Estrogen receptor- directly regulates the hypoxia-inducible factor 1 pathway associated with antiestrogen response in breast cancer.

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http://hdl.handle.net/10026.1/5244

10.1073/pnas.1422015112
Proc Natl Acad Sci U S A

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INTRODUCTION

During cancer growth, tumour cell adaptation is driven by adverse microenvironmental conditions such as hypoxia and starvation. Mechanistic target of rapamycin complex 1 (mTORC1) responds to both local nutrient status and growth factor signalling through phosphatidylinositol 3-kinase to regulate protein synthesis and cellular homeostasis, thereby modulating cancer cell growth, metabolism and metastasis. However, attempts to block tumour growth using the allosteric mTOR inhibitor rapamycin or its analogues have met with limited success. Although these drugs strongly reduce signalling to one of the two well-characterised mTORC1 targets, ribosomal protein p70-S6 kinase 1 (S6K1), they often have more limited effects on the other, eukaryotic translation initiation factor 4E-binding protein 1 (4E-BP1), a negative regulator of eukaryotic initiation factor 4E (eIF4E). This resistance can sometimes be circumvented by using adenosine triphosphate (ATP)-competitive mTOR inhibitors, which also block the other mTOR kinase-containing complex, mTORC2. Nonetheless, how changes in mTOR structure or mTOR regulators modulate rapamycin sensitivity remains of considerable interest.

Members of the proton-assisted amino-acid transporter (PAT) or solute-linked carrier 36 (SLC36) family were identified as positive regulators of growth and mTORC1 signalling through an in vivo genetic overexpression screen in flies. These effects were shown to be conserved by characterisation of the two ubiquitously transcribed human PATs, PAT1 (SLC36A1) and PAT4 (SLC36A4). The prototypic PAT family member, PAT1, is a lysosomal amino-acid transporter (AAT). In rapidly growing cells, it is located at the surface of nutrient-rich late endosomal and lysosomal (LEL) compartments, where mTOR accumulates in response to amino-acid stimulation. The recruitment of mTOR requires assembly of a multiprotein complex, which includes Raptor, a heterodimeric pair of Ras-related GTPases, the pentameric Ragulator, and the vacuolar-H+-ATPase proton pump at the compartment surface (reviewed in Bar-Peled and Sabatini and Malik et al). PAT1 also interacts with this complex to promote mTOR localisation on LELs and...
subsequent mTORC1 signalling. Amino-acid sensing by the PATs may involve transport or signalling via a so-called ‘transceptor’ mechanism. 4,13,17 Recent studies have identified an AAT in the related SLC38 family, SLC38A9, which also interacts on LELs with the mTORC1-regulatory machinery, potentially in response to arginine, 18,19 suggesting that different LEL-located, mTORC1-regulatory AATs may sense different amino acids. Furthermore, the identification of molecules such as Golgi-localised Rab1A,20 and ADP ribosylation factor Arf1 21 and phospholipase D 22,23 as regulators of Rag-independent, mTORC1 activation, suggests that other amino-acid-sensing mechanisms remain to be discovered.

Here we investigate PAT4 function in colorectal cancer. Colorectal cancers are frequently rapamycin-resistant 6 and often metastatic, seriously impacting on clinical outcome. 24,25 We show that PAT4 upregulation is associated with cancer progression. By using an inducible PAT4 shRNA knockdown in HCT116 colorectal cancer cells, we find that PAT4 responds to two rapidly metabolised, non-essential amino acids, glutamine and serine,26,27 to drive rapamycin-resistant, mTORC1-mediated cell proliferation. Furthermore, we provide evidence that PAT4 interacts with Rab1A and mTORC1 on the Golgi, suggesting a role in amino-acid-sensing from this compartment.

RESULTS
Validation of a novel PAT4 monoclonal antibody
We generated a highly specific mouse monoclonal antibody against PAT4 (antibody Pat4/9/H10). Staining with this antibody revealed that PAT4 was localised to an asymmetric perinuclear region in formalin-fixed, paraffin-embedded 786-O renal cancer cells (Figures 1a and b). Bands of 60–75 kDa that is strongly reduced by IPTG-induced PAT4 knockdown (+IPTG), suggesting that they are PAT4-specific. Western blots were also probed with an anti-tubulin antibody as a loading control. (d) Western blot of cell lysates from 786-O cells and from a GFP-PAT4-overexpressing HEK-293 cell line treated with PNGase F before electrophoresis to remove glycosyl groups. This resolves the crossreacting molecules seen in untreated cell lysates into more specific bands migrating at ~ 30 and 50 kDa, respectively, smaller than the predicted molecular weights of 55 kDa (PAT4) and 85 kDa (GFP-PAT4), a phenomenon also reported for other transmembrane proteins.42

