ICA 2013 Montreal  
Montreal, Canada  
2 - 7 June 2013  

Biomedical Acoustics  
Session 5aBAb: Imaging, Therapy, and Bubbles (Again)

5aBAb5. Temporal and spatial characteristics of nonlinear acoustic field generated by an extracorporeal shockwave therapy device: modeling and measurements

Maria Karzova*, Vera A. Khokhlova, Camilo Perez and Thomas J. Matula

*Corresponding author's address: Lomonosov Moscow State University; Ecole Centrale de Lyon, Moscow, 119991, Moscow, Russia, masha@acs366.phys.msu.ru

Extracorporeal shock wave therapy (ESWT) refers to the use of focused shock pulses to treat certain musculoskeletal disorders. Although the technology is used clinically, acoustic characteristics of ESWT fields and their relation to the bioeffects induced are not fully understood. In the present work the acoustic field of a clinical ESWT device (Duolith SD1) was characterized in water using a combined measurement and modeling approach. Simulation model was based on the nonlinear KZK equation; the boundary condition was based on the pressure waveforms measured in a plane 5 mm away from the therapy head. The model was used to simulate and to analyze pressure waveforms along the axis of the therapy head and 2D spatial distributions of peak pressures. The modeling results were found in a good agreement with experimental data.

Published by the Acoustical Society of America through the American Institute of Physics
Introduction

Extracorporeal shock wave therapy (ESWT) is a noninvasive treatment for multiple musculoskeletal disorders such as tendinopathies, plantar fasciitis, lateral epicondylitis, etc. Therapeutic effects induced by ESWT include angiogenesis, osteogenesis and antinociceptive effects. Although ESWT is used clinically and refers to the use of focused shock waves, physical mechanisms of ESWT action on bones and tissues are not fully understood. For a better understanding of ESWT mechanisms, a detailed characterization of ESWT acoustic fields is required. In the present work the acoustic field of a clinical ESWT device (Duolith SD1) was characterized in water using a combined measurement and modeling approach.

Experimental data processing

Measurements were performed on the portable Duolith SD1 T-Top ESWT device that uses a focused electromagnetic source. The electromagnetic source was coupled with the 20 mm standoff that contains the oil bag attachment to the membrane of the therapy head. The therapy head was located outside the water tank and was coupled to the tank via a tegaderm window and coupling gel. Measurements of the acoustic field were performed in water using a 3D computer-controlled positioning system (Velmex NF90, Bloomfield, NY) and a fiber optic hydrophone (FOPH).

The beam axis was found by aligning the maximum of the pressure amplitude in several planes away from the standoff. Radial symmetry of the field emitted from the device was confirmed after initial experiments (not shown here). Afterwards pressure waveforms were measured radially in a plane close to the therapy head (5 mm away from the standoff). This provided boundary conditions for the numerical work. The waveforms were measured from the beam axis at \( r = 0 \) up to the radial coordinate \( r = 14 \) mm. Although the standoff radius was 20 mm, measurements at distances \( 14 < r < 20 \) mm were not collected because of low signal-to-noise levels. A total of 71 waveforms were measured with a spatial step 0.2 mm, time step 2 ns and duration 20 μs. Signals were sampled at 500 MSample/s and each waveform was averaged over 20 individual waveforms. These data were used to set a boundary condition for numerical modeling of the ESWT field.

Representative examples of averaged waveforms collected from the experiment for setting the boundary condition are shown in Fig. 1 (a,b,c) in blue. In order to make them applicable for the numerical simulations it was necessary 1) to reduce the noise level in the measured signal; 2) to add the tail to each waveform for zero mean value of the signal (which is necessary for fast Fourier transform (FFT) in numerical simulations); 3) to change the spatial step of the grid for boundary condition; 4) to add waveforms in the radial scan from 14 mm to 20 mm from the axis. Each procedure is described below in more detail.

