On-line Assessment of HIFU Beams and Lesion Monitoring Using Dual-Transducer Modes

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Abstract – A dual-transducer system was used to test concepts for on-line guidance and lesion monitoring during ultrasound therapy. The system used a spherical-cap therapy transducer with a central, A-mode transducer. Three operational modes were successfully tested in *in-vitro* liver specimens.

Mode 1 senses *in-situ* therapy-beam harmonics that affect absorption and heating. The therapy transducer emits a 2μs pulse at the same amplitude used in therapy; echoes from this pulse are received with the A-mode transducer and digitally filtered to produce A-scans at the therapy frequency and its harmonics.

Mode 2 detects lesions by virtue of their increased stiffness. A 1-ms therapy-transducer pulse produces radiation force and internal tissue motion that is tracked by cross-correlating sequential A-scans. The procedure is repeated after therapy to detect motion changes due to formed lesions.

Mode 3 uses the A-mode transducer (pulse-echo) to sense lesions with increased attenuation and scattering using sliding-window spectrum analysis.

I. Introduction

Our laboratories are investigating the use of a dual transducer configuration to address several needs in high-intensity focused ultrasound (HIFU). The current test configuration consists of a spherical-cap HIFU transducer with a central broadband diagnostic transducer that is aligned to be colinear and confocal with the HIFU transducer. [1]

The operation of these transducers is synchronously controlled to provide three operational modes to support HIFU procedures. The first mode semi-quantitatively evaluates the *in-situ* harmonic content of the incident HIFU beam and verifies proper positioning of the HIFU focal zone. The second mode detects and monitors lesion formation by inducing internal tissue motion (*via* radiation force) and tracking resultant tissue displacements; this mode senses changes in motion that are associated with increases in stiffness and attenuation found in HIFU lesions. [1] The third mode uses ultrasonic spectrum analysis [2] to detect backscatter changes, which arise due to alterations in tissue morphology, and shadowing, which occurs posterior to highly attenuating HIFU lesions.

This report summarizes each mode of operation and presents *in-vitro* data supporting their feasibility and potential utility for HIFU procedures.

II. System and Operational Descriptions

The current transducer assembly consists of a spherical-cap PZT-4 HIFU transducer with a 90-mm focal length, 42-mm diameter, and an operating frequency of 4.1 MHz. [1] The transducer has a central aperture housing a colinear focused broadband transducer with a 10-mm diameter and a center frequency of 7.5 MHz. Acoustic coupling is achieved with a cone filled with degassed water.

The operation of both transducers is synchronously controlled by a computer-based system. HIFU excitation is provided by a programmed signal generator (Agilent 33250A) and an ENI power amplifier. The broadband diagnostic transducer is excited by means of a computer-controlled Panametrics 5400 pulser/receiver whose radio-frequency (RF) echo signals are digitally acquired using an Acqiris DP-11D board; typically, 8-bit digitization is performed at 500-MHz rate. Custom LabVIEW software controls and synchronizes all operations. MATLAB software packages are used to implement required signal processing capabilities.

Harmonic Analysis

The harmonic analysis mode permits an assessment of *in-situ* harmonics in the incident HIFU beam. These arise because of non-linear propagation phenomena in coupling media and tissue segments anterior to targeted tissues. [3] The HIFU transducer is excited to launch a brief (e.g., 2-μs) ultrasonic pulse that exhibits the same spatial-peak temporal-peak (SPTP) intensity intended for therapy.

Backscattered RF signals from the target zone are acquired using the diagnostic transducer in a synchronous receive mode. The bandwidth of this transducer is large enough to receive at least the second harmonic of the launched HIFU pulse. Acquired RF echoes are filtered into several bands centered at the fundamental as well as harmonic frequencies of the HIFU pulse. The fundamental and harmonic signals are then presented in A-mode formats for evaluation of their relative amplitudes. This is usually done at several excitation-voltage amplitudes so that harmonic increases can be measured as a function of increasing energy.

Radiation-force Displacement

The radiation-force displacement mode detects lesions by anomalies in tissue displacement induced by radiation force. [1, 4] The force is produced with a brief (e.g., 1-ms) "push" exposure from the HIFU transducer; the amplitude of the exposure is typically several hundred W/cm^2 to produce motion of several μm. As previously described [1], the diagnostic transducer acquires pre-push RF echo data (to establish initial positions of tissue elements) and also acquires post-push data. These data are analyzed with cross-correlation algorithms to quantify tissue displacement and recovery.

This sequence of measurements is performed before and after HIFU exposures so that lesions can be evaluated by changes in induced motion. Our ongoing theoretical analyses and *in-vitro* experiments have shown that increased lesion stiffness reduces motion, but increased lesion attenuation enhances motion in anterior lesion segments and suppresses it in a "shadow-like" manner in posterior tissues. [5]

Spectrum Analysis

Spectrum analysis techniques are applied to RF echoes acquired from the central diagnostic transducer operated in a pulse-echo mode. Calibrated backscatter spectra are computed before and after HIFU exposures to detect changes in tissue morphology and also to detect shadowing that occurs posterior to lesions with elevated acoustic attenuation. Spectral processing entails procedures described in previous reports. [2] A sliding Hamming gate multiplies RF signals and Fourier transforms are used to compute local power spectra along the transducer axis. Spectra are then converted to dB and linear-regression analysis is employed over the bandwidth with useful signal-to-noise ratios. Local values of spectral slope (dB/MHz) and midband fit (dB) are then computed. Midband fit, numerically related to integrated backscatter, is the value of the regression line at the center frequency of the analysis band.