High PAT4 expression is associated with poor outcome in colorectal cancer patients
To test whether PAT4 expression is altered in human colorectal cancer, we stained primary tumour tissue microarrays from 107 patients, who had been treated by surgical resection only. The intensity of cytoplasmic staining was scored by a pathologist (CS) into three categories (Figures 2a and b; see Materials and methods), all of which were higher than normal colorectal epithelium. Statistical analysis showed no association between...
high PAT4 expression and standard clinical or pathological variables, including site of tumour, tumour stage, nodal or distant metastases, age, lymphatic, vascular or neural invasion, differentiation or gender (Supplementary Table S1).

In univariate analyses, high PAT4 levels \( (P = 0.01) \) as well as high tumour stage \( (P < 0.01) \), tumour stage score \( (P < 0.01) \), the presence of bowel perforation \( (P = 0.02) \), neural invasion \( (P < 0.01) \), nodal \( (P < 0.01) \) and synchronous metastasis \( (P < 0.01) \) significantly correlated with shorter relapse-free survival (Supplementary Table S2). Patients with cancers that had higher PAT4 expression had a significantly shorter mean relapse-free survival compared with those with lower levels \( (P < 0.01; \text{Figures } 2c \text{ and } d) \). Additionally, higher PAT4 levels showed statistical significance in multivariate survival analysis \( (P < 0.01; \text{Supplementary Table } S3) \). The multivariate model included all variables significantly associated with relapse in univariate analysis, apart from overall stage, as this is calculated from tumour stage (T), nodal metastases (N) and distant metastases (M) stages. We conclude that increased PAT4 levels are associated with worse prognosis in patients with colorectal cancer.

PAT4 regulates HCT116 cell proliferation

To analyse PAT4 function in HCT116 colorectal cancer cells, we generated stably transduced cell lines, each carrying one of three different lentiviral constructs expressing a PAT4 short hairpin RNA (shRNA) under isopropyl \( \beta \text{-D-1-thiogalactopyranoside (IPTG)-inducible control}. \) For each construct, pooled cells representing many individual transduction events had reduced PAT4 transcript levels, as determined by quantitative real-time PCR.
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PAT4 regulates the growth of HCT116 cells in vitro and in vivo. (a) Proliferation of clones of HCT116 cells stably transduced with one of two independent IPTG-inducible shRNA constructs targeting PAT4, namely shPAT4(4.8) and shPAT4(7.1), or the IPTG-inducible non-targeting control construct (shNT) was measured in the presence and absence of IPTG (n = 3). (b) and (c) Mean growth curves (± s.e.m.) of human HCT116 tumour xenografts in immunodeficient mice carrying pools of cells transduced with shNT (filled squares) with (empty circles) or without (filled squares) IPTG induction, or shPAT4-transduced HCT116 cells (c) with (empty squares, outlined in red) or without (filled squares) IPTG induction (n = 7). Data in (b) and (c) were analysed by unpaired two-tailed independent Student’s t-test. (d) and (e) Kaplan–Meier survival curves of seven animals with and without IPTG induction of shNT- (d) and shPAT4-containing (e) HCT116 tumours; log-rank (Mantel–Cox) test: P = 0.019 for (e). For shPAT4-inducible cells, all but one of the seven non-induced mice (filled squares) needed to be killed within 36 days (median survival time of 36 days), whereas all seven induced mice (empty squares, outlined in red) were killed from 38 days onwards with a median survival time of 50 days. Cell proliferation experiment was repeated three times. *P < 0.05, **P < 0.01.

In vivo culture of these clones together with HCT116 cells containing an IPTG-inducible, non-targeting shRNA (shNT) gene revealed that IPTG induction specifically inhibited proliferation of shPAT4-expressing cells (P < 0.05; Figure 3a) with no significant effect on cell death (Supplementary Table S4).

