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DETERMINATION OF LESION SIZE AS FUNCTION OF HIFU SONICATION TIME USING MRI MONITORED HIFU ABLATIONS

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ABSTRACT

The purpose of this study is to determine the dependence of the size of the thermal lesion on sonication time in an *ex-vivo* porcine liver sample during simulated High Intensity Focused Ultrasound (HIFU) tissue ablation. MRI guided HIFU ablations were performed on a freshly *excised* porcine liver sample at 70 W acoustic power. The size of the lesion (ablated zone) was measured at sonication times, 20 s, 30 s and 40 s. Numerical calculations were performed to validate the experimental lesion size. Also, a histology study of the ablated liver sample was performed to confirm cell necrosis within the ablated zones. It was found that the HIFU induced lesion size is strongly dependant on sonication time and lesion size almost doubles (increases from 0.368 to 0.715 cm^2) as sonication time increases from 20s to 40s. The area of lesions, determined experimentally, agreed within 5% with results of numerical calculations.

INTRODUCTION

Instant conversion of acoustic energy to thermal energy at the focus of High Intensity Focused Ultrasound (HIFU) transducers results in rapid temperature elevation in tissues, causing cellular death or necrosis at the focal zone. Hence, HIFU ablation procedures can be used to selectively ablate tumors deep within the body while sparing the surrounding healthy tissue. The sonication time is a major factor influencing lesion size and temperature rise. Kang [1] used theoretical calculations to report that the lesion size could be controlled by adjusting the sonication time. Quantification of the effect of sonication time on lesion formation is essential for the clinician to decide the optimum duration of sonication for a lesion of desired size and for improved therapeutic outcome. The main *objective* of this study is to evaluate, both experimentally and numerically, the dependence of HIFU lesion size on the duration of sonication.

METHODOLOGY

Figure 1A shows the schematic of the experimental setup used in this study. The MR compatible transducer (frequency: 1.1 MHz and focal length: 10 cm) was aligned with the liver sample taken in a plexiglass tank of degassed water, and placed inside the orifice of the 3T MRI machine (Fig.1B). The ablations were performed at 70 W acoustic power for 20 s, 30 s and 40 s durations. An MRI image of the resulting lesion was recorded in each case and the area of the lesion was determined by using image processing software (NIH Image J software). Due to noise generated by electronic instruments during the heating phase, we could only record the temperature decay during the cooling phase when the transducer was switched off. This way we could get the peak temperature rise and subsequent temperature decay after the end of each sonication.

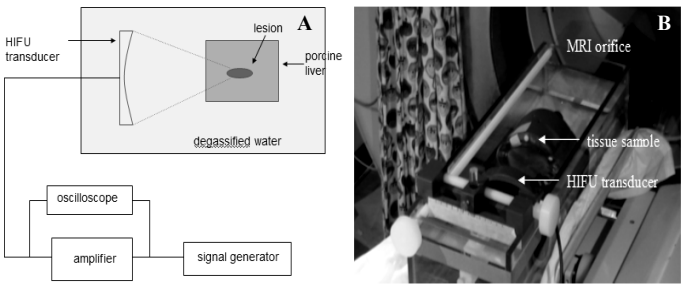

Figure 1A: Schematic diagram of HIFU apparatus; and B: Photograph of experimental set up in the MRI scanner

Numerical calculations, similar to Hariharan et al. [2], were performed to validate the experimental data. The KZK parabolic wave equation (eq.1) was solved to get acoustic pressure, p(r,z), and power deposition rate, Q, was then calculated from the relation $Q = 2\alpha p^2/2\rho c$, where α is absorption coefficient of tissue. The heat equation (eq. 2) was solved to generate the transient temperature field in the material.

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

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

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 thermal-dose parameter is expressed as:

$$t_{43}(x,y)=\int_{t=0}^{t=t_{final}} R^{43-T(t)}dt, \quad (3)$$

The t_{43} was calculated to generate the lesion size based on a threshold value of 240 minutes at 43°C as per the criterion of Saperto and Dewey [3]. At the end of the experiments, the ablated liver was evaluated for a histological examination of the ablated zones.

