Something new in spectrum analysis: Parameter imaging of harmonics

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INTRODUCTION

In typical ultrasound applications, radiofrequency (RF) backscatter data are available for analysis. *Prima facie*, Fourier analysis requires signals of infinite extent in the time domain in order to satisfy the lower and the upper integration limits. In practice, of course, one selects a finite duration RF signal for analysis. This process was made mathematically rigorous by Wigner [1], Gabor [2] and Page [3]. The generalized concept is that of joint time frequency analysis (JTFA) [4]. We define "weak JTFA" as the multiplication of a windowing function with the original signal in order to select a particular time interval for frequency analysis. We define "strong JTFA" as wavelet and related analyses. In this presentation, we are concerned only with weak JTFA.

Windowing functions commonly used in weak JTFA include rectangular, Gaussian, Hanning, and Hamming windows. In the analysis presented here, we employ only the last, which (non-uniquely) reduces high frequency artifacts.

Consider the common scanning geometry portrayed in Fig. 1. A single element ultrasound transducer emits a broadband pulse that propagates through a medium of interest. The same transducer detects the backscattered ultrasound energy from the emitted pulse. In the usual way, the time course of the received data are digitized and recorded and called a scan line. A series of parallel scan lines forms a scan plane and a series of parallel scan planes forms a scan volume.

We slide a Hamming window over the RF data in a regular fashion. We can select the length of the window (i.e., how many data samples are included along a single scan line), the number of adjacent scan lines to average together for our analysis, and the numbers of samples by which we slide the window along the scan line and orthogonal to that in the scan plane. At each window location, we perform a fast Fourier transform (FFT) to produce a power spectrum that is *diagnostic* of the spatial region corresponding to that window location. The contributions of the transducer and the associated electronics to the spectrum can be eliminated by subtracting a calibration spectrum (which is the spectrum from an ideal specular reflector coincident with the focal plane of the transducer); see, e.g., Fig. 2.

Next, we reduce the power spectrum to a small set of measures that can be computed at the corresponding window locations to produce a set of parametric images [5, 6]. For certain types of scattering media (with uniformly random distributions of Rayleigh scatterers, typical of many biological tissues), Lizzi [7] showed that the parameters of straight line fits to the power spectra are related to the sizes, concentrations, and relative acoustic impedances of the scatterers.

Recently, we have found that by restricting the bandwidth over which the spectrum analysis is performed to the frequency band centered about the second harmonic, we get two beneficial effects. First, we improve the resolution; this is reasonable because we are exploiting higher frequencies. Second, we substantially enhance our ability to detect certain biological tissue lesions. These are lesions that have been made for therapeutic purposes by thermally treating tissue with high intensity focused ultrasound (HIFU).

The detection of HIFU lesions is clinically important because, although the lesion formation process is highly predictable on average [8], the process varies considerably from lesion to lesion as a result of underlying tissue heterogeneity. HIFU lesions come in two varieties: bubbly lesions made under conditions that favor cavitation or tissue fluid vaporization, and protein denaturing lesions (PDLs), made at lower intensities and higher frequencies. PDLs can be difficult to detect with conventional gray scale signal envelope (B-mode) imaging. With our new technique, we have successfully detected such lesions. So far, this is a phenomenological result; however, we are currently examining the underlying theoretical reasons for this new method of reliably detecting and monitoring HIFU lesions.

METHODS

We made in vitro HIFU lesions using a therapeutic transducer, and recorded ultrasound RF backscatter with a coaxial, confocal, diagnostic transducer. We then processed the RF data to produce B-mode images and spectral parameter images.

The HIFU assembly consisted of a single-element PZT spherical shell with a diameter of 33 mm and focal length of 35 mm, excited with a continuous 5 MHz sine wave. A diagnostic transducer with a 9 MHz center frequency was inserted through a hole in the center of the HIFU element. The diagnostic transducer, a Panametrics-NDT (Waltham MA USA) Videoscan V312, had a diameter of 10 mm and a focal length of 35 mm.