PAT4 promotes human tumour growth in xenograft models
To assess the role of PAT4 in tumour growth, pooled clones of HCT116 cells carrying shPAT4(49 387), were used in xenograft experiments. We reasoned that the variable level of PAT4 knockdown in these cells might better model changes taking place in heterogeneous tumours expressing different levels of PAT4. The effect on tumour growth of IPTG-induced PAT4 knockdown in shPAT4 HCT116 cells was assessed in mice over a 60-day period. Immunodeficient mice were provided with IPTG in their drinking water to induce shRNA expression. IPTG did not alter the size of tumours formed from shNT cells (Figure 3b). However, IPTG-induced shPAT4 expression reduced tumour growth significantly compared with non-induced shPAT4 controls (Figure 3c; P < 0.01). In addition, shPAT4 induction extended median survival time of mice from 36 to 50 days (ratio: 0.72; 95% confidence interval of ratio: 0.36–1.07; Gehan–Breslow–Wilcoxon Test, P = 0.008; Figures 3d and e). Induction of PAT4 knockdown in a second experiment also significantly reduced mean tumour volume (P < 0.05) and improved animal survival (P < 0.05), demonstrating that PAT4 promotes HCT116 tumour growth in vivo.

PAT4 regulates a rapamycin-resistant form of mTORC1
To determine how PAT4 knockdown might inhibit tumour growth, we analysed mTORC1 signalling in stably transfected HCT116 clones carrying inducible PAT4 shRNAs, shPAT4(4.8) and shPAT4(7.1), and in the non-targeting clone, shNT. PAT4 protein is expressed at much lower levels in HCT116 cells compared with 786-O cells, thus lysates from large pools of HCT116 cells were pretreated with PNGase F to detect PAT4, which resolved into a specific 30 kDa band that was clearly reduced after IPTG addition in knockdown cells (Figures 4a and b).

IPTG-induced PAT4 knockdown selectively reduced the most highly phosphorylated form of 4E-BP1, designated the γ-band on western blots, whereas levels of less phosphorylated forms increased (Figures 4c and f). Human 4E-BP1 has at least eight phosphorylation sites. Phosphorylation of 4E-BP1 at Ser65, a key residue for eukaryotic initiation factor 4E binding, is typically required to form the γ-band. An anti-phospho-Ser65-4E-BP1 antibody verified that phosphorylation of this residue (p-S65-4E-BP1) was strongly decreased by PAT4 knockdown. In contrast, overall phosphorylation of p-T37/46-4E-BP1 was maintained, but sometimes led to a modest reduction in p-S240/244-S6 phosphorylation sites. PAT4 regulates a rapamycin-resistant form of mTORC1 from the Golgi.
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Figure 4. PAT4 selectively affects the mTORC1 target 4E-BP1. Western blots of protein extracts from HCT116 cells carrying either IPTG-inducible shNT or shPAT4(4.8) (a and c) or shNT and shPAT4(7.1) constructs (b and d) cultured in the presence and absence of IPTG. (a and b) PAT4 knockdown reduces the levels of PAT4 protein detected following incubation of cell lysates with PNGase F before electrophoresis. (c-f) PAT4 knockdown significantly reduced the level of the most phosphorylated γ-form of 4E-BP1, visualises both with an anti-phospho-Ser65-4E-BP1 antibody (p-S65-4E-BP1) and as the upper band with a pan-4E-BP1 antibody (arrow; quantified in three independent experiments as a proportion of total 4E-BP1 staining in histograms in (e) and (f), respectively). Phospho-S6K (p-T389-S6K1), phospho-S6 (p-S240/244-S6), phospho-Akt (p-S473-AKT) and phospho-ERK (p-T202/Y204-ERK) levels are essentially unaffected by PAT4 knockdown. Blots were probed with an anti-tubulin antibody as a loading control. Effects were essentially unaffected by Akt (p-S473-AKT) and phospho-ERK (p-T202/Y204-ERK) levels.

As PATs are implicated in amino-acid-dependent mTORC1 activation, we hypothesised that PAT4 might sense levels of specific amino acids that regulate rapamycin-resistant mTORC1. We starved HCT116 cells of specific amino acids, including two non-essential amino acids required for HCT116 growth. Non-essential serine is diverted into glycolysis, whereas glutamine fuels the tricarboxylic acid cycle via glutaminolysis in cancer cells, including HICT116 cells,6 where 4E-BP1 phosphorylation is particularly resistant to glutamine and serine starvation. Our PAT4 knockdown also had additive effects on HICT116 cell proliferation (Figure 5c), demonstrating they inhibit different mTORC1 complexes, which both have a role in cell proliferation.

To test the link between PAT4 expression and rapamycin resistance, we overexpressed a green fluorescent protein (GFP)-tagged form of PAT4 in HEK-293 cells. We have previously shown in these cells that siRNA-induced knockdown of PAT4 reduces both 4E-BP1 and S6K/S6 phosphorylation, and this was confirmed using shRNA knockdown (Supplementary Figure S3). We observed that 4E-BP1 hyperphosphorylation shows some rapamycin resistance in HEK-293 cells (Supplementary Figure S2F). Strong overexpression of GFP-PAT4, which produced several protein bands resolving to a 50 kDa band on western blots after PNGase pretreatment (Figure 1d), increased rapamycin resistance of hyperphosphorylated, p-Ser65-4E-BP1 (Figures 5d and e). This suggests that high PAT4 levels can induce resistance to rapamycin in multiple different cell types.

