High power density prototype for high precision transcranial therapy

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Abstract. A high power prototype dedicated to transskull therapy has been built by the Laboratoire Ondes et Acoustique. For the first time, it is possible to induce very high precision necrosis through the human skull with electronic beam steering around the geometrical focus. To achieve this goal, our prototype has to rely on 200 individual transducers mounted on a spherical surface with a semi-random distribution. In order to reach the therapeutic objectives, high power density transducers are required. To do so, a specific technology has been developed by Imasonic, based on 1-3 piezocomposite active material. Acoustic power density of 20W/cm² during the 10s excitation sequence at 1 MHz has been achieved at the surface of each source, with a 1/6 duty cycle. The interest of using piezocomposite material for high-power generation will be illustrated in this application, as well as the importance to consider the whole transducer design, including the piezocomposite part but also surrounding passive and functional materials as well as the electrical environment. The resulting technology offers high level of power, while insuring the reproducibility and an acceptable ageing of the performances. Necrosis obtained in fresh liver and brain samples through an ex vivo human calvaria will be presented. The minimum size of the induced necrosis is 2mm diameter and thanks to electronic beam steering any shape can be obtained within a volume of 30 mm* 30mm* 50mm. Even for complex shapes, the size of the necrosis obtained through the skull fits the predicted size obtained by calculating thermal dose.

INTRODUCTION

Non invasive surgery of brain tumors using High Intensity Focused Ultrasound (HIFU) has been envisioned two decades ago [1]. During the last decade, many studies have shown at low power the feasibility of correcting the aberrations induced by the skull by using minimally invasive methods [2,3,4,5,6] or even non invasive methods based on CT scans [7,8,9,10]. Due to dissipation and strong reflection on the skull surface, it is difficult to implement these techniques practically. This is why new therapeutic transducers have been specifically designed for transskull therapy [5,6,9,10,11]. During the last three years, a prototype devoted to brain HIFU has been designed and built in the Laboratoire Ondes et Acoustique (ESPCI, Paris) in close collaboration with Imasonic (Besançon, France). The design and first ex vivo experiments have been presented in [9]. The characteristics of the new transducer technology developed specifically by Imasonic are discussed here. The high precision steering capabilities of the array are experimentally tested and validated by inducing large necrosis on sample tissues placed behind a human skull.

TRANSDUCER TECHNOLOGY

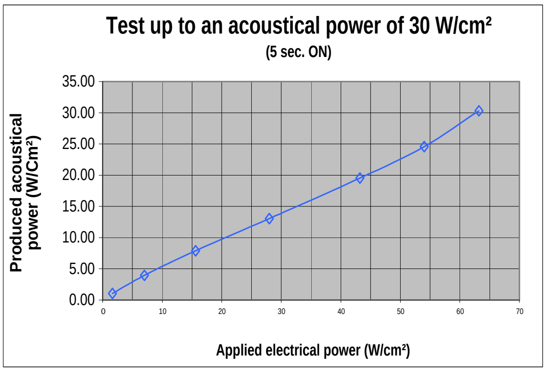
As the acoustic beam has to pass through the skull, the level of acoustic power required from the transducer is much higher compared with most of the other therapeutic applications. Acoustic densities in the order of 20W/cm² are necessary to obtain enough intensity at the focus in different conditions of electronic steering. A specific technology named HI-2 was therefore developed by Imasonic based on a high intensity piezocomposite material [13].

While allowing to generate high power density [13,14], this technology benefits also from the other advantages of the 1-3 piezocomposite materials, notably the piston-mike vibration mode. Indeed, as the application requires to electronically steer the beam, the ratio between the diameter and the thickness of the active element (8 mm active diameter at 1 MHz) could lead to lateral modes that may have a strong influence on the vibration mode and hence create hotspots out of the focal zone in the brain. Piezocomposite materials attenuate strongly these spurious modes and the mechanical behavior of the transducer becomes a uniform piston-like mode with a good efficiency and predictability [15].

Starting from the acoustical design of the single element source, the electro-acoustical structure and the materials were chosen in order to increase the acoustical power generated at the surface of the transducer. A particular attention was devoted to the choice of the materials constitutive of the composite, i.e. a piezoceramic with high Curie temperature and low electrical and mechanical losses and polymer materials with high glass transition temperature. Furthermore a solid backing material was chosen to improve the mechanical resistance and the thermal behavior of the transducer. From the electrical point of view, the impedance of the transducer was matched to 50 Ohms thanks to an external matching circuit.

FIGURE 1 : single element transducer and external matching circuit

Two hundred transducers were built based on this technology and tested in order to measure the output power available at the surface of the transducer. Figure 2 illustrates the linearity of the acoustical power generated as a function of the applied electrical power up to output power of 30 W/cm². The maximum output power was measured at more 40 W/cm² during 5 seconds. Ageing tests were also performed at different sollicitation level : 15 W/cm², 17 W/cm² and 20 W/cm². Figure 3 shows that the transducer performance is stable during 24 hours at 20 W/cm² during 10 seconds firing with a 1/6 duty cycle.



