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1 Type of the Paper (Review)

2 Applications of Microwave Energy in Medicine

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8 **Abstract:** Microwaves are a highly utilized electromagnetic wave, used across a range of industries
9 including food processing, communications, in the development of novel medical treatments and
10 biosensor diagnostics. Microwaves have known thermal interactions and theorized non-thermal
11 interactions with living matter; however, there is significant debate as to the mechanisms of action
12 behind these interactions and the potential benefits and limitations of their use. This review
13 summarizes the current knowledge surrounding the implementation of microwave technologies
14 within the medical industry.

15 **Keywords:** microwaves, medicine, bacteria

16

17 1. Introduction

18 Microwaves are a section of the electromagnetic (EM) spectrum (Figure 1; [1]): this spectrum ranges
19 from radio waves to gamma rays. The EM spectrum can be expressed as frequency, which is
20 measured in Hertz, wavelength and energy. Shorter waves with a higher value of energy such as
21 ultraviolet are classed as ionizing as they generate sufficient energy to produce ions at a molecular
22 level, causing damage to DNA and proteins. Whilst longer waves such as visible light are classified
23 as non-ionizing, these can still cause thermal damage, however, this damage is not caused through
24 ions. Microwaves are a type of electromagnetic radiation with free-space wavelengths ranging from
25 1 meter to 1 millimeter, with the frequency ranging between 300 MHz and 300 GHz, respectively [2].
26 The most common microwave frequency used is centered at approximately 2.45 GHz, which lies
27 within the Industrial Scientific and Medical (ISM) radio band and is reserved for such purposes [3].
28 In recent years, microwave energy has been successfully exploited within medicine to treat diseases
29 such as cancer and microbial infections via ablation therapy. However, there is now increased interest
30 in using a range of microwave frequencies other than 2.45GHz in treatment of diseases; however,
31 there is still limited understanding of the mechanisms of action of microwaves which induce
32 biological changes in organisms. In this review, we focus primarily on microwave interactions at a
33 cellular level with bacteria as model organisms. Herein we examine current literature regarding the
34 functionality, current and prospective uses of microwave energy across a range of frequencies to
35 demonstrate state of the art microwave advances in the medical industry (Figure 2) [4,5].

36 2. Electromagnetic Fields

37 An electromagnetic field consists of both a magnetic and an electric field produced by positively or
38 negatively charged particles (Figure 3;[2]). An electric field is generated when particles gain a charge,
39 either positive or negative via the transfer of electrons. If the electrically charged particles start to
40 move, they produce an electric current; this current produces a magnetic field around the electric
41 current. The electric field does not have to be moving in order to produce a magnetic field, if the
42 charge of the electric field is fluctuating then a fluctuating magnetic field will be induced. Due to their

43 coupled nature, if the correct balance is achieved, the fields can sustain each other and once sustained,
44 an electromagnetic field emits directional electromagnetic waves as the fields fluctuate [6].

45 Both magnetic and electric fields are bound by laws of attraction which state that opposite charges
46 always attract while ‘like’ charges repel. The strength of the attraction or repulsion is negatively
47 proportional to the distance of the charges. One of the best examples of these laws is the chemical
48 bonding between atoms via charged electrons and protons, these interactions can be described
49 mathematically with Coulomb’s law [7]. Magnetic fields are produced by the presence of two charges
50 that create field lines, where these lines intersect is described as poles, an example of this is the Earth’s
51 North and South pole, such magnetic charges can only exist as dipoles, not monopoles. Mathematical
52 equations such as Maxwell’s equations prove the model for electromagnetism, furthermore these
53 equations describe how fluctuating electric and magnetic fields (Figure 3) travel at a constant speed
54 [8]. Electromagnetic fields can act as waves and particles simultaneously; the waves travel outwards
55 from their source and can move through a medium or through a vacuum. In a vacuum, the wave
56 travels at the speed of light, similarly the air in our atmosphere is thin enough not to affect the
57 propagation of the wave, however when travelling through media the refractory index of the media
58 will affect the waves movement. For media such as water there are other factors that alter the
59 propagation; the high permittivity and electrical conductivity of water greatly increases the angle of
60 refraction [9, 10]. Another factor to consider is the microwaves ability to interact with polar molecules;
61 water molecules are polar and so as the microwave passes through the water as a medium it also
62 interacts with it. Polar molecules rotate when exposed to microwaves as they attempt to align with
63 the waves’ fluctuating charges; the rotation produces heat and is the basis of microwave heating [11].