PAT4-dependent sensitivity of rapamycin-resistant mTORC1 to glutamine and serine

As PAT4s are implicated in amino-acid-dependent mTORC1 activation, we hypothesised that PAT4 might sense levels of specific amino acids that regulate rapamycin-resistant mTORC1. We starved HCT116 cells of specific amino acids, including two non-essential amino acids required for HCT116 growth. Non-essential serine is diverted into glycolysis, whereas glutamine fuels the tricarboxylic acid cycle via glutaminolysis in cancer cells, including HICT116 cells,6 where 4E-BP1 γ-phosphorylation and S6K activity in HCT116 cells are mediated via a PAT4-dependent sensing mechanism, as we reasoned that modest changes in PAT4 levels might alter the sensitivity of HICT116 cells to glutamine and serine starvation. Our PAT4 knockdown clones displayed leaky IPTG-independent shRNA knockdown (Supplementary Figure S1B), which normally did not affect 4E-BP1 phosphorylation (Figure 5a) or proliferation (Figure 3a). We tested the amino-acid sensitivity of these cells in the absence of IPTG. 4E-BP1 hyperphosphorylation was more sensitive to reduction in glutamine and serine levels in both shPAT4(4.8) (Figures 6b and c) and shPAT4(7.1) (Supplementary Figures S4) clones, indicating that PAT4 is involved in the sensing of these metabolically important amino acids. Interestingly, S6 phosphorylation also appeared to be more sensitive to reduced glutamine and serine in these experiments, suggesting either that rapamycin-resistant mTORC1 can directly or indirectly modulate S6K activity under certain conditions or that starvation affects the specificity of PAT4 for rapamycin-resistant mTORC1. Combining glutamine or serine starvation with rapamycin treatment had a greater effect on 4E-BP1 hyperphosphorylation.
compared with either treatment alone (Figures 6d and e), supporting our conclusion that these amino acids are sensed by PAT4-regulated, rapamycin-resistant mTORC1.

Golgi-localised PAT4 interacts with mTORC1
Immunofluorescence staining of HCT116 cells revealed that PAT4 is concentrated on and adjacent to the trans-Golgi network (Figure 7a). A similar localisation was observed in 786-O cells (Supplementary Figure S5A). A previous report also suggested that overexpressed PAT4 in HEK-293T cells is not on LELs.32 Interestingly, although under normal culture conditions, most mTOR is localised around the LELs, some colocalisation with the trans-Golgi network was also observed (Figure 7b), raising the possibility that it might be associated with PAT4 in this compartment.

To investigate this further, we used rapamycin-resistant HEK-293 cells expressing GFP-tagged PAT4 (Figure 5d). GFP-PAT4 also localised on and around the trans-Golgi network (Figure 8a). Golgi-localised Rab1A, a monomeric GTPase involved in membrane trafficking events, has recently been implicated in amino-acid-dependent activation of mTORC1 from the Golgi.20 We tested
whether Rab1A might interact with PAT4. We used the proximity ligation assay (PLA), which detects specific protein–protein interactions in situ, when antibodies recognising these molecules are in close proximity.33 Although anti-Rab1A staining primarily localised to the cis-Golgi (Figure 8b), Rab1A and GFP antibodies produced a PLA signal on an adjacent compartment (Figure 8c), which was not present in cells that did not express GFP-PAT4 (Supplementary Figure S5B). This signal frequently overlapped with GFP-PAT4 and was partly within the trans-Golgi network (Figure 8d), suggesting that Rab1A and PAT4 can interact on the Golgi. In addition, PLA using either anti-mTOR (Figure 8e) or anti-Raptor (Figure 8f and Supplementary Figure S5C) antibodies with anti-GFP also produced a specific signal primarily in GFP-PAT4-containing compartments that included the trans-Golgi network. This indicates that mTORC1 interacts with PAT4 on the Golgi, consistent with the idea that PAT4 can regulate mTORC1 activity from this compartment.

**DISCUSSION**

Although resistance of mTORC1 to inhibitors can be partly explained by differential in vitro sensitivity of substrate target sites,34 increasing evidence indicates there are also different mTORC1 complexes in cancer cells,20–23,35 which may make them differentially sensitive to drugs such as rapamycin. In this study, we demonstrate that PAT4 regulates rapamycin-resistant mTORC1 in HCT116 cells and can induce increased rapamycin resistance when overexpressed in HEK-293 cells. PAT4 and rapamycin-resistant mTORC1 are essential for normal cell proliferation in vitro.

