MONITORING THERMALLY-INDUCED LESIONS WITH SUPERSONIC SHEAR IMAGING

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Abstract

Thermally induced lesions are generally stiffer than surrounding tissues. Here, we propose to use the Supersonic Shear Imaging technique (SSI) for monitoring a HIFU therapy. This new elasticity imaging technique is based on creating shear sources using the acoustic radiation force at different locations in the medium. In these experiments a HIFU probe is used to thermally induce lesions in fresh tissue samples. A diagnostic transducer, controlled by our ultrafast scanner, is located in the therapeutic probe focal plane. It is used for both generating the shear waves and imaging the resulting propagation at frame rates reaching 5000 images/s. Movies of the shear wave propagation can be computed off-line. The therapeutic and imaging sequences are interleaved, and a set of propagation movies is performed during the heating process. From each movie, elasticity estimations have been performed using an inversion algorithm. It demonstrates the feasibility of monitoring HIFU therapy with SSI.

Introduction

The real time monitoring of high intensity focused ultrasound (H.I.F.U.) treatments is a research field of main interest. Indeed, in order that HIFU may be used clinically in optimal conditions, the monitoring methods of the treatment represent a crucial point. A number of thermal imaging techniques have been suggested and investigated such as magnetic resonance imaging [1], [2], or impedance tomography as well as ultrasound based temperature imaging [3,4]. In 1999, the use of static elastography for the visualization of HIFU induced thermal lesions was investigated *in vitro* by Kallel *et al.* in the rabbit paraspinal skeletal muscle [1] and by Righetti et al. in canine liver [2]. Recently, the visualisation of High-Intensity Focused Ultrasound (HIFU)-Induced Lesions in the Human Prostate was investigated *in vivo* by Souchon et al. using Static Elastography. For deep organs like liver or brain, static elastography cannot be used to date as as monitoring technique for HIFU. In these cases, dynamic elastography techniques, such as sonoelastography, transient elastography or acoustic radiation force based approaches must be envisioned. We propose here to combine transient elastography with the use of the acoustic radiation force to image the elasticity of organs during an HIFU treatment. This technique has the advantage to be insensitive to motion artifacts. Moreover, the use of the acoustic radiation force to remotely generate shear motion allows to reach deep sited regions of interest and avoid the use of heavy low frequency vibrators.

Supersonic Shear Imaging

Supersonic Shear Imaging (SSI) is a new ultrasound-based technique able to provide quantitative shear modulus mapping of an organ in less than 30 ms. SSI relies on the acoustic radiation force induced by an ultrasonic focused beam to remotely generate low frequency shear waves in tissues and can be achieved using the same piezoelectric arrays than the ones used in conventional ultrasonic scanners. Such a radiation force acts as a dipolar source of shear waves and mainly radiates in transverse directions. We propose, with SSI, to create quasi plane shear waves of stronger amplitude by moving the shear source at a supersonic speed. Such a shear source, which moves faster than the shear waves, can be created by successively focusing the ultrasonic "pushing" beam at different depths, see Figure 1. All resulting shear waves interfere constructively along a Mach cone creating two quasi-plane shear wave-fronts propagating in opposite directions. The angle between both plane waves is proportional to the ratio between the shear wave speed and the speed of the moving source, i.e. to the Mach number. The ultrafast ultrasonic scanner developed for the technique is able to generate this supersonic shear source and image the propagation of the resulting transient plane shear waves by reaching frame rates of a few kHz. Establishing such a supersonic regime brings several essential innovations. First, constructive interferences between shear waves create a cumulative effect which induces high mechanical displacements in the medium (up to 100 µm in phantoms and 40 µm *in vivo*). This is an indispensable condition for the *in vitro* and *in vivo* feasibility of the technique, particularly in strongly viscous media (breast, liver). Secondly, the supersonic regime generates two spatially extended plane shear waves increasing the area where mechanical shear information is available. Finally, changing the speed of the moving "pushing" beam allows us to change the Mach cone angle and then insonify the same medium with different steered plane waves. With this method, called shear compound, it is possible to gather the same mechanical information from

different "points of view" and therefore improve the robustness of the technique.