64 3. Thermal Interactions with Bacteria

65 Microwaves are commonly used to heat food whilst reduce the microorganisms found within.
66 Microwave heating reduces the number of microorganisms within food via direct thermal killing of
67 cellular targets that render the bacteria either dead or inactive and therefore unable to replicate [12].
68 The microwave heating process relies on the interaction between polar molecules and the
69 microwaves; in a 2.45GHz microwave oven, the microwaves’ frequency is strong enough to cause
70 water molecules in food to rotate at a speed which generates heat to cook food safely (Figure 4) [13].

71 Bacterial walls, capsules and the media in which the bacteria are cultured within contain polar
72 molecules that will rotate and produce heat when exposed to microwaves [14, 15]. Direct thermal
73 killing results in the death of the bacterial cell by an increase in temperature which in turn severely
74 damage the peptidoglycan wall. In *Staphylococcus aureus* the cell loses D-alanine from the teichoic
75 acids, this results in the cell’s inability to perform certain metabolic processes. Proteins are directly
76 damaged by heating as the bonds holding them together are destroyed, this can damage enzymes
77 and structural proteins that result in a loss of functionality [16, 17, 18]. Heat can also affect the
78 integrity of many cellular aspects causing the cell to become inactive, in Gram negative bacteria the
79 outer membrane is damaged by heat and becomes sensitive to lysozyme and hydrophobic antibiotics
80 [19]. Due to the dependency microwave heating has with polar molecules, dried samples are not
81 affected due to the lack of polar molecules, while those in the presence of water are able to reach
82 lethal temperatures [20]. There is debate that the non-thermal effects could contribute to the
83 mechanism of destruction, as at sub lethal temperatures enzyme activity is altered in *S. aureus* and in
84 turn, could result in a change in bacterial functionality [21].

85 4. Non-thermal Interactions with Bacteria

86 Electroporation is one of the non-thermal effects believed to be caused by microwave irradiation. In
87 this concept the microwaves at sub-lethal temperatures induce the formation of pores in a cellular
88 membrane due to their interaction with polar molecules. Although this is yet to be fully understood,
89 current theories suggest that the polar molecules in the cell membrane rotate and create reversible

90 pores; once the microwave is removed the pores close and returns to the original structure [22, 23, 24,
91 25]. These pores allow the cellular contents to leak outside, including substances such as DNA that
92 are not normally able to cross the cell membrane. These released components from the cell are fully
93 intact at sub lethal temperatures and once purified can be used for further research and pure DNA
94 separated from other cellular content can be used for identification [26]. Cells have shown to initially
95 shrink after non-lethal microwave exposure, however, once the pores close, within 30 seconds the
96 cell has been observed to return to its original size [21, 26]. Utilising electroporation in the
97 development of medical treatments and diagnostics is desirable due to its speed and low cost. Many
98 researchers have found that electroporation is a viable tool for identification, DNA extraction and as
99 a delivery system for molecules into cells, some of these developments and methods are discussed
100 below.

101 5. Healthcare Developments

102 Microwaves have a wide variety of uses within and outside of healthcare. In the 1950's microwaves
103 were developed for communication and later for navigation with the use of relay links and satellites
104 utilizing their properties as electromagnetic waves [27,28]. However it is the interactions with polar
105 molecules in substances that has led to the development of many uses within the healthcare setting.
106 The thermal interactions have been adapted for sterilization, sample preparation and ablation of
107 cancerous cells, the rapid heating and thermal killing induced by the microwaves interactions with
108 polar molecules makes this viable and effective. While the non-thermal interactions with polar
109 molecules are being exploited for microwave imaging and extraction of intracellular components for
110 rapid diagnostics, the permittivity of the wave and mechanism of electroporation make these uses
111 practical although not yet perfected [29, 30].

112 Sterilisation via microwave exposure has been developed through microwave heating and a series of
113 treatments. Microwaves between 225MHz to 100GHz are primarily suited for sterilisation: the
114 primary microwave used for heat sterilization of food in this range is 2.45GHz [31]. 2.45GHz
115 microwaves have also proven to be able to sterilise glass and plastics in as little as 180 seconds, this
116 too requires the presence of water within the microwave to act as a heat sink and interact with the
117 electromagnetic waves. This method of sterilisation can be used on both laboratory and medical
118 equipment in place of an autoclave [32, 33].