Furthermore, PAT4 expression levels are predictive of early relapse in colorectal cancer, suggesting a pathophysiological role in the acquisition of more aggressive tumour phenotypes.

Our findings support a model in which rapamycin-resistant and -sensitive forms of mTORC1 can be independently controlled, and provide a new genetic tool to separate these two signalling functions (Figure 9). Rapamycin-resistant mTORC1 selectively, but
not exclusively, regulates 4E-BP1 hyperphosphorylation, which is also specifically targeted by PS3 activation in murine erythroleukemia cells, further supporting the idea that it is a distinct complex. However, this selective effect (Figure 4 and Supplementary Figure S2C) is not universal. In other cell types, PAT4 primarily appears to regulate an mTORC1 complex controlling 4E-BP1 and S6K (Supplementary Figure S3; Heublein et al.14), suggesting that cell-type-specific regulatory factors or PAT4 expression levels modulate this transporter’s specificity in controlling mTORC1. Indeed, it is only upon PAT4 overexpression that HEK-293 cells exhibit detectable PAT4-dependent rapamycin resistance (Figure 5d).

It has been suggested that PAT4 regulates mTORC1 signalling by transporting amino acids across the plasma membrane. However, this seems unlikely in our cell models for three reasons: first, cell surface PAT4 protein levels are very low (Figures 1a, 7a and 8); second, PAT4 appears to be a low-capacity transporter; third, it is difficult to explain how a cell surface transporter might affect only rapamycin-resistant mTORC1. We favour a model where PAT4 interacts with mTOR on the Golgi, although it may also regulate mTORC1 from other subcellular compartments.

Our study also revealed selective sensitivity of the mTORC1 target 4E-BP1 in HCT116 cells to reduction of two non-essential amino acids, glutamine and serine, but not to the mTORC1 regulator leucine, whose intracellular levels can be modulated by transporting amino acids across the plasma membrane. Several other amino acids, including glutamine and serine, bind with lower affinity, and can compete with high-affinity PAT4 substrates, although they may not be transported. This could provide a transport-independent, amino-acid-sensing ‘transceptor’ mechanism, in keeping with previous suggestions for the PATs.17 Cells would become more resistant to depletion of highly metabolised amino acids by expressing more PAT4, explaining the clinical data from colorectal cancer patients.

In conclusion, our study suggests that pharmacological inhibition of an upstream mTORC1 activator such as PAT4 in colorectal cancer could complement the actions of rapamycin, by blocking a rapamycin-resistant, 4E-BP1-selective pathway. PAT4 may also provide a new biomarker for more aggressive colorectal tumours that are rapamycin-resistant.

MATERIALS AND METHODS
Cell culture
HCT116 cells were cultured in McCoy’s 5A modified medium (Gibco, Invitrogen, Paisley, UK) containing 10% foetal calf serum (Gibco, Invitrogen), unless otherwise specified. The 786-O and HEK-293 cells were cultured in 10% foetal calf serum-containing Dulbecco’s modified Eagle’s medium. Cells were incubated at 37°C in 5% CO2. Rapamycin treatment was carried out 24 h after seeding. Cells were treated for 24 h typically, or 72 h for cell proliferation analysis, with 3 μM (HCT116) or 100 nM (HEK-293) rapamycin, diluted from a stock solution in dimethyl sulfoxide (R8781; Sigma, Gillingham, UK), or as specified for dose–response curves. Founder cell lines were obtained from ATCC (LGCS Standards, Teddington, UK) and used within 6 months of resuscitation (<25 passages). si435 used to knockdown PAT4 expression and the scrambled control siRNA (Figure 1) were previously described in Heublein et al.14

Inducible shRNA-expressing lentiviruses
Sigma Mission lentiviral particles carrying the following clones: TRCN0000043984, 5′-CCGCGCTTGATAAATGACGAGAATTCCTCAAGATCTCGTCTCTATTTAGGTGTTTGG-3′ (referred to as shPAT4(43984)); TRCN0000043985, 5′-CCGCGCTTGAGAAATGCGAGAAGTACCTCAAGATCTCGTCTCTATTTAGGTGTTTGG-3′; TRCN0000043987, 5′-CCGCCGAGTAGTGTGTCAGAGAACACTCCCTCAGATCTCGTCTCTATTTAGGTGTTTGG-3′ (shPAT4(43987)) and TRCN0000043988, 5′-CCGCCCTGCTGAGGAACACTCCCTCAGATCTCGTCTCTATTTAGGTGTTTGG-3′ (shPAT4(43988)) were transduced into HCT116 cells. Although shPAT4(43984) partially overlaps with siRNA (435), shPAT4(43985) and shPAT4(43987) have no overlap with previously used siRNAs. For most experiments, clone shPAT4(4.8) produced a stronger knockdown compared with clone shPAT4(4.8), with greater effects on proliferation and mTORC1 signalling.