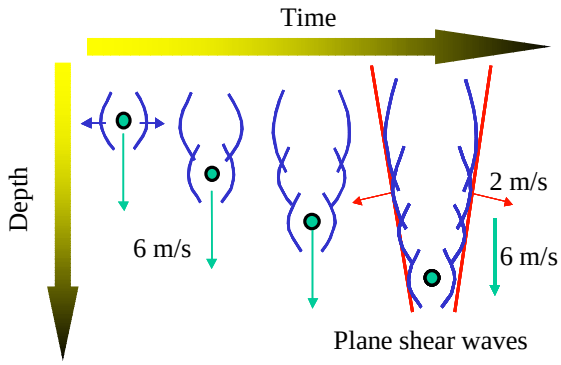


Figure 1. Generation of the supersonic moving shear source : it results in the propagation of two plane shear waves propagating into a Mach cone.

The axial displacements induced in soft tissues by the shear waves propagation are estimated by cross-correlating successive echographic images acquired at 3000 frame.s^{-1}. This ultrafast frame rate compared to conventional scanners (50 frames.s^{-1}) is reached by reducing the step by step transmit focusing to a single plane wave illumination, see Fig. 2. The image formation is achieved during the receive beamforming process. The great versatility of our prototype allows moreover to interleave "pushing sequences" and "imaging sequences" as desired.

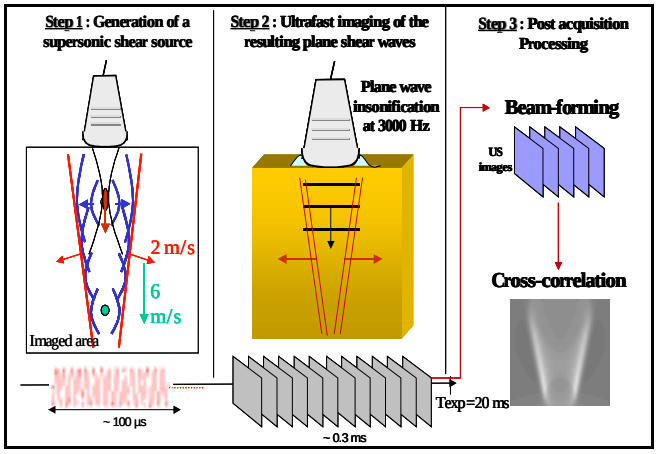


Figure 2. Basic Principle of Supersonic Shear Imaging.

An experiment conducted in homogeneous Agar-Gelatin phantoms shows the ability of the system to generate and image the shear waves. The axial displacements are induced and measured using a 1D linear probe (128 elements, 4.3 MHz) located on the upper border of the images in Figure 3. A Mach 3 supersonic regime was achieved as the shear wave speed is around 2 m.s^{-1} while the shear source is moved electronically by the array at 6 m.s^{-1}.In order to generate the radiation force, the ultrafast scanner emits an ultrasonic focused beam in the phantom at 5 chosen locations (Figure 2). The typical ultrasound pulse is made of 400 oscillations at 4.3Mhz. This corresponds to a "pushing time" of 100 µs. The shear waves propagates clearly in a Mach cone.

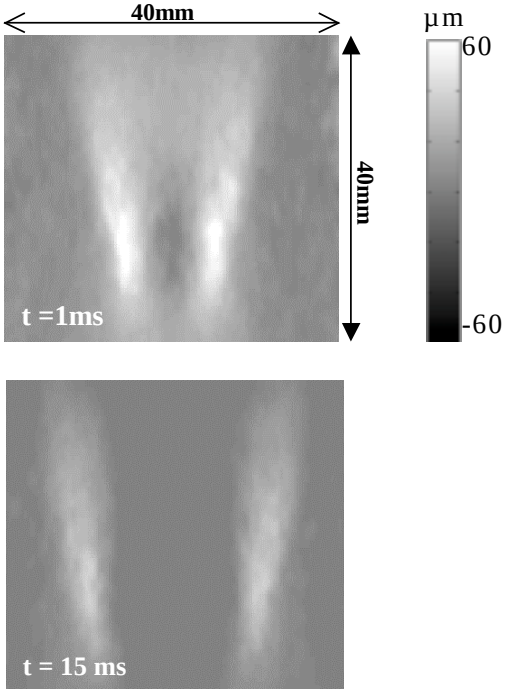


Figure 3. Two successive images of the axial displacements induced in a Agar-Gelatin phantom. The acoustic radiation force source is moved electronically at 6 m.s^{-1} by a 1D linear array located at the upper border of each image. The generated shear waves propagate at 2 m.s^{-1} in the phantom resulting in a Mach 3 experiment.

