Acoustical imaging through a multiple scattering medium using a time-reversal mirror

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Abstract: Acoustical imaging is based on the ability to focus an acoustic beam inside the zone of interest. This remains an issue through a high-order multiple scattering medium because the electronic delay lines that enable one to focus through a multiple scattering medium are *a priori* unknown. Using time-reversal principles, we show that images can be obtained through a very disordered medium. Surprisingly, the images are better than those obtained in a homogeneous medium with a classical imaging device.

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Introduction

The use of ultrasound for medical imaging dates back more than 50 years and has matured in the last two decades to the level of routine use in hospitals.[1-2] The last developed techniques use ultrasonic arrays. An image is classically constructed using a repetitive procedure. First, a beam is focused at a given point through the zone of interest using adapted delay lines, and the array records the back-scattered field; second, the brightness of the image at the focus is the correlation coefficient between the back-scattered field and the emitted delay lines; last, the delay lines are changed to focus at another point, thus closing the loop. To reduce the run time and obtain images in real time, only a few delay lines are used, and it is assumed that the time of arrival of the back-scattered echoes corresponds to depth via the sound velocity. In a homogeneous medium, the quality of the image classically depends on the size of the focal spot, which is itself defined by the array aperture according to diffraction laws. Roughly speaking, the larger the array, the smaller the focal spot and the better the image. However, this procedure no longer works when a multiple scattering medium is placed between the array and the treatment volume. First, delay lines do not permit a focus through multiple scattering; second, the time of arrival of the back-scattered echoes no longer corresponds to depth. Thus, acoustical imaging through a multiple scattering medium remains an issue.

The aim of this study is to show that images can be obtained through a multiple scattering medium using time-reversal principles. More precisely, we compare the quality of images obtained with the same ultrasonic array in two configurations: in the first case, the phantom to be imaged is placed in water in front of the array; in the second case, a multiple scattering medium is placed between the array and the phantom. It appears that the detection of scatterers is better through multiple scattering than in water.

This study is divided into three parts. The first section deals with time-reversal principles and their application to ultrasonic focusing through a multiple scattering medium. In the second section, we describe the procedure used to construct the image of a phantom through a high-order multiple scattering medium. Finally, we compare in the final section the quality of images obtained with the same array in a homogeneous medium and through a multiple scattering medium.

Time-reversal focusing

A classic time-reversal experiment consists of :

1. transmitting a short pulse from a source;
2. recording the acoustic field on an array of transducers (the time-reversal mirror or TRM) after refraction and/or scattering through the propagation medium;
3. time-reversing and retransmitting the time-reversed field through the same propagation medium;

Because of the reversibility of acoustic propagation in a motion-less and loss-less medium, the time-reversed field temporally and spatially focuses back onto the source whatever the heterogeneity of the medium. Since the early 1990s, experimental demonstrations of time-reversal focusing have been achieved through various media, such as ultrasonic or underwater acoustic wave guides, human skull, metallic plates and high-order multiple scattering media.[3-6] It has been shown that the larger the heterogeneities of the propagation medium, the smaller the focal spot after time-reversal. Actually, after time-reversal, the heterogeneities of the medium act as a set of secondary sources, which serve to increase the wave number diversity, thereby decreasing the size of the focal spot. For example, TRMs achieve good focusing in wave guides.[3-4] However, the TRM must then span the whole wave guide section to correctly sample the wave number diversity, and the optimal size of the guide[3] may prevent practical applications to ultrasonic imaging. Therefore, in this work, we prefer to use a multiscattering medium with which a part of the acoustic field is naturally redirected with wide-angle wave numbers toward a small TRM.

