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DETERMINATION OF HIFU INDUCED TEMPERATURE RISE AT FOCAL LOCATION USING NUMERICAL APPROACH

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INTRODUCTION

High Intensity Focused Ultrasound (HIFU) is a hyperthermia therapy that deposits high amount of acoustic energy at a point resulting in a high temperature rise. It is used in treatment of uterine fibroids, prostate and other cancers where the diseased tissue is heated to a specific temperature. Thus, accurate prediction of temperature rises during such scenarios is extremely important. Measurement of temperature rises with experiments is challenging. In addition, errors due to artifacts are possible during temperature measurements [1]. Therefore, it is advantageous to perform numerical studies to estimate the temperature rise.

The *objective* of this study is to predict the HIFU induced temperature rise in a tissue phantom for different acoustic powers using the software PZFlex and compare that with experimental results.

METHODS

Numerical model: The computational model involves a HIFU transducer and a 2D axisymmetric nonlinear tissue mimicking material (TMM). The TMM was surrounded by water. The default values for the initial temperature of TMM and the surrounding water were 37 °C and 25°C, respectively. The transition distance or the distance between the transducer and the material was maintained at 15 mm (Fig. 1). The computations were performed for an ultrasound frequency of 3.3 MHz, for different input powers of 5, 10, 20, 30, 40, 50 and 60 W.

The governing equations used for simulation of ultrasound in tissue models are the conventional momentum and constitutive equations. Taking into account, the first two terms of pressure expansion in power series, we obtain the 'B/A' model.

$$p = -K\left(\nabla . u + \frac{1}{2}\frac{B}{A}(\nabla . u)^2\right) \tag{1}$$

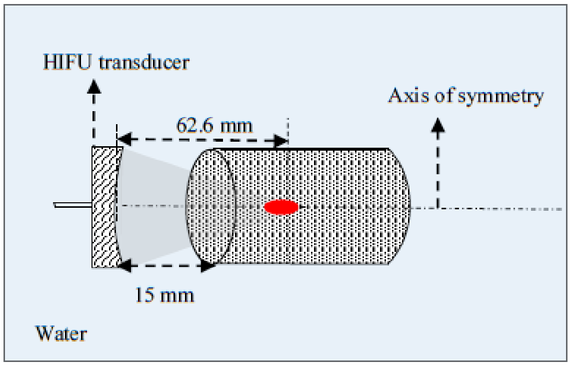

Figure 1: Geometry of the HIFU model

where p is the pressure (Pa), K or ρc^2 is the bulk modulus of the tissue material (Pa), ρ is the TMM density (Kg/m^3), c is the bulk velocity of sound (m/s) and u is the displacement vector (m), *B/A* is the parameter of nonlinearity (dimensionless) [2].

$$I = < p^2 > / \rho c \tag{2}$$

$$Q = \textstyle\sum_{n=1} 2\alpha I_n \tag{3}$$

Heat source, Q (W/m^3) can be calculated using intensity, I (W/m^2) which is obtained from acoustic pressure. α is the acoustic absorptivity (dB/m).

The thermal transient response was obtained by solving the Pennes bioheat transfer equation [3]. The perfusion term was neglected because of the absence of microvasculature in the TMM:

$$\rho C \frac{\partial T}{\partial t} = k(\nabla^2 T) + Q \tag{4}$$

where T is the temperature (°C), C is the specific heat of the TMM (J/Kg.°C), k is the thermal conductivity of the TMM in (W/m.°C).

Computations for the seven different applied acoustic powers were conducted keeping the sonication time as 30 s. The calculated pressure values at the transducer surface for each of the applied powers were used as the input along with the transducer properties (Table 1) to obtain the focal temperature rise. The difference between the peak temperature of the material and the initial temperature was used as the value for temperature rise. The properties of the nonlinear TMM used in the computations are presented in Table 2.