From the movie of these axial displacements, the elasticity map of the medium can be recovered by solving a local inverse problem. By assuming that soft tissues behave like isotropic solids and that compressional waves are much faster than shear waves, we have shown (3) that the spatio-temporal axial displacements $u(\vec{r},t)$ at any location $\vec{r}$ are linked in our transient experiments to the local shear modulus $\mu(\vec{r})$:

$$\rho \frac{\partial^2}{\partial t^2} u(\vec{r},t) = \mu(\vec{r}) \Delta u(\vec{r},t) \qquad (1)$$

where ρ is the density of the medium and can be considered as uniform in tissues. Δ corresponds to the Laplacian operator. The inversion algorithm consists in locally estimating a temporal average of the shear modulus :

$$\mu(\vec{r}) = \frac{1}{T}\int \rho \frac{\partial^2 u(\vec{r},t)/\partial t^2}{\Delta u(\vec{r},t)}\, dt \qquad (2)$$

where T is the movie duration. So, an elasticity map of the medium can be computed in post-treatment. The elasticity obtained in the phantom experiment presents a mean value of 2.1 kPa with a spatial variance of 0.1 kPa.

Experimental Setup

The experimental setup is presented in Figure 4. The Supersonic Shear Imaging system (1D linear array, 4.3 MHz) is imaging the transverse focal plane of an H.I.F.U. transducer (spherical shape, 60 elements, 70 mm focal distance, 1.5 MHz). The HIFU electronic driving system and the ultrafast imaging system are triggered. The experiment is conducted in fresh and degased tissues samples of chicken breast.

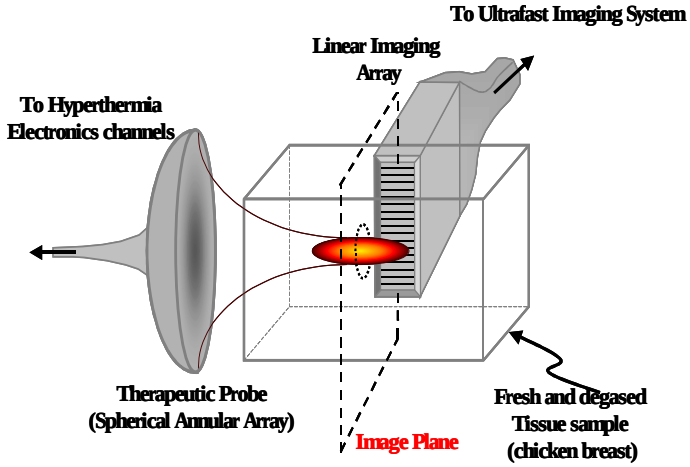


Figure 4. Experimental setup. The Supersonic Shear Imaging system is imaging the transverse focal plane of a H.I.F.U. system.

At the maximum power level, the HIFU beam deposits 1000 W.cm^{-2} at focus. The insonication time was varied from 1 second to 40 seconds. In addition to the monitoring of the elasticity change, a temperature increase map was achieved by the 1D linear array during the HIFU insonication using a compound technique developed in our lab [6]. It allowed to checked the evolution of the shear modulus versus temperature.

Results

First experiments were conducted without reaching the necrosis threshold. Figure 5 shows an echographic image of the tissues sample achieved with the 1D linear imaging array. A corresponding temperature increase map is superimposed and shows clearly a cross-section of the HIFU beam. The HIFU treatment parameters were here 250 W.cm^{-2} during a insonication time ranging from 5 to 50 s. During these first set of experiments, we did not notice a significant change in the shear modulus of the heated region. This small dependence of the shear modulus versus temperature before necrosis can be intuitively explained by the fact that null divergence motion induces less temperature changes than null rotational motion. In other words, the temperature dependence of compressional wave speed seems to be more important than the one of shear wave speed. This point will be addressed in further works.

