Measurement of Power Density in a Lossy Material by means of Electromagnetically induced acoustic signals for non-invasive determination of spatial thermal absorption in connection with pulsed hyperthermia

F. Caspers* and J. Conway**

Abstract

For non-invasive determination of the spatial power density distribution during RF- and microwave hyperthermia it is proposed to apply the electromagnetic energy as short, high intensity pulses. This pulsed signal should have the same average power and thus give the same temperature elevation as the CW source usually applied. Due to the high peak power of the equivalent pulsed signal, with a duty cycle < 1:100, externally measurable thermoacoustic oscillations are induced in the irradiated object. They can be evaluated for the reconstruction of a spatial power density profile.

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MEASUREMENT OF POWER DENSITY IN A LOSSY MATERIAL BY MEANS OF ELECTROMAGNETICALLY INDUCED ACOUSTIC SIGNALS FOR NON-INVASIVE DETERMINATION OF SPATIAL THERMAL ABSORPTION IN CONNECTION WITH PULSED HYPERTHERMIA

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ABSTRACT

For non-invasive determination of the spatial power density distribution during RF- and microwave hyperthermia it is proposed to apply the electromagnetic energy as short, high intensity pulses. This pulsed signal should have the same average power and thus give the same temperature elevation as the CW source usually applied. Due to the high peak power of the equivalent pulsed signal, with a duty cycle < 1:100, externally measurable thermoacoustic oscillations are induced in the irradiated object. They can be evaluated for the reconstruction of a spatial power density profile.

INTRODUCTION

Microwave pulse-induced acoustic signals have been studied by many investigators with measurements performed on spherical head models [4]. The analysis of the involved thermoelastic mechanism has also been developed [1-3]. In this paper we consider the case where the microwave pulses are sufficiently separated in time so that practically no overlapping of the induced acoustic signals with those from the previous pulse occurs. Then the influence of boundary conditions can be eliminated by time filtering to simplify the acoustic signal analysis.

Reconstruction of acoustic and thus of electromagnetic power density levels along the axis of a microphone positioned at the surface of an irradiated body is possible if we assume that the microphone has a very narrow directional characteristic (directional diagram) so that only events occurring in the shaded area shown in Fig. 1 contributed to the signal received by the microphone. When a microwave pulse of short duration hits the body at time $t = 0$, it gives rise to an acoustic intensity $A(r,t)$ at time $t$ and a distance $r$ from the microphone. If the duration of the acoustic response is also negligibly short, then with $A(r,t) = 0$ for $t < 0$

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Fig. 1 Reconstruction model

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A_1(r, t = 0) = f_1(r) \cdot \delta(t) \tag{1}

for t = 0. With v = group velocity of the acoustic wave, the intensity \( A \) (e.g., acoustic pressure) at the receiver \( (r = 0) \) is for \( t > 0 \)

\[
A_1(r = 0, t) = K_1 f_1(v \cdot t)/v \cdot t
\]

if we assume that the microphone is operating in the far field and we neglect acoustic absorption. If the duration of the acoustic response is not negligible, then we have

\[
A_2(r = 0, t) = K_2 \int_0^{vt} f_2(r, t - \frac{r}{v})/r \, dr
\]

Simple reconstruction of the power density profile should be possible using short high intensity microwave pulses (\( \leq 1 \) usec) giving high frequency acoustic signals (> 100 kHz) with sufficient spectral power density. Multiple reflections can be rejected due to their relatively long time delays, and reflections from the body boundary may be avoided by microphone directivity.

Theoretical analysis of acoustic signal generation by Borth [1] and Lin [2] in a half space indicates that for a thermal expansion mechanism the Fourier transform of the time function of pressure will approach its maximum at an acoustic frequency of about 40-50 kHz for 10 usec wide microwave pulses and at about 500 kHz for 1 usec pulse width. Using the theoretical data as a base, an experiment has been set up to measure the parameters of the spatial reconstruction. In a water bath 4 open-ended (semi-rigid) coaxial cables acted as thermoacoustic "point-sources" (Fig. 2), and the response of a 50 kHz and of a 500 kHz microphone was recorded (Figs. 3 and 4). In both cases the same microwave signal (9 GHz, 1 usec pulse width, 200 Hz

Fig. 2 Experimental arrangement

Fig. 3 50 kHz microphone response
repetition rate and 25 W incident microwave peak power into each coaxial cable) was applied. The VSWR of these open-ended cables was measured < 2 at 9 GHz with the inner conductor protruding 0.75 mm to form a λ/4 antenna in water. Thus the diameter of the equivalent "point source" may be regarded as approximately 2 mm (skin-depth of water at 9 GHz ≈ 1 mm).

To prove that the measured acoustic signals were not produced by thermo-acoustic effect from the waveguide power divider (3 T-hybrids with dummy load, Fig. 2), or from the semi-rigid cables themselves, experiments have been performed using open-ended X-band waveguides instead of the coaxial lines. The apertures of the waveguides were kept 2 mm above the water surface. At 50 kHz no significant change, apart from an amplitude factor of the acoustic signals, was to be observed, but at 500 kHz the diameter of the water surface close to the waveguide aperture is no more negligible in comparison with the acoustic wavelength, thus causing a distinct directive pattern. The relative bandwidth of the microphones is 10%, and the aperture diameters are 50 mm (50 kHz) and 38 mm (500 mHz) respectively. The curves show that with the 50 kHz response a power density reconstruction would be very difficult, due to reflections from the boundaries of the acoustic waveguide (i.e. water tank with soft boundaries, Fig. 2) and the poor time resolution caused by the low absolute bandwidth. In the second case (500 kHz response) the four "point sources" are clearly discernible and not blurred by boundary reflections. It was also proven experimentally that the optimum microwave pulse width for maximum acoustic signal is in good agreement with the theoretical results from Borth [1]. For practical applications, it may be useful to determine the acoustical refractivity profile along the microphone axis with conventional methods and include this information into the reconstruction process to increase accuracy.

CONCLUSION

The authors suggest that this method of resolving power density variations in microwave irradiated materials could be developed as a means of assessing power and by integrating thermal distribution in patients undergoing pulsed microwave hyperthermia therapy. Possible risks due to cell damage by electric breakdown of membranes have to be considered only for very high microwave-pulse intensities [5], [6].

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