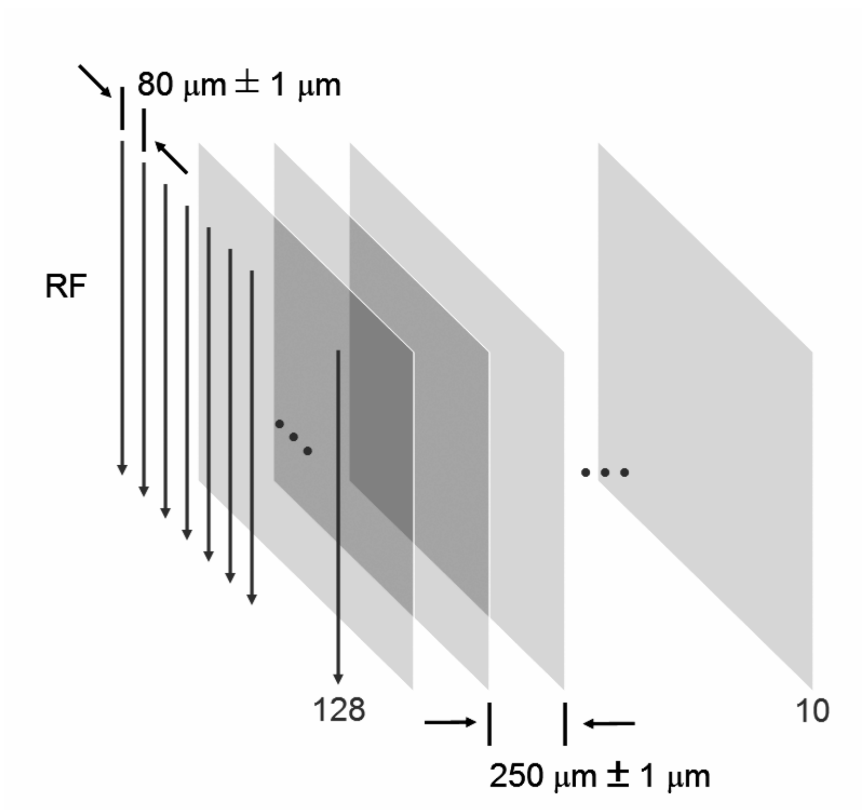

FIGURE 1. Scan geometry.

We produced lesions in chicken breast using 15 second exposures of up to 6 $kWcm^{-2}$. Degassed normal saline was used as the coupling medium.

Before and after lesions were generated, the transducer assembly was scanned across the treatment site and diagnostic data were acquired from the coaxial diagnostic ultrasound probe under computer control (Fig. 1).

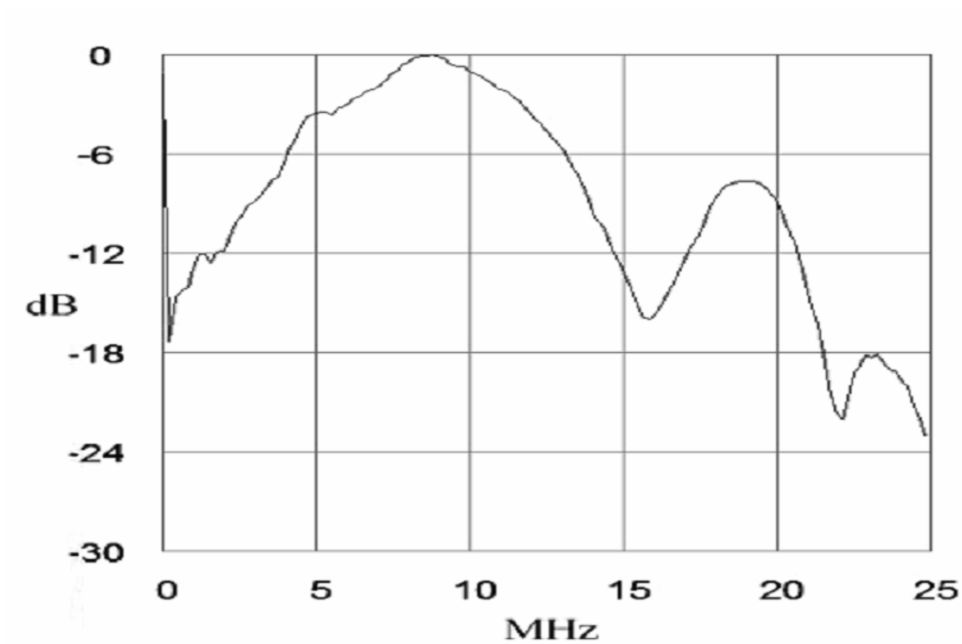

FIGURE 2. Glass plate power spectrum of Panametrics-NDT Videoscan V312 transducer.

