3D FINITE DIFFERENCES SIMULATION OF COUPLED ACOUSTIC WAVE AND BIO-HEAT EQUATIONS: SKULL HEATING PREDICTION FOR NON INVASIVE BRAIN HIFU THERAPY

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Abstract

Medical applications of ultrasound to the human brain are highly limited by the strong phase and amplitude aberrations induced by the heterogeneities of the skull. However it has been shown that time reversal coupled with amplitude compensation enables to correct these aberrations. In this paper we propose a model for computing the temperature elevation in the skull during a High Intensity Focused Ultrasound (HIFU) transcranial therapy. Based on CT scans, the wave propagation through the skull is computed with a 3D finite differences software. The acoustic simulation is combined with a 3D thermal diffusion code and the temperature elevation inside of the skull is computed. A new positioning technique was also developed to position the array with respect to the skull. Finally, the simulation is experimentally validated by measuring the temperature elevation in several locations of the skull.

I. Introduction

High Intensity Focused Ultrasound (HIFU) brain therapy remains very limited due to the strong aberrations induced by the skull. Indeed, a large discrepancy between the skull high acoustic velocity (about 3000 m.s^{-1}) and the brain velocity (about 1540 m.s^{-1}) combined with a severe attenuation of ultrasound in the bone strongly degrade the beam shape [1]. However, in the last decade, several ultrasonic techniques have been developed to achieve minimally invasive therapy of brain tumors. Thomas and Fink [2] proposed in 1996 to use a time reversal mirror with amplitude compensation to correct the skulls aberrations. In this technique a hydrophone is previously implanted, and the signals relating this hydrophone to the transducers of the HIFU array are recorded. Then, one has to emit the time reversed signals with amplitude compensation in order to correct both phase and amplitude aberrations induced by the skull.

Recently, several studies have shown the feasibility of a completely non-invasive procedure based on high resolution CT scans [3],[4]. The acoustic properties, such as sound velocity, density, and attenuation can be extracted from the CT images at each point of the skull. Thanks to a finite differences numerical simulation of the complete wave equation, it is indeed possible to model the 3D propagation of an acoustic wave through the skull [5]. Thus, the positioning of the HIFU array in regard to the skull is a critical point.

In this paper, we propose to couple the acoustic propagation software with a 3D thermal diffusion algorithm based on the bio-heat equation. In order to position experimentally the array with respect to the skull we determined experimentally the geometrical shape of the skull, and matched it to the high resolution CT scans data. Then a complete non-invasive time reversal procedure combined with amplitude compensation is numerically performed. Finally, the increase of temperature in the skull is investigated and compared to experimental thermocouples data.

II. Skull modelling

The local acoustic properties (density, sound velocity and attenuation coefficient) of a human skull were deduced from high-resolution CT images (0.33 mm in-plane resolution, slices 1mm thick), according to Aubry *et al.* [5] models. An example of the velocity map deduced from the raw CT data is given in Fig.1.

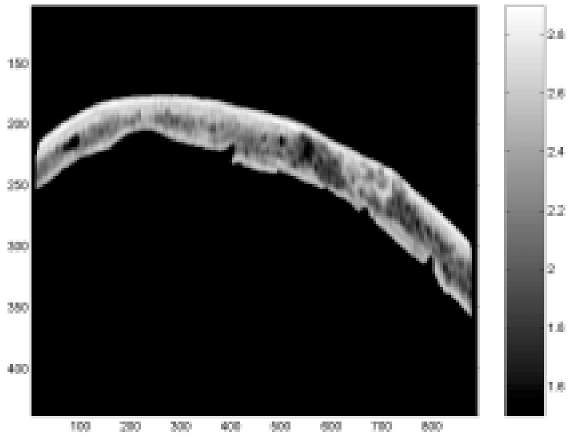

Figure 1: Slice of the 3D velocity map (mm.µs^{-1}).

The wave propagation was computed using a finite differences code (ACEL) of the full 3D wave equation [5],[6].

