HIGH INTENSITY FOCUSED ULTRASOUND THERAPY COMBINED WITH 3D REAL TIME TRACKING MOTION SYSTEM

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Abstract

For optimal treatment conditions, patient motion, particularly respiratory motion, must be monitored and corrected during HIFU treatments. We propose here a new generation of multi-channel HIFU systems able to track and correct in real-time the 3D motion of tissues. It is based on an accurate ultrasonic speckle tracking method for both following and compensating the motion of the tumor. The displacement estimation is based on 1D cross-correlation of the RF signals at two different times. The complete 3D motion estimation requires using at least three sub-apertures on a large phased array. The motion tracking sequences are interleaved with HIFU sequences at a high repetition rate. This provides a feedback for the HIFU beam steering correction and HIFU experiments combined with 3D real-time motion correction are successfully performed in moving fresh tissues samples.

I. Introduction

Accurate targeting of a range of abdominal tumors in HIFU therapy may be difficult because of respiration-induced organs motion. Several studies have shown that organs can move 10 to 20 mm over the breathing cycle at a speed up to 15 – 20 mm.s^{-1} [1]. Several tracking methods have been extensively investigated in intensity modulated radiation therapy (IMRT) and 3D CT tomography. In these motion tracking techniques, called optical [2] or magnetic tracking [3], implants markers are monitored and used to synchronize the therapy-imaging device with organ motion. Most of these systems are limited to the motion displacement and act as alarms preventing a critical motion. In other words, no feedback is introduced in order to correct the therapy system.

We propose here a completely new ultrasound-based technique that can be fully integrated in HIFU systems. Contrary to previous methods, our technique enables to track the motion of tissues located deep within organs without any implants markers. This technique is based on an accurate ultrasonic speckle tracking that provides in real-time the 3D displacement of the tissue. Speckle tracking has been widely used in diagnosis ultrasound imaging, such as elastographic [4] or temperature [5] imaging. We have applied this technique to 3D motion estimation and integrated it in a HIFU multi-channel device. The motion tracking system provides in real-time the motion of the tissue sample. Another very important innovation of the proposed process consists in using the 3D position information as a feedback for the HIFU system: The transmit delays are modified instantaneously in order to electronically steer the high power ultrasonic beam towards a corrected location. High power experiments coupled with real-time 3D motion tracking are performed in biological moving tissue samples.

II. 3D ultrasonic motion tracking

The motion vector can be estimated in three dimensions by using at least three separate transmit-receive subapertures. For each transmitting subaperture an ultrasonic wave is focused at a predetermined location inside of the tissue. Then the same subaperture receives the RF pulse echo. The axial displacement is estimated for each subaperture by implementing a classical speckle tracking technique on successive RF signal: a 1-D cross-correlation algorithm enables to estimate the time-shift due to the tissue motion. Each of these time-shifts corresponds to the projection of the 3D displacement vector $\vec{d}(d_x,d_y,d_z)$ along the beam axis of its corresponding sub-aperture. Thus on the subaperture *i* the time shift is given by the relation:

$$t_i = 2\frac{a_{ix}dx + a_{iy}dy + a_{iz}dz}{c} \qquad (1)$$

dx, dy and dz are completely determined if the time-shifts have been estimated on three separate subapertures. In the case of having more subapertures the mean square solution of the overdetermined system is calculated. It will ensure the stability of the displacement estimation, especially if the displacement vector is normal to the direction of one subaperture.

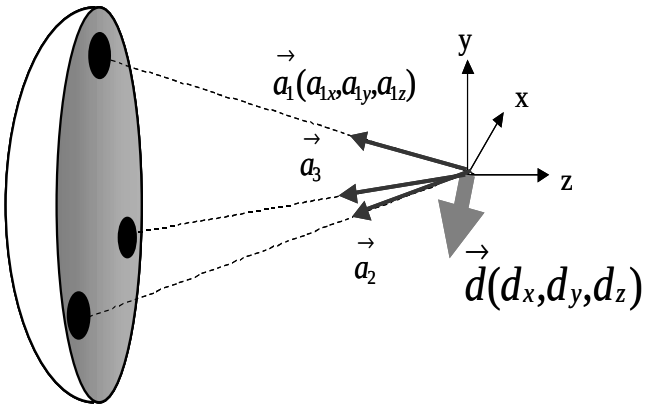

Figure 1. Motion tracking setup with three transmitting-receiving transducers.

