11 Electromagnetic Deep Heating Technology

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11.1 Physical Considerations

Deep heating represents an attempt to achieve effective temperatures in and around large extended tumors of the pelvis and abdomen. The term regional hyperthermia is used for heat treatments of such extensive volumes. It is important to realize that tumor lesions considered for regional hyperthermia are typically nonresectable, i.e., they infiltrate surrounding tissues, are not clearly delimited, and are adherent to neighboring tissues and organs such as bone and bladder wall. Consequently, an effective heat treatment should generously cover a larger volume (known as the biological or clinical target volume in radiotherapy) containing a macroscopic tumor and tumor boundaries as well as parts of the suspicious vicinity. The target volume can also include different types of tissues, e.g., tumor, infiltrated fatty tissue, and infiltrated bone. Typical depths of tumors (absorption lengths) as derived from human cross-sections are in the range of 10–15 cm. Disagreement persists as to whether electromagnetic radiation is suitable for heating deep-seated tumors. Several issues will be discussed in this chapter.

Every kind of electromagnetic heating technology generates an alternating electric field of amplitude $E$ in human tissue. The initial assumption is that the excitation of frequency $\omega$ is time-harmonic, i.e., sinusoidal. In this case $E$ can be represented as a phasor, i.e., vector with length and direction (indicated by a bold letter) and a complex number (indicated by underlining) contributing a phase $\phi$ with respect to a reference point (e.g., the exciting generator). One specific feature of this representation is the additivity of $E_j$ at every point if several sources $j$ with a fixed phase relation generate $E_j$. That means that the final electric field is simply $E = \Sigma E_j$. The electric field (V/m) deposits a power density measured in mW/g in the exposed tissue, the so-called specific absorption rate, SAR = $(\sigma/2\rho)E^2$. Here, $\sigma$ is the electrical conductivity of the absorbing tissue in S/m, which together with the relative dielectric constant $\varepsilon_r$ determines the absorption and wavelength of electromagnetic waves, and $\rho$ in g/cm$^3$ is the density. The dielectric distribution of $(\sigma, \varepsilon_r)$ in the human body is only approximately known. A quick estimation of heating capabilities is obtained by differentiating between high water...
content tissue ($\varepsilon_r = 70-80, \sigma = 0.6-0.8 \text{S/m}$) and low water content tissue ($\varepsilon_r = 5-10, \sigma = 0.05 \text{S/m}$, at a frequency around 100 MHz). A 2/3-conductivity of $\sigma = 0.55 \text{S/m}$ is a reasonable estimate when averaging the electrical behavior of patient cross-sections in the abdomen or pelvis. Two-dimensional calculations support this. In the interesting frequency range from 30 to 100 MHz (see below) a slight decrease in $\varepsilon_r$ as well as a slight increase in $\sigma$ with increasing frequency has been established.

The very first investigations into applying electromagnetic waves for deep heating examined the penetration of a plane wave of given frequency illuminating a homogeneous lossy medium with the propagation direction perpendicular to the medium boundary. We call this the one-dimensional electromagnetic problem of radiofrequency hyperthermia. The E field in the medium is an attenuated harmonic wave of the form $\exp(-\gamma z)$ in the propagation direction $\mathbf{z}^0$. The propagation constant $\gamma = \alpha + j\beta$ is derived from the attenuation constant $\alpha$ and the phase constant $\beta$ which depends on frequency and electrical constants according to the formulas in Table 11.1. The 50% depth $d_{1/2}$ is defined as the depth where the SAR is reduced to 50% (normalized to the maximum at zero depth), and is equal to $0.346/\alpha$.

According to Table 11.1, values of ($\sigma$, $\varepsilon_r$), the clinical 50% depth for muscle ($\sigma = 0.8 \text{S/m}$) are limited, with $d_{1/2} = 3.2 \ldots 6.7 \text{cm}$ if the frequency decreases from 100 \ldots 30 MHz. For a medium with lower 2/3-conductivity ($\sigma = 0.55 \text{S/m}$), the 50% depth increases slightly up to $d_{1/2} = 3.7 \ldots 7.8 \text{cm}$ (same frequency range). The wavelength $\lambda$ in the medium under consideration is derived from $\beta$ and ranges from about 30 cm (for 100 MHz) to 80 cm (for 30 MHz), thus indicating the required dimensions of the applicators, which should be on the order of several $\lambda$ (but at least $\lambda/2$) for appropriate radiation into the medium.

Obviously, illuminating a lossy medium from several directions to create an interference pattern in the interior should improve penetration depth as well as steering capabilities (BACH ANDERSEN 1985). Thus the concept of annular phased arrays (APAs) came into being very early (TURNER 1984b). The APA principle deals with a suitable arrangement of applicators/antennas controlled in phase and power around the volume to be heated. Several technical implementations of this concept are introduced and discussed in the next section.

It is interesting to inspect the best case of an SAR distribution which is physically possible for idealized cases of homogeneous media with given

<table>
<thead>
<tr>
<th>$f [\text{MHz}]$</th>
<th>$\varepsilon_r = 80, \sigma = 0.8 \text{S/m}$</th>
<th>$\varepsilon_r = 80, \sigma = 0.55 \text{S/m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha [1/\text{m}]$</td>
<td>$\beta [1/\text{m}]$</td>
<td>$d_{1/2} [\text{cm}]$</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>100</td>
<td>10.9</td>
<td>21.6</td>
</tr>
<tr>
<td>70</td>
<td>8.7</td>
<td>15.8</td>
</tr>
<tr>
<td>50</td>
<td>7.1</td>
<td>11.7</td>
</tr>
<tr>
<td>30</td>
<td>5.1</td>
<td>7.6</td>
</tr>
</tbody>
</table>

\[
\alpha [\text{1/m}] = 0.0148 f \sqrt{\varepsilon_r} \sqrt{\frac{1 + 1800 \sigma}{\varepsilon_r f}} - 1
\]

attenuation constant

\[
\beta [\text{1/m}] = 0.0148 f \sqrt{\varepsilon_r} \sqrt{\frac{1 + 1800 \sigma}{\varepsilon_r f}} + 1
\]

phase constant

\[\gamma = \alpha + j\beta\]

propagation constant

\[\gamma [\text{1/m}] = (1.9 \times 10^{-7} \varepsilon_r^2 f^4 + 62.2 \sigma^2 f^2)^{1/4}\]

\[\lambda = 2\pi/\beta\]

wavelength

\[d_{1/2} = 0.346/\alpha\]

50% depth (for SAR/2)

$f [\text{MHz}]$ frequency, $\sigma [\text{S/m}]$ electrical conductivity, $\varepsilon_r$ relative dielectric constant