The thermal properties of a typical skull were found in [6]. The temperature was computed using a 3D finite differences code based on Penne’s bio-heat equation [7]:

$$\rho C_t \frac{\partial T}{\partial t} = \nabla . k \nabla T + Q_0 + Q$$

where Q_0 is a blood perfusion term and Q the heat source term that is computed by tacking in account the local pressure p, absorption α, density ρ and sound velocity c.

$$Q = \frac{\alpha |p|^2}{\rho c}$$

III. Experimental setup

Experiments were performed with a high power ultrasonic array specially designed for transcranial therapy [8]. It is composed of 200 high power transducers randomly distributed on a spherical holder, and working at 1MHz. Each transducer was linked to its 50 electrical matching and could generate a monochromatic wave with intensity of 20 W.cm^{-2} during 5 s (the electrical to acoustical efficiency reached 50%). The transducers present also very good performances in terms of bandwidth since the cut frequencies at -6 dB are 0.63 MHz and 1.17 MHz.

The transducers are connected to a 200 channel electronic driving system. Each electronic channel is fully programmable and has its own high power emission electronic board that could generate 16 W. Moreover, 80 electronic channels have also a reception electronic board.

Figure 2: 200 Elements HIFU array.

In order to position the skull at the exact location of the skull in the simulation, we have developed a new positioning technique. A skull surface detection process was performed, based on measuring the time of flight of pulse-echo signals transmitted by 80 of the 200 transducers of the HIFU array. The detected surface was matched to the CT scans data, using a surface-matching algorithm based on Powell’s minimization method. This technique enables to position the skull with an accuracy of about 1 mm.

In order to validate the temperature simulation, 3 thermocouples sensors were placed on the outer surface of the skull, 3 sensors were set on the inner surface, and 2 thermocouples were inserted inside of the diploë. The sensors were connected to a multichannel temperature acquisition board.

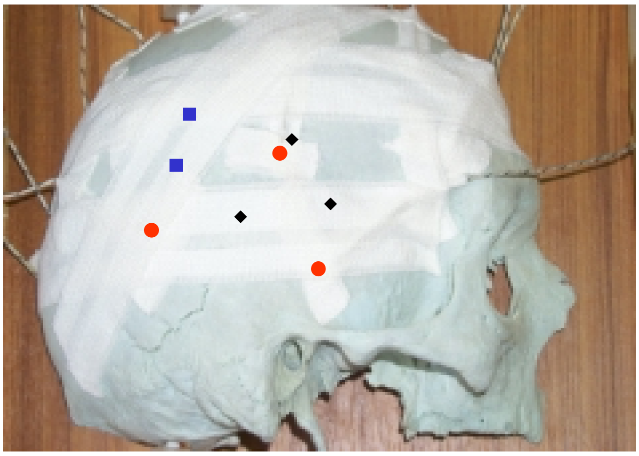

Figure 3: Location of the 8 thermocouples sensors. (on the outer surface ●, on the inner surface ◆, inside of the skull ■).

IV. Experiments and results

A first experiment was performed with high intensity at focus. The skull aberrations were corrected by a time reversal process using a hydrophone. The signals relating each element of the HIFU array and the hydrophone were recorded, time-reversed and the amplitudes were adjusted at the maximum level. A 5s sonication was performed and the intensity at focus was found to be 1200 W.cm^{-2}. During the sonication, the temperature was recorded by the thermocouple with a repetition time of 0.2 s.

The simulation corresponding to this particular experiment was also performed: the initial temperature was 31°C, the output intensity of each transducer was set to 16 W.cm^{-2}, the aberrations were corrected by a time reversal process and the perfusion was not taken into account. Fig 4. and Fig 5. show the temperature distribution after 5s of sonication. The distribution was found to be highly inhomogeneous, and the temperature elevations could reach from 1 °C to 17 °C at several locations. High temperature elevations are observed on the outer surface, but one should notice that the inner surface is particularly preserved from overheating (fig 5 and 6). In the inner table, the temperature elevation was found to be between 1°C and 4°C.

The computed temperature was compared to the temperature recorded by the thermocouples in the experiment. As it is shown in Fig 6. the simulation is in very good agreement with the experiment. The error in the temperature was found to be less than 1.5°C for the 8 different locations, as well as on the outer surface, on the inner surface or inside of the skull.