III. Experimental setup

The feasibility of this motion tracking technique was validated by integrating it in a high power 200 elements sparse array [6]. However, this technique can be applied to any kind of classical array distributions. The 200 high power piezocomposite transducers (8 mm diameter, 0.5 cm^2 active area, 900 kHz central frequency, Imasonic, Besançon, France) are mounted in a sealed spherically curved holder with a 12 cm radius of curvature. The transducers are connected to a 200-channels electronic driving system. Each electronic channel is fully programmable and possesses its own emission/reception electronic board. This array has been optimized for electronic beamsteering in HIFU applications and the focus can be moved +/-15 mm radially and +/-20 mm axially from the geometric focus.

Taking advantage of the great versatility of the multi-element technology, the subapertures can be completely designed to produce a focus with appropriate dimensions. Indeed, the vector motion is estimated in a volume that is directly linked to the size of the subapertures. In Fig 2., the four subapertures are about 25-mm in diameter so that each will produce a focus with a lateral dimension of about 7-mm at 1MHz. In addition, the steering angles between all motion tracking subapertures must be chosen as the maximum available angle, in order to maximize the accuracy of the displacement estimation [4].

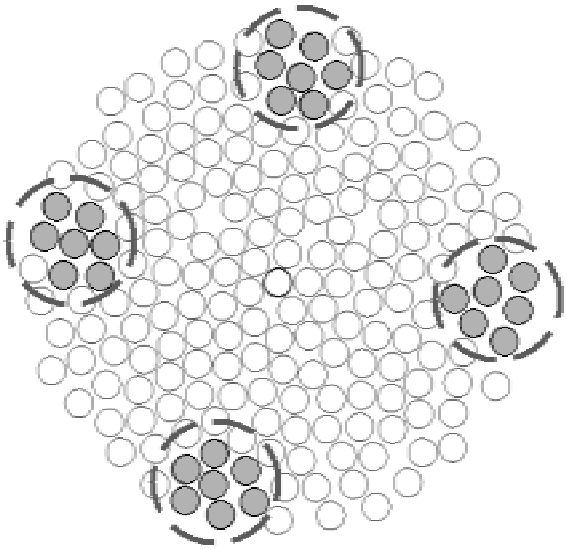

Figure 2. Four subapertures selected on the particular quasi-random phased array used in experiments in order to maximize the accuracy of the 3D displacement estimation.

In the receive mode, the subapertures can be also sized to any dimension. The transmitting and receiving subapertures can be of different size depending of the desired focusing quality. However, according to the technical characteristics of the electronic system, the signals are recorded in the receive mode by the driving system and then transmitted to the computer. Thus, the transmission time increases with the number of receiving transducers. As a consequence, the data transfer rate of our ISA bus limits the number of receive transducers used during the real time motion tracking estimation. Though it is not a critical point at this time, these features could be implemented in hardware if we want to diminish the time needed for the motion estimation.

Real-time motion tracking experiments have been performed in PVA phantoms. The phantom is moved using a stepper-motor-controlled 3D positioning system (Newport). The transmitting subapertures are chosen as drawn in fig 2, and the transducer located in the center of each subaperture is used in receive mode. A first transmitting/receiving sequence is performed with one subaperture, and the process is repeated for the following ones. The recorded signals are then transmitted to a computer, and a cross-correlation algorithm estimates the time-shifts. Finally by inversing equation (1) the vector displacement is calculated and added to the initial position. The whole process can be repeated at a frame rate up to 200 Hz. Since one transmitting-receiving sequence takes about 200 μs and the ISA bus transmission duration is about 3ms, the whole process takes about 5ms including cross-correlations and vector displacement estimation.

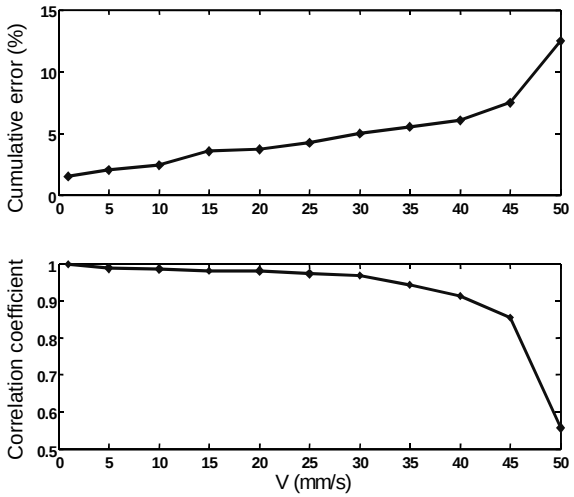

Figure 3. Cumulative error on the position as a function of the phantom speed. The phantom was moving 10-mm laterally at a constant speed. The correlation coefficient is plotted below.