Reducing the noise level

To facilitate the modeling effort, each experimental waveform was numerically smoothed to reduce the noise level in the measured signal. To avoid decreasing the signal amplitude in the smoothing process each waveform was divided into two parts. The first part contained the region around the maximum of the peak positive pressure (within 1.25 μs) and the second part contained the other smoother parts of the pulse. The first part was numerically smoothed 3 times over 5 points that allowed for keeping the same amplitude level. The second part of the signal was smoothed 3 times over 30 points. The resulting smoothed waveforms are also shown in Fig. 1 (a,b,c) in red.

Requirement of zero mean value of the waveform

The general properties of the solution to the KZK equation yield that the time integral over the pulse must be equal to zero, as the zero frequency component in the FFT series expansion of the signal is eliminated by diffraction.

To ensure that the pulses used for the boundary condition satisfy this requirement, a tail of \( \Delta t = 30 \) μs duration was added at the end of each pulse as:

\[
p(t) = p_1 \cos^2\left(\frac{\pi}{2\Delta t}\right) - \left(p_1 + \frac{2S}{\Delta t}\right)\sin^2\left(\frac{\pi}{2\Delta t}\right)
\]

(1)

Here \( p_1 \) is the pressure value at the last measured time point of each waveform, \( t \) is time counted from this last point, \( S \) is the integral over the averaged waveform. The absolute value of the maximum pressure in the tail did not
exceed 1.6 MPa, i.e. it was of the same order as the level of noise in the measured waveforms (± 0.7 MPa). The tails adding to waveforms are shown in Fig.1 (a,b,c) as black lines.

Changing steps of the grid

The radial step in the numerical modeling was further refined by adding 36 waveforms in between each two experimental waveforms. Each of these 36 additional waveforms was obtained by linear interpolating the pressure for each time point in the neighboring experimental waveforms. The coefficients for interpolation were $i/36$ and $(1-i/36)$ where $i$ is the number of an additional waveform between the two experimental ones. As a result, the radial step was refined to 5.4 μm instead of 0.2 mm in the experiment.

With the numerically added tail, the number of time points increased to 25000, with a time step of 2 ns. A requirement for FFT version used in our simulation program is setting the number of time points as a power of 2. In order to satisfy this requirement the number of time points was increased up to 32768 by padding the signals with zeros.

Adding waveforms at the edges of the source

To account for non-measured waveforms in the radial coordinate from 14 mm to 20 mm from the axis, additional waveforms were numerically introduced in the boundary condition by taking the very last radial waveform obtained at 14 mm and exponentially decreasing its amplitude along the radial coordinate with a linear time delay that followed the overall geometry of the measured field. The decrease in the pressure amplitude along the radial coordinate is shown on Fig.1 (d) as a red line, additional waveforms were introduced with the amplitude shown in Fig.1(d) by a green line.

![Figure 1](image)

**FIGURE 1.** (a),(b),(c) Radial scan waveforms in a plane 5 mm from the standoff at radial distances $r = 0$, 7 and 14 mm, respectively. Typical measured waveforms are shown in blue, the waveforms after averaging in red, and the numerical tails added to each waveform are shown in black. (d) the red curve shows the decreasing pressure amplitude with radial distance. Additional waveforms were introduced from 14 mm to 20 mm with the amplitude shown in green color.

Numerical model

Radial symmetry of the emitted field from the device allowed us to use the 2D KZK nonlinear parabolic equation:

$$
\frac{\partial}{\partial \tau} \left( \frac{\partial p}{\partial \tau} - \frac{\beta}{\rho_0 c_0^2} \frac{\partial p}{\partial \tau} - \frac{b}{2\rho_0 c_0^3} \frac{\partial^2 p}{\partial \tau^2} \right) = \frac{c_0}{2} \left( \frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} \right)
$$

(2)
Here \( p \) is the acoustic pressure, \( \tau = t - z/c_0 \) is the retarded time, \( r \) is the radial distance from the beam axis, \( c_0 \) is the ambient sound speed, \( \rho_0 \) is the density of water, \( z \) is the propagation distance, \( \beta \) is the coefficient of nonlinearity and \( b \) is the thermoviscous absorption of water. The equation accounts for the combined effects of nonlinearity, diffraction, and weak thermoviscous absorption in water.