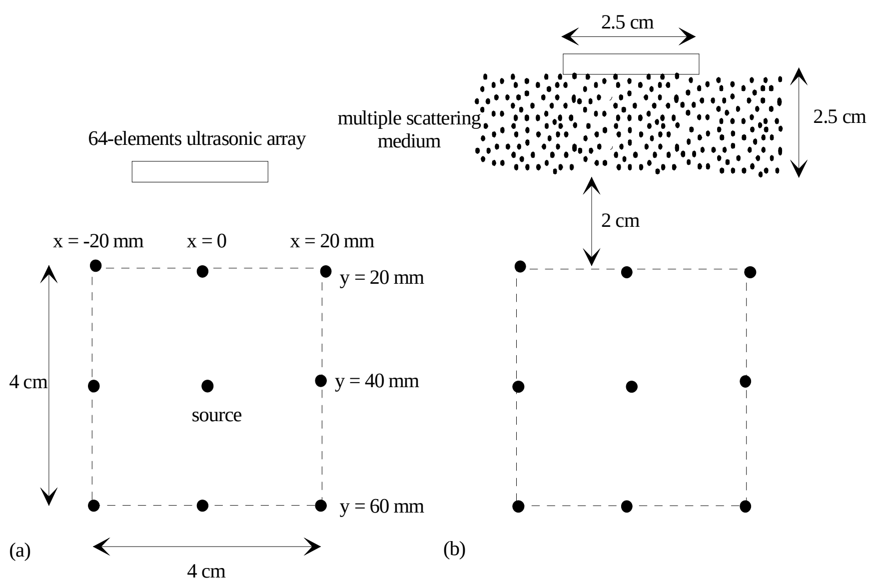

Fig. 1. Schematic of the experimental set-up: (a) the homogeneous case; (b) the multiple scattering case. The nine positions of the source correspond to the results of Figs. 2 and 3.

In the following, we compare the focal spot after time-reversal in two configurations. In the first case, a point source is placed in the water in front of a 64-elements linear array (Fig. 1a). Each element width is 0.4 mm with central frequency 3.3 MHz (wavelength ~ 0.45 mm). The total aperture of the array is 25 mm. Both the source and the array are reversible devices: they work as transmitters as well as receivers.

In the second case, a high-order multiple scattering medium is placed between the source and the array (Fig. 1b). The multiple scattering medium is a random set of parallel steel rods.[7] The rods are 0.8 mm in diameter, approximately 10 cm in length, and the average distance between two rods is 2.3 mm. Since the source and the array elements are 12 mm in length, which is significantly larger than the wavelength and the width of each element, the set-up can be considered two-dimensional in the xy plane. The rod concentration is ~18 rods/cm^2, the multiple scattering region is 2.5cm x 5cm, and its front face is stuck on the array.

A time-reversal experiment is achieved following stages 1-3 described above. After stage 3, the maximum of the time-reversed field is recorded at and around the initial point source now using the source as a receiver. Figures 2 and 3 show the focal spots obtained at nine different positions (see Fig. 1) of the point source relative to the array in the two studied configurations. Two points are important. First, the focal spot is more concentrated when the multiple scattering medium is present between the source and the array; the focal spot is smaller and the average maximum is 5 times larger. Second, the maximum of the time-reversed field is more stable over the nine focal spots. The average maximum has a 18% standard deviation in the multiple scattering case whereas it reaches 48% in the case of a homogeneous medium. These results are important to ultrasonic imaging. Indeed, the quality of an image depends on the size of the focal spot as well as the variation of amplitude of the focused field in the region of interest.

