Chapter 1

Theory

This chapter reviews the established models of mm-wave absorption in biological systems that are principally related to **dielectric heating**. Other mechanisms have been postulated where a portion of the energy is not thermalized but channelled into higher processes. A brief description of non-thermal absorption mechanisms, which must be considered conjectural, is also presented. In connection with the absorption mechanisms, a simple model of a prokaryotic cell is described. Features such as the **cell membrane**, bacterial **chromosome** and **organelles** are identified as are some important parameters relating to biological systems.

The **millimetre wave** (**mm-wave**) range is part of the electromagnetic spectrum situated between the microwave and infrared ranges. It spans a frequency range extending from 30 to 300 GHz, which corresponds to an *in-vacuo* wavelength between 1.0 - 10 mm. This spectral region is also called "**Extremely High Frequency**" or **EHF**. Mm-wave photons possess less than the minimum energy required to remove an electron from an atom or molecule and are therefore non-ionising.

1.1 Biological systems

All living organisms are subject to a background level of mm-wave radiation. The Earth radiates in the mm-wave spectral range. This emission has been exploited in Earth observation technologies, with **passive radiometry**. Organisms are also subject to solar exposure, although some frequency ranges are strongly attenuated by the atmosphere (see appendix A).

The cell forms the basic structural and functional unit of all organisms and may exist as independent units of life or may form colonies or tissues as in higher plants and animals. Cells are capable of self-replication and possess a barrier or **membrane** that is structurally important and provides control of the intercellular environment. Collectively, the processes that are necessary for life are termed metabolism. Metabolic processes drive biological systems away from equilibrium. The establishment of a stable yet non-equilibrium state is a pre-requisite for the establishment of the **Fröhlich condensation** at physiological temperatures cf. Fröhlich condensation (1.4.1).

A major taxonomical division exists between **eukaryotic** and **prokaryotic** cells. Eucarya can be differentiated in a number of ways including a membrane surrounded nucleus and mitochondria which are needed for energy production. These are the constituent cell type in plants, fungi and animals. Prokaryotes contain two domains: the Bacteria and the Archaea. Bacteria are both ubiquitous and important in terms of their interaction with humans and ecological systems. Morphologically, bacteria are heterogeneous with spherical, rod-shaped and helical species identified. The size of a typical bacterium ranges between 0.5 and 20 µm although some examples exist significantly outside this range.

The cell contents or **cytoplasm** are enclosed within the plasma membrane, which is a phospholipid bilayer. The plasma membrane controls the transport of ions, solutes and metabolites between the environment and cytoplasm. Energy-producing processes are also located in the cell cytoplasmic membrane. A charge difference accumulates which results in the formation of a potential gradient. Protons flow through channels in the cell membrane into the cytoplasm and drive the **electron transport chain** involved in the synthesises of **ATP**. ATP molecules release energy when the triple phosphate bonds are broken. Most bacterial and plant cells also possess a wall that provides structural and other functions.