Table 1: Transducer properties and setup

Diameter	64 mm
Focal length	62.6 mm
Transition distance	15 mm
Sonication time	30 s

Table 2: TMM material properties

Density	1040 Kg/m^3
Bulk velocity	1534 m/s
Bulk attenuation	46 dB/MHz/m
B/A	7
Specific heat capacity	3780 J/Kg.°C
Thermal conductivity	0.58 W/m.°C

Experimental setup: Experiments were performed to estimate the focal temperature rises in a TMM for similar scenarios as in numerical method. The TMM was prepared as per the protocol presented in King et al [4]. The TMM was mixed in liquid form and poured into a cylindrical fixture of diameter 8 cm. The fixture was embedded with eight thin wire thermocouples (TCs) [5], positioned in four separated layers, with two TCs in each layer. The TCs in the same layer were placed 4 mm apart, while the adjacent layers were separated by a distance of 3 mm.

The HIFU beam was positioned inside the TCs array and away from the TCs junction to avoid any errors due to the artifacts. In order to evaluate the focal temperature rise using the remote TCs measurements, a localization algorithm [5] was first implemented to determine the location of beam focus inside the TCs array. After finding the relative location of the beam focus, the focal temperature prediction was made using an estimating function [5]. The estimating functions can be developed from common fitting functions where the unknown parameters can be determined based on the TCs measurements. Here, assuming that the heat production has Gaussian profile in radial direction (with no axial variation), the estimating function was written in terms of exponential integral as shown by Dillon et al [6]. The focal temperature estimation using the exponential integral was performed for the acoustic powers of 30, 40 and 50 W.

RESULTS

The values shown in the Fig. 2 correspond to the maximum focal temperature rise attained numerically for the sonication period of 30 s. The focal temperature rise values obtained numerically were 6.8 °C, 13.6 °C, 27.2 °C, 40.8 °C, 54.6 °C, 68.1 °C and 81.9 °C for the input acoustic powers of 5, 10, 20, 30, 40, 50 and 60 W, respectively. The nonlinearity in the peak temperature rise at higher powers (40 W, 50 W and 60 W) cannot be observed and further investigation is required.

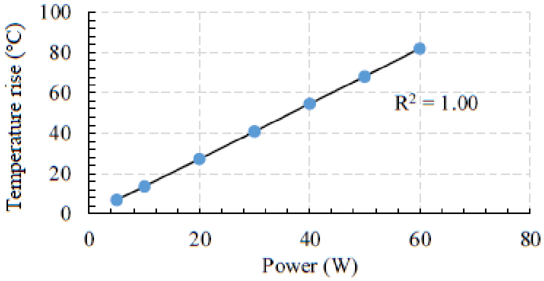

Figure 2: Variation of temperature rise with input power

Comparison of the computational results with the experimental [5] values shows a deviation of 13.2 % for 30 W, 1.0% for 40 W, and 2.6 % for 50 W of input power (Fig.3), while the average deviation for the three powers is 5.7%.

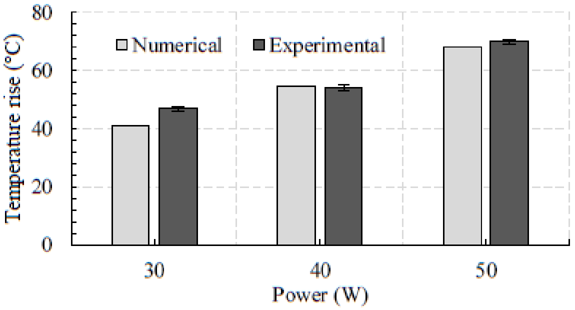

Figure 3: Comparison of numerical and experimental values of temperature rise

DISCUSSION

The temperature rise values achieved for various power inputs based on computations for nonlinear TMM have been presented in this study. The numerical temperature rises show good agreement with experimental temperature rises for 30 W, 40 W and 50 W. Numerical results match within 5.7% of the experimental values when averaged for all the three powers. Hence, numerical methods can provide reliable estimates of focal temperatures when conducting experiments is difficult.

Assumptions and limitations. All the computations have been performed assuming that the tissue properties are uniform. Nonlinear temperature rise at higher power needs further assessment.

Future scope. The current study will be extended to estimate the temperature rise by incorporating different TMM properties. A comparison of the numerically obtained results will be made with *in-vivo* experimental temperature values.

ACKOWLEDGEMENTS

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