology and pathology. *Physiol Rev*, 88, 841-86.
- Malavasi, F., Deaglio, S., Zaccarello, G., Horenstein, A. L., Chillemi, A., Audrito, V., Serra, S., Gandione, M., Zitella, A. and Tizzani, A. 2010. The hidden life of NAD⁺-consuming ectoenzymes in the endocrine system. *J Mol Endocrinol*, 45, 183-91.
- Malavasi, F., Funaro, A., Roggero, S., Horenstein, A., Calosso, L. and Mehta, K. 1994. Human CD38: a glycoprotein in search of a function. *Immunol Today*, 15, 95-7.
- Mallone, R., Funaro, A., Zubiaur, M., Baj, G., Ausiello, C. M., Tacchetti, C., Sancho, J., Grossi, C. and Malavasi, F. 2001. Signaling through CD38 induces NK cell activation. *Int Immunol*, 13, 397-409.
- Mallone, R., Ortolan, E., Baj, G., Funaro, A., Giunti, S., Lillaz, E., Saccucci, F., Cassader, M., Cavallo-Perin, P. and Malavasi, F. 2001a. Autoantibody response to CD38 in Caucasian patients with type 1 and type 2 diabetes: immunological and genetic characterization. *Diabetes*, 50, 752-62.
- Mallone, R., Ortolan, E., Pinach, S., Volante, M., Zanone, M. M., Bruno, G., Baj, G., Lohmann, T., Cavallo-Perin, P. and Malavasi, F. 2002. Anti-CD38 autoantibodies: characterisation in new-onset type I diabetes and latent autoimmune diabetes of the adult (LADA) and comparison with other islet autoantibodies. *Diabetologia*, 45, 1667-77.
- Maloney, D. G., Donovan, K. and Hamblin, T. J. 1999. Antibody therapy for treatment of multiple myeloma. *Semin Hematol*, 36, 30-3.

- Mathews, C. K., Van Holde, K. E. and Ahern, K. G. 2000. *Biochemistry* Addison-Wesley: San Francisco, CA
- Matrai, Z. 2005. CD38 as a prognostic marker in CLL. *Hematology*, 10, 39-46.
- Matsunaga, T., Kudo, J., Takahashi, K., Dohmen, K., Hayashida, K., Okamura, S., Ishibashi, H. and Niho, Y. 1996. Rotenone, a mitochondrial NADH dehydrogenase inhibitor, induces cell surface expression of CD13 and CD38 and apoptosis in HL-60 cells. *Leuk Lymphoma*, 20, 487-94.
- Mauer, A. M., Athens, J. W., Ashenbrucker, H., Cartwright, G. E. and Wintrobe, M. M. 1960. Leukokinetic Studies. Ii. A Method for Labeling Granulocytes in Vitro with Radioactive Diisopropylfluorophosphate (Dfp). *J Clin Invest*, 39, 1481-6.
- Mehta, K. 2000. Retinoid-mediated signaling in CD38 antigen expression. *Chem Immunol*, 75, 20-38.
- Mehta, K., Mcqueen, T., Manshour, T., Andreeff, M., Collins, S. and Albitar, M. 1997. Involvement of retinoic acid receptor- α -mediated signaling pathway in induction of CD38 cell-surface antigen. *Blood*, 89, 3607-14.
- Mehta, K., Mcqueen, T., Neamati, N., Collins, S. and Andreeff, M. 1996a. Activation of retinoid receptors RAR α and RXR α induces differentiation and apoptosis, respectively, in HL-60 cells. *Cell Growth Differ*, 7, 179-86.
- Mehta, K., Ocanas, L., Malavasi, F., Marks, J. W. and Rosenblum, M. G. 2004. Retinoic acid-induced CD38 antigen as a target for immunotoxin-mediated killing of leukemia cells. *Mol Cancer Ther*, 3, 345-52.
- Mehta, K., Shahid, U. and Malavasi, F. 1996b. Human CD38, a cell-surface protein with multiple functions. *FASEB J*, 10, 1408-17.
- Mellor, A. L. and Munn, D. H. 2004. IDO expression by dendritic cells: tolerance and tryptophan catabolism. *Nat Rev Immunol*, 4, 762-74.
- Meszaros, L. G., Bak, J. and Chu, A. 1993. Cyclic ADP-ribose as an endogenous regulator of the non-skeletal type ryanodine receptor Ca^{2+} channel. *Nature*, 364, 76-9.
- Michan, S. and Sinclair, D. 2007. Sirtuins in mammals: insights into their biological function. *Biochem J*, 404, 1-13.
- Mistry, A. R., Felix, C. A., Whitmarsh, R. J., Mason, A., Reiter, A., Cassinat, B., Parry, A., Walz, C., Wiemels, J. L., Segal, M. R., Ades, L., Blair, I. A., Osheroff, N., Peniket, A. J., Lafage-Pochitaloff, M., Cross, N. C., Chomienne, C., Solomon, E., Fenaux, P. and Grimwade, D. 2005. DNA topoisomerase II in therapy-related acute promyelocytic leukemia. *N Engl J Med*, 352, 1529-38.
- Mitsui-Saito, M., Kato, I., Takasawa, S., Okamoto, H. and Yanagisawa, T. 2003. CD38 gene disruption inhibits the contraction induced by α -adrenoceptor stimulation in mouse aorta. *J Vet Med Sci*, 65, 1325-30.
- Mizuguchi, M., Otsuka, N., Sato, M., Ishii, Y., Kon, S., Yamada, M., Nishina, H., Katada, T. and Ikeda, K. 1995. Neuronal localization of CD38 antigen in the human brain. *Brain Res*, 697, 235-40.
- Mohazzab, K. M., Kaminski, P. M. and Wolin, M. S. 1994. NADH oxidoreductase is a major source of superoxide anion in bovine coronary artery endothelium. *Am J Physiol*, 266, H2568-72.
- Morabito, F., Cutrona, G., Gentile, M., Fabbi, M., Matis, S., Colombo, M., Reverberi, D., Megna, M., Spriano, M., Callea, V., Vigna, E., Rossi, E., Lucia, E., Festini, G., Zupo, S., Molica, S., Neri, A. and Ferrarini, M. 2010. Prognostic relevance of in vitro response to cell stimulation via surface IgD in binet stage a CLL. *Br J Haematol*, 149, 160-3.

- Morabito, F., Cutrona, G., Gentile, M., Matis, S., Todoerti, K., Colombo, M., Sonaglio, C., Fabris, S., Reverberi, D., Megna, M., Spriano, M., Lucia, E., Rossi, E., Callea, V., Mazzone, C., Festini, G., Zupo, S., Molica, S., Neri, A. and Ferrarini, M. 2009. Definition of progression risk based on combinations of cellular and molecular markers in patients with Binet stage A chronic lymphocytic leukaemia. *Br J Haematol*, 146, 44-53.
- Morabito, F., Mangiola, M., Stelitano, C., Deaglio, S., Callea, V. and Malavasi, F. 2002. Peripheral blood CD38 expression predicts time to progression in B-cell chronic lymphocytic leukemia after first-line therapy with high-dose chlorambucil. *Haematologica*, 87, 217-8.
- Moreno-Garcia, M. E., Partida-Sanchez, S., Primack, J., Sumoza-Toledo, A., Muller-Steffner, H., Schuber, F., Oppenheimer, N., Lund, F. E. and Santos-Argumedo, L. 2004. CD38 is expressed as noncovalently associated homodimers on the surface of murine B lymphocytes. *Eur J Biochem*, 271, 1025-34.
- Moreschi, I., Bruzzone, S., Nicholas, R. A., Fruscione, F., Sturla, L., Benvenuto, F., Usai, C., Meis, S., Kassack, M. U., Zocchi, E. and De Flora, A. 2006. Extracellular NAD⁺ is an agonist of the human P2Y₁₁ purinergic receptor in human granulocytes. *J Biol Chem*, 281, 31419-29.
- Mosmann, T. 1983. Rapid colorimetric assay for cellular growth and survival: application to proliferation and cytotoxicity assays. *J Immunol Methods*, 65, 55-63.
- Munesue, T., Yokoyama, S., Nakamura, K., Anitha, A., Yamada, K., Hayashi, K., Asaka, T., Liu, H. X., Jin, D., Koizumi, K., Islam, M. S., Huang, J. J., Ma, W. J., Kim, U. H., Kim, S. J., Park, K., Kim, D., Kikuchi, M., Ono, Y., Nakatani, H., Suda, S., Miyachi, T., Hirai, H., Salmina, A., Pichugina, Y. A., Soumarokov, A. A., Takei, N., Mori, N., Tsujii, M., Sugiyama, T., Yagi, K., Yamagishi, M., Sasaki, T., Yamasue, H., Kato, N., Hashimoto, R., Taniike, M., Hayashi, Y., Hamada, J., Suzuki, S., Ooi, A., Noda, M., Kamiyama, Y., Kido, M. A., Lopatina, O., Hashii, M., Amina, S., Malavasi, F., Huang, E. J., Zhang, J., Shimizu, N., Yoshikawa, T., Matsushima, A., Minabe, Y. and Higashida, H. 2010. Two genetic variants of CD38 in subjects with autism spectrum disorder and controls. *Neurosci Res*, 67, 181-91.
- Munoz-Gamez, J. A., Rodriguez-Vargas, J. M., Quiles-Perez, R., Aguilar-Quesada, R., Martin-Oliva, D., De Murcia, G., Menissier De Murcia, J., Almendros, A., Ruiz De Almodovar, M. and Oliver, F. J. 2009. PARP-1 is involved in autophagy induced by DNA damage. *Autophagy*, 5, 61-74.
- Munoz, P., Mittelbrunn, M., De La Fuente, H., Perez-Martinez, M., Garcia-Perez, A., Ariza-Veguillas, A., Malavasi, F., Zubiaur, M., Sanchez-Madrid, F. and Sancho, J. 2008. Antigen-induced clustering of surface CD38 and recruitment of intracellular CD38 to the immunologic synapse. *Blood*, 111, 3653-64.
- Munoz, P., Navarro, M. D., Pavon, E. J., Salmeron, J., Malavasi, F., Sancho, J. and Zubiaur, M. 2003. CD38 signaling in T cells is initiated within a subset of membrane rafts containing Lck and the CD3-zeta subunit of the T cell antigen receptor. *J Biol Chem*, 278, 50791-802.
- Munoz-Gamez, J. A., Martin-Oliva, D., Aguilar-Quesada, R., Canuelo, A., Nunez, M. I., Valenzuela, M. T., Ruiz De Almodovar, J. M., De Murcia, G. and Oliver, F. J. 2005. PARP inhibition sensitizes p53-deficient breast cancer cells to doxorubicin-induced apoptosis. *Biochem J*, 386, 119-25.
- Munshi, C., Aarhus, R., Graeff, R., Walseth, T. F., Levitt, D. and Lee, H. C. 2000. Identification of the enzymatic active site of CD38 by site-directed mutagenesis. *J Biol Chem*, 275, 21566-71.
- Munshi, C., Thiel, D. J., Mathews, Ii, Aarhus, R., Walseth, T. F. and Lee, H. C. 1999. Characterization of the active site of ADP-ribosyl cyclase. *J Biol Chem*, 274, 30770-7.
- Munshi, C. B., Graeff, R. and Lee, H. C. 2002. Evidence for a causal role of CD38 expression in granulocytic differentiation of human HL-60 cells. *J Biol Chem*, 277, 49453-8.