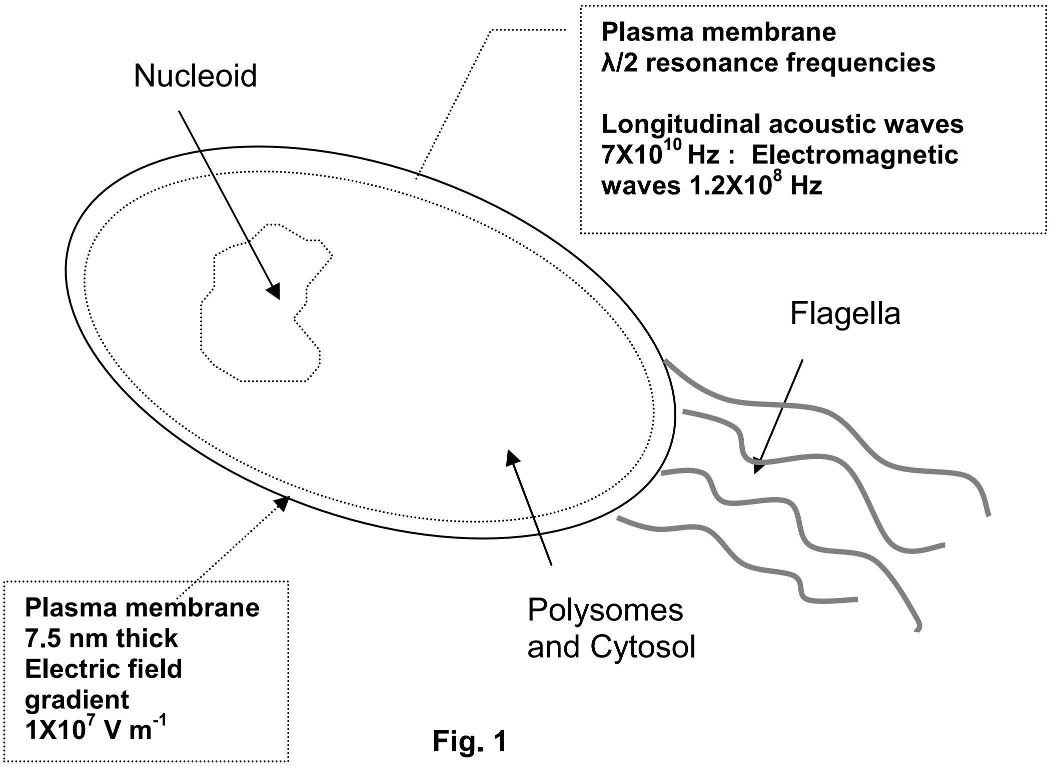

Fig. 1

Some basic features of a typical Prokaryotic cell such as *Escherichia coli*.

Nearly all biosynthesis occurs in the cytoplasm where the apparatus for translating mRNA into proteins, the ribosomes, are located. A typical cell contains approximately 1000 organelles known as polysomes. These contain the macromolecule producing machinery such as ribosomes and accessory **enzymes**. Basic structural units of all proteins include the α helix, important in Davydov's **soliton** model, and the β sheet. The nucleoid is the region that contains the bacterial chromosome, a covalently closed circular molecule made from **DNA**. Encoded in this sequence is information for cell reproduction and the synthesis of proteins, lipids etc. DNA can also encode information through its conformation, although the extent of this role in the functioning of biological systems is not fully understood (Rich 1993).

1.1.1 Bond energies

Covalent bonds link atoms together to form molecules in biological systems and are relatively strong. In addition to covalent bonds, weak bonds such as hydrogen bonds and Van der Waal's interactions are also important to the functioning of biological systems.

Covalent bond disruption	5 eV
Van der Waals interaction	1 eV
Hydrogen bond disruption	0.08 – 0.02 eV
Reversible conformational change	0.4 eV
Thermal motion (27 ^{o}C)	0.026 eV
30 GHz photon	0.0000124 eV

Table 1. Some important activation energies in biological systems

1.1.2 Vibrations and conformational transitions in proteins

The spectrum of vibrational periods extends from 10^{-14} s (weakly damped localized N-H or C-H stretching modes) to 10^{-11} s (overdamped collective modes) (Brooks & Karplus 1983; Brooks & Karplus 1985). The vibrational modes of proteins are related to the number of degrees of freedom. In proteins such as **DNA** the **vibrational modes** are overdamped in the mm-wave spectral region (Kurzynski 1998). They cannot be observed spectroscopically and are predicted by simulation only (Kurzynski 1998). Because of the effects of quantization, only low-frequency vibrations are thermally excited (Kurzynski 1998).

A **conformational state** is defined here as being surrounded by inter-conformational energy barrier heights of at least a few units of thermal noise, K_BT. Conformational transitions are not oscillatory. They are characterized by a spectrum of relaxation times, extending from 10^{-11} s to 10^{3} s.

1.2 Theoretical models

1.2.1 Quantum and classical electrodynamics

According to Wave-Particle Duality, electromagnetic radiation can simultaneously exhibit wave and particle-like properties. This being the case, interactions with matter may be described in terms of discrete packets or “quanta” having particle properties, or as electromagnetic waves as predicted by Maxwell’s equations.