119 Another use that makes use of thermal interactions is Microwave Metal Sample preparation through
120 microwave digestion. Microwave digestion is a technique to dissolve heavy metal in the presence of
121 organic matter. This process exposes samples to strong acids and then raises the temperature using
122 focused microwaves. This method can be used for environmental samples to measure for
123 contaminants that could affect human health, such as lead. In order for samples of soil to be analysed
124 they must be transformed into liquid samples through microwave digestion. The samples can then
125 be analysed via Inductively coupled plasma mass spectrometry (ICP-MS) for trace metals or flame
126 atomic absorption spectroscopy (FAAS) for major elements [34]. Microwave digestion and the
127 subsequent spectrophotometry can be used to analyze trace metals in human tissue such as hair, nails
128 and gallstones. Gallstones have trace amounts of metal that are associated with bilirubinate and black
129 pigmented gallstones, thus by determining the amounts and variety of metals within gallstones their
130 origin of these metals may be determined [35,36].

131 Ablation therapy is a state of the art treatment and destructive tool for abnormal tissues via heating
132 by radiowaves or microwaves [37]. Microwave ablation is a method of thermal tumour ablation
133 where tumours are heated in order to damage the cells structure and proteins. As tumours have a
134 higher water content than healthy tissues, the microwaves induce rapid heating via interacting with
135 the polar water molecules within the tumour cells. Due to the microwaves ability to propagate
136 through media, it can pass through and heat various tissues making it an applicable thermal ablation
137 therapy for a variety of tissues [4, 5, 38, 39]. Microwave ablation therapy for hepatocellular carcinoma

138 is being viewed as a potential first line treatment for tumours on the liver surface, in which the
139 tumour is exposed to a 2.45 GHz microwave with a wattage of 80-100 (Figure 5) [5, 40]. Microwave
140 ablation therapy has not only been successful within the liver, clinical studies have also shown
141 complete ablation of tumours within the kidneys, lungs and bone, the majority of studies have
142 resulted in no recurrent tumours [41]. Despite the success of microwave ablation the use of this
143 treatment is not as widely practiced as expected, this is partly due to the expertise and equipment
144 needed to perform the therapy, alongside competing ablation therapies, such as radiofrequency
145 ablation therapy [42, 43, 44]. Radiofrequency ablation yields similar successful tumour ablation
146 results, however there are advantages to microwave ablation, microwaves produce higher
147 temperatures with shorter ablation times and a smaller heat sink effect [45, 46]. Ablation therapy is a
148 key development in the treatment of tumours, allowing the destruction of them without the need for
149 surgery, the increased usage of both ablation techniques could reduce the cost and time needed to
150 treat small tumours [47, 48].

151 Microwaves can play a role in both the detection and treatment of breast cancer. Microwave imaging
152 has been researched as an alternative to X-rays and ultrasound screening which have a variety of
153 limitation [5, 49]. Microwave imaging is an appropriate alternative as it is low cost, harmless and
154 potentially easier to preform compared to current methods with high sensitivity. Imaging techniques
155 rely on the knowledge of the permittivity and conductivity of malignant, benign and healthy breast
156 tissue. Due to the higher water content in cancer cells the dielectric properties of the tissue differs
157 when exposed to microwaves [50]. Despite the nearly 40 years of research into microwave breast
158 imaging there are still many limitations that prevent a commercially available device which includes
159 inappropriate algorithms and sensors; however, with wider clinical trials a viable microwave
160 imaging system may be feasible in the near future [39, 40]. Microwave ablation has also been trialed
161 for the treatment of breast cancer and so far has proved to be successful in thermal ablation [51,52].

162 Other than ablation and rapid heating, treatments for damaged and keratinized cells have been
163 researched and developed with controlled heating. The Swift® microwave is an approved state of
164 the art treatment for plantar warts caused by the human papilloma virus (HPV). Directly exposing
165 the wart to 8GHz microwaves at 8 Watts for 2 seconds causes the wave to interact with the keratinized
166 skin and result in controlled heating of the tissue. There is also the suggestion that microwaves
167 enhance the cross-presentation of dendritic cells that are key for the immune defense against HPV
168 [53, 54]. A similar method has been developed for the potential treatment of actinic keratosis (AK).
169 The Swift 8GHz® microwave is used to expose the ulceration to 4W for hyperkeratotic AK or 3 Watts
170 for nonhyperkeratonic AK for 3 seconds repeated in triplicate with a 20-second time gap between
171 pulses. This treatment has resulted in the clearance of actinic keratosis with brief pain and minimal
172 long term adverse side effects in 90% of applied sites [55]. Following this the use of microwaves to
173 treat benign cancerous and precancerous lesions caused by high-risk HPV has been investigated.
174 High-risk HPV results in an increased expression of 2 viral oncoproteins; E6 and E7. When *in vitro*
175 grown tumors were exposed to microwaves for 10 seconds both tumor cell death and a reduction in
176 E6 and E7 in the treated zone and transition zone were observed. This reduction suggests that
177 microwave interactions can reverse the cancerous phenotype caused by HPV; and that once an
178 effective and proven method is developed it could provide a less invasive treatment for HPV benign
179 tumors [56, 57].