- Muruganandham, M., Alfieri, A. A., Matei, C., Chen, Y., Sukenick, G., Schemainda, I., Hasmann, M., Saltz, L. B. and Koutcher, J. A. 2005. Metabolic signatures associated with a NAD synthesis inhibitor-induced tumor apoptosis identified by 1H-decoupled-31P magnetic resonance spectroscopy. *Clin Cancer Res*, 11, 3503-13.
- Musso, T., Deaglio, S., Franco, L., Calosso, L., Badolato, R., Garbarino, G., Dianzani, U. and Malavasi, F. 2001. CD38 expression and functional activities are up-regulated by IFN-gamma on human monocytes and monocytic cell lines. *J Leukoc Biol*, 69, 605-12.
- Nakamura, T., Peng, K. W., Harvey, M., Greiner, S., Lorimer, I. A., James, C. D. and Russell, S. J. 2005. Rescue and propagation of fully retargeted oncolytic measles viruses. *Nat Biotechnol*, 23, 209-14
- National Institutes of Health, 1998. Clinical Guidelines on the Identification, Evaluation, and Treatment of Overweight and Obesity in Adults. The Evidence Report. *Obes Res*, 6, 51S-209S.
- Newburger, P. E., Chovaniec, M. E., Greenberger, J. S. and Cohen, H. J. 1979. Functional changes in human leukemic cell line HL-60. A model for myeloid differentiation. *J Cell Biol*, 82, 315-22.
- Nicholls, D. G., Budd, S. L., Ward, M. W. and Castilho, R. F. 1999. Excitotoxicity and mitochondria. *Biochem Soc Symp*, 66, 55-67.
- Nishina, H., Inageda, K., Takahashi, K., Hoshino, S., Ikeda, K. and Katada, T. 1994. Cell surface antigen CD38 identified as ecto-enzyme of NAD glycohydrolase has hyaluronate-binding activity. *Biochem Biophys Res Commun*, 203, 1318-23.
- Noguchi, N., Takasawa, S., Nata, K., Tohgo, A., Kato, I., Ikehata, F., Yonekura, H. and Okamoto, H. 1997. Cyclic ADP-ribose binds to FK506-binding protein 12.6 to release Ca²⁺ from islet microsomes. *J Biol Chem*, 272, 3133-6.
- Ohkawa, H., Ohishi, N. and Yagi, K. 1979. Assay for lipid peroxides in animal tissues by thiobarbituric acid reaction. *Anal Biochem*, 95, 351-8.
- Okamoto, H., Takasawa, S., Tohgo, A., Nata, K., Kato, I. and Noguchi, N. 1997. Synthesis and hydrolysis of cyclic ADP-ribose by human leukocyte antigen CD38: inhibition of hydrolysis by ATP and physiological significance. *Methods Enzymol*, 280, 306-18.
- Opitz, C. A., Wick, W., Steinman, L. and Platten, M. 2007. Tryptophan degradation in autoimmune diseases. *Cell Mol Life Sci*, 64, 2542-63.
- Ortin, X., Giralt, M., Romeu, M., Lejeune, M., Nogues, M., R., Sanchez-Martos, V., Rodriguez-Luaces, M., Sans, T. and Font, L. 2012. Oxidative Stress in Patients With Early Stage Chronic Lymphocytic Leukemia, Assessment and Correlation With Prognostic Factors. *J Hematol*, 1(4-5), :77-88.
- Ortolan, E., Vacca, P., Capobianco, A., Armando, E., Crivellin, F., Horenstein, A. and Malavasi, F. 2002. CD157, the Janus of CD38 but with a unique personality. *Cell Biochem Funct*, 20, 309-22.
- Ota, H., Tamaki, S., Itaya-Hironaka, A., Yamauchi, A., Sakuramoto-Tsuchida, S., Morioka, T., Takasawa, S. and Kimura, H. 2012. Attenuation of glucose-induced insulin secretion by intermittent hypoxia via down-regulation of CD38. *Life Sci*, 90, 206-11.
- Ottaggio, L., Viaggi, S., Zunino, A., Zupo, S., Rossi, E., Spriano, M., Abbondandolo, A. and Ferrarini, M. 2003. Chromosome aberrations evaluated by comparative genomic hybridization in B-cell chronic lymphocytic leukemia: correlation with CD38 expression. *Haematologica*, 88, 769-77.
- Palis, J., King, B. and Keng, P. 1988. Separation of spontaneously differentiating and cell cycle-specific populations of HL-60 cells. *Leuk Res*, 12, 339-44.
- Pallesen, G. and Plesner, T. 1987. The third international workshop and conference on human leukocyte differentiation antigens with an up-to-date overview of the CD nomenclature. *Leukemia*, 1, 231-4.

- Pan, K., Wang, H., Chen, M. S., Zhang, H. K., Weng, D. S., Zhou, J., Huang, W., Li, J. J., Song, H. F. and Xia, J. C. 2008. Expression and prognosis role of indoleamine 2,3-dioxygenase in hepatocellular carcinoma. *J Cancer Res Clin Oncol*, 134, 1247-53.
- Paraskevas, S., Aikin, R., Maysinger, D., Lakey, J. R., Cavanagh, T. J., Agapitos, D., Wang, R. and Rosenberg, L. 2001. Modulation of JNK and p38 stress activated protein kinases in isolated islets of Langerhans: insulin as an autocrine survival signal. *Ann Surg*, 233, 124-33.
- Parato, K. A., Senger, D., Forsyth, P. A. and Bell, J. C. 2005. Recent progress in the battle between oncolytic viruses and tumours. *Nat Rev Cancer*, 5, 965-76.
- Park, K. H., Kim, B. J., Kang, J., Nam, T. S., Lim, J. M., Kim, H. T., Park, J. K., Kim, Y. G., Chae, S. W. and Kim, U. H. 2011. Ca²⁺ signaling tools acquired from prostasomes are required for progesterone-induced sperm motility. *Sci Signal*, 4, 2001595.
- Partida-Sanchez, S., Cockayne, D. A., Monard, S., Jacobson, E. L., Oppenheimer, N., Garvy, B., Kusser, K., Goodrich, S., Howard, M., Harmsen, A., Randall, T. D. and Lund, F. E. 2001. Cyclic ADP-ribose production by CD38 regulates intracellular calcium release, extracellular calcium influx and chemotaxis in neutrophils and is required for bacterial clearance in vivo. *Nat Med*, 7, 1209-16.
- Partida-Sanchez, S., Goodrich, S., Kusser, K., Oppenheimer, N., Randall, T. D. and Lund, F. E. 2004a. Regulation of dendritic cell trafficking by the ADP-ribosyl cyclase CD38: impact on the development of humoral immunity. *Immunity*, 20, 279-91.
- Partida-Sanchez, S., Iribarren, P., Moreno-Garcia, M. E., Gao, J. L., Murphy, P. M., Oppenheimer, N., Wang, J. M. and Lund, F. E. 2004b. Chemotaxis and calcium responses of phagocytes to formyl peptide receptor ligands is differentially regulated by cyclic ADP ribose. *J Immunol*, 172, 1896-906.
- Partida-Sanchez, S., Randall, T. D. and Lund, F. E. 2003. Innate immunity is regulated by CD38, an ectoenzyme with ADP-ribosyl cyclase activity. *Microbes Infect*, 5, 49-58.
- Patten, P. E., Buggins, A. G., Richards, J., Wotherspoon, A., Salisbury, J., Mufti, G. J., Hamblin, T. J. and Devereux, S. 2008. CD38 expression in chronic lymphocytic leukemia is regulated by the tumor microenvironment. *Blood*, 111, 5173-81.
- Pavon, E. J., Munoz, P., Navarro, M. D., Raya-Alvarez, E., Callejas-Rubio, J. L., Navarro-Pelayo, F., Ortego-Centeno, N., Sancho, J. and Zubiaur, M. 2006. Increased association of CD38 with lipid rafts in T cells from patients with systemic lupus erythematosus and in activated normal T cells. *Mol Immunol*, 43, 1029-39.
- Peck, B., Chen, C. Y., Ho, K. K., Di Fruscia, P., Myatt, S. S., Coombes, R. C., Fuchter, M. J., Hsiao, C. D. and Lam, E. W. 2010. SIRT inhibitors induce cell death and p53 acetylation through targeting both SIRT1 and SIRT2. *Mol Cancer Ther*, 9, 844-55.
- Perraud, A. L., Fleig, A., Dunn, C. A., Bagley, L. A., Launay, P., Schmitz, C., Stokes, A. J., Zhu, Q., Bessman, M. J., Penner, R., Kinet, J. P. and Scharenberg, A. M. 2001. ADP-ribose gating of the calcium-permeable LTRPC2 channel revealed by Nudix motif homology. *Nature*, 411, 595-9.
- Pfahl, M., Apfel, R., Bendik, I., Fanjul, A., Graupner, G., Lee, M. O., La-Vista, N., Lu, X. P., Piedrafita, J. and Ortiz, M. A. 1994. Nuclear retinoid receptors and their mechanism of action. *Vitam Horm*, 49, 327-82.
- Pieper, A. A., Verma, A., Zhang, J. and Snyder, S. H. 1999. Poly (ADP-ribose) polymerase, nitric oxide and cell death. *Trends Pharmacol Sci*, 20, 171-81.

