ON THE ENHANCEMENT OF ULTRASOUND BACKSCATTER FROM MICROBUBBLES FOR OPTIMAL PARTICLE IMAGE VELOCIMETRY

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INTRODUCTION

We have developed a non-invasive ultrasound-based method for performing particle image velocimetry *in vivo*. This method provides high resolution multi-component blood flow data with high temporal resolution. The method takes advantage of the non-linear ultrasound backscatter characteristics of small gas-filled microbubbles (ultrasound contrast) that are seeded into the blood stream [1]. Preliminary data under in vitro and in vivo conditions are highly promising [2,3].

The method now needs to be developed further in order to be used in a wide range of physiological flow conditions. As part of this, significant optimization needs to be performed. While part of the optimization involves signal and image processing manipulation of the ultrasound signals to maximize parameters such as signal-to-noise ratio, an equally important component involves further understanding of the fundamentals of the backscatter process, as it applies to our method. This report documents the development of the theoretical model describing ultrasound backscatter from microbubbles.

MODEL DEVELOPMENT

Backscatter of ultrasound from gas-filled microbubbles of 2 – 6 microns in diameter is shown schematically in Figure 1 and is described by the Rayleigh-Plesset equation [4,5]:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 + \frac{4\mu}{\rho}\frac{\dot{R}}{R} + \frac{2\sigma}{\rho R} = \frac{1}{\rho}\left[P_B(R,t) - P(t) - P_\infty\right] \quad (1)$$

Where R is bubble radius, ρ the blood density, μ the blood viscosity, σ the surface tension coefficient of the blood, P_B the pressure of gas in the bubble, P the pressure of the driving (incident) sound wave, and P_∞ the ambient pressure.

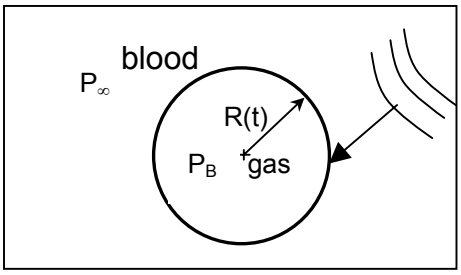

Figure 1: Schematic of ultrasound interaction with a microbubble.

In the clinical situation, the mechanical index is a variable that can be adjusted to optimize the ultrasound contrast image. The mechanical index is defined as:

$$\text{MI} = P/\sqrt{\omega}$$

Where P is incident acoustic pressure and ω is incident signal frequency.

The question of what optimal MI produces high quality echo-PIV images is still unanswered. Typically, both pressure and wavelength will affect backscatter characteristics.

The Rayleigh-Plesset model was solved numerically under a variety of incident frequency (2 – 10 MHz) and incident pressure conditions. MI was varied from 0.2 to 1.4 (typical values for ultrasound contrast imaging [6]). The microbubble cross-sectional scattering area was obtained for each condition.

IN VITRO STUDIES

In vitro studies examining the radio-frequency backscatter from ultrasound transducers at various frequencies were conducted for comparison with model results. Optison®, a commercially available

contrast agent, consisting of perfluorocarbon gas within a protein sheath, was used. These microbubbles are approximately 3.9μ in diameter. Both primary and secondary harmonics of the backscatter signal were examined.

RESULTS

The numerical model results show a biomodal relationship of backscatter characteristics to pressure and incident wavelength. Pressure and wavelength affect backscatter cross-sectional area and backscatter signal characteristics, especially at the harmonic frequencies.

In vitro data also show a strong dependence of backscatter characteristics based on harmonic components. Figure 2 shows differences between primary and secondary harmonic backscatter signals from a tube flow model with microbubbles. The secondary harmonic component can clearly distinguish bubble signatures (2 microbubble signatures are seen here) while distinguishing between tissue signals and microbubble signals is much more difficult for the primary harmonic.

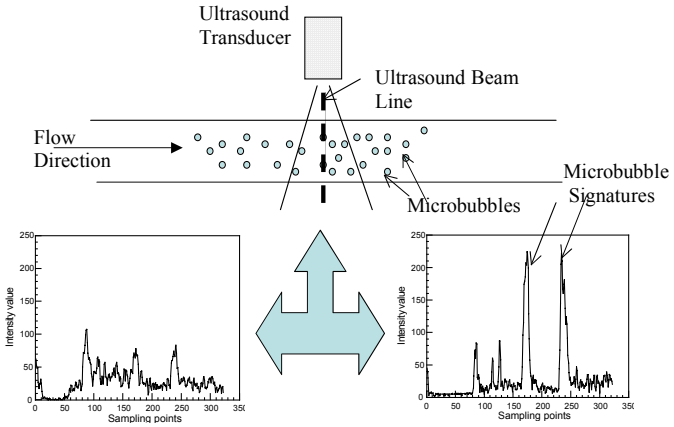

Figure 2: Backscatter characteristics from microbubbles seeded into a tube-flow system, as a function of distance (sampling points) from the ultrasound transducer, for a mechanical index of 0.35. On the bottom left is shown the backscatter at the primary (incident) frequency. On the bottom right is shown the backscatter at the secondary harmonic. The secondary harmonic contains clear delineation of the microbubbles within the flow field, indicating the superiority of harmonic processing in taking advantage of the non-linear backscatter characteristics of these microbubbles.

DISCUSSION

Optimization of the echo-PIV technique is required before implementation in a general in vivo setting. This report focuses on examining the effect of mechanical index on non-linear backscatter generation from microbubbles. Too high a mechanical index produces significant bubble destruction, while too low an index does not initiate significant non-linear behavior. In this respect, optimization of MI for echo-PIV analysis is different from optimization of MI for the conventional uses of ultrasound contrast, namely myocardial and other organ perfusion studies. For organ perfusion, the highest level of backscatter is needed for short periods of time; this usually requires sufficiently high MI in order to burst bubbles and produce strong, transient backscatter signals that can be detected by the ultrasound system. For echo-PIV, it is important that the bubbles remain intact and still backscatter in the non-linear region. This requires an intermediate range of MI values.

CONCLUSION AND FUTURE WORK

A variety of optimization techniques need to be implemented for echo-PIV imaging to become routine. Understanding the fundamentals of microbubble backscatter characteristics provides the initial pathway toward such optimization. Integrating model results with comprehensive in vitro measurements should provide additional guidance regarding optimization. These studies are ongoing.

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