The accuracy of the displacement estimation was investigated by moving the phantom at different speeds. The cumulative error on the final position is plotted as a function of the phantom speed in Fig 3. The error on the position increases with the speed whereas the correlation coefficient decreases. A threshold of 0.9 can be set on the correlation coefficient. It fixes a maximum speed of 40 mm.s^{-1}.

IV. HIFU experiments

HIFU experiments coupled with motion tracking have also been performed. The vector displacement estimation is used to feedback the electronic driving system. Phase shifts are then calculated for each of the 200 elements of the array in order to steer electronically the HIFU beam on the new estimated position. The successive sequences are shown in Fig 4. A duty cycle of about 85 % is performed during the HIFU treatment.

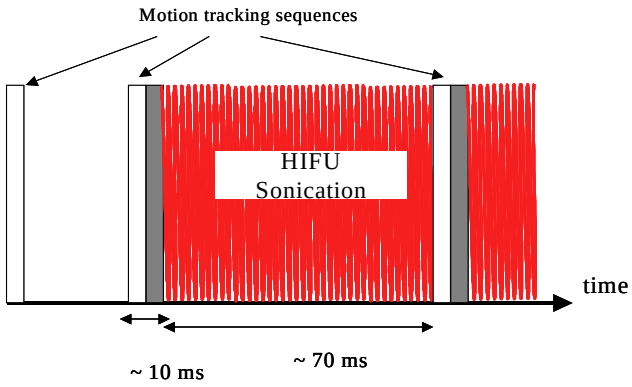

Figure 4. Successive sequences for motion tracking process and 85% duty-cycle HIFU sonication.

In a first experiment, a liver sample was moved 10 mm in the lateral direction at the constant speed of 10 mm.s^{-1}. During the motion, the tissue was sonicated without motion tracking with an intensity at focus about 2000 W. cm^{-2}.

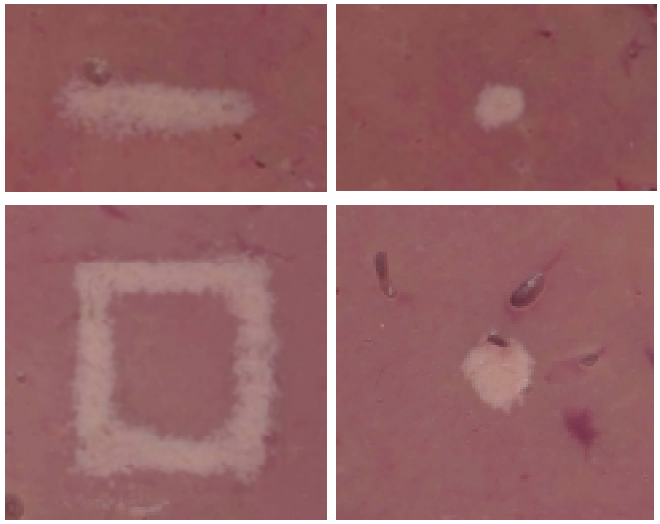

Figure 5. lesion induced in liver moving at 10 mm/s a) without motion tracking b) with motion tracking. Square shaped lesion induced in liver moving at 8 mm/s in the focal plane c) without motion tracking d) with motion tracking.

Then, a new sonication was performed while the motion of the sample was being tracked in a zone located 10 mm behind the focus. In fig 5., it is clearly demonstrated that HIFU sonication coupled with motion tracking enables to perform very localized and precise lesions.
In the second experiment, the liver sample is moved in 2D in the focal plane at 8 mm.s^{-1}. A 10x10 mm square shaped lesion is achieved without motion tracking. The “square motion” of the liver sample is achieved three times for a total insonication time of about 15 seconds (each “square motion” lasts 5 seconds). In a similar experiment, the liver sample motion is tracked in a zone located 10 mm behind the HIFU focus and the previous 5s sonication (one square) is repeated with motion tracking and correction. The necrosis is again very well defined and localized. Note that the necrosis size in fig 5d. is quite important (2 mm). It is not due to a bad precision on motion estimates, but to the fact that the heat deposit is much more important at focus in the motion corrected experiment. It results in an enlarged necrosis area. This point is very important and illustrates one of the major advantages of the motion correction technique. As the heat deposit is optimally distributed in space, the insonication time could be strongly decreased. This should lead to greatly improved treatment durations.

Conclusion

We have developed a new ultrasound-based motion tracking technique. It enables to follow the motion deep in tissues with a very good accuracy at typical respiratory induced motion speeds. Moreover, this new motion tracking technique can be integrated in HIFU systems relying on transmit/receive capabilities. By performing HIFU experiments coupled with the motion tracking process, we have demonstrated that motion corrections permit significant improvement in the accuracy of HIFU targeting, but also should lead to reduce strongly the treatment duration.

References

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