- Pillai, J. B., Isbatan, A., Imai, S. and Gupta, M. P. 2005. Poly(ADP-ribose) polymerase-1-dependent cardiac myocyte cell death during heart failure is mediated by NAD⁺ depletion and reduced Sir2alpha deacetylase activity. *J Biol Chem*, 280, 43121-30.
- Pollak, N., Dolle, C. and Ziegler, M. 2007. The power to reduce: pyridine nucleotides--small molecules with a multitude of functions. *Biochem J*, 402, 205-18.
- Prasad, G. S., Mcree, D. E., Stura, E. A., Levitt, D. G., Lee, H. C. and Stout, C. D. 1996. Crystal structure of Aplysia ADP ribosyl cyclase, a homologue of the bifunctional ectozyme CD38. *Nat Struct Biol*, 3, 957-64.
- Progrebniak, A., Schemainda, I., Azzam, K., Pelka-Fischer, R., Nüssler, V. and Hasmann, M. 2006. Chemopotentiating effects of a novel NAD biosynthesis inhibitor, FK866, in combination with antineoplastic agents. *Eur J Med Res*. 11, 313-321.
- Pupilli, C., Giannini, S., Marchetti, P., Lupi, R., Antonelli, A., Malavasi, F., Takasawa, S., Okamoto, H. and Ferrannini, E. 1999. Autoantibodies to CD38 (ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase) in Caucasian patients with diabetes: effects on insulin release from human islets. *Diabetes*, 48, 2309-15.
- Rah, S. Y., Park, K. H., Nam, T. S., Kim, S. J., Kim, H., Im, M. J. and Kim, U. H. 2007. Association of CD38 with nonmuscle myosin heavy chain IIA and Lck is essential for the internalization and activation of CD38. *J Biol Chem*, 282, 5653-60.
- Ramaschi, G., Torti, M., Festetics, E. T., Sinigaglia, F., Malavasi, F. and Balduini, C. 1996. Expression of cyclic ADP-ribose-synthetizing CD38 molecule on human platelet membrane. *Blood*, 87, 2308-13.
- Ravanat, J. L., Douki, T. and Cadet, J. 2001. Direct and indirect effects of UV radiation on DNA and its components. *J Photochem Photobiol B*, 63, 88-102.
- Reinherz, E. L., Kung, P. C., Goldstein, G., Levey, R. H. and Schlossman, S. F. 1980. Discrete stages of human intrathymic differentiation: analysis of normal thymocytes and leukemic lymphoblasts of T-cell lineage. *Proc Natl Acad Sci U S A*, 77, 1588-92.
- Revollo, J. R., Grimm, A. A. and Imai, S. 2004. The NAD biosynthesis pathway mediated by nicotinamide phosphoribosyltransferase regulates Sir2 activity in mammalian cells. *J Biol Chem*, 279, 50754-63.
- Rodgers, J. T., Lerin, C., Haas, W., Gygi, S. P., Spiegelman, B. M. and Puigserver, P. 2005. Nutrient control of glucose homeostasis through a complex of PGC-1alpha and SIRT1. *Nature*, 434, 113-8.
- Rongvaux, A., Andris, F., Van Gool, F. and Leo, O. 2003. Reconstructing eukaryotic NAD metabolism. *Bioessays*, 25, 683-90.
- Rongvaux, A., Shea, R. J., Mulks, M. H., Gigot, D., Urbain, J., Leo, O. and Andris, F. 2002. Pre-B-cell colony-enhancing factor, whose expression is up-regulated in activated lymphocytes, is a nicotinamide phosphoribosyltransferase, a cytosolic enzyme involved in NAD biosynthesis. *Eur J Immunol*, 32, 3225-34.
- Roos, G., Krober, A., Grabowski, P., Kienle, D., Buhler, A., Dohner, H., Rosenquist, R. and Stilgenbauer, S. 2008. Short telomeres are associated with genetic complexity, high-risk genomic aberrations, and short survival in chronic lymphocytic leukemia. *Blood*, 111, 2246-52.
- Rozman, C. and Montserrat, E. 1995. Chronic lymphocytic leukemia. *N Engl J Med*, 333, 1052-7.
- Salmina, A. B., Malinovskaya, N. A., Okuneva, O. S., Taranushenko, T. E., Fursov, A. A., Mikhutkina, S. V., Morgun, A. V., Prokopenko, S. V. and Zykova, L. D. 2008. Perinatal hypoxic and ischemic

- damage to the central nervous system causes changes in the expression of connexin 43 and CD38 and ADP-ribosyl cyclase activity in brain cells. *Bull Exp Biol Med*, 146, 733-6.
- Sanni, L. A., Rae, C., Maitland, A., Stocker, R. and Hunt, N. H. 2001. Is ischemia involved in the pathogenesis of murine cerebral malaria? *Am J Pathol*, 159, 1105-12.
- Sanz, M. A., Grimwade, D., Tallman, M. S., Lowenberg, B., Fenaux, P., Estey, E. H., Naoe, T., Lengfelder, E., Buchner, T., Dohner, H., Burnett, A. K. and Lo-Coco, F. 2009. Management of acute promyelocytic leukemia: recommendations from an expert panel on behalf of the European LeukemiaNet. *Blood*, 113, 1875-91.
- Schaller, M. D. 2010. Cellular functions of FAK kinases: insight into molecular mechanisms and novel functions. *J Cell Sci*, 123, 1007-13.
- Scheuplein, F., Schwarz, N., Adriouch, S., Krebs, C., Bannas, P., Rissiek, B., Seman, M., Haag, F. and Koch-Nolte, F. 2009. NAD⁺ and ATP released from injured cells induce P2X7-dependent shedding of CD62L and externalization of phosphatidylserine by murine T cells. *J Immunol*, 182, 2898-908.
- Schimmer, A. D., Pedersen, I. M., Kitada, S., Eksioglu-Demiralp, E., Minden, M. D., Pinto, R., Mah, K., Andreeff, M., Kim, Y., Suh, W. S. and Reed, J. C. 2003. Functional blocks in caspase activation pathways are common in leukemia and predict patient response to induction chemotherapy. *Cancer Res*, 63, 1242-8.
- Schlicker, A., Peschke, P., Burkle, A., Hahn, E. W. and Kim, J. H. 1999. 4-Amino-1,8-naphthalimide: a novel inhibitor of poly(ADP-ribose) polymerase and radiation sensitizer. *Int J Radiat Biol*, 75, 91-100.
- Schroeksadel, K., Fiegl, M., Prassl, K., Winkler, C., Denz, H. A. and Fuchs, D. 2007. Diminished quality of life in patients with cancer correlates with tryptophan degradation. *J Cancer Res Clin Oncol*, 133, 477-85.
- Schroeder, R. J., Ahmed, S. N., Zhu, Y., London, E. and Brown, D. A. 1998. Cholesterol and sphingolipid enhance the Triton X-100 insolubility of glycosylphosphatidylinositol-anchored proteins by promoting the formation of detergent-insoluble ordered membrane domains. *J Biol Chem*, 273, 1150-7.
- Schroers, R., Griesinger, F., Trumper, L., Haase, D., Kulle, B., Klein-Hitpass, L., Sellmann, L., Duhrsen, U. and Durig, J. 2005. Combined analysis of ZAP-70 and CD38 expression as a predictor of disease progression in B-cell chronic lymphocytic leukemia. *Leukemia*, 19, 750-8.
- Schwartz, J. P., Passonneau, J. V., Johnson, G. S. and Pastan, I. 1974. The effect of growth conditions on NAD⁺ and NADH concentrations and the NAD⁺:NADH ratio in normal and transformed fibroblasts. *J Biol Chem*, 249, 4138-43.
- Searle, J., Kerr, J. F. and Bishop, C. J. 1982. Necrosis and apoptosis: distinct modes of cell death with fundamentally different significance. *Pathol Annu*, 17 Pt 2, 229-59.
- Self, C. 1988. Assay Method And Reagent Therefor. U.S. Patent, 4769321.
- Seman, M., Adriouch, S., Scheuplein, F., Krebs, C., Freese, D., Glowacki, G., Deterre, P., Haag, F. and Koch-Nolte, F. 2003. NAD-induced T cell death: ADP-ribosylation of cell surface proteins by ART2 activates the cytolytic P2X7 purinoceptor. *Immunity*, 19, 571-82.
- Semenza, G. L. 2008. Tumor metabolism: cancer cells give and take lactate. *J Clin Invest*, 118, 3835-7.
- Sestili, P., Martinelli, C. and Stocchi, V. 2006. The fast halo assay: an improved method to quantify genomic DNA strand breakage at the single-cell level. *Mutat Res*, 607, 205-14.

- Shalhoub, V., Elliott, G., Chiu, L., Manoukian, R., Kelley, M., Hawkins, N., Davy, E., Shimamoto, G., Beck, J., Kaufman, S. A., Van, G., Scully, S., Qi, M., Grisanti, M., Dunstan, C., Boyle, W. J. and Lacey, D. L. 2000. Characterization of osteoclast precursors in human blood. *Br J Haematol*, 111, 501-12.
- Shanafelt, T. D., Geyer, S. M. and Kay, N. E. 2004. Prognosis at diagnosis: integrating molecular biologic insights into clinical practice for patients with CLL. *Blood*, 103, 1202-10.
- Shen, M. and Yen, A. 2008. c-Cbl interacts with CD38 and promotes retinoic acid-induced differentiation and G0 arrest of human myeloblastic leukemia cells. *Cancer Res*, 68, 8761-9.
- Sims, J. L., Berger, S. J. and Berger, N. A. 1981. Effects of nicotinamide on NAD and poly(ADP-ribose) metabolism in DNA-damaged human lymphocytes. *J Supramol Struct Cell Biochem*, 16, 281-8.
- Singh, N. P., McCoy, M. T., Tice, R. R. and Schneider, E. L. 1988. A simple technique for quantitation of low levels of DNA damage in individual cells. *Exp Cell Res*, 175, 184-91.
- Sizzano, F., Durelli, I., Lusso, R., Deaglio, S., Ferrero, E., D'angelo, L., Boetto, M., Santoro, P., Genzano-Besso, F., Amoroso, A. and Horenstein, A. L. 2007. Identification of the ectoenzyme-receptor CD38 on human corneal epithelial cells *In: 21ST EFI conference edited by Vives, J., Barcelona, N.A. (eds.). Tissue Antigens*, 373.
- So Ri, K., Kyung Sun, L., Seoung Ju, P., Kyung Hoon, M., Min Hee, L., Chi Ryang, C., Hyo Jin, H., Kyoung Hwa, C., Seung Yong, P., Heung Bum, L., Yang Keun, R. and Yong Chul, L. 2011. CD38 Regulates Vascular Permeability Through HIF-1A/VEGF Activation Mediated By PI3K Signaling In Bronchial Asthma. *B33. oxidants, oxidases and redox regulation of lung disease. American Thoracic Society*, A2799-A2799.
- Solao, P. B. and Shall, S. 1971. Control of DNA replication in *Physarum polycephalum*. I. Specific activity of NAD pyrophosphorylase in isolated nuclei during the cell cycle. *Exp Cell Res*, 69, 295-300.
- Sorensen, T. I., Virtue, S. and Vidal-Puig, A. 2010. Obesity as a clinical and public health problem: is there a need for a new definition based on lipotoxicity effects? *Biochim Biophys Acta*, 1801, 400-4.
- Soriano, F. G., Virag, L. and Szabo, C. 2001. Diabetic endothelial dysfunction: role of reactive oxygen and nitrogen species production and poly(ADP-ribose) polymerase activation. *J Mol Med (Berl)*, 79, 437-48.
- Southan, G. J. and Szabo, C. 2003. Poly(ADP-ribose) polymerase inhibitors. *Curr Med Chem*, 10, 321-40.
- Sporn, M. B., Roberts, A. B. and Goodman, D. S. 1994. *The Retinoids: Biology, Chemistry, and Medicine*, New York, NY, Raven,
- Starkov, A. A. and Fiskum, G. 2003. Regulation of brain mitochondrial H₂O₂ production by membrane potential and NAD(P)H redox state. *J Neurochem*, 86, 1101-7.
- States, D. J., Walseth, T. F. and Lee, H. C. 1992. Similarities in amino acid sequences of *Aplysia* ADP-ribosyl cyclase and human lymphocyte antigen CD38. *Trends Biochem Sci*, 17, 495.
- Stevens, H. P., Ostlere, L. S., Begent, R. H., Dooley, J. S. and Rustin, M. H. 1993. Pellagra secondary to 5-fluorouracil. *Br J Dermatol*, 128, 578-80.
- Stevenson, F. K., Bell, A. J., Cusack, R., Hamblin, T. J., Slade, C. J., Spellerberg, M. B. and Stevenson, G. T. 1991. Preliminary studies for an immunotherapeutic approach to the treatment of human myeloma using chimeric anti-CD38 antibody. *Blood*, 77, 1071-9.
- Stevenson, G. T. 2006. CD38 as a therapeutic target. *Mol Med*, 12, 345-6.