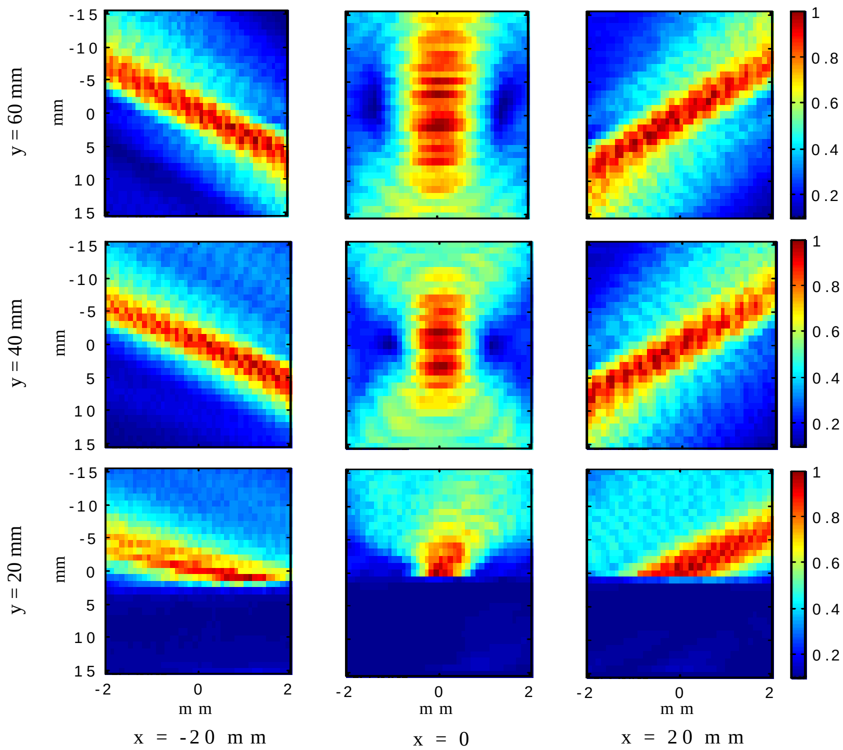

Fig. 2. Focal spots after time-reversal in a homogeneous medium for 9 positions of the source. It was not possible to scan the pressure field at less than 20 mm from the array. Each picture is normalized by its own maximum. The standard deviation between the maxima is equal to 48% of the average maximum.

Ultrasonic imaging through multiple scattering

Usually, acoustical imaging is performed with arrays. Here, we define the ensemble “array plus multiple scattering medium” as a new imaging device. The quality of an imaging system lies in its ability to focus an acoustic wave at any point inside the region of interest. We have shown that the focusing quality of an array is improved after time-reversal when the propagation medium is a multiple scattering medium. This requires knowledge of the complicated electronic signals that focus back onto the source after time-reversal from the array. This first point differs significantly from a classic imaging system for which focusing is performed with simple electric delay lines. However, this set of signals can be recorded only once when the ensemble “array plus multiple scattering medium” is built. Indeed, these signals depend only on the geometry of the system and are completely independent of the medium to be imaged. A second point is also important: with a classic imaging system, the back-scattered energy comes only from the medium to be imaged. In our case, the multiple scattering medium will back-scatter more energy than the treatment volume. This acoustic field has then to be subtracted from the total back-scattered field before the construction of the image.