Figure 7. PAT4 and mTOR are located on the Golgi in HCT116 cells. (a) Endogenous PAT4 (green) is expressed in compartments that include the trans-Golgi network (TGN46; red) in HCT116 cells. (b) Although most mTOR (green) is located on LAMP2-positive late endosomes and lysosomes (blue) in HCT116 cells, some mTOR staining also overlaps with the trans-Golgi network (red). DAPI (4′,6-diamidino-2-phenylindole) marks the nucleus in (a) (blue) and (b) (white). Scale bars are 5 μm. Confocal channels are indicated as follows in the merged images: green (G), blue (B) and red (R).
Generation and induction of shRNA lines

Cells were transduced with lentiviral vectors at a multiplicity of infection of three (viral particles to cells) in the presence of polybrene. Puromycin selection began 2 days after transduction to generate pools of cells derived from multiple transduction events. Single-cell clones were isolated soon after transduction using the limiting dilution method. IPTG (100 μM) was added for induction. IPTG-treated cells were preinduced for 5 days before plating.

Figure 8. PAT4 interacts with Rab1A and mTORC1 on the Golgi. (a) GFP-PAT4 fusion protein (green) in HEK-293 cells shows a similar subcellular localisation to HCT116 cells on the trans-Golgi (TGN46; red). An alternative cell at higher resolution is stained with the same markers in (d). (b) Rab1A (blue) is localised primarily on the cis-Golgi, labelled by the GM130 marker (red). (c) In situ PLA (red) reveals interaction between Rab1A (blue) and GFP-PAT4 (green) primarily associated with GFP-PAT4-containing compartments (overlap between GFP-PAT4 and PLA signal is yellow in merge, top right panel; arrow). The PLA signal is also adjacent and partially overlapping with compartments on which Rab1A is concentrated in merge of Rab1A and PLA, bottom right panel. Rab1A/PAT4 PLA signals are only observed in GFP-PAT4-expressing cells (see Supplementary Figure S5B). (d) Some of the GFP-PAT4/Rab1A PLA-positive interacting compartments (red) also appear to be partly or entirely labelled by trans-Golgi network marker TGN46 (blue; arrow), but not trans-Golgi regions lacking GFP-PAT4. (e) PLA (red) reveals an interaction between mTOR (blue) and GFP-PAT4 (green) partially overlapping with GFP-PAT4-containing compartments (yellow in merges containing green and red channels, including magnified image in top right panel; arrow). In the low magnification merge image, the two upper cells not expressing GFP-PAT4 do not give a PLA signal, indicating that this assay specifically detects the GFP-PAT4/mTOR interaction. Blue and red channel merge (lower right-hand panel) reveals that mTOR staining is often in close proximity to PLA signal, but is also found in many other locations within the cell. (f) PLA (red) reveals an interaction (red) between Raptor and GFP-PAT4 (green), in and adjacent to compartments containing GFP-PAT4 (yellow, arrow in merge). PLA signals are only observed in GFP-PAT4-expressing cells (see Supplementary Figure S5C). DAPI marks the nucleus in (a) (blue) and (b–f) (white) in the merge. Confocal channels are indicated as follows in the merged images: green (G), blue (B) and red (R). Scale bars are 5 μm.
Figure 9. Schematic diagrams of rapamycin-sensitive and -resistant mTORC1 complexes in HCT116 cells. S6K and 4E-BP1, a negative regulator of eukaryotic initiation factor 4E (eIF4E), are the best characterised downstream targets of mTORC1. Although rapamycin treatment strongly inhibits S6K phosphorylation, it has a weaker effect on 4E-BP1 γ-band phosphorylation at Ser65. Less phosphorylated forms of 4E-BP1 bind to eIF4E leading to translational repression. Reducing PAT4 activity primarily affects the rapamycin-resistant form of mTORC1. This leads to a reduction in a Ser65-phosphorylated form of 4E-BP1, but has less effect on S6K phosphorylation. Other AATs in the SLC36 (PAT) and/or SLC38 family are likely to be involved in rapamycin-sensitive mTORC1 regulation, for example, PAT1 and SLC38A9. PP242 is an mTORC1 ATP kinase inhibitor that acts on both the rapamycin-sensitive and -resistant forms of mTORC1. Arrows signify positive signals and cross-bars mark inhibitory signalling events.