RESULTS AND DISCUSSION

Figure 2 shows the numerically generated HIFU temperature rise above the initial temperature of 22°C after 20 s and 30 s of sonication and the subsequent temperature decay curves. The experimental cooling curves are compared to the numerical cooling curves. It is calculated that during the heating phase for 30 s there is a 79°C rise in temperature. The experimental temperature rise after 30 s is 71°C. Hence, the numerical and experimental temperature rises agree within 10%. This shows the capability of the MRI scanner to record HIFU induced temperature rise within an acceptable accuracy.

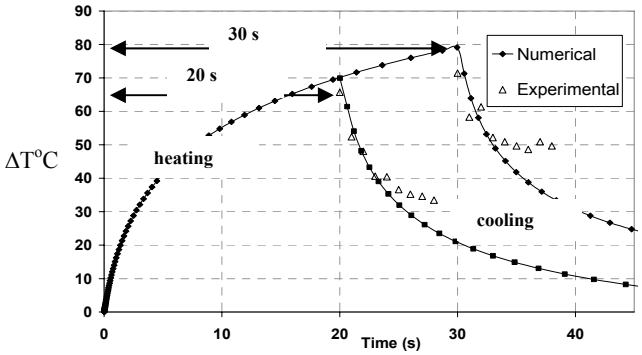

Figure 2: Transient temperature profile (20 s and 30 s ablation)

Figure 3A shows MRI images of HIFU lesions on the liver sample seen as distinct white elongated zones at varying sonication times, 20, 30 and 40 s. The 30 s and 40 s lesions are seen to have a *tadpole-shape* attributed to boiling. The corresponding numerically generated lesion contours shown in black lines have been superimposed on the experimental images. The area of the experimental lesions increases linearly with sonication time as seen in Figure 3B with $R^2 = 0.989$. It was found that the experimental lesion size increases from 0.368 cm^2 at 20 s sonication time to 0.715cm^2 at 40 s sonication time, which is an almost 2-fold increase. Similarly, the numerical lesion size increases from 0.353 cm^2 at 20 s sonication time to 0.689 cm^2 at 40 s sonication time. The experimental and numerical lesion areas agree within 5% (0.368-0.353/0.353) of each other, thus validating our experimental results.

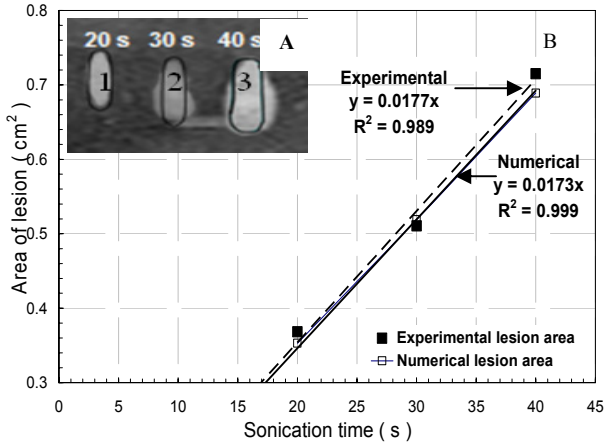

Figure 3A: MRI lesion images at 20 s, 30 s, 40 s sonication
3B: Lesion area vs. sonication time (expt. and num.)

Figure 4 A shows the photographic image of a lesion prior to the histology examination. This is a qualitative picture only. Figure 4B shows the results of the histology study. It is seen from the magnified view that the necrosed zone appears as a continuous smudge indicating coagulative necrosis and is clearly distinguishable from the normal tissue which appears as a collection of discrete cells.

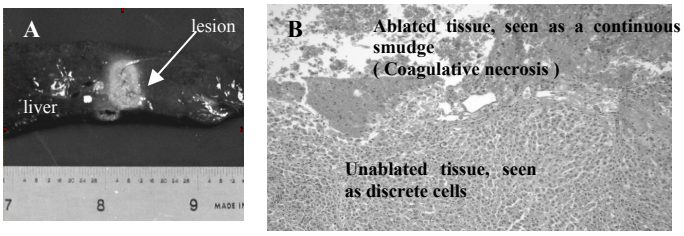

Figure 4A: Photograph of HIFU lesion; 4B: Histology image of lesion

CONCLUSION

Our experimental and numerical results show that the lesion size can be controlled by adjusting the sonication time, which may lead to improved therapeutic outcome. In future, MRI-monitored HIFU ablations may be performed to study the effect of acoustic power, transducer gain, frequency and focal length, on the HIFU induced lesion size.

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