- Stoeckler, J. D., Stoeckler, H. A., Kouttab, N. and Maizel, A. L. 1996. 1 α ,25-Dihydroxyvitamin D₃ modulates CD38 expression on human lymphocytes. *J Immunol*, 157, 4908-17.
- Streb, H., Irvine, R. F., Berridge, M. J. and Schulz, I. 1983. Release of Ca²⁺ from a nonmitochondrial intracellular store in pancreatic acinar cells by inositol-1,4,5-trisphosphate. *Nature*, 306, 67-9.
- Stryer, L. 1995. Biochemistry, 4th Ed. New York, W.H. Freeman and Co.
- Sun, F., Dai, C., Xie, J. and Hu, X. 2012. Biochemical issues in estimation of cytosolic free NAD/NADH ratio. *PLoS One*, 7, e34525.
- Sun, L., Iqbal, J., Dolgilevich, S., Yuen, T., Wu, X. B., Moonga, B. S., Adebajo, O. A., Bevis, P. J., Lund, F., Huang, C. L., Blair, H. C., Abe, E. and Zaidi, M. 2003. Disordered osteoclast formation and function in a CD38 (ADP-ribosyl cyclase)-deficient mouse establishes an essential role for CD38 in bone resorption. *FASEB J*, 17, 369-75.
- Swierczynski, J., Slominska, E., Smolenski, R. T. and Mayer, D. 2001. Increase in NAD but not ATP and GTP concentrations in rat liver by dehydroepiandrosterone feeding. *Pol J Pharmacol*, 53, 125-30.
- Tallman, M. S., Andersen, J. W., Schiffer, C. A., Appelbaum, F. R., Feusner, J. H., Woods, W. G., Ogden, A., Weinstein, H., Shepherd, L., Willman, C., Bloomfield, C. D., Rowe, J. M. and Wiernik, P. H. 2002. All-trans retinoic acid in acute promyelocytic leukemia: long-term outcome and prognostic factor analysis from the North American Intergroup protocol. *Blood*, 100, 4298-302.
- Tang, D. G., Chen, Y. Q., Newman, P. J., Shi, L., Gao, X., Diglio, C. A. and Honn, K. V. 1993. Identification of PECAM-1 in solid tumor cells and its potential involvement in tumor cell adhesion to endothelium. *J Biol Chem*, 268, 22883-94.
- Tenca, C., Merlo, A., Zarcone, D., Saverino, D., Bruno, S., De Santanna, A., Ramarli, D., Fabbi, M., Pesce, C., Deaglio, S., Ciccone, E., Malavasi, F. and Grossi, C. E. 2003. Death of T cell precursors in the human thymus: a role for CD38. *Int Immunol*, 15, 1105-16.
- Tennant, D. A., Duran, R. V., Boulahbel, H. and Gottlieb, E. 2009. Metabolic transformation in cancer. *Carcinogenesis*, 30, 1269-80.
- Terhorst, C., Van Agthoven, A., Leclair, K., Snow, P., Reinherz, E. and Schlossman, S. 1981. Biochemical studies of the human thymocyte cell-surface antigens T6, T9 and T10. *Cell*, 23, 771-80.
- Tesar, M. 2007. Fully human antibody MOR202 against CD38 for the treatment of multiple myeloma and other blood-borne malignancies. *Journal of Clinical Oncology*, 25: 8106.
- Thomas, J. M., Summerhill, R. J., Fruen, B. R., Churchill, G. C. and Galione, A. 2002. Calmodulin dissociation mediates desensitization of the cADPR-induced Ca²⁺ release mechanism. *Curr Biol*, 12, 2018-22.
- Tice, R. R., Agurell, E., Anderson, D., Burlinson, B., Hartmann, A., Kobayashi, H., Miyamae, Y., Rojas, E., Ryu, J. C. and Sasaki, Y. F. 2000. Single cell gel/comet assay: guidelines for in vitro and in vivo genetic toxicology testing. *Environ Mol Mutagen*, 35, 206-21.
- Tilton, W. M., Seaman, C., Carriero, D. and Piomelli, S. 1991. Regulation of glycolysis in the erythrocyte: role of the lactate/pyruvate and NAD/NADH ratios. *J Lab Clin Med*, 118, 146-52.
- Tirumurugaan, K. G., Kang, B. N., Panettieri, R. A., Foster, D. N., Walseth, T. F. and Kannan, M. S. 2008. Regulation of the cd38 promoter in human airway smooth muscle cells by TNF-alpha and dexamethasone. *Respir Res*, 9, 26.

- Tohgo, A., Munakata, H., Takasawa, S., Nata, K., Akiyama, T., Hayashi, N. and Okamoto, H. 1997. Lysine 129 of CD38 (ADP-ribosyl cyclase/cyclic ADP-ribose hydrolase) participates in the binding of ATP to inhibit the cyclic ADP-ribose hydrolase. *J Biol Chem*, 272, 3879-82.
- Tohgo, A., Takasawa, S., Noguchi, N., Koguma, T., Nata, K., Sugimoto, T., Furuya, Y., Yonekura, H. and Okamoto, H. 1994. Essential cysteine residues for cyclic ADP-ribose synthesis and hydrolysis by CD38. *J Biol Chem*, 269, 28555-7.
- Trachootham, D., Zhang, H., Zhang, W., Feng, L., Du, M., Zhou, Y., Chen, Z., Pelicano, H., Plunkett, W., Wierda, W. G., Keating, M. J. and Huang, P. 2008. Effective elimination of fludarabine-resistant CLL cells by PEITC through a redox-mediated mechanism. *Blood*, 112, 1912-22.
- Trayner, I. D., Bustorff, T., Etches, A. E., Mufti, G. J., Foss, Y. and Farzaneh, F. 1998. Changes in antigen expression on differentiating HL60 cells treated with dimethylsulphoxide, all-trans retinoic acid, alpha1,25-dihydroxyvitamin D3 or 12-O-tetradecanoyl phorbol-13-acetate. *Leuk Res*, 22, 537-47.
- Trubiani, O., Guarnieri, S., Eleuterio, E., Di Giuseppe, F., Orciani, M., Angelucci, S. and Di Primio, R. 2008. Insights into nuclear localization and dynamic association of CD38 in Raji and K562 cells. *J Cell Biochem*, 103, 1294-308.
- Tsiftoglou, A. S., Pappas, I. S. and Vizirianakis, I. S. 2003. Mechanisms involved in the induced differentiation of leukemia cells. *Pharmacol Ther*, 100, 257-90.
- Tyler, J. K. and Kadonaga, J. T. 1999. The "dark side" of chromatin remodeling: repressive effects on transcription. *Cell*, 99, 443-6.
- Urano, A., Noguchi, N., Matsuda, K., Nata, K., Yoshikawa, T., Chikamatsu, Y., Kagechika, H., Harigae, H., Ito, S., Okamoto, H. and Sugawara, A. 2011. All-trans retinoic acid and a novel synthetic retinoid tamibarotene (Am80) differentially regulate CD38 expression in human leukemia HL-60 cells: possible involvement of protein kinase C-delta. *J Leukoc Biol*, 90, 235-47.
- Vaisitti, T., Audrito, V., Serra, S., Bologna, C., Brusa, D., Malavasi, F. and Deaglio, S. 2011. NAD⁺-metabolizing ecto-enzymes shape tumor-host interactions: the chronic lymphocytic leukemia model. *FEBS Lett*, 585, 1514-20.
- Vaisitti, T., Aydin, S., Rossi, D., Cottino, F., Bergui, L., D'arena, G., Bonello, L., Horenstein, A. L., Brennan, P., Pepper, C., Gaidano, G., Malavasi, F. and Deaglio, S. 2010. CD38 increases CXCL12-mediated signals and homing of chronic lymphocytic leukemia cells. *Leukemia*, 24, 958-69.
- Van Beijnum, J. R., Moerkerk, P. T., Gerbers, A. J., De Bruine, A. P., Arends, J. W., Hoogenboom, H. R. and Hufton, S. E. 2002. Target validation for genomics using peptide-specific phage antibodies: a study of five gene products overexpressed in colorectal cancer. *Int J Cancer*, 101, 118-27.
- Van Bockstaele, F., Verhasselt, B. and Philippe, J. 2009. Prognostic markers in chronic lymphocytic leukemia: a comprehensive review. *Blood Rev*, 23, 25-47.
- Van Der Sluijs, K., Singh, R., Dijkhuis, A., Snoek, M. and Lutter, R. 2011. Indoleamine-2,3-dioxygenase activity induces neutrophil apoptosis. *Critical Care*, 15, P208.
- Van Der Veer, M. S., De Weers, M., Van Kessel, B., Bakker, J. M., Wittebol, S., Parren, P. W., Lokhorst, H. M. and Mutis, T. 2011. Towards effective immunotherapy of myeloma: enhanced elimination of myeloma cells by combination of lenalidomide with the human CD38 monoclonal antibody daratumumab. *Haematologica*, 96, 284-90.
- Van Raam, B. J., Sluiter, W., De Wit, E., Roos, D., Verhoeven, A. J. and Kuijpers, T. W. 2008. Mitochondrial membrane potential in human neutrophils is maintained by complex III activity in the absence of supercomplex organisation. *PLoS One*, 3, e2013.

