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 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.
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, \( Q \). The resulting extrapolated experimental transient temperature profile, \( T_{\text{exp}} \), is obtained at the thermocouple junction for the no flow and flow cases. The corresponding numerical profiles are also extrapolated (shown in Figure 3A). This iterative process is performed repeatedly until the percentage artifact is seen to be reduced no further. The location corresponding to minimum \( \varepsilon \) is taken to be the final beam location with respect to the thermocouple.

RESULTS AND DISCUSSION

Figure 2 shows the temperature rise, \( \Delta T \), after 30 s ablation as a function of the beam-thermocouple displacement computed by the iterative algorithm. It is seen that \( \Delta T \) decreases with increasing beam-vessel displacement. The temperature data is curve fitted with a parabolic function such that the heat flux or \( \partial T/\partial x \) is 0 at the \( y \) axis. When the parabolic function is evaluated at the \( y \) axis, \( \Delta T \) 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: \( \Delta T \) vs beam-vessel displacement at power level 17.3 W and flowrates: 0 and 400 ml/min. Extrapolation to correct positional error](image)

Figure 3A shows the percentage artifact expressed as the difference between the experimental \( \Delta T \) and the numerical \( \Delta T \), normalized by the numerical \( \Delta T \). 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

This work was funded by the National Science Foundation (Grant No. 0552036).

REFERENCES