180 State of the art microwave-based molecular diagnostics that incorporate the non-thermal effects of
181 microwaves are currently under development in order to tackle the delays and complexities of
182 current methods; these include microwave assisted metal enhanced fluorescence and nanotube
183 assisted microwave electroporation. Microwave assisted metal enhanced fluorescence (MAMEF) is a
184 rapid diagnostic method being developed to detect bacterial infections at point of care. MAMEF
185 combines the use of silver nanoparticles deposited on microscope slides which are impregnated with
186 anchored DNA sequences specific to the target sequence- such as a bacterial species [58, 59]. Low
187 power microwave heating kinetically accelerates the hybridisation of the target DNA and a

188 fluorescent DNA target (usually a conserved region of bacterial genomic DNA) is excited and
189 detected by the process. This method is currently crude and not yet manufactured for wider
190 laboratory use [60]. If commercialized appropriately and manufactured into an integrated device,
191 MAMEF would be a useful point of care diagnostic due to its speed, specificity, low cost and
192 simplicity [61].

193 Lyse-It is advertised as a rapid “single step” process that lyses cells and causes DNA/RNA
194 fragmentation. It uses a glass slide with gold nanolayers deposited in a “bow-Tie” shape. Using a
195 sticky silicone isolator (Sigma Aldrich), the sample is placed on the slide in the centre of the gold bow
196 and microwaved in the centre of a conventional 2.45 GHz microwave oven for lysis. The theory is
197 that the gold focuses the microwaves to release the fragmented DNA [62]. This method of lysing
198 DNA is much quicker than the current diagnostic DNA extraction methods and could be
199 incorporated into point of care diagnostics. However, crucially there are currently no benefits in
200 sensitivity as the samples are contaminated by the microwaved gold, and currently due to the cost of
201 the Lyse It Slides this method is not yet suitable to be used as a common DNA extraction method
202 within diagnostic laboratories [63, 64].

203 MAMEF and Lyse-It are not the only devices exploiting the proposed non-thermal effects of
204 microwaves as a method of DNA extraction for molecular diagnostics. Methods using micro
205 centrifuge tubes as an alternative to the expensive Lyse It slides are being researched, however these
206 processes are still somewhat time consuming due to the required centrifuge and wash procedures
207 [65]. Development of other rapid diagnostic devices that utilize microwave-based DNA extraction
208 and fragmentation as a first step to sample processing are in the early stages of development [66].

209 Microwaves are also being used in DNA extraction outside of a healthcare setting, in environmental
210 samples such as sediment and soil; these ecosystems are hard to culture due to the diversity of
211 organisms and growth conditions, therefore genetic typing is the primary form of identification.
212 There are limitations with current enzymatic lysis methods as the high molecular weight genomic
213 DNA required for further research needs to be relatively pure, whereas the DNA from environmental
214 samples have a variety of contaminants. Through implementing a microwave based thermal shock
215 lysis method in which environmental samples are exposed to 2.45GHz, 600-700W microwaves for 45
216 seconds, a relatively large amount of good quality DNA (20-23kb) can be extracted; in a sample size
217 of 300 µl of activated sludge, up to 50 µg of DNA was extracted via microwave thermal shock
218 compared to the 30 µg extracted via enzyme based protocols. After the lysis of the environmental
219 samples, appropriate washing and amplification can be performed for identification of the 16S
220 ribosomal gene. The same thermal shock method can be used to extract RNA, followed by an
221 alternative suitable washing and amplification step can be used for further identification of the 16S
222 rRNA gene. This method of lysis is not only cost effective and quicker at identifying environmental
223 samples but could be developed and implemented to detect infectious microorganisms within stool
224 samples in patients in a healthcare setting once these methods have been proven to be robust [67, 68].