- Veld, C. W. O. H., Van Hees-Stuivenberg, S., Van Zeeland, A. A. and Jansen, J. G. 1997. Effect of nucleotide excision repair on hprt gene mutations in rodent cells exposed to DNA ethylating agents. *Mutagenesis*, 12, 417-424.
- Vinograd, J., Lebowitz, J., Radloff, R., Watson, R. and Laipis, P. 1965. The twisted circular form of polyoma viral DNA. *Proc Natl Acad Sci U S A*, 53, 1104-11.
- Virag, L. and Szabo, C. 2002. The therapeutic potential of poly(ADP-ribose) polymerase inhibitors. *Pharmacol Rev*, 54, 375-429.
- Vodenicharov, M. D., Ghodgaonkar, M. M., Halappanavar, S. S., Shah, R. G. and Shah, G. M. 2005. Mechanism of early biphasic activation of poly(ADP-ribose) polymerase-1 in response to ultraviolet B radiation. *J Cell Sci*, 118, 589-99.
- Warburg, O. 1956. On the origin of cancer cells. *Science*, 123, 309-14.
- Warrell, R. P., Jr., Frankel, S. R., Miller, W. H., Jr., Scheinberg, D. A., Itri, L. M., Hittelman, W. N., Vyas, R., Andreeff, M., Tafuri, A. and Jakubowski, A. 1991. Differentiation therapy of acute promyelocytic leukemia with tretinoin (all-trans-retinoic acid). *N Engl J Med*, 324, 1385-93.
- Watson, E. R., Halnan, K. E., Dische, S., Saunders, M. I., Cade, I. S., McEwen, J. B., Wiernik, G., Perrins, D. J. and Sutherland, I. 1978. Hyperbaric oxygen and radiotherapy: a Medical Research Council trial in carcinoma of the cervix. *Br J Radiol*, 51, 879-87.
- Whiteside, S. T., Visvanathan, K. V. and Goodbourn, S. 1992. Identification of novel factors that bind to the PRD I region of the human beta-interferon promoter. *Nucleic Acids Res*, 20, 1531-8.
- Wilhelm, F. and Hirrlinger, J. 2012. Multifunctional roles of NAD⁽⁺⁾ and NADH in astrocytes. *Neurochem Res*, 37, 2317-25.
- Willimott, S., Baou, M., Huf, S., Deaglio, S. and Wagner, S. D. 2007. Regulation of CD38 in proliferating chronic lymphocytic leukemia cells stimulated with CD154 and interleukin-4. *Haematologica*, 92, 1359-66.
- Wilson, H. L., Dipp, M., Thomas, J. M., Lad, C., Galione, A. and Evans, A. M. 2001. Adp-ribosyl cyclase and cyclic ADP-ribose hydrolase act as a redox sensor. a primary role for cyclic ADP-ribose in hypoxic pulmonary vasoconstriction. *J Biol Chem*, 276, 11180-8.
- Winter, S. L. and Boyer, J. L. 1973. Hepatic toxicity from large doses of vitamin B3 (nicotinamide). *N Engl J Med*, 289, 1180-2.
- Wright, S. C., Wei, Q. S., Kinder, D. H. and Larrick, J. W. 1996. Biochemical pathways of apoptosis: nicotinamide adenine dinucleotide-deficient cells are resistant to tumor necrosis factor or ultraviolet light activation of the 24-kD apoptotic protease and DNA fragmentation. *J Exp Med*, 183, 463-71.
- Wu, G., Fang, Y. Z., Yang, S., Lupton, J. R. and Turner, N. D. 2004. Glutathione metabolism and its implications for health. *J Nutr*, 134, 489-92.
- Wu, H., Scher, B. M., Chu, C. L., Leonard, M., Olmedo, R., Scher, G. S., Stecker, S., Scher, W. and Waxman, S. 1991. Reduction in lactate accumulation correlates with differentiation-induced terminal cell division of leukemia cells. *Differentiation*, 48, 51-8.
- Wykes, M. N., Beattie, L., Macpherson, G. G. and Hart, D. N. 2004. Dendritic cells and follicular dendritic cells express a novel ligand for CD38 which influences their maturation and antibody responses. *Immunology*, 113, 318-27.
- Xu, M., Zhang, Y., Xia, M., Li, X. X., Ritter, J. K., Zhang, F. and Li, P. L. 2012. NAD(P)H oxidase-dependent intracellular and extracellular O₂⁻ production in coronary arterial myocytes from CD38 knockout mice. *Free Radic Biol Med*, 52, 357-65.

- Xu, R. H., Pelicano, H., Zhou, Y., Carew, J. S., Feng, L., Bhalla, K. N., Keating, M. J. and Huang, P. 2005. Inhibition of glycolysis in cancer cells: a novel strategy to overcome drug resistance associated with mitochondrial respiratory defect and hypoxia. *Cancer Res*, 65, 613-21.
- Yagui, K., Shimada, F., Mimura, M., Hashimoto, N., Suzuki, Y., Tokuyama, Y., Nata, K., Tohgo, A., Ikehata, F., Takasawa, S., Okamoto, H., Makino, H., Saito, Y. and Kanatsuka, A. 1998. A missense mutation in the CD38 gene, a novel factor for insulin secretion: association with Type II diabetes mellitus in Japanese subjects and evidence of abnormal function when expressed in vitro. *Diabetologia*, 41, 1024-8.
- Yalcintepe, L., Turker-Sener, L., Sener, A., Yetkin, G., Tiryaki, D. and Bermek, E. 2005. Changes in NAD/ADP-ribose metabolism in rectal cancer. *Braz J Med Biol Res*, 38, 361-5.
- Yamada, M., Mizuguchi, M., Otsuka, N., Ikeda, K. and Takahashi, H. 1997. Ultrastructural localization of CD38 immunoreactivity in rat brain. *Brain Res*, 756, 52-60.
- Yamamoto-Katayama, S., Ariyoshi, M., Ishihara, K., Hirano, T., Jingami, H. and Morikawa, K. 2002. Crystallographic studies on human BST-1/CD157 with ADP-ribosyl cyclase and NAD glycohydrolase activities. *J Mol Biol*, 316, 711-23.
- Yamasaki, M., Churchill, G. C. and Galione, A. 2005. Calcium signalling by nicotinic acid adenine dinucleotide phosphate (NAADP). *FEBS Journal*, 272, 4598-4606.
- Yang, H., Yang, T., Baur, J. A., Perez, E., Matsui, T., Carmona, J. J., Lamming, D. W., Souza-Pinto, N. C., Bohr, V. A., Rosenzweig, A., De Cabo, R., Sauve, A. A. and Sinclair, D. A. 2007. Nutrient-sensitive mitochondrial NAD⁺ levels dictate cell survival. *Cell*, 130, 1095-107.
- Ying, W. 2006. NAD⁺ and NADH in cellular functions and cell death. *Front Biosci*, 11, 3129-48.
- Ying, W. 2007. NAD⁺ and NADH in brain functions, brain diseases and brain aging. *Front Biosci*, 12, 1863-88.
- Ying, W. 2008. NAD⁺/NADH and NADP⁺/NADPH in cellular functions and cell death: regulation and biological consequences. *Antioxid Redox Signal*, 10, 179-206.
- Ying, W., Alano, C. C., Garnier, P. and Swanson, R. A. 2005. NAD⁺ as a metabolic link between DNA damage and cell death. *J Neurosci Res*, 79, 216-23.
- Ying, W., Garnier, P. and Swanson, R. A. 2003. NAD⁺ repletion prevents PARP-1-induced glycolytic blockade and cell death in cultured mouse astrocytes. *Biochem Biophys Res Commun*, 308, 809-13.
- Yu, S. W., Wang, H., Poitras, M. F., Coombs, C., Bowers, W. J., Federoff, H. J., Poirier, G. G., Dawson, T. M. and Dawson, V. L. 2002. Mediation of poly(ADP-ribose) polymerase-1-dependent cell death by apoptosis-inducing factor. *Science*, 297, 259-63.
- Yue, J., Wei, W., Lam, C. M., Zhao, Y. J., Dong, M., Zhang, L. R., Zhang, L. H. and Lee, H. C. 2009. CD38/cADPR/Ca²⁺ pathway promotes cell proliferation and delays nerve growth factor-induced differentiation in PC12 cells. *J Biol Chem*, 284, 29335-42.
- Yun, J. K., McCormick, T. S., Judware, R. and Lapetina, E. G. 1997. Cellular adaptive responses to low oxygen tension: apoptosis and resistance. *Neurochem Res*, 22, 517-21.
- Zelante, T., Fallarino, F., Bistoni, F., Puccetti, P. and Romani, L. 2009. Indoleamine 2,3-dioxygenase in infection: the paradox of an evasive strategy that benefits the host. *Microbes Infect*, 11, 133-41.
- Zenz, T., Mertens, D., Kupperts, R., Dohner, H. and Stilgenbauer, S. 2010. From pathogenesis to treatment of chronic lymphocytic leukaemia. *Nat Rev Cancer*, 10, 37-50.

- Zerez, C., Lachant, N. and Tanaka, K. 1990. Impaired erythrocyte methemoglobin reduction in sickle cell disease: dependence of methemoglobin reduction on reduced nicotinamide adenine dinucleotide content. *Blood*, 76, 1008-1014.
- Zhang, H., Graeff, R., Chen, Z., Zhang, L., Zhang, L., Lee, H. and Hao, Q. 2011. Dynamic conformations of the CD38-mediated NAD cyclization captured in a single crystal. *J Mol Biol*, 405, 1070-8.
- Zhang, J. 2003. Are poly(ADP-ribosyl)ation by PARP-1 and deacetylation by Sir2 linked? *Bioessays*, 25, 808-14.
- Zhang, Q., Piston, D. W. and Goodman, R. H. 2002. Regulation of corepressor function by nuclear NADH. *Science*, 295, 1895-7.
- Zhang, T., Berrocal, J. G., Frizzell, K. M., Gamble, M. J., Dumond, M. E., Krishnakumar, R., Yang, T., Sauve, A. A. and Kraus, W. L. 2009a. Enzymes in the NAD⁺ salvage pathway regulate SIRT1 activity at target gene promoters. *J Biol Chem*, 284, 20408-17.
- Zhang, W., Trachootham, D., Liu, J., Chen, G., Pelicano, H., Garcia-Prieto, C., Lu, W., Burger, J. A., Croce, C. M., Plunkett, W., Keating, M. J. and Huang, P. 2012. Stromal control of cystine metabolism promotes cancer cell survival in chronic lymphocytic leukaemia. *Nat Cell Biol*, 14, 276-86.
- Zhang, X., Tallini, Y. N., Chen, Z., Gan, L., Wei, B., Doran, R., Miao, L., Xin, H. B., Kotlikoff, M. I. and Ji, G. 2009b. Dissociation of FKBP12.6 from ryanodine receptor type 2 is regulated by cyclic ADP-ribose but not beta-adrenergic stimulation in mouse cardiomyocytes. *Cardiovasc Res*, 84, 253-62.
- Zhao, Y. J., Lam, C. M. and Lee, H. C. 2012. The membrane-bound enzyme CD38 exists in two opposing orientations. *Sci Signal*, 5, 2002700.
- Ziegler, M. 2000. New functions of a long-known molecule. Emerging roles of NAD in cellular signaling. *Eur J Biochem*, 267, 1550-64.
- Zilber, M. T., Gregory, S., Mallone, R., Deaglio, S., Malavasi, F., Charron, D. and Gelin, C. 2000. CD38 expressed on human monocytes: a coaccessory molecule in the superantigen-induced proliferation. *Proc Natl Acad Sci U S A*, 97, 2840-5.
- Zilber, M. T., Setterblad, N., Vasselon, T., Doliger, C., Charron, D., Mooney, N. and Gelin, C. 2005. MHC class II/CD38/CD9: a lipid-raft-dependent signaling complex in human monocytes. *Blood*, 106, 3074-81.
- Zocchi, E., Daga, A., Usai, C., Franco, L., Guida, L., Bruzzone, S., Costa, A., Marchetti, C. and De Flora, A. 1998. Expression of CD38 increases intracellular calcium concentration and reduces doubling time in HeLa and 3T3 cells. *J Biol Chem*, 273, 8017-24.
- Zocchi, E., Franco, L., Guida, L., Benatti, U., Bargellesi, A., Malavasi, F., Lee, H. C. and De Flora, A. 1993. A single protein immunologically identified as CD38 displays NAD⁺ glycohydrolase, ADP-ribosyl cyclase and cyclic ADP-ribose hydrolase activities at the outer surface of human erythrocytes. *Biochem Biophys Res Commun*, 196, 1459-65.
- Zocchi, E., Franco, L., Guida, L., Calder, L. and De Flora, A. 1995. Self-aggregation of purified and membrane-bound erythrocyte CD38 induces extensive decrease of its ADP-ribosyl cyclase activity. *FEBS Lett*, 359, 35-40.
- Zocchi, E., Usai, C., Guida, L., Franco, L., Bruzzone, S., Passalacqua, M. and De Flora, A. 1999. Ligand-induced internalization of CD38 results in intracellular Ca²⁺ mobilization: role of NAD⁺ transport across cell membranes. *FASEB J*, 13, 273-83.
- Zong, W. X., Ditsworth, D., Bauer, D. E., Wang, Z. Q. and Thompson, C. B. 2004. Alkylating DNA damage stimulates a regulated form of necrotic cell death. *Genes Dev*, 18, 1272-82.