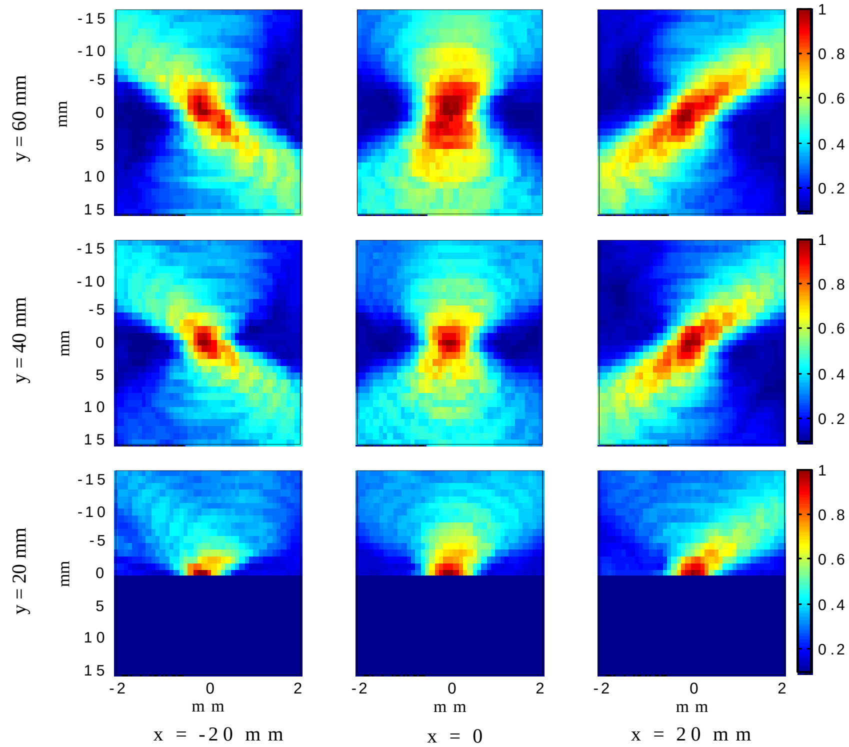

Fig. 3. Focal spots after time-reversal through a multiscattering medium for 9 positions of the source. For consistency with Fig. 2, the pressure field has not been scanned at less than 20 mm from the multiple scattering medium. Each picture is normalized by its own maximum. The standard deviation between the maxima is equal to 18% of the average maximum.

As a consequence, the procedure to create an image through a multiple scattering medium is the following :

1. We define the size and the resolution of the future image. We place a point source at the center of each pixel and, for each transducer of the array, we record the electronic signals which will allow us to focus back onto the source after time-reversal;

2. For each pixel, we transmit the previously-recorded time-reversed field and record the pressure field back-scattered by the multiple scattering medium alone. This is called the reference field;

Stages 1 and 2 are performed without the medium to be imaged and done only once when the system “array plus multiple scattering medium” is built. We now place the “array plus multiple scattering medium” in front of the region of interest.

3. For each pixel, we transmit the electronic time-reversed codes from the array and record the back-scattered field;

4. For each pixel, we subtract the reference field from the back-scattered field and correlate the difference with the electronic signal recorded during stage 1. The correlation coefficient corresponds to the brightness of the image for this pixel.

Experimental results

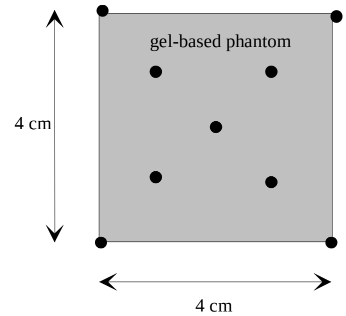

Fig. 4. Schematic of the phantom, made of 9 rods included in a gel-based phantom.

We have tested this algorithm on a medium made of 9 rods placed in a gel-based phantom. The rods are identical to the ones that compose the multiscattering medium, and the medium is also considered two-dimensional. Four rods were placed at the corners of a 4 cm square, and the other 5 were arranged regularly on the diagonal of the square (Fig. 4). The two-dimensional imaging device is placed in the same plane as the two-dimensional medium at two centimeters from one side of the square (see Fig. 1). Everything is immersed in a water bath. The imaging device is either the 2.5-cm 64-elements array described above alone or the system “array plus multiple scattering medium”. In the latter case, the phantom is placed at two centimeters from the multi scattering medium (see Fig. 1b).

Considering the size of the phantom, we choose to image a 50mm x 60mm area sampled by 51 x 21 pixels (stage 1 is performed with a 1-mm resolution along the x axis and a 3-mm resolution along the y-axis). Figures 5 and 6 show the images of the phantom obtained with the two different imaging devices. In the case of the multiscattering imaging system, the phantom has not been well centered on the predefined image area, which explains why the extreme left side of the phantom misses the image. As expected, we get a better detection of the phantom scatterers with the multiscattering imaging system: the axial and lateral resolutions are better, and each rod appears with the same strength. On the other hand, the noise level is 10-dB higher. This is due to the subtraction between the total and the reference back-scattered field done imperfectly during our experiment. Actually, some rods of the multiscattering medium have moved slightly between the recording of the reference field (stage 2) and the acquisition of the total back-scattered field (stage 3). More generally, the noise level is due to small heterogeneities of the phantom and should be comparable to the noise observed with a classic imaging device.