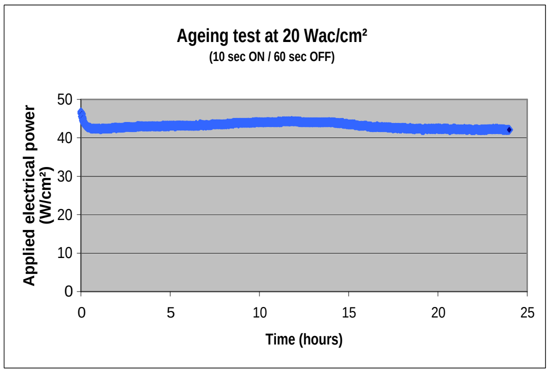
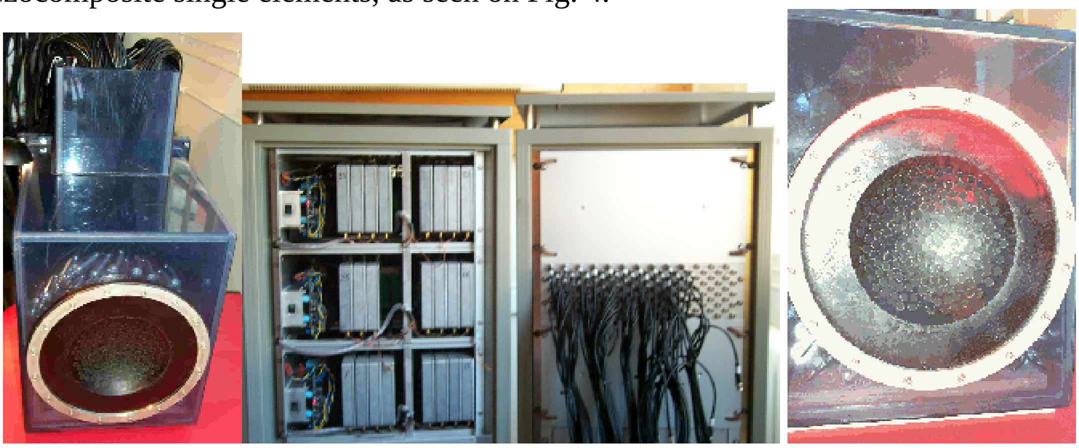


FIGURE 2 : output acoustical power measurement on a single element transducer up to 30 W/cm²

FIGURE 3 : ageing test on a single element transducers during 24 h at an acoustical power level of 20W/cm²

PROTOTYPE

A quasi-random sparse array has been constructed with 200 high power piezocomposite single elements, as seen on Fig. 4.



(a) (b) (c)

FIGURE 4. (a) 200 elements sparse array prototype and the electronic system. The waterproof plastic box contains the 200 electrical matching boxes. (b) High Power electronic (individual channels) Quasi random distribution of transducers embedded in spherical shaped Ureol. (c) Front view of the array: the transducers are mounted on a spherical surface.

The transducers have been mounted on a spherical surface (Fig. 4c) with a semi random distribution in order to minimize the side lobe level in the focal plane as well as the pressure level in the near field [10].

EXPERIMENTS

In a first step, a time reversal experiment is conducted through a human skull. The impulse response of a hydrophone (white arrow on Fig. 5a) placed at the geometrical center of the therapeutic array is recorded on the array after propagation through the skull. The signals are stored in the electronics for further processing. The whole experiment is immersed in deionized and degassed water at 25°C. One has to mention here that in such an experiment, the hydrophone is not used as an active element but as a receiver. Indeed, thanks to spatial reciprocity, it is equivalent to emit a signal with one transducer of the array and record it on the hydrophone or to use an active acoustic source at the location of the hydrophone and record the signal received on the transducer of the array. The advantage of using spatial reciprocity is that one single receive electronic board can be used. All the time reversal experiments conducted in our lab during the past decade [2,3,7,9,11] have been conducted by using spatial reciprocity.

a) b)

