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Experimental Comparison of Diagnostic Imaging Pressure Fields through the Abdominal Wall with Water

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***Abstract*—We previously showed in simulations that the Mechanical Index is inaccurate for estimating peak rarefaction pressure (PRP) and can overestimates PRP by more than 40%. In this work, we created a new experimental method to measure *in situ* pressures when accounting for propagation through the abdominal wall and liver. Our experimental results show concordance with the previous simulation work.**

***Index Terms*—mechanical index, in situ, pressure**

I. Introduction

Even though ultrasound is generally considered safe, extremely high dosages can cause harmful bioeffects. One tissue damaging mechanism from ultrasonic wave exposure is inertial cavitation. Inertial cavitation is caused by excessive negative pressure amplitudes. The Mechanical Index is a metric that models the likelihood of inertial cavitation in tissue by estimating *in situ* peak rarefaction pressure (PRP) from linearly derating PRP measurements in water. There are some limitations associated with the assumptions made for the MI model. First, acoustic attenuation in tissue varies greatly between 0.3-1.1dB/cm/MHz compared to the negligible acoustic attenuation in water. Second, tissue heterogeneity causes differences in speed of sound of the wave front and refraction to defocus the wave. We previously used simulations to demonstrate that MI consistently overestimates *in situ* PRP when focusing more tightly than F/3 and demonstrated correlation between spatial coherence and the decrease in PRP from MI predictions [2] [1]. In order to experimentally validate these simulated predictions, herein we present a new experimental protocol to measure the *in situ* PRP for a typical liver scan. We then show experimental measurements of *in situ* pressure fields and compare with the corresponding linearly derated water measurements.

II. Methods

Experimentally, our goal was to model the propagation path consistent with a typical focused abdominal liver scan and measure the pressure field within the liver near the focus. A typical propagation path for an abdominal liver scan can be broken down into two distinct layers. The first layer is the body wall which consists of skin, fat, connective tissue, and muscle. The second layer is the liver, which is generally considered homogenous. Porcine body wall was used to model the human body wall due to similarities in their composition and availability. For our experiments, we secured 2-3 cm thick porcine abdominal walls to the face of a curvilinear Siemens 4C1 transducer (Siemens Healthcare, Issaquah WA USA), which is a transducer typically used in abdominal imaging.

In order to accurately measure the pressure waveforms, we used a Sonora 804 PVDF membrane hydrophone with magnitude calibration from 2-20 MHz (Acertera Acoustic Laboratories, Longmont CO USA). Because the membrane hydrophone cannot be used to raster scan the in situ pressure field within solid liver, we mimicked liver tissue using a liquid evaporated milk mixture. The hydrophone was submerged in the milk solution. Attenuation was tuned by diluting the evaporated milk with water to achieve an attenuation coefficient of 0.5 $dB/cm/MHz$, equivalent to that of liver reported in literature. The attenuation coefficient was verified using a substitution method.

We used a typical clinical harmonic imaging sequence on the Siemens Acuson S3000 scanner with the following parameters: 2-cycle excitation with a center frequency of 2.2 MHz, F/1.5 focal configuration with a focus at 5 cm axially. The transducer and pork belly were positioned by a 3-axis translation stage to scan the field across an 1.5 x 3 x 20 mm ROI around the geometric focus in 0.05 mm increments. In situ pressure fields were compared with linearly derated pressure fields in water.

III. Results & Discussion

For all abdominal wall samples mimicking the liver imaging propagation path, pressure magnitudes were lower compared to the derated pressure measurements made in water. Per IEC MI definition, pressure waveforms measured in water were derated by 0.3 dB/cm/MHz to estimate for in situ PRP.

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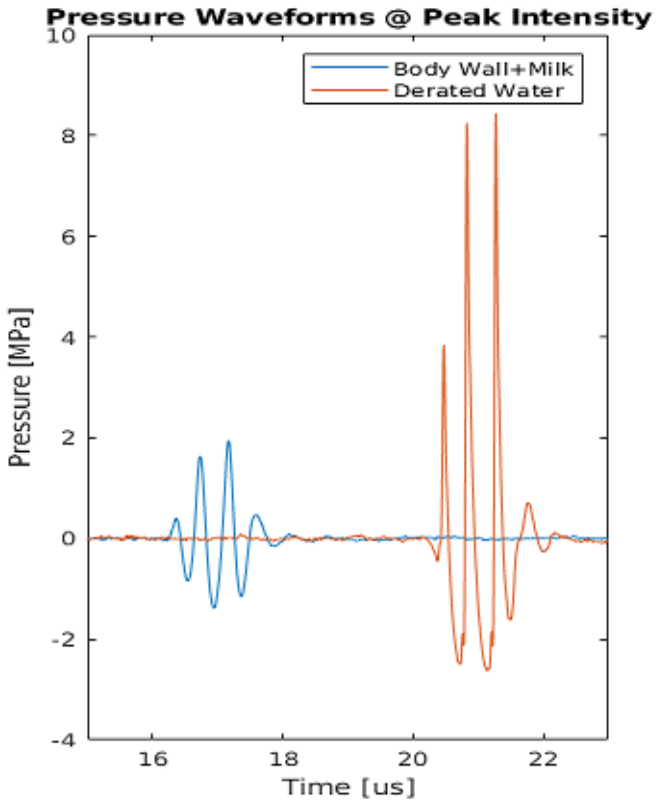

Fig. 1. The pressure waveforms at peak pulse intensity integral in space were plotted for both a sample abdominal wall+milk (blue) and the standard water (red) propagation path. For the waveform measured in water, a linear derating of 0.3 dB/MHz/cm is applied per MI metric definition.