For numerical simulation, a method of fractional steps with an operator splitting procedure was used to march the solution over the axial coordinate \( z \). Combined time and frequency domain solutions were used. The effect of diffraction was calculated in the frequency domain using a finite-difference implicit backward algorithm at shorter distances from the initial plane (up to 4.4 mm) and then using the Crank–Nicholson algorithm for each harmonic. Absorption was also calculated in the frequency domain using the exact analytic solution for each harmonic. Nonlinear effects were calculated in the time domain using a Godunov-type scheme. Transition between the spectral and time domains was performed using the FFT. The parameters for the modeling were: 16384 harmonics, 32768 time-steps, 65.5 \( \mu \)s time window, 2 ns time step, 43.2 mm radial window, 8000 radial grid points, 5.4 \( \mu \)m radial step, 0.11 mm axial step.

**Results**

For comparison, the experimental and numerical results waveforms were obtained along the axis of the beam from 5 mm up to 54 mm away from the therapy head with 0.5 mm spatial step. A comparison of the measurement and modeling results for peak positive and negative pressures along the axis is shown in Fig. 2 (a). Experimental results are shown by black circles and numerical results by red lines. The position of the therapy head is marked by blue dashed line. Modeling results are in a good agreement with the experimental data for the peak positive pressure and there are some discrepancies for the peak negative pressure, but they are all within the experimental error. It was observed that the maximum of the peak negative and positive pressures were achieved in different spatial locations – at 25 mm away from the therapy head for \( p^+ \) and at about 11 mm for \( p^- \). This difference is caused by a combination of nonlinear and diffraction effects. The measured and modeled waveforms at the focus of the source (25 mm away from the source) are shown in Fig. 2 (b). Red color corresponds to the simulated waveform and grey color corresponds to the experimental one. The waveform has a sharp pressure jump at the front of the pulse formed due to nonlinear propagation effects in the focused beam.

![Figure 2](image)

**FIGURE 2.** (a) Axial distribution of the measured peak positive and peak negative pressures (black circles) compared to the modeling results (red line). Blue dash line corresponds to the position of the therapy head of the standoff. (b) Waveforms at the focus of transducer. Grey color corresponds to the measured profile and red color to the modeled one.

While measurements were performed only along the axis and radially in the focal plane, simulations provided a full reconstruction of the spatial structure of the field. Shown in Fig. 3 are the results of simulations of the 2D spatial distributions of the peak positive (left) and peak negative (right) pressure. The plots indicate that the spatial distributions of the peak pressures are very different. The region of the maximum negative pressure is located closer to the therapy head and is much broader than the region of the peak positive pressure. This may have important
consequences for therapy, depending on whether the positive (associated with stress) or negative (associated with cavitation) component is responsible for a therapeutic bioeffect.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{2D spatial distributions of the peak positive (left) and peak negative (right) pressures obtained from the modeling effort.}
\end{figure}

**Conclusion**

The acoustic field of a clinical ESWT device (Duolith SD1) was characterized in water using a combined measurement and modeling approach. The model relied on the KZK equation; the boundary condition was based on the pressure waveforms measured in a plane 5 mm away from the therapy head. A method of experimental data processing to fit requirements for numerical simulations was proposed. The model was used to simulate and to analyze pressure waveforms in the focus of the therapy head and on its axis. Modeling results were found to be in good agreement with experimental data.

**Acknowledgments**

The work was partially supported by RFBR 12-02-31830 and 12-02-31418 grants, the National Institute of Health (NIAMS: AR053652 and NIBIB: EB007643) and by the student stipend from the French Government. The numerical simulations were done using the resources of the MSU supercomputer center.

**References**