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FDTD SIMULATION OF TRANSCRANIAL FOCUSING USING ULTRASONIC PHASE-CONJUGATE ARRAYS

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INTRODUCTION

Focusing ultrasonic fields onto selected targets within the body with good accuracy and sufficient intensity to allow controlled necrosis of a region of tissue is a topic of great interest in medical acoustics. Several techniques have been demonstrated through simulation and laboratory experiment to achieve promising results [1, 2, 3]. The purpose of the present paper is to demonstrate the use of acoustic phase conjugation, or more narrowly in this context, time reversal as a valid focusing technique in biological tissue, which does not require *a priori* knowledge of the inhomogeneous propagation medium's properties. Another goal of this paper is to demonstrate the effectiveness of the finite-difference time-domain (FDTD) method for the simulation of linear acoustic propagation in an inhomogeneous propagation medium.

DESCRIPTION OF THE PROBLEM

It is desired to use a sparse linear acoustic array to back-propagate a signal scattered from a point-like source deep within a modeled human head. A finite-aperture array is modeled as 64 point source elements outside the head in a water bath used as a coupling medium.

An arbitrary acoustic signal, here a pulse from a spark source (lithotripter), is used as the model waveform for illuminating the target. Any pulse shape can be used, but the illustration of the concept without using ideal narrowband signals was to demonstrate the utility of the time reversal technique for arbitrary waveforms using the FDTD code.

Brief Description of the Time Reversal Method

The theory and operation of time reversal mirrors (TRM) is described by Fink [4]. A brief description of the time reversal technique follows: Consider a scatterer or specular reflector within an inhomogeneous medium. The scatterer is our target in this case, and is assumed to have an acoustic impedance mismatch causing it to scatter an incoming signal that could be originated at some element of the array for example. The scattered signal is distorted as it passes through the inhomogeneous propagation medium and undergoes boundary reflections. We record the arriving field at each of the array elements digitally, and store these into buffers during the *receive mode* of the operation. Once the main scattered signal is stored, the array is switched into its *transmit mode*. In transmit mode the recorded data from each channel buffer is reemitted *time reversed*, and amplified if needed. The unchanged medium will back-propagate the signals from all the array elements to focus onto the original scattering target.

It is the time-invariance of the lossless wave equation and the medium's Green's function that allow the use of linear acoustic time reversal. The reciprocity of the system and the medium are necessary for acoustic phase conjugation to be an exact solution. Note that this receive/transmit cycle can be performed more than once (iteratively) to achieve better focusing, and can allow temporal windowing and target selection as well. In our example we assume a single scatterer exists in the medium.

Certain caveats apply to the phase conjugation method. Foremost perhaps is that a well-defined scatterer can be found within the illuminated region. The other main requirement for perfect phase conjugation is that the propagation medium be reciprocal. Strong attenuation, dynamic medium, and dispersion can have detrimental effects on the effectiveness of a real time reversal mirror. Other effects such as phase distortion, nonlinear transfer functions, or jitter in the phase of the signals can also degrade the focusing of the TRM.

DESCRIPTION OF THE SIMULATIONS

The simulations are carried out in two dimensions (x, y). The example presented uses a 1024 x 1024 spatial grid, with a uniform square grid spacing of 0.13-mm, and the time stepping is done using 8-nsec steps. Absorbing boundary conditions were used to minimize reflection from the outer boundaries of the computational domain. The 2-dimensional head model, inspired by the Shepp and Logan phantom for tomography [5], was composed of 21 ellipses that form the major cross-sectional features. Data for the ultrasonic properties were obtained from empirical values given in the literature, as in Goss [6].

The Wave Equation

The inhomogeneous linear acoustic wave equation for a lossy medium is

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - \frac{1}{\rho}\nabla p \cdot \nabla \rho + \frac{\delta}{\rho c^4}\frac{\partial^3 p}{\partial t^3} = 0 \tag{1}$$

which is obtained from the equations of fluid mechanics, and solved for the acoustic pressure, p. With the exception of the the finite-amplitude terms, equation (1) retains all terms from the Westervelt equation, described by Tjøtta and Tjøtta [7], and Cleveland [8]. The attenuation comes from the sound diffusivity, δ, and accounts for viscous and thermal effects. The attenuation term implicitly contains a second power dependence on the central pulse frequency, f_c, that can be seen if the equation is rewritten using nondimensional time and space variables, $\hat{t}$ and $\hat{x}$, in one dimension for clarity

$$\frac{\partial^2 p}{\partial \hat{x}^2} - \frac{\partial^2 p}{\partial \hat{t}^2} - \frac{1}{\rho}\left(\frac{\partial p}{\partial \hat{x}}\frac{\partial \rho}{\partial \hat{x}}\right) + \frac{\delta}{\rho c^3} f_c^2 \frac{\partial^3 p}{\partial \hat{t}^3} = 0 \tag{2}$$

where the non-dimensional variables are defined to be $\hat{x} = x/\lambda_c$, and $\hat{t} = tf_c$. The wave equation is solved to second-order accuracy in space and time using the finite-difference time-domain (FDTD) method described by Yee [9]. Note that five time frames of the pressure field are required to be stored at all times due to the third-order time derivative in (1).