225 Diagnostic and identification methods that do not rely on the extraction of intracellular components
226 have also been researched. Nanotube assisted microwave electroporation (NAME) is a method that
227 utilises electroporation, NAME however aims for visual identification rather than DNA extraction
228 [69]. This technique can be applied to not only extract the contents of a bacterial cell, but to act as a
229 transport system to deliver molecules such as biosensors into the cells (Figure 6). In this method,
230 carbon nanotubes are used as an antenna for coupling microwave energy; this localizes the
231 electromagnetic field that induces bacterial electroporation in the cellular wall to the areas around
232 the nanotube. This enhanced electroporation to specific areas (caused by the nanotubes) allows for
233 the delivery of intracellular probes that consist of double stranded nucleic acid targeting specific
234 bacterial 16S rRNA and fluorophores, enabling the identification of *Escherichia coli*, *Klebsiella*
235 *pneumoniae* and *Pseudomonas aeruginosa* for example at the single-cell level. An individualized probe
236 was designed for each bacterial species. Bacterial samples of *E. coli*, *K. pneumoniae* and *P. aeruginosa*,

237 after appropriate washing steps and the addition of the nanotube solution, were exposed to a
238 2.45GHz microwave for 10 seconds, enabling electroporation and probe delivery. Once the probe was
239 delivered into the bacterial cell via NAME the samples were mounted onto glass slides for
240 observation under a fluorescent microscope; cells that were fluorescent were accurately identified.
241 This delivery and identification method can be used directly on samples, and the whole process from
242 the initial sample to microscopic identification can take as little as 30 minutes. NAME can identify
243 pathogens such as those mentioned previously at a single cell level enabling accurate quantification
244 via cell counts of fluorescent cells under the microscope, however further instrument development is
245 required before this method can be clinically evaluated [70, 71].

246 When comparing the state of the art microwave based DNA extraction methods with current
247 commercially available DNA extraction kits, the overall opinion is that microwave methods are more
248 efficient, cost effective and simpler, so could be implemented without the need for specialised
249 training [62, 72]. The quantity and quality of DNA extracted by both techniques appear to be similar
250 for cultured samples, while microwave techniques on specific samples such as blood can have
251 varying results. If techniques and instruments are appropriately developed, microwaves have
252 significant potential to enhance rapidity and development of point of care diagnostic devices, for
253 example to tackle global healthcare challenges such as antimicrobial resistance [73]. The future
254 perspectives of microwave use throughout the medical industry are increasingly positive. Microwave
255 ablation has been approved as an effective treatment for a range of cancers with promising results to
256 be implemented for use . If development of methods and equipment continue then this could be a
257 cost effective, minimally invasive method of treating a variety of sized and shaped tumours [39, 74].
258 Although positive the development of such techniques are not without challenges, controlling the
259 direction and reflection of the wave is important in all treatments in order to not damage healthy
260 tissue as well as the size of the delivery antennas [75]. Utilising microwaves for diagnosing breast
261 cancer is in need of further research to refine the understanding of the dielectric properties of
262 cancerous tissues and the required equipment. If these developments are made microwave imaging
263 could be pain free, harmless and quicker than current screening methods such as mammography and
264 X-ray [76].

265 6. Wider Impacts of Microwave Use

266 The impact of microwaves is widespread across medicine and has clear economic benefits; for
267 example, the cost of cancer treatments could be reduced by thousands of dollars per person [77].
268 Another example is microwave sterilisation which, when compared to chemical sterilisation for
269 medical equipment, has a variety of economic and environmental impacts. The production of
270 microwaves responsible for sterilisation is expensive, but is a one-time cost other than routine
271 equipment maintenance and the running cost of electricity needed for microwave sterilisation is also
272 not small, however, environmental impact is limited in correlation to the production and power
273 supply of the microwaves. Chemicals for sterilisation are cheaper to purchase in small quantities,
274 however, this is no more expensive than microwave use on a larger scale. Moreover, the
275 environmental impacts are high throughout the manufacturing process, use and disposal of the
276 chemicals [78, 79].

277 The same economic and environmental effects of microwave use can be applied throughout all
278 microwave developments. The cost of producing the microwave is high due to the resources,
279 equipment and power required and therefore the environmental impact is high due to these resources
280 being often non-renewable.

281 The disposal of microwaves is one of the greatest sources of environmental impacts in the process if
282 disposed of incorrectly, however, due to the Waste Electrical and Electronic Equipment recycling
283 (WEEE) directives a wide array of microwaves are recycled safely [80]. The environmental and
284 economic impacts created from microwaves and point of care technology is always changing and

285 generally reducing due to advances in consumer electric drives; as new technology is developed the
 286 parties involved will be actively attempting to reduce their environmental footprint and act
 287 sustainably [81].Table 1: Summary of Microwave Applications in Medicine