- Zoratti, M. and Szabo, I. 1995. The mitochondrial permeability transition. *Biochim Biophys Acta*, 1241, 139-76.
- Zubiaur, M., Fernandez, O., Ferrero, E., Salmeron, J., Malissen, B., Malavasi, F. and Sancho, J. 2002. CD38 is associated with lipid rafts and upon receptor stimulation leads to Akt/protein kinase B and Erk activation in the absence of the CD3-zeta immune receptor tyrosine-based activation motifs. *J Biol Chem*, 277, 13-22.
- Zubiaur, M., Guirado, M., Terhorst, C., Malavasi, F. and Sancho, J. 1999. The CD3-gamma delta epsilon transducing module mediates CD38-induced protein-tyrosine kinase and mitogen-activated protein kinase activation in Jurkat T cells. *J Biol Chem*, 274, 20633-42.
- Zucchetto, A., Benedetti, D., Tripodo, C., Bomben, R., Dal Bo, M., Marconi, D., Bossi, F., Lorenzon, D., Degan, M., Rossi, F. M., Rossi, D., Bulian, P., Franco, V., Del Poeta, G., Deaglio, S., Gaidano, G., Tedesco, F., Malavasi, F. and Gattei, V. 2009. CD38/CD31, the CCL3 and CCL4 chemokines, and CD49d/vascular cell adhesion molecule-1 are interchained by sequential events sustaining chronic lymphocytic leukemia cell survival. *Cancer Res*, 69, 4001-9.
- Zupo, S., Rugari, E., Dono, M., Tadorelli, G., Malavasi, F. and Ferrarini, M. 1994. CD38 signaling by agonistic monoclonal antibody prevents apoptosis of human germinal center B cells. *Eur J Immunol*, 24, 1218-22.

Appendices

Background

Human CD38 is a cell surface glycoprotein expressed in a wide variety of cell types that has both enzymatic and receptor functions. As a receptor, CD38 controls signaling pathways involved in the activation, growth and survival of lymphoid and myeloid cells. As an enzyme, CD38 uses NAD(P) as a substrate to form a number of biologically active compounds including cADPR, NAADP and ADPR (1) although the major physiological role would seem to be in control of NAD levels. Such control has wide ranging implications on cell physiology not only due to modulation of basic metabolism but also as NAD has recently been identified as a substrate in a variety of signaling reactions. CD38 and its metabolites have been proposed to be involved in a number of human diseases ranging from Diabetes to HIV infection. CD38 is also a widely used negative prognostic marker (2) in chronic lymphocytic leukemia (CLL) where increased CD38 expression correlates with a worse prognosis. While much is known about how the receptor activity of CD38 contributes to the CLL effects, the enzymatic activity has not been studied.

Objectives

- To understand the relationship between CD38 expression and NAD levels.
- To understand how this relationship may influence the physiology of CLL cells

Methods

- RAJI cells were used as CD38+ cells. HL-60 (CD38-) were treated with all trans retinoic acid (ATRA; 1 μ M) to induce differentiation to neutrophil-like cells.
- ADP-ribosyl cyclase activity of CD38 was measured using the fluorescent NGD assay. The initial rate was monitored by measuring the rate of formation of cGDPR (3).
- NAD was extracted and its levels were determined using a modification of the protocol described by Leonardo *et al.* (4).

Results

CD38 is expressed during differentiation

HL-60 cells were stimulated to differentiate to Neutrophil-like cells with ATRA (1 μ M) for 5 days. The initial rate of CD38 cyclase activity was measured after 1, 3, and 5 days in HL-60 cells (not treated with ATRA) and in differentiated cells. Cyclase activity increased during differentiation (Figure 1) confirming the expression of CD38 on the plasma membrane.

Effect of CD38 Expression on NAD levels

To investigate the effect of CD38 expression on NAD levels in cells, NAD levels were determined after 1, 3 and 5 days of differentiation (Figure 2).

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Data

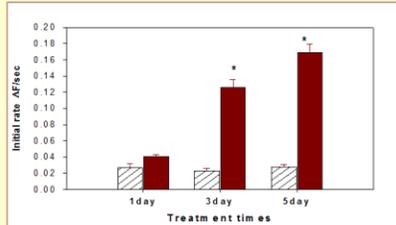


Figure 1: Time-course of ATRA induced differentiation of HL-60 cells showing the increase in plasma membrane CD38 cyclase activity. (n = 9-11), *P<0.05

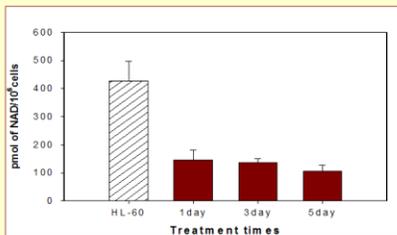


Figure 2: NAD levels in differentiated cells compared to control (HL-60). Data are mean \pm SE, (n=9-11).

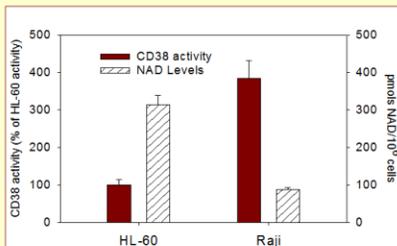


Figure 3: Cyclase activity (red columns) and NAD levels (hatched columns) in RAJI and HL60 cells. Data are mean \pm SE (n = 9-11).

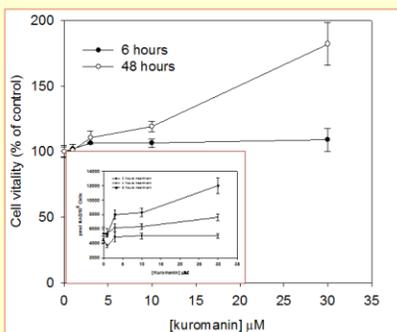


Figure 4: Effect of kuromanin on Raji cell vitality (MTT assay). Inset, effect of kuromanin on NAD levels in RAJI cells. Data are mean \pm SE (n=9)

Results (cont.)

CD38 and NAD levels in RAJI cells

To confirm that the relationship was not peculiar to HL-60 cells, a CD38+ leukaemic cell line, RAJI was used to confirm our previous results (Figure 3). In these cells, expression of high CD38 activity correlated negatively with intracellular NAD levels.

Effect of CD38 inhibition on NAD levels

Inhibition of CD38 was achieved by using the novel flavonoid compound kuromanin. As expected, kuromanin treatment caused a rise in intracellular NAD levels in Raji cells (Figure 4 inset).

In order to see the effect of lowered NAD levels on cell vitality, we treated cells with kuromanin and performed the MTT cell vitality assay. The increase in NAD levels was mirrored by an increase in cell vitality.

Discussion

These results would tend to suggest a strict relationship between CD38 expression and NAD levels. We expect that CD38 may be expressed intracellularly, possibly on the nuclear membrane, as well as on the plasma membrane as it is hard to consolidate extracellular enzyme activity with the effect on intracellular NAD levels. In terms of CLL cells expressing CD38, we would expect a similar relationship and thus the reduced NAD levels may play a role in the negative prognosis associated with CD38 expression in patients. However, our initial cell vitality results would tend to suggest that low NAD levels reduce cell vitality.

Future Directions

- Measurement of CD38 expression by PCR/Western Blot in both the Plasma Membrane and intracellular compartments.
- Measurement of intracellular NAD levels in CD38 positive and negative cells from CLL patients.
- Measurement of activity of other NAD consuming enzymes during HL-60 differentiation.
- Further investigation into the physiological consequences of reduced NAD levels in CD38+ cells (eg NAD-dependent metabolism and signaling processes).

References

- Lee HC (2006) Mol Med 12: 317-323.
- Deaglio, S., et al. (2008). Trends Mol Med 14(5): 210-218
- Lee HC et al. (1997) Methods Enzymol 280: 331-340
- Leonardo MR, et al. (1996) J Bacteriol 178: 6013-6018.

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CD38 expression regulates NAD(H) levels during HL-60 differentiation



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Background

Human CD38 is a cell surface glycoprotein expressed in a wide variety of cell types that displays both enzymatic and receptorial functions. As a receptor, CD38 controls signaling pathways involved in the activation, growth and survival of lymphoid and myeloid cells. As an enzyme, CD38 uses NAD(P) as a substrate to form a number of biologically active compounds including cADPR, NAADP and ADPR (1) although the major physiological role would seem to be in control of NAD levels. Such control may have wide ranging implications on cell physiology not only due to modulation of basic metabolism but also as NAD has recently been identified as a substrate in a variety of signaling reactions. CD38 and its metabolites have been proposed to be involved in a number of human diseases ranging from Diabetes to HIV infection. CD38 is also a widely used negative prognostic marker (2) in chronic lymphocytic leukemia (CLL) where increased CD38 expression correlates with a worse prognosis.

Objectives

- To understand the relationship between CD38 expression and NAD levels.
- To understand how this relationship may influence the physiology of CLL cells.

Methods

- HL-60 (CD38-) were treated with all trans retinoic acid (ATRA; 1 μ M) to induce differentiation to granulocytes/neutrophil-like cells.
- ADP-ribosyl cyclase activity in whole cells was measured using the fluorescent NGD assay. The initial rate of formation of cGDPR was determined (3). CD38 expression was determined by quantitative real-time PCR using SYBR Green PCR master mix.
- NAD, NADH were extracted as appropriate in acidic/basic conditions and their levels were determined using a modification of the enzymatic cycling assay described by Leonardo *et al.* (4).
- Lactate levels were measured using LDH.

Results

CD38 is expressed during differentiation

HL-60 cells were stimulated to differentiate to Neutrophil-like cells with ATRA (1 μ M) for 5 days. Cyclase activity was measured after 1, 3, and 5 days. Plasma membrane cyclase activity increased during differentiation (Figure 1A) confirming the expression of CD38 on the plasma membrane. Figure 1B shows the increase in CD38 mRNA with time during differentiation determined by qPCR.