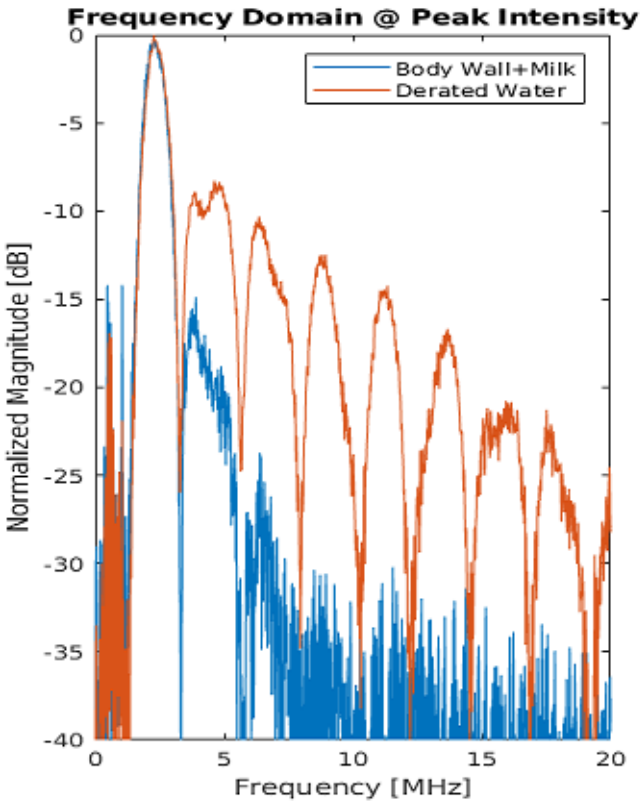

Fig. 2. The corresponding frequency domain plot for the two waveforms measured through a sample abdominal wall+milk (blue) and the standard water (red) propagation path. The y-axis is normalized by the peak magnitude of each waveform on a dB scale.

In a typical case with a 2.5 cm thick abdominal wall, fig. 1, the in situ PRP measured was about 60% the amplitude of the derated water PRP. This trend agrees with the observations of decreased PRP seen from previous simulation work. For the positive peak pressure (PPP), the in situ measurement was about 25% the amplitude of the derated water case. The waveform that passed through the abdominal propagation path appears less nonlinear compared to the derated pressure waveform measured in water. Figure 2 plots the two waveforms in the frequency domain. In the frequency domain, the relative magnitude of the harmonics for the abdominal wall case are much lower than the derated water case; the second harmonic magnitude is -15 dB from the fundamental for the abdominal wall case and -8 dB for the derated water case. Above the second harmonic, the signal from the abdominal wall case is limited by the noise floor of the hydrophone. Propagation through the abdominal wall causing the resulting waveform to be more linear compared to propagation through water follows the intuition that frequency dependent attenuation in the tissue model preferentially prevents the propagation of higher harmonic signals. Additionally, the waveform propagating through the abdominal wall arrive earlier in time compared to the water case. This suggests a faster speed of sound in the liver imaging mimicking case compared to 1490 m/s speed of sound in water at room temperature.

Figure 3 shows the effects of phase aberration in broadening the intensity beamwidth when propagating through the body-wall which increases the FWHM by 40%. The broadening of beamwidth validates the same effects seen in simulations from previous work. In addition to broadening the ultrasonic beamwidth, the presence of the abdominal wall also shifts the peak intensity about 0.3 mm to the left.

IV. Conclusions

We were able to successfully create an experimental protocol for modeling and measuring *in situ* PRP of a typical abdominal liver scan. In the model we incorporated both the heterogeneity of the abdominal wall and the attenuation of homogeneous liver. From our experimental model, we were able to show concordance in decreased PRP and defocusing of beamwidth with simulation results from previous work. This further suggests that the MI is grossly inaccurate in estimating *in situ* PRP and motivates the exploration of new techniques to more accurately estimate *in situ* PRP.

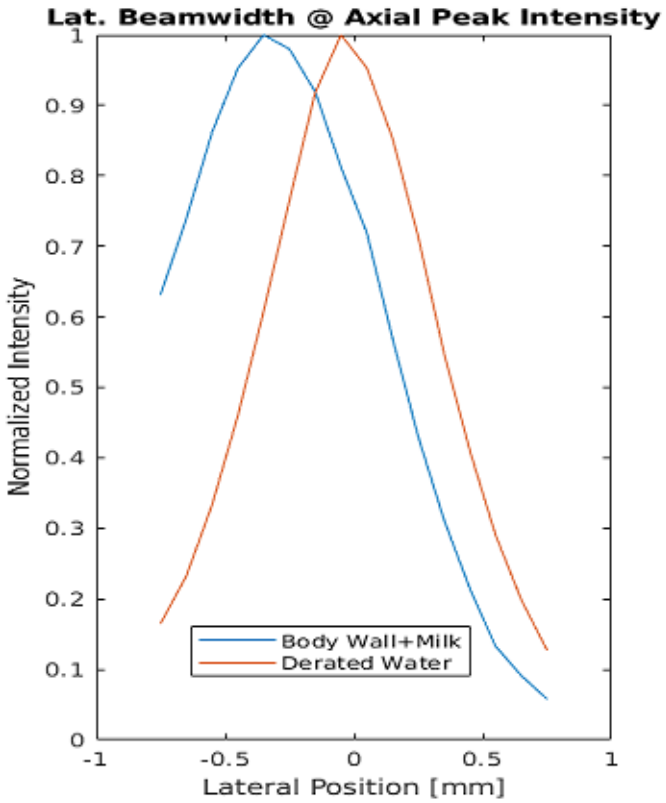

Fig. 3. The lateral beamwidth plot for the two waveforms measured through a sample abdominal wall+milk (blue) and the standard water (red) propagation path. The beamwidth plot is a function of the normalized pulse intensity integral.

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