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“Ultrasonic stars” for time-reversal focusing using induced cavitation bubbles

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Ultrasound waves can be focused by multichannel arrays through heterogeneous media using a time-reversal focusing method. In this method, it is required that a reference signal be either sent by a small active source embedded in the medium or backscattered by a strong scatterer acting as a passive source. The potential of this method in ultrasonic medical imaging has been already envisioned for aberration corrections. However, in many practical situations it is not possible to insert an active source in the medium or to rely on the presence of a unique strong scatterer in order to generate the reference signal. Analogous to the field of adaptive optics in astronomy, we propose here to create artificial “ultrasonic stars” in the body. The trick consists of first creating a bubble inside the medium using a section of the ultrasonic array. Due to cavitation, the bubble generates a spherical wave that propagates through a heterogeneous medium to the ultrasound array. The time-reversal method is then applied to the ultrasonic wave received by the array. This technique is experimentally validated for aberrations corrections in tissue mimicking phantoms. © 2006 American Institute of Physics. [DOI: 10.1063/1.2162700]

Aberrations induced by heterogeneities of biological tissues remain a general problem in medical ultrasound imaging. The speed of sound varies by nearly 10% between muscle and fat, and this slight discrepancy can distort the final image.¹ An extreme case of phase and amplitude aberrations occurs in bones where the speed of sound is nearly twice as fast than in soft tissues.² As a consequence, the distortions caused by bones considerably limit some applications of medical ultrasound, particularly ultrasonic imaging of the brain and the possibility of brain therapy using high-intensity focused ultrasound (HIFU).³

Time reversal is a well known adaptive focusing technique for the correction of aberrations induced in heterogeneous and complex media.⁴ This method is based on two steps. Firstly, a point source is embedded in the medium and transmits a short ultrasound pulse that propagates through the aberrating medium to a set of transducers. The signal received by the transducers is digitized and stored in memory. Secondly, the received signals are time reversed and sent back from the transducers to the medium. Due to the time-reversal invariance of the wave equation, the wave generated by the transducers propagates in the medium as if time was going backwards. As a consequence, the ultrasonic wave refocuses at the initial source location inside the medium. This method has been extensively investigated in various application areas such as nondestructive testing, underwater acoustics, and telecommunications.^{5–7} This is an elegant and robust adaptive focusing method, but it requires a point source to be placed inside the medium. Based on the same principle, it is also possible to use backscattered echoes from a strong scatterer inside the medium as an ultrasound source. This approach shows potential for kidney stone tracking and destruction in lithotripsy.⁸ However, in many practical situations for medical imaging, there are no strong scatterers that could be used as an ultrasound source. Differ-

ent techniques using backscattered random noise have been developed to correct the aberrations.⁹ However, the statistical estimation of the time delays compensation is noisy and often not good enough to achieve aberration corrections.

In this article, we propose to solve this problem by using ultrasound to create a bubble that acts as a small “ultrasonic star.” This technique is analogous to laser guided stars used for optics adaptive focusing in astronomy.¹⁰ We propose to use a section of the ultrasound array to transmit an intense pulse that generates a cavitation bubble in the area of interest. The collapse of the bubble generates a shock wave that propagates towards the ultrasound array where the time-reversal method can then be applied.

The experimental setup is based on an ultrasound probe made of two different arrays of piezoelectric transducers (Fig. 1). An array of 200 transducers working at 0.9 MHz central frequency is placed in a spherically curved holder and is able to focus a high power pulse (6 MPa peak negative pressure at 15 cm depth in free water). This array is used to create the cavitation bubble and will be referred in this paper as the high power system. Another array referred to as the time-reversal array is a standard ultrasound imaging array made of 64 elements operating at a frequency of 3.5 MHz and is embedded in the center of the high-power system. Each element of the imaging array is connected to an independent electronic emission/reception board. The backscattered signals can be stored, time reversed, and re-emitted by each transducer.