In bioelectromagnetics, it is necessary to consider both aspects of the duality, as the application of one or another under certain circumstances may give misleading results (Vistnes & Gjotterud 2001). As a general approach, high-energy interactions such as those involving x-rays are best modelled as single-photon interactions. Owing to the Uncertainty Principle, the spatial localisation of a photon is dependent on its wavelength, which, in the case of x-rays, is on the same scale as bonds and other atomic structures. The case is quite different with mm-wave photons, where the wavelength is between 1 and 10 mm. With mm-wave interactions with matter, the reality is multi-photon interactions. With man-made sources an additional property is that they are highly coherent. In this case, as Vistnes states, “the classical field results form a coherent superposition of quantal amplitudes of a great number of photons” (Vistnes & Gjotterud 2001). Vistnes uses a criterion to determine the validity of a classical approximation (Vistnes & Gjotterud 2001). At first approximation, using this criterion, it would appear that the classical field description is adequate for describing bioelectromagnetic interactions.

On the other hand, a quantum-mechanical description is required for the interpretation of very low field intensity effects (Belyaev et al. 2000a) and the Fröhlich condensate is essentially a macroscopic manifestation of a quantum mechanical effect. In addition, quantum tunnelling and other processes that are not represented in the classical model may be important.

1.2.2 Thermal masking

All components of biological systems are subject to constant motion. This motion or thermal noise is random and related to the temperature of the system. The thermal energy of each degree of freedom in the system has an average of $\frac{1}{2}kT$. At 310 K, $\frac{1}{2}kT$ has the value of 0.027 eV (Polk 1995a). It is frequently argued that thermal masking militates against low intensity effects in biological systems. Individually, mm-wave photons do not have sufficient energy to interact with and break weak chemical bonds such as **hydrogen bonds**.

The concept of a “resonant” interaction or window effect is often invoked in the context of low intensity interactions. In its simplest form, this is because only thermal noise associated with frequencies close to the resonance need to be considered. In this way, a biological system may become sensitive to weak electromagnetic fields. In electronic systems heterodyne tuning, lock-in and other frequency-selective amplifiers allow the reception of weak electromagnetic waves by electronic systems. These can recover signals that would otherwise be masked by thermal noise. It is stressed that no analogous mechanism has been elucidated in biological systems but it shows that the possibility of the existence of such a mechanism cannot be ignored.

1.3 Dielectric heating

Three different dispersion regions have been identified through experimental investigations. Different absorption mechanisms are operative in each region. These are designated α, β and γ (Schwan 1983). The α and β dispersions predominate at frequencies below 1 GHz and are related to cell membrane effects and the motion of counterions (Schwan 1983).

At higher frequencies, such as those encountered in this study, the γ dissipation predominates (Grant & Gabriel 1991). The γ dissipation is related to the relaxation of water molecules (Grant & Gabriel 1991). The water molecule is a dipole where the hydrogen atom is positively charged and the oxygen negatively charged. The electric field directly couples with the dipole moment of water molecules. These attempt to align with the alternating electric field. The friction induced during this process affects distribution of heat leading through conduction and convection to bulk temperature rise. For pure water and other dipoles, Debye derived an expression for the relative permittivity (1.1). Additional attractive forces between polar water molecules are due to hydrogen bonds.

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+\varpi^2\tau^2} \quad (1.1)$$

Where ε_s is the static relative permittivity, ε_∞ the infinite frequency relative permittivity, ϖ Angular frequency and τ the relaxation time ε' the relative permittivity. The dielectric loss is given in (1.2)

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\varpi\tau}{1+\varpi^2\tau^2} \quad (1.2)$$

The dielectric loss (ε'') is maximal when ϖ and τ are both unity. For pure water at physiological temperatures, this occurs at approximately 25 GHz. Additional terms can be used to model relative permittivity for simple ionic solutions such as NaCl (Stogryn 1971). From the equations, it can be shown that the dielectric loss is both frequency and temperature dependent.

1.3.1 Absorption in a lossy dielectric

Penetration depth (1.3) is defined here as the distance at which the power density of an incident plane wave is reduced to 13 % of the initial value i.e. $1/e^2$ (0.13) (Gandhi 1983).

$$P = P_i e^{-2x/\delta} \quad (1.3)$$

In water and cell cultures, mm-wave radiation is rapidly absorbed. Penetration depth and specific absorption rate are frequency and temperature dependent for a given dielectric (Grant & Gabriel 1991).