The Loss Term

A detailed study of the relaxation mechanisms of tissue is beyond the scope of the present study, however Khokhlova, *et al.* [10] and Averkiou, *et al.* [11] have shown that the propagated field with a frequency to the η power dependence gave similar results for η between 1.1 and 2. The studies cited were done for finite-amplitude waveforms, so the results would be conservative when used for our linear case due to the absence of excessive energy in the higher harmonics. Thus, effective attenuation coefficients can be used for the linear simulations. The sound diffusion in (1) is directly related to the absorption coefficient by

$$\alpha = 2\frac{\delta f^2}{\rho c^3} \tag{3}$$

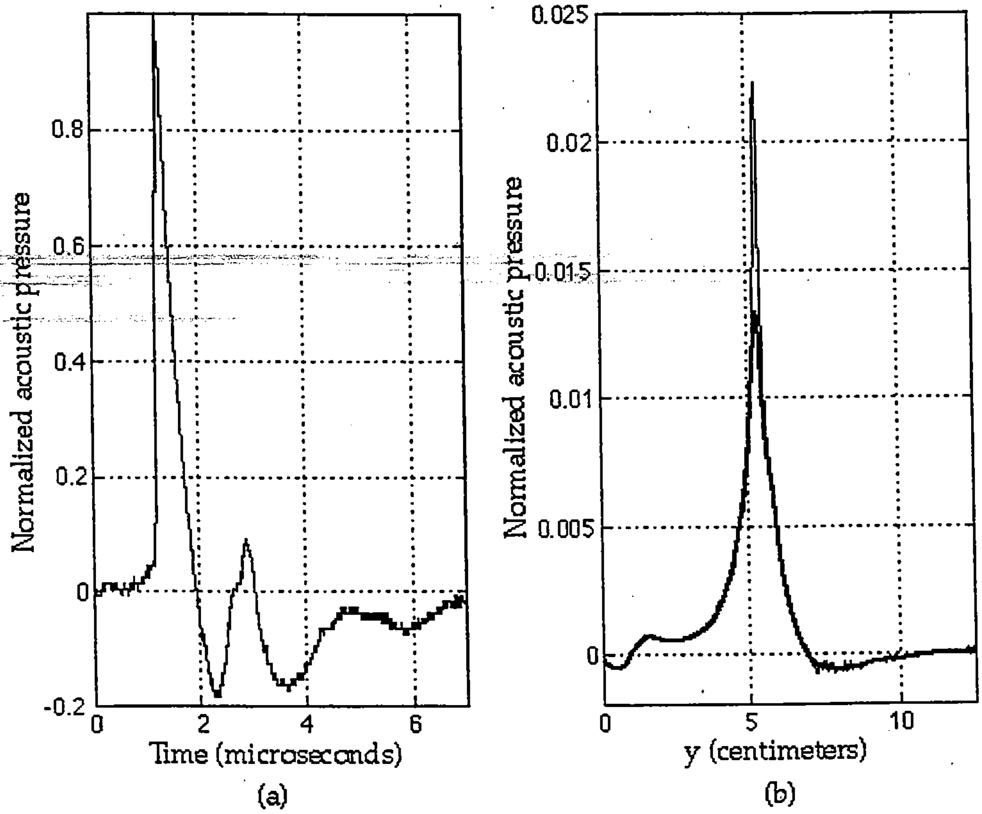

Figure 1: (a) The illuminating pressure waveform, normalized to its maximum value (b) Acoustic pressure slices through the focal spot normalized to illuminating signal maximum. The FWHM extent for the case with attenuation (bold line) is approximately twice the FWHM for the non-attenuating case (fine line).

SIMULATION RESULTS

Output files are generated throughout the simulation to create images such as those shown in figure 2. These frames show snapshots of the acoustic pressure field normalized to the peak pressure of the illuminating signal. An outline of the head model is overlayed on the fields for reference. A small circle is drawn around the location of the scatterer in the receive mode frames. The vertical line to the left of the head shows the position and aperture of the linear array. The large feature within the head in the Receive mode frames is the wavefront reflected by the inner surface of the skull, while the fainter circular traces outside are the transmitted wavefronts. Figure 2 compares the case $\delta = 0$ (no attenuation) with the case having modeled attenuation for the human head during the transmit mode. It is clear that the TRM is capable of focusing acoustic energy back onto the scatterer as predicted by the theory for the reciprocal case. What is not so obvious is what effect the reciprocity-violating factors would have upon the focusing ability of the array. Any terms containing odd-order time derivatives, such as the attenuation term, will reduce the effectiveness of the time reversal system.

