Abstract: The time reversal process is applied to focus pulsed ultrasonic waves through the human skull bone. The aim is here whether to treat brain tumors, which are difficult to reach with classical surgery means, or to achieve ultrasonic imaging of the brain. Such medical applications require precise control of the size and location of the ultrasonic focal beam. But, the severe ultrasonic attenuation in the skull reduces the efficiency of the time reversal process. Nevertheless, an improvement of the time reversal process in absorbing media has been investigated and applied to the focusing through the skull (1). An extension of this technique is developed in order to focus on a set of points surrounding an initial artificial source implanted in the tissue volume to treat. Such technique could become completely non invasive and hence, be used in medical imaging if the initial source is located on the other side of the skull.

Most ultrasonic therapeutic or imaging systems don’t take into account the inhomogeneities of human tissues: the acoustic velocity is assumed to be constant, while steering and focusing the acoustic energy. In fact, the spatial variations of the speed of sound (from approximately 1440 m.s\(^{-1}\) in fat to 1580 m.s\(^{-1}\) in muscle) induce a phase and amplitude distortion of the wavefront propagating in the medium. These aberrations degrade the spatial resolution, which can reduce the therapeutic performance or mask important diagnostic information. This problem was first discovered by White et al (2) during investigation into brain imaging. Indeed, in the particular case of the skull, a large discrepancy in acoustic velocities between brain tissue and skull tissue (about 1500 m.s\(^{-1}\) versus 3000 m.s\(^{-1}\) respectively) and a severe attenuation of ultrasound in the skull bone magnify the degradation of the beam shape.

Time reversal represents an original way to compensate for distortion due to various inhomogeneous media. Time reversal mirrors (TRM) take advantage of the invariance of the wave equation in a lossless medium under a time reversal operation. This means that if focusing through any inhomogeneous medium is the objective, the distorted wavefield coming from a source (active or passive) located at the desired focal point should be recorded and then transmitted in time reversed form. The time reversed wavefield back propagates through the inhomogeneities and optimally focuses on the source. Such an adaptive system is locked on the point-like reflector position or on the brightest point of an extended target. In most of practical situation, such an acoustic source is not available in the region of interest. Besides, the time reversal focusing is related to the invariance of the wave equation under the change of \( t \) to \(-t\). This property implies that time appears in second order derivative only. However, this property becomes obsolete in an absorbing medium, like bone: Acoustic losses are taken into account in the wave equation by a first derivative in time and are not time reversal invariant. To solve these problems, another procedure has been developed. In the first step of a therapeutic procedure, a small artificial acoustic source is implanted inside the tumors during the biopsy. For medical imaging, the piezo-electric transducers are very small and omnidirectional and this source could be located on the other side of the skull. Then time reversal is combined with an amplitude compensation procedure which takes into account the absorption. In a second step, from the knowledge of the Green’s function matched to this initial source location we deduce the new Green’s function matched to various points of interest in order to treat or image the whole volume.

In the case of absorbing heterogeneous media, time-reversal is no longer the optimal solution to focus on a source implanted in the medium. A transducer element that received a weak signal is located in front of a strongly absorbing area of the skull. After the time reversal operation, this weak signal backpropagates through the same area of the skull and hence, the amplitude modulation of the wavefront is increased by a power of two. However, in a particular case, when the aberrating and absorbing medium can be modeled as a thin layer placed at some distance from the transducers array, it is possible to take into account the amplitude modulation originating from acoustic losses and so, to improve the quality of TRM focusing. Thus, if this thin layer is located close to the array its effects can be modeled by a time shift and an amplitude factor on each transducer. The time delay correction is automatically accomplished by the time reversal process and we can take into account the amplitude aberration due to attenuation by inverting the amplitude modulation of the wavefield received on the array of transducers. The amplitude modulation is estimated by comparison with a reference waveform obtained in the same condition in homogeneous and lossless medium. These estimates are then employed to invert the amplitude modulation. Nevertheless, this amplitude compensation is quite efficient only when the absorbing medium is a layer located close to the array. Otherwise, additional amplitude and shape distortions may develop as the wavefront propagates in the
homogeneous and lossless medium after passing through the skull. These amplitude distortions are automatically
compensated by the time reversal processing and so, must not be taken into account a second time. The idea is to
simulate a virtual array of transducers located close to the skull. For this purpose, the wavefront received from
the source is time reversed and numerically backpropagated from the array aperture to the skull surface. Since the
medium between the array and the skull is lossless, the time reversal processing achieves an inverse wavefield
propagator. Moreover, this time reversal processing can be easily computed as soon as the medium is assumed to be
homogeneous. Amplitude distortion is then estimated on the virtual array and the estimates are used to compensate
for the backpropagated field. This compensated and converging waveform can now be time reversed and numerically
propagated from the approximated skull surface to the array aperture. This method by simulating a virtual array
located close to the skull allows discrimination between these two kinds of amplitude modulations, respectively due
to the absorption in the skull and the propagation from the skull to the array. Thus, we obtained a new set of signals
adapted to focus through the skull at the initial source location.

Although time reversal is only self-focusing onto the artificial source implanted inside the treatment volume,
we show how the array can be steered on points surrounding this beacon. In homogeneous medium, conventional
beamsteering modifies the wavefront focused on the artificial source by applying a time delay law and apodization
factors taking into account the distances between the new focus location and the array elements. Note, this process
requires only to know the sound speed of the medium. However, in heterogeneous medium, this process is only valid
for small angles or when the aberrations are located in a layer close to the array. Indeed, if the aberrating layer is
modeled as a thin layer located close to the array, the aberrations induced by the skull are independent of the source
location and then, the Green’s functions of two different points \( r_0 \) and \( r_1 \) implanted in the medium only differ from
the same time shifts and apodization factors as in homogeneous medium. On the other hand, if the thin aberrating
layer is now located at some distance from the array of transducers, the two Green’s functions associated to \( r_0 \) and \( r_1 \)
are different: The propagation between the layer and the array modifies in a different way for these two wavefronts.
Thus, as soon as the skull is not located close to the array, conventional steering of an initial wavefront is not
efficient if we want to construct the Green’s function associated to a new point of interest. Nevertheless, as well as
for the amplitude compensation, numerical backpropagation can extend the conventional steering to aberrating layers
located at any distance from the array: The initial wavefront coming from \( r_0 \) is numerically backpropagated from the
array to the surface of the skull. This wavefront is then tilted in order to focus on \( r_1 \), time reversed and numerically
backpropagated from the skull to the array. Thus, from the knowledge of the Green’s function associated to the
initial point \( r_0 \), we a new synthesized Green’s function associated to \( r_1 \). By combining the amplitude compensation
and the steering of the wavefronts, we are now able to construct the optimal set of signals in order to focus around
the initial source location.

Focusing and steering of an ultrasonic beam through the skull is possible in spite of the severe ultrasonic
attenuation of the bone. We propose a method of steering combined with an amplitude compensation to improve the
time reversal focusing when an artificial acoustic source is available in the medium. Thus, although time reversal is
only self-focusing onto this initial source implanted inside the treatment volume, we learn how to focus the ultrasonic
beam onto many new others focal points in order to investigate the whole tumor. A new set of signals is calculated
from the knowledge of the initial ones corresponding to the artificial source location. The proposed method is valid
when the inhomogeneities can be modeled as a thin screen varying in absorption and time delay, located at any depth
from the array. Experimental results show that this assumption can be done in the case of the skull.

REFERENCES