Effect of CD38 Expression on NAD levels

Intracellular NAD levels were determined after 1, 3 and 5 days of differentiation (Figure 2) and were found to be reduced to below 50% of HL-60 levels by 5 days. There was already a significant reduction after one day.

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Results

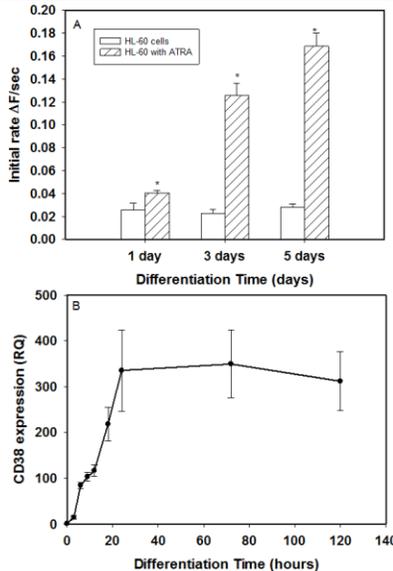


Figure 1: Time-course of ATRA induced differentiation of HL-60 cells showing (a) the increase in plasma membrane CD38 cyclase activity. (n = 9-11). *P<0.05 (b) the increase in CD38 expression, data points represent the means of 6 experiments.

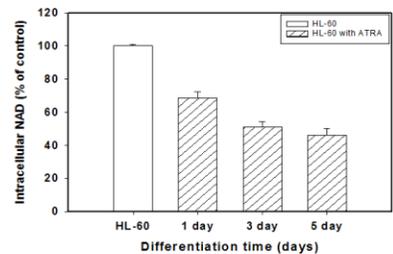


Figure 2: NAD levels in differentiated cells compared to control (HL-60). Data are mean \pm SE, (n=9-11).

Effect of CD38 inhibition on NAD levels

Inhibition of CD38 was achieved by using the novel flavonoid compound kuromanin. As expected, kuromanin treatment stopped the reduction in intracellular NAD levels (Figure 3A) and seemed to modulate CD38 expression (Figure 3B).

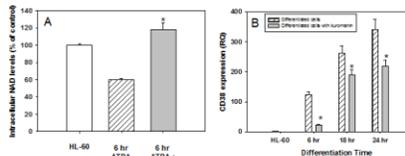


Figure 3: Effect of kuromanin on (A) NAD levels and (B) CD38 expression. Data are mean \pm SE (n=9) for 3 experiments.

Results (cont.)

Effect of lowered NAD levels on metabolism

In order to assess the effect of lowered NAD levels on basic cell metabolism, we measured both the NAD⁺/NADH ratio and (Figure 4A) lactate levels (Figure 4B). As might be expected, lactate levels were reduced in cells where NAD was depleted probably due to partial inhibition of glycolysis. However, the NAD⁺/NADH ratio was not significantly altered.

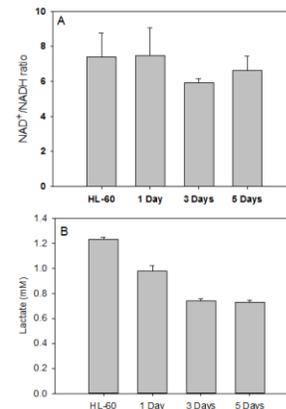


Figure 4: Time-course of ATRA induced differentiation of HL-60 cells showing (a) the NAD⁺/NADH ratio (b) a decrease in lactate levels. Data are mean \pm SE, (n=9-11) for 3 experiments.

Discussion

These results would tend to suggest a strict relationship between CD38 expression and NAD levels. We expect that active CD38 may be expressed intracellularly, possibly on the nuclear membrane (5,6), as well as on the plasma membrane as it is hard to consolidate extracellular enzyme activity with the effect on intracellular NAD levels.

The results with the novel CD38 inhibitor, kuromanin in CD38 expression studies tend to suggest the exciting possibility that CD38 expression and CD38 activity or NAD levels are linked.

In terms of CLL cells expressing CD38, we would expect a similar relationship and thus the reduced NAD levels may play a role in the negative prognosis associated with CD38 expression in patients although this may not be at the level of basic metabolism.

References

- Lee HC (2006) Mol Med 12: 317-323.
- Deaglio, S., et al (2006) Trends Mol Med 14(5): 210-218
- Lee HC et al (1997) Methods Enzymol 280: 331-340
- Leonardo MR, et al (1996) J Bacteriol 178: 6013-6018.
- Yalcintepe, L., I. Albeniz, et al (2005) Exp Cell Res 303(1): 14-21.
- Zhao YJ, Zhang HM, Lam CM, Hao Q, Lee HC (2011) J Biol Chem 286(25):22170-7

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Introduction

CD38 is a multifunctional transmembrane glycoprotein expressed in a wide variety of cell types that displays both enzymatic and receptor functions. As a receptor, CD38 controls vital cellular functions, such as cell activation, adhesion (binding to CD31), differentiation and survival of lymphoid and myeloid cells. CD38 as an ectoenzyme uses NAD to generate cyclic ADP-ribose (cADPR) and NADP to generate nicotinic acid dinucleotide phosphate (NAADP). These products act as second messengers that release calcium from intracellular stores (1). Perhaps more importantly, CD38 seems to be able to regulate the levels of intracellular NAD as the wide range of reactions that it performs consume NAD. Such control may have wide ranging implications on cell physiology not only due to modulation of basic metabolism but also as NAD has recently been identified as a substrate in a variety of signaling reactions. CD38 and its metabolites have been proposed to be involved in a number of human diseases ranging from Diabetes to HIV infection. CD38 is also a widely used as a negative prognostic marker (2) and a disease modifier in chronic lymphocytic leukemia (CLL) where increased CD38 expression correlates with a worse prognosis. While the receptor functions of CD38 are well known little effort has been directed at investigating potential roles of the enzymatic functions in CLL. Here we present data from a CD38 expression system, HL-60 cells.

Results

CD38 expression correlates with a drop in intracellular NAD(H) levels

- HL-60 cells were differentiated using 1 μM ATRA for 5 days. Enzymatically active CD38 (measured via the NGD assay) was found on the plasma membrane after 24 hours (Fig 1A).
- CD38 and CD157 (a CD38 homologue) mRNA expression were determined by qPCR (Fig 1B). CD38 expression was upregulated over 400 times during the first 24 hours while CD157 expression increased only slightly.

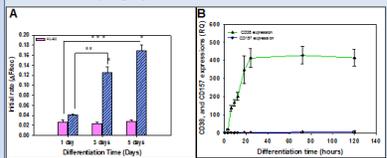


Figure 1: Time-course of ATRA induced differentiation of HL-60 cells showing: (a) CD38 cyclase activity (b) CD38 mRNA expression (green line), CD157 mRNA expression (blue line).

- Western blotting confirmed CD38 protein expression (Fig 2).



Figure 2: Western blot of differentiating cells for CD38 showing the 45kDa band corresponding to CD38.

- Intracellular NAD levels were determined using an enzymatic assay (Fig 3 black line). Levels fell rapidly with the induction of CD38 expression and by the 5th day of differentiation, were less than 50% of their starting values.

Results

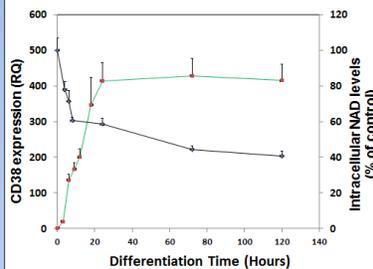


Figure 3: Time-course of ATRA induced differentiation of HL-60 cells showing the increase in CD38 expression (green line) are concomitant to the reduction in intracellular NAD levels (dark line).

- As the drop in NAD levels seems to follow the increase in CD38 expression closely, we hypothesised that CD38 may be responsible for the change. We used the novel CD38 (enzymatic) inhibitor, kuromanin, to investigate this relationship. Kuromanin counteracted the drop after 6 hours suggesting that CD38 is degrading NAD (Fig 4).

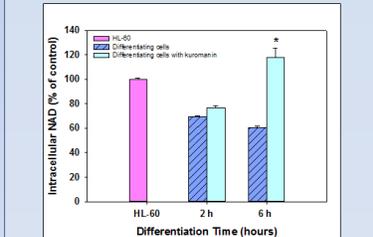


Figure 4: Time-course of ATRA induced differentiation of HL-60 cells showing the effect of inhibited CD38 activity by kuromanin on intracellular NAD levels

Effect of low intracellular NAD levels on cell physiology

- NAD is an important cofactor/substrate involved in multiple metabolic and signaling reactions. To assess the effect of lowered NAD levels on basic cell metabolism, we measured both the NAD⁺/NADH ratio (Fig 5A) and lactate levels (Fig 5B) as glycolysis proxies. As might be expected, glycolytic activity was lowered but the NAD⁺/NADH ratio was not significantly affected.
- We also measured two indicators of antioxidant capacity, TBARS (Fig 5C) and total glutathione (Fig 5D). A clear increase in TBARS levels (a marker of oxidative stress) was noted.

References

1- Lee HC (2006) Mol Med 12: 317-323.
2- Deaglio S, et al. (2008). Trends Mol Med 14(5): 210-218

Results

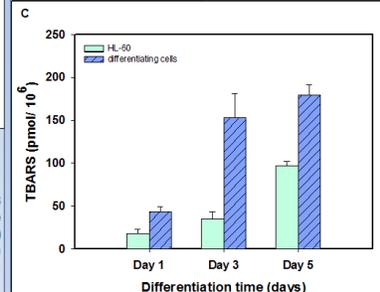
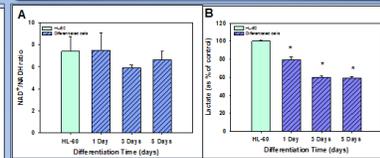


Figure 5: Time-course of ATRA induced differentiation of HL-60 cells showing (a) NAD⁺/NADH ratio (b) extracellular lactate levels (c) The increase in oxidative damage represented by TBARS levels and the drop in (d) total glutathione levels.

Conclusion

These results suggest a strict relationship between CD38 expression and NAD levels and NAD-dependent processes in this cell model of CD38 expression. In terms of CLL, cells expressing high levels of CD38 (patients with poor prognosis) would also be expected to show a similar relationship.

It is hard to imagine how a drop in NAD levels associated with increased CD38 expression might be linked to the disease progression in CLL that is associated with increased CD38. We hypothesise that the increase in CD38 expression will be linked with reduced glycolytic activity and an increase in oxidative damage and these characteristics might lead to increased resistance to cell death (as ATP generated via oxidative metabolism is required for apoptosis) and increased cell/DNA damage (presumably via a reduction in activity of a protective mechanism using NADH), possibly leading to increased mutation rates. Furthermore, we are currently investigating whether lower NAD levels might lead to alterations in the DNA damage response via the PARP pathway (that uses NAD for the formation of poly ADP-ribose(PAR)). PAR is known as an inducer of apoptosis and lower PARP activity may lead to defective induction of apoptosis and thus cell survival after DNA damage which may lead to accumulation of mutations. These factors may influence the association between CD38 expression and disease progression and prognosis.