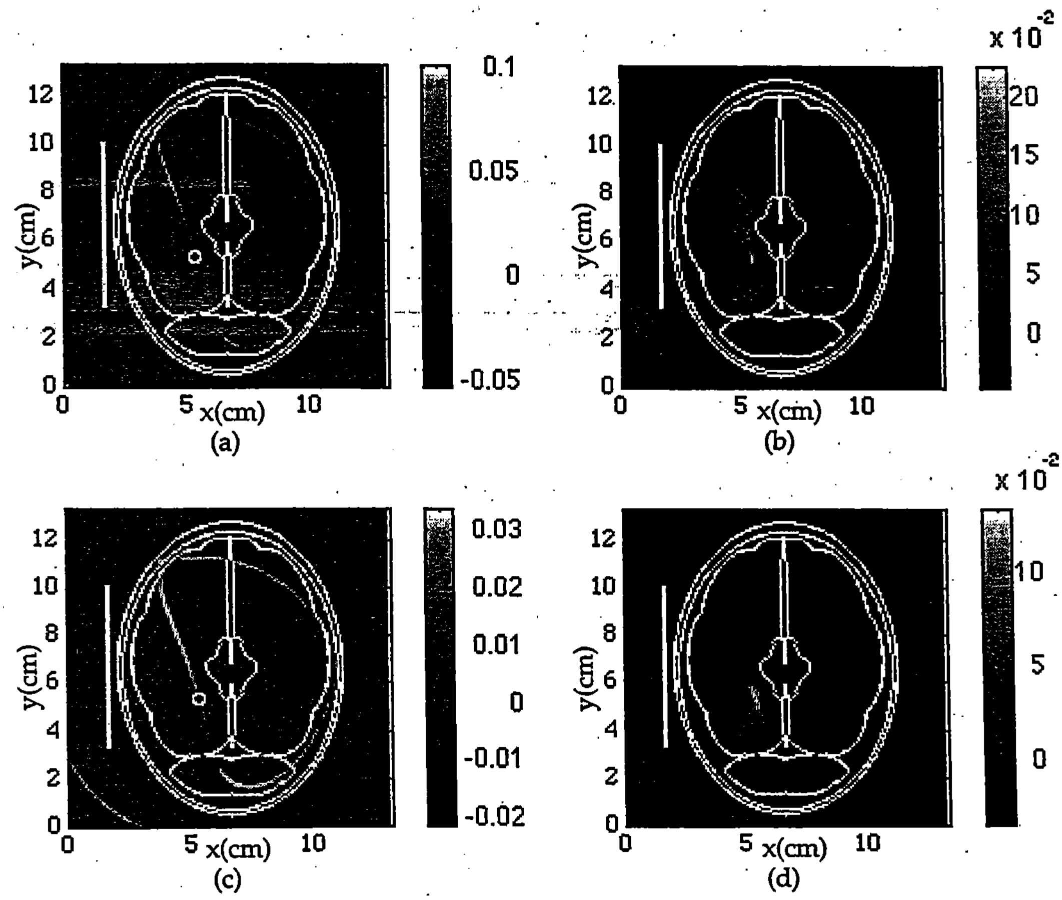

Figure 2: Acoustic pressure field normalized to the peak pressure of the illuminating waveform. The outline of the major modeled structures is also shown. The vertical line to the left of the head is the aperture of the array. (a) Receive mode pressure at some time, t_o, without attenuation (b) Transmit mode pressure at the time of maximum focusing, t_{max}, without attenuation (c) Receive mode pressure at time, t'_o, with attenuation (d) Transmit mode pressure at the time of maximum focusing, t'_{max}, with attenuation. Note that each frame is scaled individually to make full use of the grayscale color map.

LIMITATIONS OF THE TIME-REVERSAL METHOD

Quantitative knowledge of the limitations of the time reversal technique is required to determine whether the technique can be effectively used for medical purposes, especially in the brain. The present study does not attempt to serve as proof of the feasibility of using a TRM for brain tumor ablation. The use of high-intensity phase-conjugate systems is probably more appropriate at this stage for kidney stone comminution and other, less critical, procedures. Thomas and Fink [12] have shown experimentally that the attenuating skull has a detrimental effect on a TRM focus, and suggested a method for amplitude distortion compensation.

