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REDUCTION IN BEAM POSITIONING ERROR DURING HIFU ABLATION STUDIES IN TISSUE PHANTOMS

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ABSTRACT

Measurements of high intensity focused ultrasound (HIFU) induced temperature rise using thermocouples in tissue phantoms are subject to several types of error which must be accounted for in order to accurately assess the thermal field and predict the outcome of clinical procedures. Thermocouple artifacts due to viscous heating is one source of error. A second source of error involves displacement of the beam relative to the targeted thermocouple junction, due to the difficulty in precisely positioning the very narrow beam. This paper presents an iterative method for removing inaccuracies due to positioning error from the measured temperature data. The refined data is used to quantify the effect of blood flow through large vessels on the efficacy of HIFU procedures. It was determined that blood flow cooling effect causes an order of magnitude decrease in thermal dose at the target within 2 mm of the blood vessel, potentially resulting in incomplete ablation of the tumor. The technique also reveals that thermocouple artifacts exist in significant proportions from about 0.5 to 2.2 times the computed temperature rise in the initial few seconds. The iterative method can aid in clinical procedure planning, especially in predicting the proper HIFU intensity and duration for complete destruction of tumors.

INTRODUCTION

Tissue-mimicking phantoms and animal tissues embedded with thermocouples are often used to test the ability of HIFU transducers to thermally ablate tumors. The thermocouple measurements are subject to errors [1, 2], including the uncertainty involved with positioning the narrow HIFU beam directly atop a thermocouple junction. In this study, HIFU induced temperature rise is measured in a tissue mimicking material [3], using embedded thermocouples near an artificial blood vessel, with the purpose of assessing the effect of blood flow on treatment efficacy. A computational method is used to refine the measured data of positional inaccuracies. Thermocouples artifacts are also determined. The refined data is analyzed to quantify the effect of blood flow on the outcome of the procedures.

METHODOLOGY

Figure 1A shows the tissue mimicking material with an artificial blood vessel. Thermocouples are embedded 2, 4 and 6 mm away from the blood vessel (Fig.1B). The HIFU beam is positioned on the thermocouple 2 mm away from the vessel by a manual procedure of moving the beam till maximum temperature rise for a brief sonication time of 10 s is recorded. Ablations are performed for 30 s, at flowrates, 0 and 400 ml/min. The power levels used are 5, 10.3, 17.3 and 24.8 W. Temperature rise is recorded during each ablation procedure. Experiments are repeated on three different days. Simulated ablations are performed on the 4 and 6 mm thermocouples. A novel numerical algorithm, described below, is used to refine the beam–vessel displacement on each day.

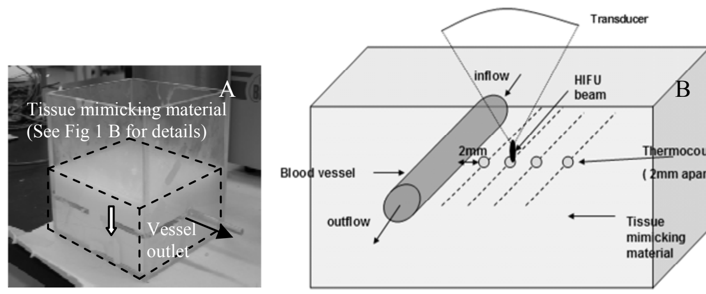

Figure 1A: Tissue mimicking material with blood vessel; and B: Schematic of thermocouples embedded near blood vessel

The location of the beam with respect to the thermocouple junction is assumed and supplied to the algorithm as an initial prediction. Numerical calculations, similar to Hariharan et al. [4] of our lab, are then performed to calculate the temperature rise at the junction based on the initial location. The KZK parabolic wave equation (eq.1) is solved to obtain acoustic pressure, p(r,z), and power deposition rate, Q, is then calculated using $Q = \alpha p^2/\rho_o c_o$, where α is absorption coefficient of tissue. The heat equation (eq. 2) is solved to generate the transient temperature field in the material.

$$\frac{\partial}{\partial t}\left[\frac{\partial p}{\partial z}+\frac{D}{2c_0^3}\frac{\partial^2 p}{\partial t^2}\right]=\frac{c_0}{2}\left(\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}\right) \qquad (1)$$

$$\left(\rho_0 c_p\right)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right)+Q \qquad (2)$$

Here, p is the acoustic pressure amplitude, t is time, c_0 is speed of sound in the tissue (~1540 m/s), D is sound diffusivity, ρ_0 is density (~999 kg/cm^3) and c_p is the specific heat (~3770 J/kg.K).

The transient numerical and experimental temperature rise at the thermocouple are compared to obtain the error, ε [= $(T_{exp}-T_{num})/T_{num}$]. In the next step, the initial prediction for beam location is refined by an optimization algorithm (Nelder mead) to reduce the error value. This iterative process is performed repeatedly until ε can be reduced no further. The location corresponding to minimum ε is taken to be the final beam location with respect to the thermocouple.