The propagation medium was deionized and degassed water. A tissue phantom made of 4% gelatin gel and 2% agar powder (acting as scatterers for the ultrasonic waves) was placed at the focus of the high-power system. The phantom could be easily removed and a hydrophone mounted on a three-dimensional step motor could scan the focal spot.

A rubber aberrator made of semicircles of 10 mm of diameter was placed in front of the echographic array. At 3.5 MHz, very strong phase and amplitude aberrations were

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FIG. 1. (Color online) Experimental setup. (a) 200 single-element 8 mm diameter transducers, working at 0.9 MHz central frequency, are placed in a spherically curved holder (only a small number) of these transducers are shown on the figure. A standard echographic array is embedded in the center of the power array. A phantom mimicking tissue is placed at focus in front of the high-power system. (b) Front view of the spherical holder showing the 200 transducers and the echographic array in the middle. The transducers are located at quasi-random positions to avoid strong side lobes in the focal plane.

induced with attenuation differences of approximately 10 dB and phase shifts exceeding more than 2π .

The focused pulse emitted by the high-power system was three sinusoid cycles at 0.9 MHz. At low emission amplitudes, no cavitation was induced at the focus and the echo of the scatterers were received by the echographic array [Fig. 2(a)]. The backscattered echoes corresponded to the signature of many scatterers randomly distributed in space but no strong scatterer could be used as a reference source for the time-reversal adaptive focusing method. After increasing the amplitude emitted by the high-power system a bubble appeared and suddenly collapsed generating the signature of a specular echo coming from a specific position [Fig. 2(b)]. A negative pressure of approximately -1 to -5 MPa was used to create this micrometer-sized bubble, but these pressure values depend on the medium (concentration of dissolved gas, temperature, etc.). The wave resulting from the collapse of the bubble was a short pulse¹¹ and had a very different spectrum than that of the original pulse at 0.9 MHz used to generate the bubble (Fig. 3). It had a wideband spectrum with high-frequency components. As a result, the bubble signal could be selected using a simple high-pass filter. It is important to note that at high power the nonlinear spectrum was due to both the bubble and the nonlinear propagation in the water. The nonlinear effect of the bubble, however, was dominant and the nonlinear signal recorded could be considered to be mostly from the bubble.

Figure 2(c) shows the filtered signal corresponding to the bubble signature. Due to the aberrations induced by the medium, the spatio-temporal wave field received on the array was strongly distorted, and this wave front presented both phase and amplitude aberrations. As a result, the signal could

FIG. 2. (Color online) Echoes received by the echographic array after an excitation pulse of the high-power system. (a) At a low-power level, no cavitation effects are induced, backscattered echoes do not present punctual targets. (b) At a high-power level, cavitation occurs and an important signal of a cavitating bubble is received on the imaging array. (c) After high-pass filtering, we select the signal coming from the bubble.

be used as a reference signal for the time-reversal method. The signal was then time reversed and re-emitted by the imaging array in order to refocus through the aberrating medium at the location of the bubble. The phantom was removed and the hydrophone was placed at the focus in order to scan the focal spot. It is important to note that the phantom has almost the same sound speed as water, so that we do not have to modify the aberration correction process and the resulting focal spot when we remove the phantom. The focus was scanned using the time-reversed signals previously obtained from the bubble signature. Figure 4(a) shows a two-dimensional scan of the focal spot in the xy plane [according to axes of Fig. 1(a)]. A sharp focus was generated and the lateral dimension of the focal spot was about 2 mm in diameter (-6 dB contour). The focus was then scanned again us-

FIG. 3. (Color online) Spectrum received by one element of the array without bubble cavitation and (b) with a cavitating bubble.