Amino-acid starvation media
Medium was based on Dulbecco's modified Eagle’s medium (11995-065; Invitrogen), but made in-house, so that different amino acids could be omitted individually. For glutamine, a medium lacking this amino acid was already available (McCoy's 5A without glutamine (M8403; Sigma)). Cells were starved of amino acids for 4 h.

Generation of GFP-PAT4 stable cell line
The PAT4 open reading frame from IMAGE Clone ID:531323 was recombined into a POPINE vector containing an in-frame C-terminal GFP sequence (POPINE-GFPC; gift from J Beale and S Newstead). The following errors in the PAT4 cDNA sequence (compared with the annotated transcript sequence) were corrected using the Quickchange Site-Directed Mutagenesis Kit (Invitrogen): 1209L (ATA -> CTA) H376P (CTC -> CAT) I429L (ATA -> CTA). The PAT4-GFP fusion was amplified by PCR and cloned into pcDNA3.1 (+) vector using Lipofectamine 2000 (Invitrogen). Stably transfected cells were selected 48 h later using 800 μg/ml Geneticin (Gibco, Invitrogen), as described in Heublein et al.14

Xenograft studies
All protocols were carried out under Project Licence 30/2771 following Home Office regulations39 using 6- to 7-week-old female BALB/c SCID nu/nu mice (Harlan Sprague Dawley Inc., Bicester, UK). A total of 2.5 × 10^6 HCT116 cells in 50 μl serum-free medium and 50 μl Matrigel (BD Bioscience, Oxford, UK) were subcutaneously injected into one flank (seven mice per group; animals not randomized and investigator not blinded; numbers were based on previous xenograft studies). In all, 10 μm ITPG (Carbosynth Inc., Compton, UK) was added to drinking water of treated mice. Tumour growth was measured three times a week using calipers and volume calculated from the formula 1/6π x length x width x height. The experiment was repeated and produced similar significant reductions in growth and effects on survival time.

Quantitative real-time PCR
RNA extraction and quantitative real-time PCR were carried out as described previously,14 with Ct values for PAT4 normalised against the HPRT1 housekeeping gene.

Rapamycin-sensitive mTORC1 Rapamycin-resistant mTORC1

Amino acids other

PP242 rapamycin

mRNA translation

ATA

PP242 rapamycin

mRNA translation

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Cell proliferation analysis
Cell proliferation experiments, each using a minimum of three wells, were repeated three times. Where statistically significant results were found, these were observed on all occasions. Cells were counted according to the methodology described in Heublein et al.14

Western blots
Protein lysates were routinely loaded on 10% polyacrylamide gels. For immunoblotting, the following primary antibodies were used at recommended dilutions: phospho-S6K1 Thr389 (Cell Signalling Technology, Hitchin, UK) (CST; no. 9205), S6K1 (CST; no. 9202), phospho-Ser245/244-ribosomal S6 protein (CST; no. 2215), S6 ribosomal protein (CST; no. 2217), phospho-Ser65-4E-BP1 rabbit polyclonal (CST; no. 9451), 4E-BP1 (CST; no. 9644), phospho-Ser473-Akt (CST; no. 4060), Akt (CST; no. 9272), phospho-Thr202/Tyr244/Akt rabbit polyclonal kinase (Erk1/2; CST; no. 4370), p44/42 mitogen-activated protein kinase (Erk1/2; CST; no. 4693) and α-tubulin (Sigma; no. T6199). They were detected with secondary antibodies (Promega, Southampton, UK; nos. W401B and W402B and visualised using the SuperSignal West Pico Chemiluminescent Substrate Kit (Thermoscientific, Loughborough, UK). PAT4 was deglycosylated with PNGase F (New England Biolabs, Hitchin, UK; no. P0704) according to the manufacturer's instructions.

Generation of PAT4 monoclonal antibody
A monoclonal antibody against PAT4 was created by immunising mice with a keyhole limpet haemocyanin-conjugated, cysteine-coupled peptide (Severn Biotech Ltd., Kidderminster, UK) based on an antigenic amino-acid sequence within the N-terminus of PAT4 (REELDMVMRPLINE-C).