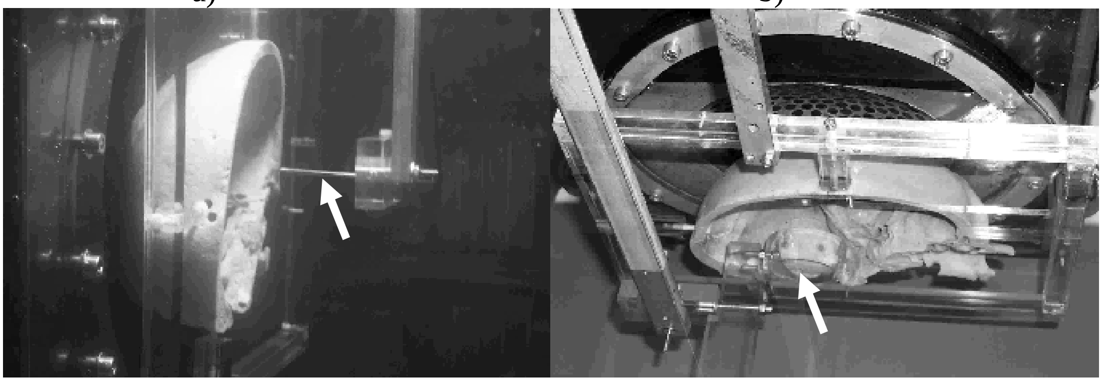
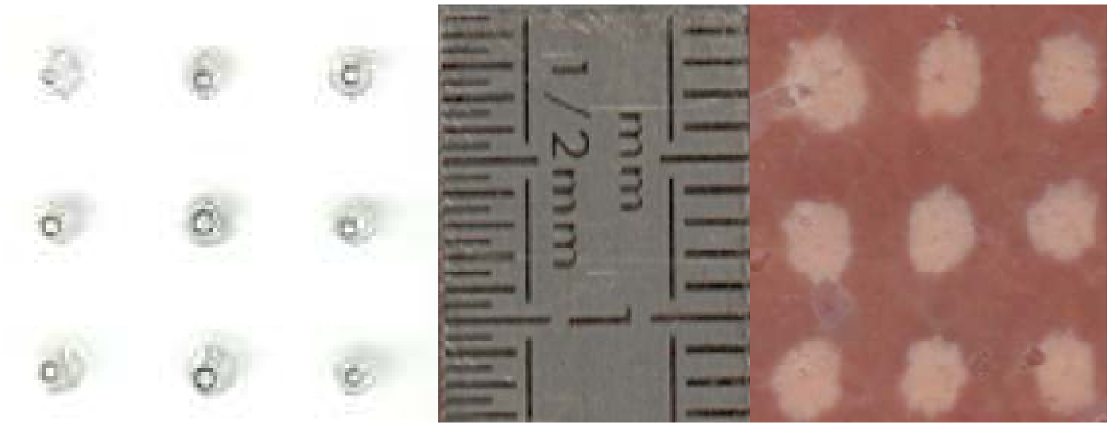


FIGURE 5. Experimental setup

A time reversal process combined with amplitude compensation was performed at the geometric center of the array in order to correct for phase and amplitude aberrations induced by the bone on the ultrasonic beam [3]. The calculated phase shifts and amplitudes where applied to continuous (5s) excitation of the transducers in order to burn tissues. The resulting intensity field was checked in the focal plane and compared with the one obtained without any aberration corrections. The uncorrected beam is strongly degraded by the skull. The focal spot is not at the desired location and is widely spread in comparison with the corrected one. Moreover, the pressure amplitude at focus of the corrected beam (a mean 70 Bars) is higher than the pressure amplitude of the uncorrected one, resulting in a mean 5 times higher heat deposit.
Secondly, in order to demonstrate the feasibility of using the array for high-power therapeutic applications, thermally induced lesions were produced through a human skull in polymethylmethacrylate (PMMA), which is frequently used as a test material [12]. A 2 seconds sonication was achieved and induced a burning at the center of the PMMA interface. The emission signals were then tilted electronically in order to focus at 7.5 mm in the four cardinal directions. As one can notice in Fig. 6a), the targets are clearly defined, with a mean 1.5 mm diameter of the impacts.

Finally, a fresh piece of cow liver (white arrow on Fig. 5b) was inserted in water between the hydrophone and the array, replacing the PMMA plate. Emission signals where tilted electronically in order to reproduce the dotted square shape obtained on PMMA. Two high intensity focused beams of duration 5s (with a waiting time of 10 s between each shot) were emitted at each location. Fig 6.b shows the sub millimetric precision of the prototype.



(a) (b)

FIGURE 6. a) Impacts induced in a slice of plexiglas located in the focal plane (Z = 120 mm) through the skull. The impact size is about 2 mm. Aberration corrections were achieved at center by using an hydrophone and next impacts were achieved by tilting electronically the beam. b) same experiment on liver.

SUMMARY AND CONCLUSIONS

A new transducer technology has been specially developed by Imasonic in order to build a high power 200 elements sparse array devoted to high precision brain hyperthermia. Its steering capabilities through a human skull have been demonstrated by inducing regularly spaced necroses spot by spot on fresh liver samples. It has been shown that the therapeutic array coagulates tissues through a human skull in a volume of 15x15x50 mm^3 around the geometrical focus thanks to electronic steering. Thus, a whole tumor could be treated spot by spot without mechanically moving the system. Moreover, the single transducer technology is very flexible, resulting in an easily upgradable system. A news spherical mould is currently under construction in order to add 100 transducers and reach a 300 element sparse array. This would minimize the temperature rise on the outer skull surface. Thanks to the fully programmable electronics, the 300 elements array will also be used to focus through another strong defocusing medium: the ribcage, partially shadowing the liver.

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