Physical interactions of electromagnetic fields with living tissue

Kari Jokela

STUK Radiation and Nuclear Safety Authority,
Non-Ionizing Radiation Laboratory,
P.O. Box 14, FIN-00881 Helsinki Finland
Email:kari.jokela@stuk.fi

INTRODUCTION

From the macroscopic perspective the interaction of electromagnetic (EM) fields on the human body is determined by electromagnetic theory and dielectric properties of tissues [1]. The dielectric properties are mainly determined by the high water content (60-70 %) and its' salinity (0.9 %), but we cannot still neglect the huge complexity arising from cell structure of the living matter.

COUPLING OF EM FIELDS TO THE HUMAN BODY

At low frequencies the coupling of the electric and magnetic fields to the body is governed by the high conductivity of the tissues due to the high salinity (0.9 %) of the tissue liquids. As a good approximation the body is a "metallic" conductor where the electric field is greatly attenuated due to the formation of surface charges, which effectively cancels the primary field leaving only a weak residual field. The magnetic field penetrates effectively to the body, but due to the Faraday law the time varying magnetic flux induces circulating weak electric fields and currents. At high frequencies above 100 kHz the tissue resembles more and more resistive lossy material, which absorbs energy from the electromagnetic wave. The penetration depth decreases as the frequency increases: Below 30 MHz all organs are exposed to the direct effects of the field, while above 2 GHz relatively small amount of energy penetrates deeper than 3 cm. It is of interest to note that the absorbed energy increases proportionally to the square of frequency up to 30-100 MHz, where the body resonates with the wave and then decreases with frequency being by a factor of approximately five smaller at 1 GHz than at the resonance frequency.

INTERACTIONS AT CELLULAR AND MOLECULAR LEVEL

The absorbed energy is converted to the heat. The heat load of the body, however, remains within physical fluctuations, if the total Specific Absorption Rate (SAR) of the body remains below the present occupational limits of 0.4 W/kg for the whole body averaged absorption, and of 10 W/kg for a local absorption (average within 10 gram tissue). The corresponding limits for the general population are 0.08 W/kg and 2 W/kg,. For example, the maximum temperature increase on the surface of the brain in the vicinity of a mobile phone does not exceed 0.3 ^{o}C, if SAR is less than 2 W/kg.

Dosimetric calculations indicate that, due to variation dielectric properties, the local peak SAR may significantly exceed the 10 g average, within the cell dimensions by more than a factor of 10. This, however, does not result in any significant local thermal hot spot because the thermal diffusion effectively removes the heat energy from a small SAR hot spot. It has been speculated that radio-frequency (RF) energy in the biologically important macromolecules, such as DNA and proteins, could be coupled by some resonant mechanism to the oscillating RF electric field, but there is no plausible theory or experimental evidence to support these claims. Macromolecules are surrounded by weak but numerous bounds to water and other molecules and cannot freely oscillate in the electric field. Several others RF mechanisms, many of them based on direct E-field effects, have been formulated, but none has yet survived a closer scientific scrutiny to explain biological RF effects at environmental exposure levels.

At the cellular level the cells have profound effect on the distribution of induced electric field. The cells are filled with relatively well conducting intracellular medium, which is separated from a similar extracellular medium by an insulating lipid layer membrane. Below 100 kHz the electric field and current does not penetrate the membrane, but flow around the cell surface. Consequently the voltage associated with the induced electric field concentrates over the membrane. The voltage is directly proportional to the length of the cell up to ca. 1 cm. Because the membrane is very thin (approx. 10 nm) the transmembrane-induced voltage generates significant electric field inside the membrane. The neurons and other electrically excitably cells contain ionic channels, which are sensitive to the transmembrane electric field. If the resting voltage depolarizes more than 10 mV, the electric force on the charged proteins may change the conformation of the protein and trigger the channel to the open state resulting in the generation of action potential. In terms of induced electric field the stimulation threshold is in minimum (2 V/m) from at the 10 to 1 kHz frequency range. This well-known electrical stimulation clearly shows that at low frequencies the tissues are more sensitive to the electric field than to the accumulation of the heat energy. In addition to the classic stimulation there is good evidence that the neural networks in the central nervous system are more sensitive to the electric field than single neurons alone. This is clearly indicated by magnetophosphenes, which occur when a magnetically induced electric field exceeds 0.1 V/m in the retina at ELF frequencies. It is believed that these effects are due to the spatial addition of small induced voltages in the synapses.

At low frequencies there is more uncertainty on the threshold of established biological effects than in the RF range. Perhaps this is due to the basic difference in interaction mechanisms. In the RF range the effects are due to accumulation of thermal energy, which is roughly proportional to the square of the induced electric field, while at low frequencies the effects are proportional to the induced electric field itself.

REFERENCES

[1] H. Nyberg, K. Jokela (Eds.), "Sähkömagneettiset kentät (in Finnish), Säteily ja ydinturvallisuus 6. Säteilyturvakeskus, Helsinki, Finland, 2006.