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Heat Penetration in Biological Tissues During High Power Short Duration Radiofrequency Ablation

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The way heat propagates in the patient's body once it is delivered (or subtracted) in tissue ablation processes, is far from being intuitive. This aspect is particularly critical in radiofrequency ablation (RFA) for pulmonary veins isolation, a procedure extensively used for the therapy of atrial fibrillation, since the thermal energy delivered can damage surrounding organs, notably the esophagus. A rather large literature has been developed on this subject, see e.g[1]. As a manufacturer of esophageal thermal probes, FIAB S.p.A. (Vicchio, Italy) has dedicated much attention to this subject, performing theoretical studies whose results have been published in various papers[2-4].

The recently introduced technique of high-power-short-duration (HPSD) RFA has stressed the question of heat penetration even more. In the paper[5] various aspects of HPSD-RFA have been analyzed, emphasizing that luminal esophageal temperature can reach quite dangerous values and it is therefore necessary to monitor it with fast responding thermal probes.

Since in the paper just quoted the setting is necessarily complicated, here we try to highlight the phenomenon of heat penetration in biological tissues through a manageable example (i.e. keeping mathematics at the lowest possible level), which however is sufficiently close to the real case.

We consider the following situation. In a homogeneous medium (extending to infinity) at a temperature T_b a sphere of radius R is kept at a temperature $T_0 > T_b$. Such a sphere simulates the effect of the ablator and it will be present for a time of 5-10 seconds, depending on the operator choice.

We want to estimate the time at which the temperature increase $\gamma(T_0 - T_b)$, with $0 < \gamma < 1$, is reached at a distance βR from the center of the sphere ($\beta > 1$).

The spherically symmetric temperature T obeys the equation

$$\frac{\partial T}{\partial t} - \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r}\right) = 0$$

Where $r > R$ is the radial coordinate and $t > 0$ is time. The coefficient α is the medium heat diffusivity.

The solution of the said equation with the initial data $T(r,0) = T_b$ for $r > R$ and boundary data $T(R,t) = T_0$ for $t > 0$ can be shown to be

$$T(r,t) - T_b = \frac{R}{r}(T_0 - T_b)\left[1 - erf\left(\frac{r-R}{2\sqrt{\alpha t}}\right)\right]$$

Here $erf\ z = \frac{2}{\sqrt{\pi}}\int_0^z e^{-x^2}dx$ denotes the error function, tending to 1 as z tends to infinity. Thus, as $t \to \infty$ the right hand side has the limit , proportional to the fundamental harmonic function $1/r$ (in three space dimensions), i.e. the asymptotic temperature T_∞ solves the equilibrium equation $\nabla^2 T_\infty = 0$.

Tracing the isotherms of the time evolving thermal field is not an easy task. Therefore, let us revert to our former simpler problem: choose a distance $r = \beta R$ from the center of the sphere ($\beta > 1$) and compute the time t_β at which in that location the temperature undergoes the increase $\gamma(T_0 - T_b)$, with $0 < \gamma < 1$, i.e. it attains the value $T_b + \gamma(T_0 - T_b)$. The following equation is easily derived.

$$erf\,\frac{(\beta - 1)R}{2\sqrt{\alpha t_\beta}} = 1 - \beta\gamma$$

Since, as we said, the temperature asymptotic profile is $T_\infty(r) - T_b = \frac{R}{r}(T_0 - T_b)$, to which the temperature increases monotonically, it is not possible to choose β arbitrarily, as it is clearly shown from the equation above which indicates the constraint $1 < \beta < 1/\gamma$. Note that this fact is a consequence of the choice of having considered an infinite domain, which however for our purposes is sufficiently realistic.

Let us work out a specific example.

$R = 2$ mm, $T_b = 37$ °C, $T_0 = 80$ °C, $\alpha = 0.2$ mm^2/s (typical values)

$\beta = 2$ (we are looking at a distance of 4 mm from the ablator)

$\gamma = 0.05$, i.e. $\gamma(T_0 - T_b) = 2.15$ °C (thus the temperature exceeding the 39 °C threshold, frequently taken as an alarm temperature in esophageal temperature monitoring systems).

Hence = 0.9.

Let δ be such that $erf\,\delta = 0.9$. Then we look for t_β such that $\frac{(\beta-1)R}{2\sqrt{\alpha t_\beta}} = \delta$, i.e.

$$t_\beta = \frac{1}{\alpha}\left[\frac{(\beta-1)R}{2\delta}\right]^2$$

In our case $\delta \sim 1.2$ (error function calculators can be found on line), so we get $t_\beta \sim 3.5$s.

The result is interesting since the time we found is definitely shorter than the typical application time of a HPSD-RFA pulse (e.g. 6 seconds).

To have an idea of how sensitive the result is on the choice of β, we take now

$\beta = 3$ (a distance of 6 mm from the ablator), leaving other data unchanged.

Since $1 - \beta\gamma = 0.85$, we must look for δ such that $erf\,\delta = 0.85$ and we get $\delta \sim 1$, so eventually $t_\beta \sim 20$s.

Thus, we stress that this toy model is very sensitive to the parameter β. The reason is that if we increase β then $1 - \beta\gamma$ decreases making δ decrease too. Therefore, the ratio $\frac{(\beta-1)R}{2\delta}$ increases and this factor appears squared in the formula giving t_β and multiplied by the rather large factor $1/\alpha$.

Choosing instead the distance of 5mm from the ablator requires $\beta = 2.5$, therefore $1 - \beta\gamma = 0.875$ and consequently $\delta \sim 1.09$, eventually leading to $t_\beta \sim 9$s, still comparable to the HPSD-RFA pulse duration.

In addition, it must be kept in mind that the overall effect of the esophageal temperature during an ablation session is the sum of the effects of the various applications on a single pulmonary vein and therefore it depends also on the intervals between successive applications.

In conclusion, this simple example emphasizes that temperature increments in an alarming range can be achieved in the proximity of the ablation site, such as to potentially affect the esophagus. For a deeper insight into the problem of heat penetration during HPSD-RFA procedures, we refer to the complete study performed in[5].

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