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Nonlinear Effects in Ultrasound Fields of Diagnostic-type Transducers Used for Kidney Stone Propulsion: Characterization in Water

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Abstract

Newer imaging and therapeutic ultrasound technologies require higher *in situ* pressure levels compared to conventional diagnostic values. One example is the recently developed use of focused ultrasonic radiation force to move kidney stones and residual fragments out of the urinary collecting system. A commercial diagnostic 2.3 MHz C5-2 array probe is used to deliver the acoustic pushing pulses. The probe comprises 128 elements equally spaced at the 55 mm long convex cylindrical surface with 38 mm radius of curvature. The efficacy of the treatment can be increased by using higher transducer output to provide stronger pushing force; however, nonlinear acoustic saturation effect can be a limiting factor. In this work nonlinear propagation effects were analyzed for the C5-2 transducer using a combined measurement and modeling approach. Simulations were based on the 3D Westervelt equation; the boundary condition was set to match low power pressure beam scans. Focal waveforms simulated for increased output power levels were compared with the fiber-optic hydrophone measurements and were found in good agreement. It was shown that saturation effects do limit the acoustic pressure in the focal region of the transducer. This work has application to standard diagnostic probes and imaging.

Introduction

Kidney stone disease (nephrolithiasis) is a common urological disease, which affects about 10% of the population during their lifetime.¹ Ultrasonic propulsion of kidney stones is a new stone management technique being under development.² It uses a diagnostic ultrasound probe to create a real-time B-mode image and to generate a pulse to move the kidney stone out of the urinary collecting system with acoustic radiation force. Preliminary investigative clinical results of ultrasonic propulsion have been successful and the feasibility of the displacements of kidney stones pushed by acoustic radiation force were proved in

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experiments in the porcine model.² However, the efficacy of the procedure can be increased by using higher *in situ* pressure to generate greater radiation force. In calibration measurements in water, it has been shown that an increase in power did not result in an increase in the focal pressure. The hypothesis was that the ultrasonic propulsion probe generates highly nonlinear ultrasound beams creating nonlinear saturation. The goal of this work was to test this hypothesis and to evaluate the degree of nonlinear effects at the operational power outputs.

Combined Measurement and Modeling Approach

Accurate characterization of nonlinear ultrasound fields generated by various high intensity focused ultrasound transducers has recently been performed using a combined measurement and modeling approach³⁻⁶ Both axially symmetric single sources³⁻⁵ and multi-element arrays⁶ with approximate axial symmetry were characterized. However, much less results are available for highly nonlinear fields created by standard diagnostic transducers.⁷

Here we use a combined measurement and modeling approach to characterize a diagnostic ultrasound C5-2 curved array probe (Philips Ultrasound, Andover, MA, USA) in water for different number of operating elements and at different output levels. The array comprises 128 single elements and has a cylindrical shape with the radius of curvature R , the angle of aperture 2θ , the height l_y , and two focal lengths F_x and F_y (see Fig. 1a). Steering of the focus F_x in the xz plane was performed electronically by changing the pressure phase over the probe elements in x -direction, while cylindrical acoustic lens focuses the field at the focal depth F_y in the yz plane. The array was operated at the ultrasound frequency $f = 2$ MHz and generated sinusoidal pulses of 45 μ s.

The combined measurement and modeling approach adopted here comprises four main steps:

1. Low-amplitude hydrophone measurements of linear acoustic waveforms were performed in water along the probe z -axis and in two transverse directions (x and y) at the focal plane $z = F_x$.
2. Numerical modeling based on the Rayleigh solution for the linear beam was used to find effective parameters of the equivalent source. This procedure was performed by fitting the parameters of the source in simulations to match the measured and calculated linear field with the best accuracy.
3. Effective parameters of the equivalent source were used as a boundary condition in a 3-D full-diffraction nonlinear numerical model based on the Westervelt equation. The modeling is performed for different number of operating elements and at different output levels.
4. Additional hydrophone measurements of pressure waveforms at high power levels were performed along the probe axis and at the focus of the probe to validate the nonlinear modeling.

Here we present results for 40 and 64 operating elements.

Setting a Boundary Condition Using Linear Scans

The key component to simulate the experimental conditions was to set a boundary condition for the numerical model. A simplified equivalent source model that corresponded to the geometry of the C5-2 array probe used in the stone propulsion system was developed. The pressure amplitude was assumed to be uniform over the cylindrical surface of the equivalent source; the phase was changed continuously over the transducer surface to provide the focusing; the signal was considered as a continuous sinusoidal wave. Changing number of the operating elements was accounted in the model by changing the angle of aperture θ (Fig. 1a).