RESULTS AND DISCUSSION

Figure 2 shows the temperature rise, ΔT, after 30 s ablation as a function of the beam-thermocouple displacement computed by the iterative algorithm. It is seen that ΔT decreases with increasing beam-vessel displacement. The temperature data is curve fitted with a parabolic function such that the heat flux or dT/dx is 0 at the y axis. When the parabolic function is evaluated at the y axis, ΔT for zero displacement between beam and thermocouple i.e. zero positioning error, is obtained. The extrapolation process is performed for both the no flow (0 ml/min) and the flow case (400 ml/min).

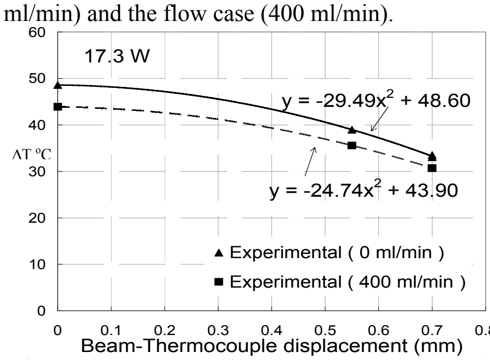

Figure 2: ΔT vs beam-vessel displacement at power level 17.3 W and flowrates: 0 and 400 ml/min. Extrapolation to correct positional error

The extrapolation procedure in Figure 2, is performed at all sonication times (0-30 s) and also for the cooling duration (31-60 s). The resulting extrapolated experimental transient temperature profile, shown in Figure 3A, is obtained at the thermocouple junction for the no flow and flow cases. The corresponding numerical profiles are also shown for comparison. It is seen that ΔT in presence of flow is lower than that in the absence of flow. The experimental ΔT drops from 48^oC under no flow conditions to 43^oC under flow conditions (10% decrease) after 30 s sonication. This is due to the convective cooling effect of blood flow. Also the experimental ΔT is higher than the corresponding numerical ΔT because of thermocouple artifacts, which cause additional heating at the thermocouple junction.

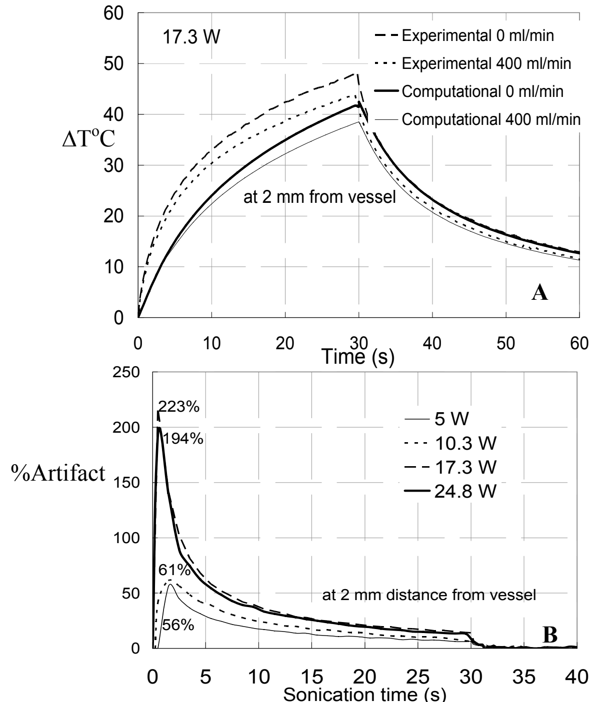

Figure 3: A) Transient temperature profile at thermocouple junction when beam-thermocouple displacement = 0, obtained by data extrapolation (shown in Fig. 2). Both no flow and flow cases are shown. B) Percentage artifact vs sonication time at 5, 10.3, 17.3 and 24.8 W.

Figure 3B shows the percentage artifact expressed as the difference between the experimental ΔT and the numerical ΔT, normalized by the numerical ΔT. The percentage artifact is seen to be high in the initial 1-2 s for all power levels. At power level 17.3 W the initial % artifact is around 223%. Subsequently the effect of artifacts decreases and attains a value of 7%, 5 seconds after initiation of sonication. In the cooling phase when the beam is no longer present at the junction, the artifacts reduce and there is a close match between the numerical and experimental cooling profiles.

CONCLUSION

The iterative algorithm presented in this paper significantly reduced the beam positioning error affecting HIFU-induced temperature measurements. The enhanced accuracy of the adjusted temperatures allowed an assessment of the effect of blood flow on temperature rise, and it was found that large vessels located 2 mm from a HIFU beam can reduce the temperature rise of a typical ablation procedure by 10%.

ACKNOWLEDGEMENT

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