Simulations for the human head provide a challenge for imaging and focusing techniques, and as such, serve as a rigorous test of the techniques. This is due to the presence of the highly attenuating and reflecting skull bone, and other internal inhomogeneities. Undesired energy deposition in the tissue other than in the region of interest can result from propagation through the bone. The removal of a section of the skull before applying the ultrasound has been suggested, and was performed on dogs by Fry, *et al.* [13], and is not a difficult or unusual procedure.

In another study [14] the authors investigated the effect of temporal jitter in the initial phase of the signals. As one would expect from a method based on phase, the initial phase of the signals was found to play an important role in the ability of the array to obtain a tight focus. Temporal jitter greater than 5 to 10 percent of one period of a narrowband system will noticeably degrade the focus of the array. Such phase jitter will occur in all systems due to sampling resolution errors as well as transient mechanical errors, which can result from the motion of the array or the target between the receive and the transmit stages of the time reversal process. These phase errors can be important for the megahertz frequencies used in medical ultrasound.

CONCLUSIONS

An explicit FDTD code to solve for the inhomogeneous acoustic wave equation with attenuation was used to simulate the use of a time reversal mirror for focusing ultrasound in a modeled human head cross-section. The head poses special challenges for imaging and focusing techniques because of the attenuation and reflection from the skull bone. The present study modeled a finite-aperture linear array to focus retrodirectively onto a well-defined scatterer deep within the modeled brain tissue. For the case of no attenuation, the time reversal method is exact, and very good focusing was obtained as expected. For the waveform used in this example, the acoustic pressure FWHM points were about 4 mm wide for the attenuation-free case. When attenuation was included, the focusing ability of the TRM was degraded, and the FWHM grew to 9mm. The FDTD is well-suited for simulations such as this, and was found in benchmark tests to be in excellent agreement with calculated focal zone widths down to one wavelength. The propagation through an inhomogeneous medium with sharp interfaces was demonstrated. Further tests can be made to test the code for use as a qualitative prediction tool for hyperthermia applications.

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References

[1] R. J. Lalonde, A. Worthington, J. W. Hunt, "Field conjugate acoustic lenses for ultrasound hyperthermia," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, 40, pp 592-602 (1993).

[2] C. J. Diederich, K. Hynynen, "The feasibility of using electrically focused ultrasound arrays to induce deep hyperthermia via body cavities," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, 38, pp 207-219 (1991).

[3] H. Wan, P. VanBaren, E. S. Ebbini, C. A. Cain, "Ultrasound surgery: Comparison of strategies using phased array systems," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, 43, pp 1085-1098 (1996).

[4] M. A. Fink, "Time reversal of ultrasonic fields- Part I: Basic principles," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, 39, pp 555-566 (1992).

[5] A. C. Kak, M. Slaney, "*Principles of Computerized Tomographic Imaging*," IEEE Press (1988) pp 52-56.

[6] S. A. Goss, R. L. Johnston, F. Dunn, "Comprehensive compilation of empirical ultrasonic properties of mammalian tissues," *J. Acoust. Soc. Am.*, 64, pp 423-457 (1978).

[7] J. N. Tjøtta, S. Tjøtta, "Nonlinear equations of acoustics, with application to parametric acoustic arrays," *J. Acoust. Soc. Am.*, 69, pp 1644-1652 (1981).

[8] R. O. Cleveland, *Propagation of Sonic Booms Through a Real, Stratified Atmosphere*, PhD Dissertation, University of Texas at Austin, (1995).

[9] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas and Propagation*, AP-14, pp 302-307 (1966).

[10] V. A. Khokhlova, O. V. Sapozhnikov, M. A. Averkiou, L. A. Crum, "Modified spectral solution of a Burgers-type equation for the description of shock wave propagation in biological media," in Proceedings: *World Congress on Ultrasonics*, (1995) pp 1099-1102.

[11] M. A. Averkiou, L. A. Crum, V. A. Khokhlova, O. V. Rudenko, "Nonlinear waveform distortion and energy attenuation of intense acoustic waves in biological tissue," in 14^{th} *Symposium on Nonlinear Acoustics: Nonlinear Acoustics in Perspective*, R. Wei, ed., Nanjing University Press (1996) pp 463-468.

[12] J.-L. Thomas, M. A. Fink, "Ultrasonic beam focusing through tissue inhomogeneities with a time reversal mirror: Application to transskull therapy," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, 43, pp 1122-1129 (1996).

[13] F. J. Fry, *et al.*, "A focused ultrasound system for tissue volume ablation in deep seated brain sites," in Proceedings:*IEEE Ultrasonics Symposium*, (1986) pp 1001-1004.

[14] I. M. Hallaj, S. G. Kargl, R. A. Roy, "Penalties of retrodirective arrays containing signal uncertainties: Implications for mine countermeasures," to appear in Proceedings:*High Frequency Acoustics in Shallow Water*, (1997).