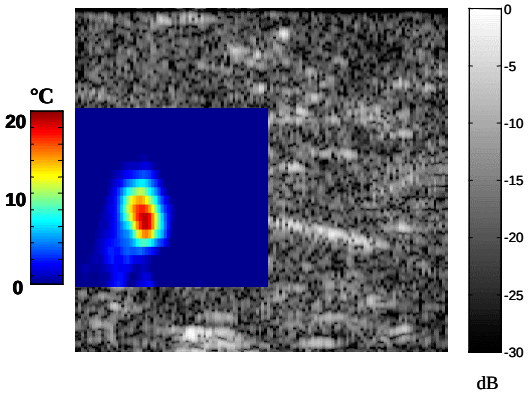
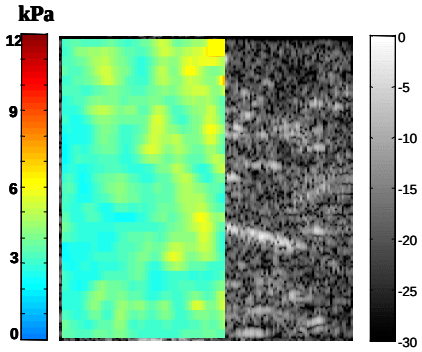


Figure 5. Map of the temperature increase superimposed on the echographic image of the breast chicken tissue sample. In this first set of experiment, the necrosis threshold was not reached. The image size is 40x40 mm^2.

In a second set of experiments, the HIFU deposit was increased up to 1000 W.cm^{-2} and the insonication time was increased to 10 successive bursts of 5 s in order to reach the necrosis threshold. Figure 6a presents a picture of the tissue sample cut in slices in order to highlight the necrosis region. The size of the imaging area of the 1D linear array is described by the black rectangle. The necrosis is clearly visible on the left side of the rectangle. Figure 6b represents the shear modulus image achieved by the Supersonic Shear Imaging technique. As one can notice, the shear modulus is quite homogeneous in the non treated regions with a mean shear modulus of 3.1 ± 0.3 kPa. The shear modulus in the necrosed area has increased of about a factor 3 where it reaches 10 ± 0.2 kPa. These results are corroborating the first *in vivo* results obtained on prostate by Souchon *et al* [5] using static elastography.

The feasibility of Supersonic Shear Imaging to image the necrosis attainment was here demonstrated *in vitro*. The next step consists currently in embedding the 1D linear array inside a new HIFU spherical multi-channel probe, thus providing a more flexible and compact probe mixing both therapy and monitoring of thermal and elasticity changes during the HIFU treatment.

a)



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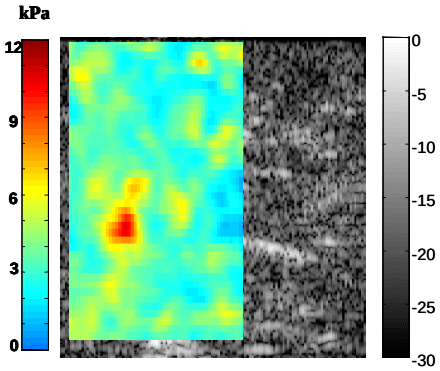

c)

Figure 6. a) Picture of the lesion induced in a tissue sample and corresponding imaged area. Map of the Shear modulus achieved using the Supersonic Imaging Technique superimposed on the echographic image b) before and c) after necrosis. The echographic image size is 40x40 mm^2.

Summary and conclusions

The combination of the acoustic radiation force and ultrafast imaging mode in order respectively to generate shear waves remotely in the organs and image their propagation allows to recover the shear modulus cartography of the soft tissues. This technique was applied *in vitro* on chicken breast tissue samples in order to monitor the elasticity change during a HIFU insonication. Before attainment of the necrosis threshold, no significant change in the shear elasticity estimates was noticed. After attainment of the necrosis, the shear modulus was 3 times higher in the necrosed area and the necrosed area was clearly highlighted. By providing shear elasticity maps of organs, the Supersonic Shear Imaging technique can monitor the attainment of necrosis in the treated area.

References

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