1.4 Nonthermal absorption mechanisms

1.4.1 The Fröhlich-condensate

Interest in this class of absorption mechanism originates from the 1960s when **Fröhlich** (Fröhlich 1968; Fröhlich 1970; Fröhlich 1982b) postulated that something akin to **Bose-Einstein condensation (BEC)** could occur in biological systems. The BEC is a phenomenon where **bosons,** which have integral spin, all occupy the same quantum state and become indistinguishable, they exhibit what has been termed *macroscopic **quantum coherence***. The BEC was theoretically predicted by Einstein and Bose in 1924 and recently observed experimentally at temperatures close to absolute zero (Anderson 1995). Under certain circumstances, non-equilibrium systems can exhibit a similar quantum coherence but at much higher (physiological) temperatures. For example, in the laser it achieves coherence in photons through a process called stimulated emission.

In the case of biological systems Fröhlich states, “If the energy fed into the branch of longitudinal electric modes exceeds a critical rate, then, under stationary conditions the excitation energy is channelled into the mode with the lowest frequency in a manner typical for a BEC”. In Fig. 2 the relationship between thermal modes in the heat bath, vibrational modes in the biological system and the external pumping source is shown. It is postulated that in the case of biological systems, metabolism acts as the energy source.

The vibrational modes of the biological system interact with the heat bath via a non-linear interaction mechanism (Degn et al. 1980). As in the BEC, the low frequency modes become macroscopically occupied. It has been hypothesized that a Fröhlich condensate may have an important role in biological system in areas such as energy storage and biocommunication (Fröhlich 1968).

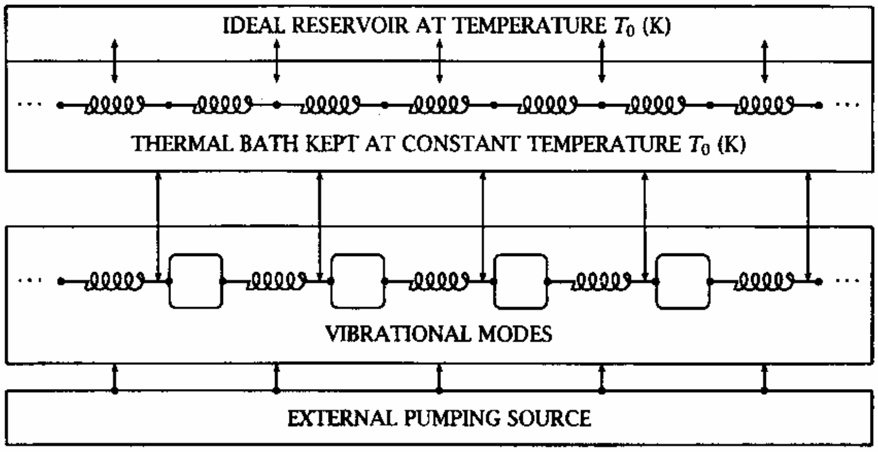

Fig. 2 Relationship between exogenous pump, system vibrational modes and thermal bath mode (Mesquita et al. 1999).

A number of variations of on the Fröhlich's model have been presented. Mesquita *et al* (Mesquita, Vasconcellos, & Luzzi 1998b) show that under certain conditions a positive-feedback effect can occur that greatly favours and enhances the formation of the condensate (Mesquita, Vasconcellos, & Luzzi 1998a). The concept of a Fröhlich condensate is rejected by Kurzynski (Kurzynski 1998) on the basis that low frequency collective normal modes cannot occur in highly inhomogeneous biomolecular structures.

1.4.2 Davydov soliton

Solitons are non-thermal coherent motions of local groups of atoms. They may propagate along the chains of alternating strong amide-I bonds and weak hydrogen bonds in α-helices (Kurzynski 1998). In the Davydov soliton model the solitary-like waves may be long lived, propagating over long distances (Scott 1992).

1.4.3 Bohr coupling

Bohr's model predicts the dynamically induced curvature of backbones in protein molecules (Bohr & Bohr 2000a; Bohr & Bohr 2000b). The "wring" mode may couple to electromagnetic radiation (Bohr, Brunak, & Bohr 1997) although the model primarily supports a broad resonance in the microwave 8 – 12 GHz region and not at higher frequencies.

Summary

The principal constituent of biological systems is water. Millimetre-wave radiation couples with the dipole moment of water molecules in biological systems. The molecules attempt to re-orientate with the oscillating electric field causing friction and heating of the dielectric. Incident power density is rapidly attenuated in lossy dielectrics such as cell culture media causing high specific absorption rates. In biological and other non-equilibrium systems, some models predict that not all energy is thermalized but may be used to maintain the coherent behaviour of a substance.