Parameters of the equivalent source were determined by fitting the shape of the simulated linear acoustic field to the measurements made at low pressure amplitudes along the z -axis and in the focal plane at $z = F_x$. Rayleigh integral was used for numerical calculation of the linear acoustic field:

$$p(\vec{r}, t) = -i\rho_0 f \int_S \frac{u(\vec{r}') \exp(ik|\vec{r} - \vec{r}'|)}{|\vec{r} - \vec{r}'|} dS', \quad (1)$$

where $\vec{r} = \{x, y, z\}$, ρ_0 is the density of the medium, $u(\vec{r}')$ is the complex amplitude of the vibration velocity on the surface S' of the probe, and k is the wavenumber. For primary numerical simulation of Eq. (1) we used nominal values of the probe geometrical parameters R , I_y , and θ given in product specification sheet from manufacturer. Approximate values of F_x and F_y for the model were estimated experimentally and equal $F_x = 50$ mm, and $F_y = 53$ mm, correspondingly. Then each of parameters R , θ , I_y , ρ_0 , F_x , and F_y was varying to match linear scan measurements along the beam axis and radially in the focal plane and 'best fit' values of the equivalent source parameters for each number of operating elements were established. These 'best fit' parameters are: $R = 38$ mm, $I_y = 12.5$ mm, $F_x = 50$ mm, $F_y = 70$ mm, $\theta = 0.2N/R$, where N is a number of active elements, $p_0 = 2.75$ MPa for 40 active elements, and $p_0 = 2.2$ MPa for 64 active elements.

A comparison of axial and focal scans of the low amplitude (linear) pressure field measured in water by the hydrophone and calculated with the Rayleigh integral is shown in Fig. 2b. The numerical results calculated with the 'best fit' parameters are in good agreement with the experimental data.

Nonlinear Propagation and a Saturation Regime

A 3-D Westervelt equation⁸ was used to simulate the nonlinear acoustic field generated in water by the diagnostic probe:

$$\frac{\partial^2 p}{\partial \tau \partial z} = \frac{c_0}{2} \Delta p + \frac{\beta}{2\rho_0 c_0^3} \frac{\partial^2 p^2}{\partial \tau^2} + \frac{\delta}{2c_0^3} \frac{\partial^3 p}{\partial \tau^3}. \quad (2)$$

Here $\tau = t - z/c_0$ is the retarded time, $p = \sqrt{2} p' \sqrt{z^2 + x^2 + y^2}$, parameters c_0 , β , ρ_0 and δ are the ambient sound speed, nonlinearity coefficient, density of the medium, and the

thermoviscous absorption of the medium, respectively. Equation (2) accounts for the combined effects of nonlinearity, diffraction and weak thermoviscous absorption. The boundary condition for the Westervelt equation was set at the plane $(x, y, z = 0)$ at the apex of the probe. This was done in two steps. First, the Rayleigh integral was used to calculate acoustic pressure at the plane $(x, y, z = 2 \text{ mm})$. Then the angular spectrum method was used to linearly backpropagate the pressure distribution from the plane $(x, y, z = 2 \text{ mm})$ to the plane $(x, y, z = 0)$. The numerical algorithm is described in detail in the earlier studies in Refs. 6, 9.

Parameters of the numerical scheme were: longitudinal step $dz = 0.075 \text{ mm}$, transversal steps $dx = dy = 0.02 \text{ mm}$. Maximum number of harmonics was set to 750. The values of the physical constants in Eq. (2) were chosen to represent the experimental measurement conditions in water at room temperature (20°C): $\rho_0 = 998 \text{ kg/m}^3$, $c_0 = 1486 \text{ m/s}$, $\beta = 3.5$, $\delta = 4.33 \cdot 10^{-6} \text{ m}^2/\text{s}$.

A comparison of measurement and modeling results for nonlinear propagation is shown in Figs. 2a, 2b. Figure 2a shows the focal experimental and simulated waveforms obtained at 20 V and 60 V power levels, while Fig. 2b depicts the dependence of the peak positive (p_+) and peak negative (p_-) pressures versus the applied power level. Starting approximately at 40 V output power level, the peak positive pressures change only slightly and reach their saturation levels. For the regime with 40 operating elements, the peak positive pressure is limited by the level about 12 MPa, for 64 elements it becomes 20 MPa. The saturation effect for the peak negative pressures is less pronounced. Waveforms in saturation regime (Fig. 2a, top waveforms) contain steep asymmetric shock front. Note that measured waveforms have greater shock rise time since the bandwidth of a fiber optic hydrophone is limited to about 100 MHz. Both peak positive and peak negative focal pressures are higher in the case of 64 active elements than for 40 elements for all output voltage levels.

Conclusions

In this work, nonlinear propagation effects were analyzed for the C5-2 transducer using a combination of measurements and modeling. It was shown that nonlinear propagation, and even saturation effects, are strongly pronounced for the probe and at the power output levels used in the current preclinical and clinical studies of stone propulsion for measurements performed in water. Accurate characterization of the nonlinear ultrasound fields generated in water are therefore important for treatment planning and further optimization of the technology.

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Figure 1.

(a) Geometry of focusing from the diagnostic 2.3 MHz C5-2 array probe. (b) Comparison of pressure amplitude obtained in the modeling and measurement in water for linear propagation on the beam axis and at the focal plane.

Figure 2.

(a) Focal waveforms obtained in numerical modeling (solid line) and measured in water (dot line) for regimes with 40 and 64 operating elements at 20V and 60V power levels. (b) Saturation curves for peak positive and negative pressures at $z = 50$ mm for 40 and 64 active elements. Experimental points are shown as circles; lines present results of numerical modeling.