288

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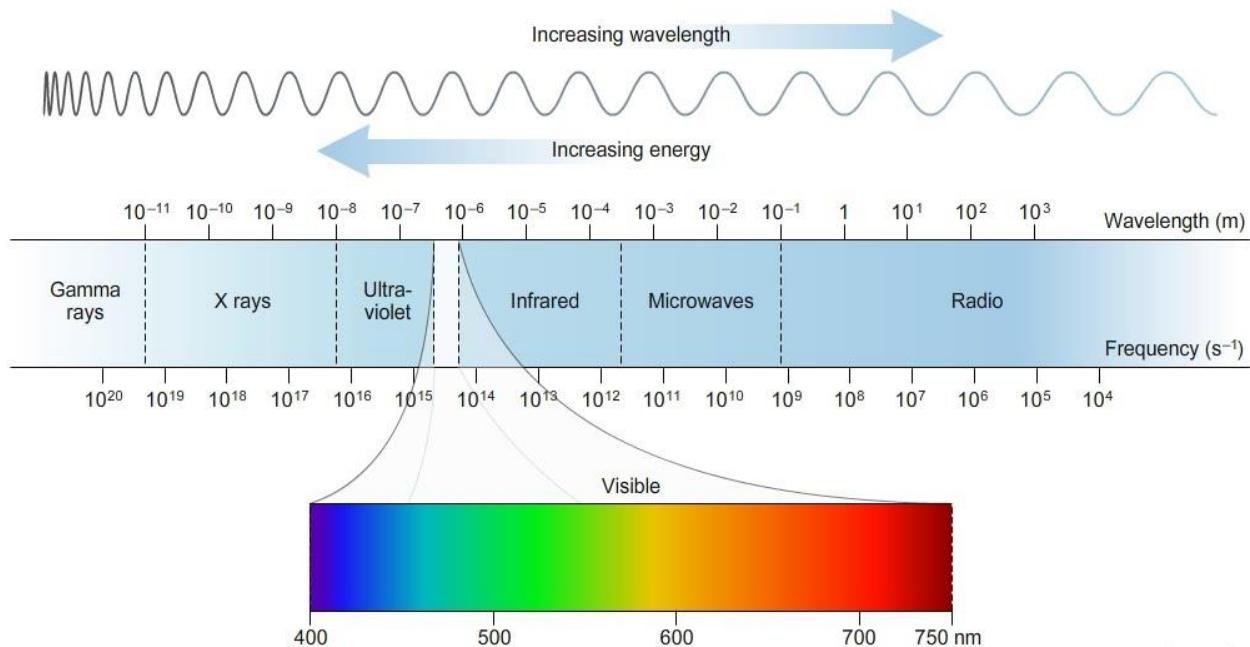
290 **7. Conclusion**

Microwave Application	Energy	Method	Example(s)	Ref.
Sterilisation		Thermal Energy. 225MHz to 100GHz; 2.45GHz	Food, Glass, Plastics	[31-33]
Heavy Metal Digestion		Thermal Energy 2.45GHz	Metals, Gallstones	[34-36]
Ablation Therapy		Thermal Energy 8GHz, ~2.45GHz	Oncogenic Tumors, Keratinised cell, Plantar Warts (HPV)	[38-40] [42-44] [53-57]
Diagnostics		Non Thermal Energy Microwave Accelerated Metal Enhanced Fluorescence (MAMEF) 2.45 GHz	Bacterial pathogens	[58-62]
Lysis		Thermal Energy 2.45GHz	Bacterial Pathogens	[63,64]
Electroporation		Non Thermal Energy 2.45GHz	Bacteria at single cell level	[69]

291 Microwaves are a versatile electromagnetic wave with a variety of uses within and beyond medicine.
 292 Currently 2.45 GHz microwaves are primarily used for heating and sterilisation within the food
 293 industry and the thermal methods of this process are relatively well known. These microwaves have
 294 also been adapted for medical treatments, microwave ablation therapy is available for a variety of
 295 cancers and reduces both the cost and length of treatment. The 8GHz microwave frequency has
 296 recently been utilised for the treatment of viruses and reduces the need for antimicrobial drugs. There
 297 are many areas in which microwaves are in development within medicine both in diagnostics and
 298 treatments, however despite all these advancements in the uses of microwaves, the knowledge
 299 behind the mechanisms as well as the impact microwaves have are limited. There is no clear
 300 mechanism behind the non-lethal interactions between microwaves and bacteria due to the limited
 301 control over the temperature and direction of microwaves there are still many risks involved with
 302 current treatments, as microwaves interact with all polar molecules. The mechanism is not the only
 303 knowledge gap that needs to be filled, limited studies regarding the environmental and economic
 304 impacts of microwave use hinder the appropriate development of microwave technology. Despite
 305 these limitations, the diverse applicability to human healthcare will improve the equality and
 306 longevity of life for many, with a reduced burden on economy.

