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An FDTD-based computer simulation platform for shock wave propagation in electrohydraulic lithotripsy

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ABSTRACT

Extracorporeal Shock Wave Lithotripsy (ESWL) is based on disintegration of the kidney stone by delivering high-energy shock waves that are created outside the body and transmitted through the skin and body tissues. Nowadays high-energy shock waves are also used in orthopedic operations and investigated to be used in the treatment of myocardial infarction and cancer. Because of these new application areas novel lithotriptor designs are needed for different kinds of treatment strategies. In this study our aim was to develop a versatile computer simulation environment which would give the device designers working on various medical applications that use shock wave principle a substantial amount of flexibility while testing the effects of new parameters such as reflector size, material properties of the medium, water temperature, and different clinical scenarios. For this purpose, we created a finite-difference time-domain (FDTD)-based computational model in which most of the physical system parameters were defined as an input and/or as a variable in the simulations. We constructed a realistic computational model of a commercial electrohydraulic lithotriptor and optimized our simulation program using the results that were obtained by the manufacturer in an experimental setup. We, then, compared the simulation results with the results from an experimental setup in which oxygen level in water was varied. Finally, we studied the effects of changing the input parameters like ellipsoid size and material, temperature change in the wave propagation media, and shock wave source point misalignment. The simulation results were consistent with the experimental results and expected effects of variation in physical parameters of the system. The results of this study encourage further investigation and provide adequate evidence that the numerical modeling of a shock wave therapy system is feasible and can provide a practical means to test novel ideas in new device design procedures.

1. Introduction

A shock wave is an acoustical wave with high-intensity peak pressure. Since 1980, shock waves have been used in the treatment of different types of health problems. The pioneering application of the shock waves used in the medical field is the Extracorporeal Shock Wave Lithotripsy (ESWL) system. ESWL is based on disintegration of the stone so that they can easily pass through the urinary tract by delivering high-energy shock waves that are created outside the body through the skin and body tissues until they hit the denser kidney

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stones. This is the most common therapeutic approach used in patients with relatively large diameter kidney stones. There are three types of ESWL systems; electromagnetic, electrohydraulic, and piezoelectric lithotriptors. Electromagnetic and electrohydraulic lithotriptors dominate the lithotripsy market today.

Extracorporeal shock waves are also employed in the treatment of musculo-skeletal conditions such as plantar heel spurs [1], plantar fasciitis [2] and tennis elbow [3]. Recently, results from several investigational studies have shown that extracorporeal shock waves could be used in the treatment of myocardial infarction [4,5] and cancer [6]. In these applications shock waves have been shown to trigger the body's own natural repair mechanisms and stimulate healing.

In order to enable the development of devices designed for the treatment of various diseases, it is necessary to estimate the associated field parameters. For this purpose, different applications require modeling and analysis of acoustical wave propagation. There are mainly two approaches in accurate modeling of a specific problem: analytical and numerical methods. Analytical modeling approaches seek solutions to the problem using analytical equations to represent the media and physical processes. However, this approach can be utilized only in simplified geometric models. On the other hand, numerical methods aim to solve the problem by discretizing the associated media and differential equations. Finite-difference time-domain (FDTD) method is a popular numerical modeling technique. In the application of electrodynamics problems time-dependent Maxwell's equations in partial differential form are discretized using central-difference approximations to the space and time partial derivatives. The resulting finite-difference equations are solved iteratively in such a manner that the electric field vector components in a volume of space are solved at a given instant in time; then the magnetic field vector components in the same spatial volume are solved at the next instant in time; and the process is repeated over and over again until the desired transient or steady-state electromagnetic field behavior is fully evolved [7,8]. The system of equations used to represent the sound wave propagation is similar to that of electromagnetic waves, and thus, FDTD method can be applied in the computer simulations of propagation of sound waves. Pressure and velocity in sound wave correspond to electrical and magnetic fields in electromagnetic waves in the computations using FDTD method.

Although extracorporeal shock waves are now widely used in medical treatment, there are few examples of numerical modeling used in wave propagation analysis. Previously, Steiger [9] and Jian et al. [10] investigated computational modeling of electromagnetic lithotriptors. Steiger and Jian et al. used a commercial lithotriptor (Storz MODULITH SL 10) and Reichenberger's experimental setup [11], respectively, to validate their simulation results. These studies presented the measured and computed wave profiles in the acoustical focus in one dimension (pressure vs. time). In addition, Ukai et al. [12] developed a computational modeling scheme of shock waves used in osteotomy (cutting bones in a body without incising skin). They have developed a FDTD-based focused ultrasound propagation simulator for their setup.

In this current study our aim was to develop a versatile computer simulation environment which would give the device designers working on various medical applications that use shock wave principle a substantial amount of flexibility while testing the effects of new parameters such as reflector size, material properties of the medium, water temperature, and different clinical scenarios. For this purpose, we created an FDTD-based computational model in MATLAB (The MathWorks, Inc., Natick, MA, USA) in which most of the physical system parameters were defined as an input and/or as a variable in the simulations. This computer simulation environment makes it possible for the user to define the shock wave source characteristic, to select and adjust material and material properties used in the propagation media, location of the focal points, and to yield one (pressure vs. time at one point in space), two (pressure distribution in the x–z plane), and three (pressure distribution in the x–y–z volume, and pressure distribution in the x–z plane changing in time) dimensional pressure distribution graphs or movies. Different materials such as kidney, fat tissue, and bones, for which acoustical properties are available in the literature, may also be incorporated appropriately in the simulation environment.

In order to test this idea in a specific application, we constructed a realistic computational model of a commercial electrohydraulic lithotriptor (LithoDiamond, HealthTronics, Inc., TX, USA). We first optimized our simulation program using the results, such as maximum positive and minimum negative pressure levels in the proximity of the focal (F2) point location, that were obtained by the manufacturer in an experimental setup using hydrophone pressure sensors. This region is where we try to position the kidney stone in a lithotripsy system. Secondly, we compared the simulation results with an experimental setup in which oxygen level in water was varied. Finally, we studied the effects of changing the input parameters like ellipsoid size and material, temperature change in the wave propagation media, and shock wave source point misalignment.

2. Materials and methods

2.1. *Acoustic wave equation*

The acoustic wave equation governs the propagation of acoustic waves through a medium. The form of the equation is a second order partial differential equation. The equation describes the evolution of acoustic pressure p or particle velocity u as a function of space and time [13]:

$$K\frac{\partial}{\partial t}p(x,t) = \nabla u \tag{1}$$

$$K\frac{\partial}{\partial t}p(x,t) = \nabla u \rho_0 \rho_r \frac{d}{dt}u(x,t) = \nabla p(x,t) \tag{2}$$

where ρ_0 and ρ_r represent the density of water and the density of the material in the medium relative to water. K is the