The forgotten role of CD38: is enzymatic activity important in CLL pathophysiology?

DISCOVER
WITH
PLYMOUTH
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Background

Human CD38 is a cell surface glycoprotein expressed in a wide variety of cell types that displays both enzymatic and receptor functions. As a receptor, CD38 controls signaling pathways involved in the activation, growth and survival of lymphoid and myeloid cells. As an enzyme, CD38 uses NAD(P) as a substrate to form a number of biologically active compounds including cADPR, NAADP and ADPR (1) although the major physiological role would seem to be in control of NAD levels. Such control may have wide ranging implications on cell physiology not only due to modulation of basic metabolism but also as NAD has recently been identified as a substrate in a variety of signaling reactions. CD38 and its metabolites have been proposed to be involved in a number of human diseases ranging from Diabetes to HIV infection. CD38 is also a widely used as a negative prognostic marker (2) and a disease modifier in chronic lymphocytic leukemia (CLL) where increased CD38 expression correlates with a worse prognosis. However, as CD38 receptor functions is well known still its enzymatic function need to be illustrated in CLL patients.

Methods

- HL-60 (CD38-) were treated with all trans retinoic acid (ATRA; 1 μ M) to induce differentiation to granulocytes/neutrophil-like cells. ADP-ribosyl cyclase activity in whole cells was measured using the fluorescent NGD assay (3). CD38 expression was determined by quantitative real-time PCR using SYBR Green PCR master mix .
- NAD, NADH were extracted as appropriate in acidic/basic conditions and their levels were determined using a modification of the enzymatic cycling assay described by Leonardo *et al.* (4).
- Lactate levels were measured using LDH, and total glutathione was measured as described by Adams *et al.*, 1983 (5).

Results

CD38 is active during differentiation and decreases intracellular NAD levels

HL-60 cells were stimulated to differentiate to Neutrophil-like cells with ATRA (1 μ M) for 5 days. CD38 mRNA expression was measured after 3 hours to 5 days. (Figure 1A red line) shows the increase with time as determined by qPCR. Intracellular NAD levels were determined after 1, 3 and 5 days of differentiation (Figure 1A blue line) and were found to be reduced to below 50% of HL-60 levels by 5 days confirming the effect of CD38 expression on NAD levels. However, inhibition of CD38 by using the novel flavonoid compound (kuromarin) stopped the reduction in intracellular NAD levels (Figure 1B).

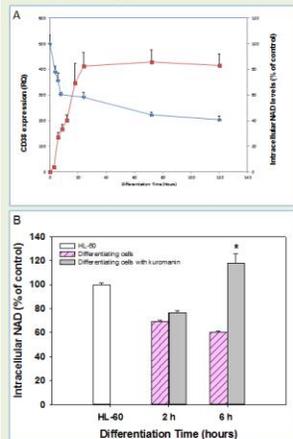


Figure 1: Time-course of ATRA induced differentiation of HL-60 cells showing: (a) the increase in CD38 expression (red line), the decrease in NAD levels (blue line) (b) Effect of kuromarin on NAD levels.

Effect of decrease of intracellular NAD on NAD-dependent processes

In order to assess the effect of lowered NAD levels on basic cell metabolism, we measured both the NAD⁺/NADH ratio (Figure 2A) and lactate levels (Figure 2B). As might be expected, lactate levels were reduced in cells where NAD was depleted probably due to partial inhibition of glycolysis. However, the NAD⁺/NADH ratio was not significantly altered. The antioxidant state represented by total glutathione was also measured (Figure 2C) which shows significant increase in GSH levels during the first day. Moreover a clear increase in TBARS levels (a markers of oxidative stress) is shown during days 3 and 5 of differentiation (Figure 2D).

It would perhaps seem surprising that a decrease in intracellular NAD(H) levels of c. 60% does not have significant effects on intracellular NAD-dependent processes and perhaps this is symptomatic of how much spare capacity the cell retains for NAD-dependent processes. One final process that may be affected is the activity of PARP enzymes and DNA repair and we are currently investigating this.

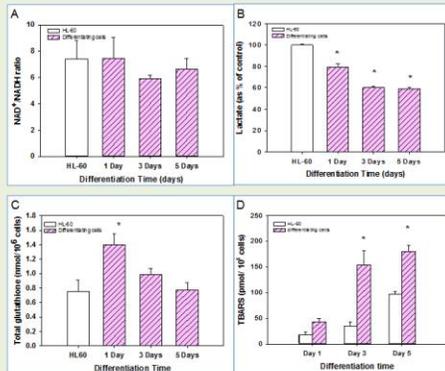


Figure 2: Time-course of ATRA induced differentiation of HL-60 cells showing (a) The NAD⁺/NADH ratio (b) A decrease in lactate levels (c) The drop in total glutathione and the increase in (d) Oxidative damage represented by TBARS levels.

Is CD38 expression NAD dependent?

In order to inhibit the NAD recycling pathway we used the NMPRTase inhibitor (FK866), and also we used the extracellular NAD application to increase intracellular NAD. The results show that treatment of HL-60 during the differentiation (Figure 3A) for 1 day either with 100 nM of the inhibitor (FK866) and/or incubation of cells with 100 μ M NAD, resulted in a significant drop in the CD38 expression. Moreover, inhibition of CD38 by kuromarin seemed to modulate CD38 expression (Figure 3B).

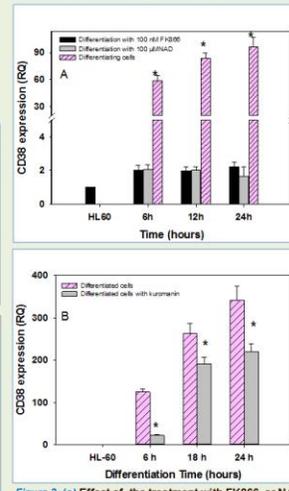


Figure 3: (a) Effect of the treatment with FK866 or NAD on CD38 expression in differentiating cells, (b) Effect of kuromarin on CD38 expression in time course of HL60 differentiation.

Discussion

These results would tend to suggest a strict relationship between CD38 expression and NAD levels. We expect that active CD38 may be expressed intracellularly, possibly on the nuclear membrane (5,6), as well as on the plasma membrane as it is hard to consolidate extracellular enzyme activity with the effect on intracellular NAD levels. The results with the novel CD38 inhibitor, kuromarin in CD38 expression studies tend to suggest the exciting possibility that CD38 expression and CD38 activity or NAD levels are linked.

In terms of CLL cells expressing CD38, we would expect a similar relationship and thus the reduced NAD levels may play a role in the negative prognosis associated with CD38 expression in patients although this may not be at the level of basic metabolism.

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References

- 1- Lee HC (2006) Mol Med 12: 317-323.
- 2- Deaglio S, *et al.* (2008). Trends Mol Med 14(5): 210-218
- 3- Lee HC, *et al.* (1997) Methods Enzymol 280: 331-340
- 4- Leonardo MR, *et al.* (1998) J Bacteriol 178: 6013-6018.
- 5- Adams JD, *et al.* 1983. J. Pharmacol. Exp. Ther. 227:749-754.

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Large changes in NAD levels associated with CD38 expression during HL-60 cell differentiation

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ABSTRACT

NAD is an important cofactor involved in multiple metabolic reactions and as a substrate for several NAD-dependent signaling enzymes. One such enzyme is CD38 which, alongside synthesising Ca^{2+} -releasing second messengers and acting as a cell surface receptor, has also been suggested to play a key role in NAD⁺ homeostasis. CD38 is well known as a negative prognostic marker in B-CLL but the role of its enzymatic activity has not been studied in depth to date. We have exploited the HL-60 cell line as a model of inducible CD38 expression, to investigate CD38-mediated regulation intracellular NAD⁺ levels and the consequences of changes in NAD⁺ levels on cell physiology. Intracellular NAD⁺ levels fell with increasing CD38 expression and this was reversed with the CD38 inhibitor, kuromanin confirming the key role of CD38 in NAD⁺ homeostasis. We also measured the consequences of CD38 expression during the differentiation on a number of functions linked to NAD⁺ and we show that some but not all NAD⁺-dependent processes are significantly affected by the lowered NAD⁺ levels. These data suggest that both functional roles of CD38 might be important in the pathogenesis of B-CLL.

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1. Introduction

The pyridine nucleotides nicotinamide adenine dinucleotide (NAD) and its phosphorylated form NADP have long been known to be essential co-enzymes in some of the most fundamental reaction pathways of basic metabolism such as glycolysis, the TCA cycle and the pentose phosphate pathway [1]. It has become clear over the past two decades that their roles in cells extend far beyond being simple electron carriers and NAD(P) has also been shown to be a substrate for enzymes that control pathways of DNA repair (via poly ADP-ribose polymerase; PARP), post-translational protein modification (via ADP-ribosyl transferases; ARTs), gene expression (via sirtuins) and Ca^{2+} -signalling (via CD38/CD157; [2–5]). This has led to a renewed interest in the pathways of NAD(P) homeostasis as it is clear that both the oxidation state and absolute levels of NAD(P) will affect cell physiology via a number of pathways. There has also been much interest in these homeostasis pathways as potential pharmacological targets for a wide variety of diseases.

When NAD(P) is used as a substrate rather than as a redox co-enzyme, the result is that the NAD(P) is consumed with all of the reactions above leading to cleavage of the nicotinamide moiety and generation of free nicotinamide along with compounds containing an ADP-ribose (phosphate) group. In order to maintain

NAD(P) levels, three distinct pathways exist to re-synthesise NAD(P) [6]. Of the pathways that consume NAD(P), the most important in terms of the general control of NAD(P) levels would appear to be that mediated by the enzyme CD38 as it is apparently constitutively active [7]. Other pathways such as the PARP pathway may also significantly affect intracellular NAD(P) levels under certain conditions (i.e. DNA damage for PARP) but such changes are likely to be transient.

CD38 is an unusual protein in that it possesses both a receptor function, mediating cell–cell contact and proliferation, and an enzymatic activity [8]. Furthermore, the enzymatic activity is unusual in itself in that the enzyme will use multiple pyridine nucleotide substrates and produce multiple products through at least three known enzymatic mechanisms. A number of the enzymatic products of CD38 have been shown to be involved in cell signalling pathways, for instance, cADPR, NAADP and ADPR [9]. While CD38 is clearly an important regulator of the synthesis of second messengers, recent evidence from the CD38 KO mouse has suggested that the principle role of CD38 may be in the control of NAD(P) levels as the KO mouse showed significantly higher tissue NAD levels than the wild-type [10]. CD38 is perhaps best known for being a prognostic marker for chronic lymphocytic leukaemia (CLL) [8]. Briefly, high levels of CD38 expression correlate with both disease stage and poor prognosis. While the receptor functions of CD38 undoubtedly contribute to high levels of cell proliferation in advanced CLL, the contribution of the enzymatic activity in pathogenesis has remained largely ignored.

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