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309 **8. Figures**

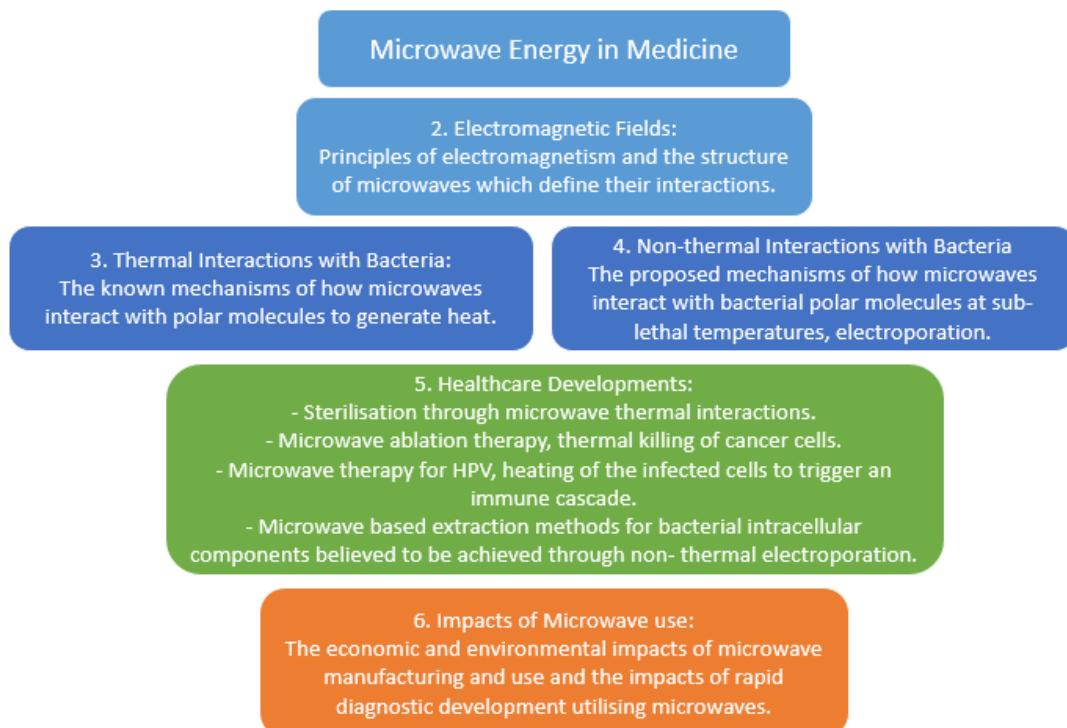
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Figure 1. Electromagnetic spectrum. A depiction of the range of frequencies and wavelengths in the electromagnetic spectrum and the sub ranges, as the wavelength increases the energy of the wave decreases [1].

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Figure 2: Summary of Topics Covered within Microwave Energy in Medicine. Diagram depicts key themes described in this review.

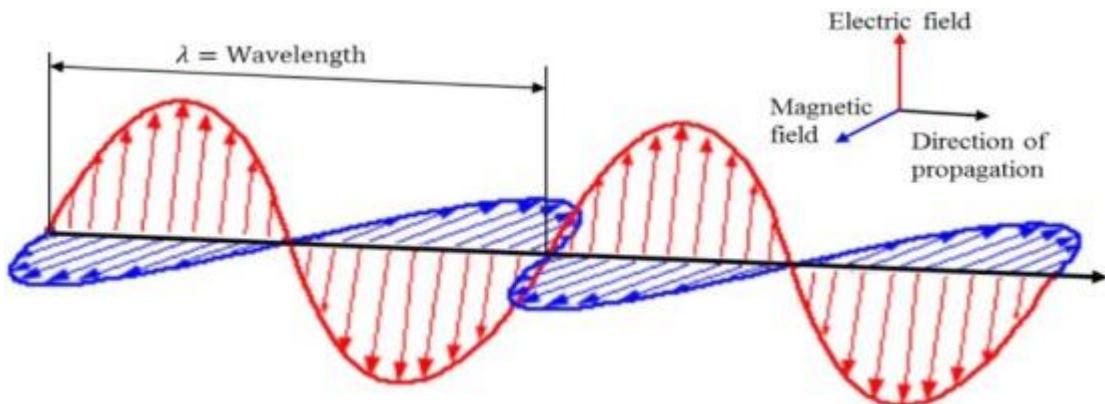
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Figure 3: Electromagnetic wave diagram. Showing the direction of the wave, the direction and oscillation of the electric field and the direction and oscillation of the magnetic field. Each runs perpendicular to another; direction travelling along the X axis, electric along the Y axis and magnetic along the Z axis [1].

