EXPERIMENTAL EVALUATION OF SOME POSSIBLE NONLINEARITY INDICATORS

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Over the past few decades, the propagation of acoustic signals through the human body has found application in medical imaging as well as the treatment of various ailments. Currently, for diagnostic ultrasound systems [1], ultrasound sources are characterized by measuring the acoustic pressure in water for almost every voltage range applied to the source and then linearly derating the measured pressure values to estimate the derated acoustic pressure levels. As a result, the characterization process is time consuming, increasing the cost and development time for each transducer.

In order to reduce the number of pressure measurements required, some have proposed to linearly extrapolate pressures rather than perform direct measurements. Unfortunately, the linear extrapolation would differ from the measured pressure values in the water bath due to the nonlinear propagation of the sound in the water. Furthermore, the nonlinear effects also corrupt the traditional derating process [2,3,4]. Hence, before the linear extrapolation and derating can be accurately performed, an indicator of nonlinearity needs to be developed to classify any focal waveform as being either "linear" or "nonlinear." Linear waveforms could be used to extrapolate the pressure levels for all smaller applied voltage settings and could also be derated to estimate the true *in situ* pressures.

In our work, eight different indicators of nonlinearity were evaluated. The goal was to determine if one of these indicators could consistently classify between "linear" and "nonlinear" focal pressure waveforms. Spherically focused ultrasound transducers were selected and excited to test the indicators sensitivity to frequency (3 – 8 MHz), f/# (1 and 2), transducer diameter (1.905 and 5.08 cm), pulse duration (1 and 3 cycles), and pulse phase (0^{o} and 180^{o}). The experimental results for the nonlinear indicators normalized with respect to their mean values for all of the transducers and drive conditions are shown in Figure 1. The mean value for each indicator is provided above the corresponding group of bars, and the experimental condition for each bar is provided in Table 1. The experimental results in Figure 1 show that none of the currently proposed indicators yield consistent results for all possible focused sources. A possible explanation for the lack of consistency can be found by comparing the behavior of the focal pressures for some of the data sets shown in Figure 2.

Table 1: Legend for Figure 1 identifying bars in each indicator group.

Bar Order (Symbol)	Dominate Frequency	Diameter (f#)	# Cycles (Phase)
1 (o)	3 MHz	1.9 cm (1)	3 (0^o)
2 (x)	3 MHz	5.1 cm (1)	3 (0^o)
3 (▽)	5.5 MHz	1.9 cm (1)	1 (0^o)
4 (◁)	5.5 MHz	1.9 cm (1)	3 (0^o)
5 (□)	5.5 MHz	1.9 cm (1)	3 (180^o)
6 (◊)	5.5 MHz	1.9 cm (2)	3 (0^o)
7 (✯)	8 MHz	1.9 cm (1)	3 (0^o)

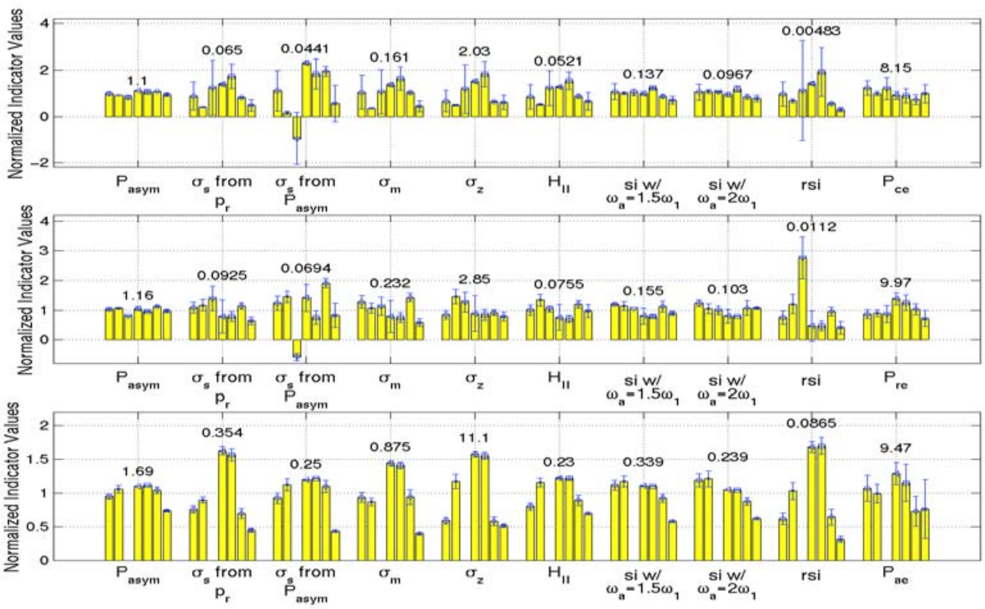

Figure 1: Normalized threshold values for the nonlinear indicators for p_c (top), p_r (middle), and p_{avg} (bottom).

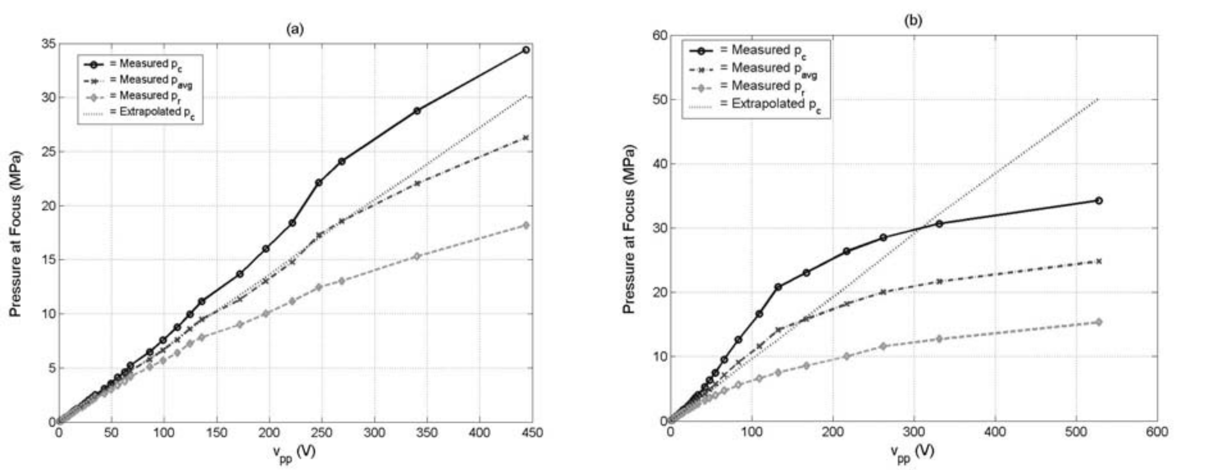

Figure 2: Direct comparison of pressures at the focus. (a) ~5.5 MHz *f#* of 1 transducer (b) ~5.5 MHz *f#* of 2 transducer

Notice that in both plots, p_c and p_{avg} initially increase away from the linear forward extrapolation line due to asymmetric distortion, but as the nonlinear absorption increases the waveform approaches saturation, the p_c and p_{avg} values approach the extrapolation line once again. However, the separation between the onset of asymmetric distortion and the dominance of nonlinear absorption is different for the different data sets. None of the indicators developed thus far have attempted to capture the effects of both nonlinear absorption and asymmetric distortion. Hence, the change in the relative importance of asymmetric distortion and nonlinear absorption is what generates the inconsistency in the nonlinear indicators between the data sets described in Table 1. Therefore, a consistent indicator may be found by further developing the theory to include both nonlinear effects.

RELATED REFERENCES

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