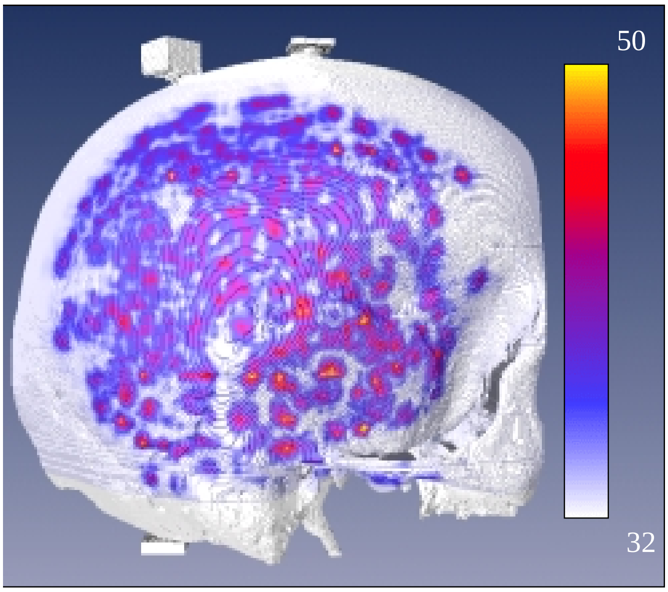

Figure 4: Temperature distribution on the surface skull after 5s sonication.

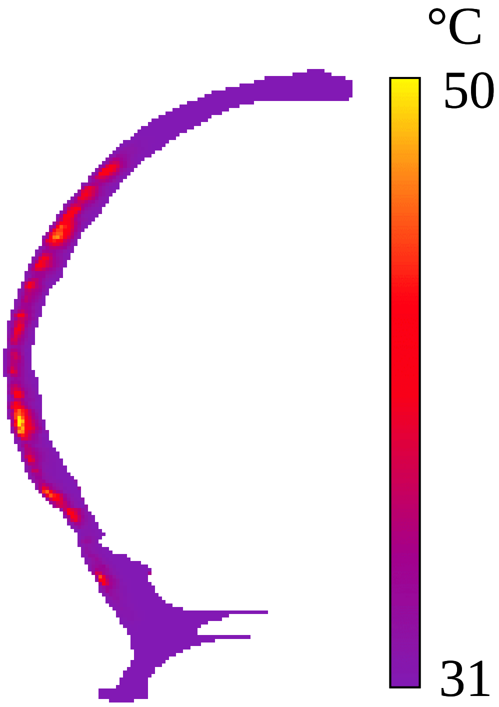

Figure 5: Temperature distribution in a CT slice of skull

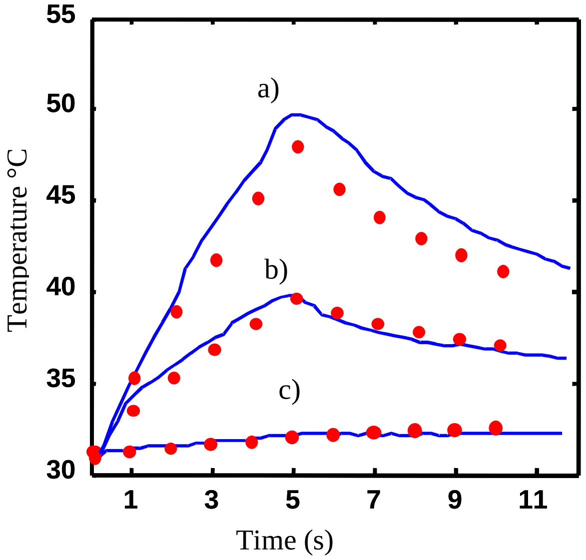

Figure 6: Temperature measured by thermocouples (-lines) and computed (●) at 3 different locations located a) on the outer surface b) inside of the skull and c) on the inner surface.

Finally, a simulation was performed with *in vivo* conditions. The initial temperature was set to 37 °C and the blood perfusion was set to 0.02 ml/min/ml of tissue. Moreover, a cooling system was achieved on the outer surface by adding a flow of water at 10°C. A 5s sonication was computed with an intensity at focus of 900 W.cm^{-2}. The temperature at focus was simulated and reached 65 °C. The temperature inside of the skull was computed during the whole sonication. The temperature distribution is again highly inhomogeneous, the mean temperature elevation was found to be 2.6°C and the standard deviation was 5.3°C.

Conclusion

A complete non-invasive procedure was achieved for HIFU brain therapy. CT scans were used both for correcting the skulls aberrations, and positioning the HIFU array with respect to the skull. The CT scans were also used for modeling the acoustic and thermal properties of the skull. The acoustic wave propagation software was coupled to the bio-heat equation and the temperature elevation was computed inside of the skull. The simulation was experimentally validated by thermocouples measurements. It shows that the temperature elevation is highly inhomogeneous inside of the skull. This results demonstrate that the amplitude of each transducer must be individually adjusted in order to avoid high temperature elevations.

References

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