FIG. 4. (Color online) Focal spot in the xy plane. (a) Focusing through the aberrator using the time-reversed signature of the cavitating bubble. (b) Focusing obtained through the aberrator using a cylindrical time delay law. (c) Focusing obtained in homogeneous medium (water) using a cylindrical time delay law.

ing the standard emission time delay law of a conventional scanner assuming the sound speed to be constant in the whole medium [Fig. 4(b)]. Due to the strong aberrations, the focus was completely lost. Finally, the aberrating medium was removed and the focus was scanned using the same classical time delay law [Fig. 4(c)], in order to provide the ideal focusing in free water as our gold standard. The focal spot obtained in free water was similar to the focal spot created using the time reversal process and generated bubble. This clearly shows that the time-reversal process was efficient in compensating the distortions induced by the aberrator.

The choice of two frequencies (0.9 MHz for the high-power system and 3.5 MHz for the echographic array) played an important role in the experiment. Firstly, cavitation is easier to generate at low frequency while echographic imaging is usually more interesting at high frequency. Secondly, the wave generated by the collapse of the bubble had a wide-band and high-frequency spectrum and it was easily

detected by the high-frequency imaging array. Since the frequency of the excitation signal was relatively low, we could use a high-pass filter to select the signals generated by the bubble. Finally, phase aberrations grow linearly with the frequency and the attenuation grows quadratically with the frequency. Thus, a low-frequency wave has the double advantage of being relatively undistorted and minimally attenuated. Hence, in many situations, it would be possible to focus a low-frequency wave without taking into account the aberrations with enough energy at the focus to generate a bubble at the desired location.

In the field of ultrasound imaging and therapy, this method should have potential applications. In transcranial ultrasound imaging, for example, a low-frequency wave of typically 0.5 MHz could be focused through the skull bone with enough energy and precision to induce only one bubble in the region to image. By detecting the signature of this bubble with the imaging array, it is then possible to refocus at the original bubble location using higher-frequency ultrasound with the time-reversal method. Assuming the skull is a thin aberrator located close to the echographic array, it is possible to use standard phase shifting to focus in other points near the bubble. This method could also be used for monitoring HIFU ablation where the pressure of the therapeutic beam is high enough to induce bubbles at the focus. In the case of standard imaging, safety limits prevent the pressure amplitude from being raised in soft tissues in order to avoid cavitation damages. This method, however, requires the generation of only a single bubble, so it could be possible to prevent the occurrence of any damage. Other authors have shown that bubbles cavitation produced by short impulses do not generate any damage.¹²

¹M. O'Donnell and S. W. Flax, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **35**, 768 (1988).

²F. Fry and J. Barger, *J. Acoust. Soc. Am.* **63**, 1576 (1978).

³M. Pernot, J.-F. Aubry, M. Tanter, J.-L. Thomas, and M. Fink, *Phys. Med. Biol.* **48**, 2577 (2003).

⁴M. Fink, *Phys. Today* **20**, 34 (1997).

⁵N. Chakraborty, M. Fink, and F. Wu, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **42**, 1087 (1995).

⁶W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla, and D. R. Jackson, *J. Acoust. Soc. Am.* **103**, 25 (1998).

⁷A. Derode, A. Tourin, J. De Rosny, M. Tanter, and M. Fink, *Phys. Rev. Lett.* **90**, 014301 (2003).

⁸J. L. Thomas, F. Wu, and M. Fink, *Ultrason. Imaging* **18**, 106 (1996).

⁹L. Nock, G. E. Trahey, and S. W. Smith, *J. Acoust. Soc. Am.* **85**, 1819 (1989).

¹⁰L. A. Thompson and C. S. Gardner, *Nature (London)* **328**, 229 (1987).

¹¹T. J. Matula, I. M. Hallaj, R. O. Cleveland, W. C. Moss, R. A. Roy, and L. A. Crum, *J. Acoust. Soc. Am.* **103**, 1377 (1998).

¹²J. A. Ivey, E. A. Gardner, J. B. Fowlkes, J. M. Rubin, and P. L. Carson, *Ultrasound Med. Biol.* **21**, 757 (1995).