Immunohistochemistry
The following commercial primary antibodies were used: mTOR (CST; no. 2983; 1/100), LAM2 mouse monoclonal (Abcam, Cambridge, UK; ab25631; 1/100), TGN46 sheep polyclonal (Novus Biologicals, Abingdon, UK; NB110-40767; 1/200), Rab1a rabbit monoclonal (CST; no. 13075; 1/100), GFP mouse monoclonal (Abcam; ab1218; 1/100), GM130 mouse monoclonal (Novus Biologicals; H00002801-B01P; 1/25), Raptor rabbit polyclonal (Merck Millipore, Watford, UK; 09-217; 1/100) and secondary antibodies in donkey (Jackson Immunoresearch, West Grove, PA, USA; 1/500). Cells were processed and imaged as described in Ogumundsdotter et al.13 and Sancak et al.50 PLAs were performed using the Duolink In Situ Orange Starter Mouse/Rabbit Kit (DUO92102; Sigma) according to the manufacturer’s instructions.

For patient samples, slides were dewaxed and rehydrated with antigen retrieval performed using citrate buffer pH 6.0 (Sigma-Aldrich, Gillingham, UK) and a pressurised decloaking chamber (Biocare Medical, Concord, CA, USA). The intensity of cytoplasmic staining was assessed by a pathologist (CS) on a semiquantitative scale from 0 to 3. High levels of expression in tumour sections were scored 3, and lower levels of expression scored 0, 1 or 2.

Immunohistochemistry was carried out as described previously.41 Paraffin-embedded tissue blocks from formalin-fixed tumour samples were sectioned, dewaxed and rehydrated using standard techniques and 4 μm sections.

Patient material
Formalin-fixed and paraffin-embedded tissue was obtained with informed consent from 111 patients with colon cancer treated by surgical resection at the John Radcliffe Hospital (Oxford, UK) from 1997 to 2000. The sample size was limited to 107 by availability of tissue with full clinicopathological data, follow-up data and ethical approval. Use of tissue in this project was approved by the Oxford Centre for Histopathological Research Panel (Project number 12/A172) and the local Research Ethics Committee (C02.216). No patients received preoperative chemotherapy. The average age at the time of surgery was 71 years (range 37–96 years), 64 patients were male (58%) and the average follow-up time was 4.1 years (as of January 2009). Based on the tumour, nodal and distant metastases, cancer stage of patients at resection was as follows: 10 patients (9%) stage 1; 55 patients (49%) stage 2; 35 patients (32%) stage 3 and 11 patients (10%) stage 4. All resections resulted in clear margins. Relapse-free survival was defined as time between tumour resection and the first documented recurrence of tumour at any site. Patients who died from unrelated causes were excluded. Tissue microarrays were assembled as described previously using two representative cores of tumour and two representative cores of adjacent normal colonic mucosal epithelium for each patient.

Statistics
All data (means ± s.e.m. (xenografts) or s.d (in vitro)) were analysed using Excel or GraphPad Prism 5 (GraphPad Software, La Jolla, CA, USA). For tumour growth analysis, a parametric generalised linear model was performed using GraphPad Prism 4.0b software. For western blot analysis, cell proliferation and quantitative real-time PCR, statistical significance was determined using the Kruskal–Wallis one-way analysis of variance. All in vitro experiments were replicated on at least three occasions. For patient data, the yield test was used to determine association between PAT4 expression and categorical clinical variables (Supplementary Table S1). Cox regression analysis was used to determine prognostic factors in univariate (Supplementary Table S2) and multivariate survival models (Supplementary Table S3). The log-rank (Mantel–Cox) test was used to assess the significance of differences in relapse-free survival between Kaplan–Meier curves. Statistical analyses were performed using SPSS Statistics (Version 21.0; IBM, New York, NY, USA).

CONFLICT OF INTEREST
The authors declare no conflict of interest.

ACKNOWLEDGEMENTS
We thank Alan McIntyre, Elena Favaro, Thomas Roberts, Aaron Leiblich and Margret Ogmundsdottir for advice and technical help during this study, Katharine Carr, Kristie McCormick and Dan Stevens for critical reading of the manuscript and are especially grateful to Richard Boyd for facilitating key collaborative interactions. This work was supported by Cancer Research UK (C191591/A6181, C19591/A9093, C7713/A6174) and C38302/A12278 grants through the Cancer Research UK Oxford Centre supported by Cancer Research UK (C191591/A6181, C19591/A9093, C7713/A6174) and Stichting de Wet Medisch Fellowship to CS, funding from the Studienstiftung des deutschen Volkes and the Max Weber Programm to SH, and a studentship from The British Province of the Society of Jesus (626791) to SMWP.

REFERENCES


Supplementary Information accompanies this paper on the Oncogene website (http://www.nature.com/onc)