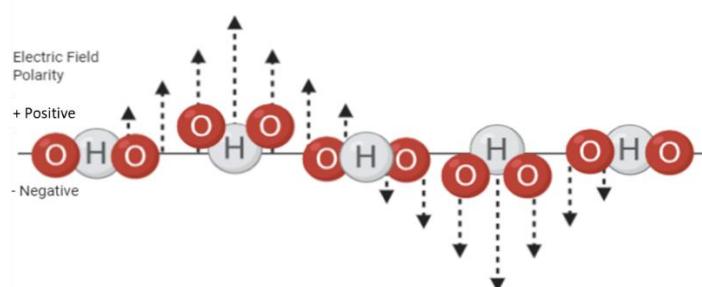
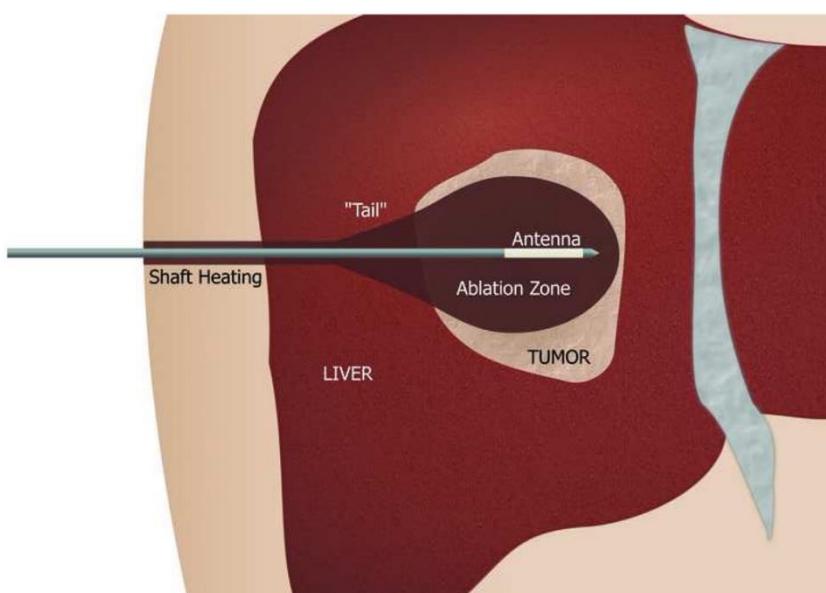
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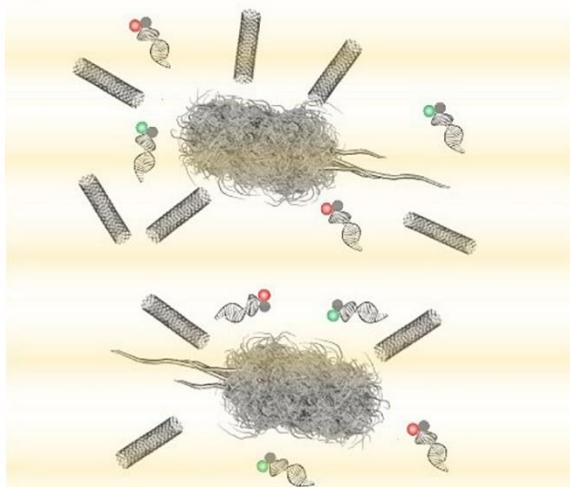
Figure 4: Water molecules rotation to align with an oscillating electric field. The electric field in a microwave oscillates between positive and negative polarity, the water molecules negative oxygen and positive hydrogen particles rotate to abide by the laws of attraction. This rotation generates thermal energy.

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Figure 5: Microwave ablation schematic. The microwave antenna is made up of a applicator shaft that has temperature monitoring in order to combat shaft heating. Shaft heating occurs due to reflection of the microwave and a cooling system is installed along the shaft to prevent burning. The antenna is most often needle shaped but can have a variety of designs including monopole, dipole and slotted antennas. The antenna design determines the tissue heating pattern and therefore impacts the ablation zone size and shape [38, 39].



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Figure 6: Nanotube assisted microwave electroporation (NAME) for single cell pathogen identification. Multiwall carbon nanotubes induce localized electroporation for the delivery of multicolour double stranded molecular probes for multiplex 16S rRNA detection [70]

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342 **Conflicts of Interest:** The authors declare no conflict of interest.

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