From the RF data we generated B-mode images and two sets of parameter images: 1) midband fit (MBF), spectral slope, and intercept images restricted to the -12 dB fundamental band (3-15 MHz), and 2) MBF, spectral slope, and intercept images restricted to the -12 dB second harmonic band (16-23 MHz).

Spectrum analysis was performed using a sliding window that was 64 samples in length by 3 vectors in width. The analysis window was rastered over the image and spectra were computed in overlapping regions-of-interest spaced at 4 sample intervals along each vector. RF data were multiplied by a Hamming function. The FFT was deconvolved with the glass plate calibration spectrum (Fig. 2). A best fit line was computed by linear regression in the appropriate frequency band, and pixel values were assigned to represent the slope, intercept, and midband values in parameter images.

RESULTS

Results showed that HIFU lesions were poorly visualized in conventional images generated from the envelope of the echo data. MBF parameter images centered at the fundamental were somewhat better than the conventional envelope, but MBF images centered at the harmonic showed the best contrast and delineation of lesion boundaries (Fig. 3). We note that MBF images formed from an emitted 18 MHz pulse were not as effective in lesion visualization as the MBF images formed from the harmonic mode.

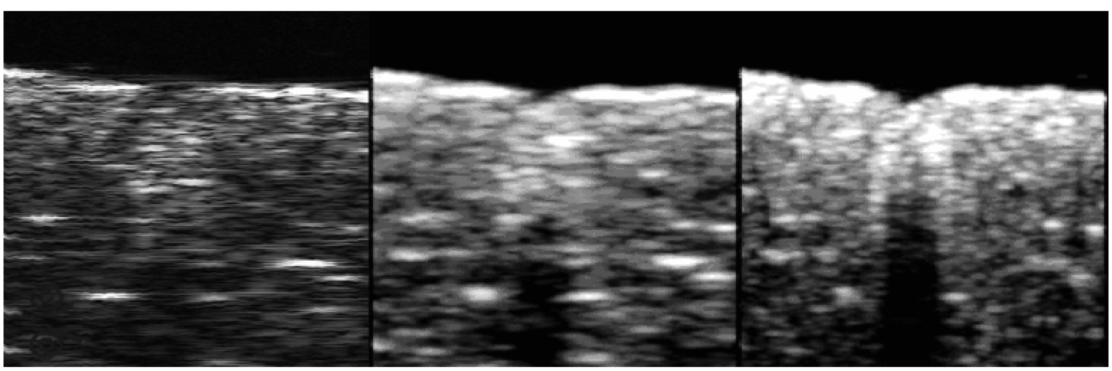

FIGURE 3. Each image shows the same 3.5-cm wide cross-section of degassed chicken breast with a HIFU lesion approximately in the middle. On the left is the B-mode image. In the center is the midband fit from 4-15 MHz. On the right is the midband fit from 16-22 MHz.

We conclude that spectrum analysis of harmonic backscatter RF data offers a unique imaging mode that can significantly improve lateral resolution compared to conventional envelope images or images generated at the fundamental. Such images can aid in the detection and monitoring of HIFU lesions in real time.

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Robert Muratore received his Ph.D. in Biophysics at Syracuse University and was a National Research Council Fellow at the NIH Clinical Center. After working at Cold Spring Harbor Labs and in academia for a few years, he joined the research staff at Riverside Research Institute in New York City. Here he has been investigating two related areas: the integration of therapeutic and diagnostic ultrasound for minimally invasive surgery and the use of acoustic radiation force as a probe of dynamic material properties.