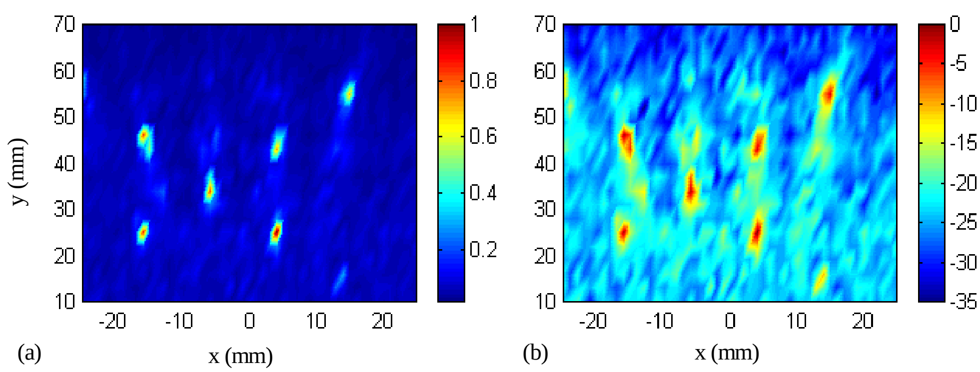

Fig. 5. Image of the phantom obtained with the multiscattering imaging device:
(a) in a linear scale; (b) in decibel.

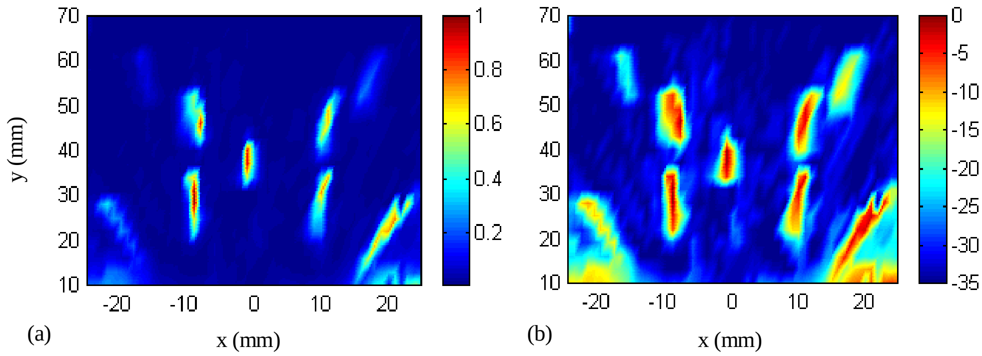

Fig. 6. Image of the phantom obtained with a classic imaging device:
(a) in a linear scale; (b) in decibel.

Finally, an image of a phantom is feasible as long as the low-amplitude signal (A) received from a phantom scatterer is measurable compared to the high-amplitude signal (B) backscattered by the multiple scattering medium itself. By measurable, we mean that the phantom signal, which is the subtraction between the total field (stage 3) and the reference field (stage 2) is higher than the electronic noise of the experiment. In our case, we have $20\log_{10}(B/A) \approx 20\,\mathrm{dB}$ which is far above the noise threshold of our transducers. Another limitation of the system is that an image cannot be obtained in real time with the multi-scattering imaging device. The time cost to transmit the electronic signals, record the back-scattered field and correlate it with the electronic codes is relatively heavy (2 hours for 51 x 21=1071 pixels on a Pentium 2 computer). On the other hand, this imaging device has many advantages besides the quality of the images. We study, for example, the possibility of reducing the number of elements in the array without degrading the quality of the image.

In conclusion, we have shown that time reversal is a solution for performing ultrasonic imaging through a multiple scattering medium. The resolution of the image of a phantom is better than the one obtained in a homogeneous medium. In future work, we will carefully investigate the influence of the number of array elements and the size of the multiscattering medium on the quality of the images (noise level, axial and lateral resolution) obtained with this new ultrasonic imaging device.

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[8] To see a picture of the experimental set up and get more information about the work done in Paris about ultrasonic time-reversal, consult the laboratory web site : http://www.loa.espci.fr