III. Illustrative Results

The harmonic mode of analysis was evaluated using an *in-vitro* liver specimen. The HIFU transducer launched a 2-μs pulse at a 4.1 MHz center frequency; the diagnostic transducer was used to acquire returning RF echoes. Digital band-pass filtering separated echo components in the fundamental frequency band and the 7.5 – 10 MHz band (encompassing the second harmonic of 8.2 MHz). A range of intensity levels was employed. Figure 1 shows that a low SPTP level (60 W/cm^2) resulted in only small harmonic echoes. It also shows that a high level (2.4 kW/cm^2) markedly increased the harmonic echoes, as expected due to enhanced non-linear phenomena.

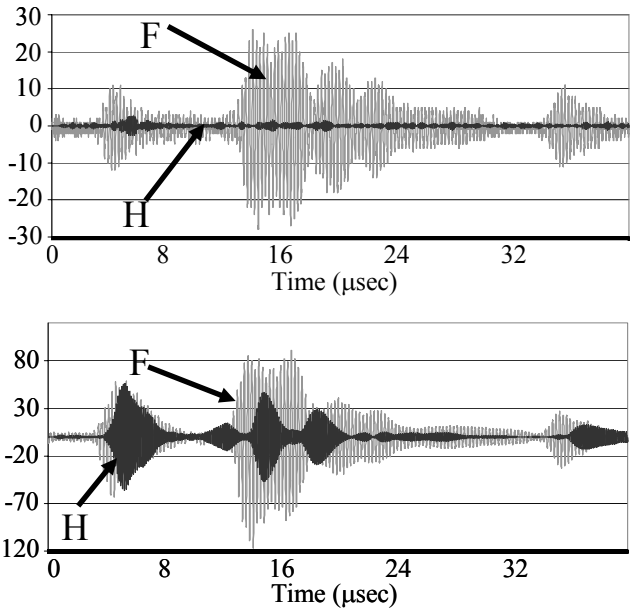

Figure 1: Fundamental (F) and second harmonic (H) filtered RF signals. Top, 60 W/cm^2; bottom, 2.4 kW/cm^2 SPTP intensity.

The radiation-force mode of operation was also evaluated using *in-vitro* liver specimens. Figure 2 shows a specimen in which the lesion was formed at a

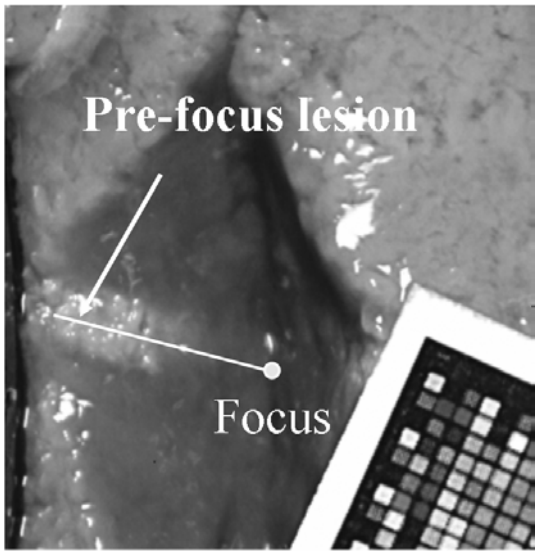

Figure 2: Sectioned *in-vitro* liver specimen showing HIFU lesion and beam path. Reference squares show 1-mm increments.

site several mm anterior to the focal point of the HIFU transducer. Figure 3 shows the displacements computed using RF cross-correlation techniques. Displacements are shown in M-mode format; the horizontal axis represents distance into the specimen and the vertical axis represents time after the end of the 2-ms "push" pulse. In this reproduction of a color-coded image, displacement values are represented in gray scale.

The pre-lesion result shows relatively large displacements persisting for more than 2 ms. The post-lesion result shows an increased displacement near the proximal surface of the specimen, where the lesion started. At deeper sites, displacements are smaller and of shorter persistence.

These post-lesion changes are consistent with increased levels of absorption and attenuation within the lesion. [6] As described in previous reports [1, 5], radiation force is proportional to $2\alpha' f\ I \exp(-2\alpha f x)$ where α' is absorption coefficient (nepers/MHz-cm), f is frequency, I is free-field beam intensity, α is attenuation coefficient, and x is tissue depth. In the anterior segment of the lesion, x is small so the exponential is approximately equal to unity; thus, the increased α' has a predominant effect increasing the force and resultant motion even though lesion stiffness increases. At deeper sites, the cumulative attenuation represented by the exponential term becomes predominant reducing the force and

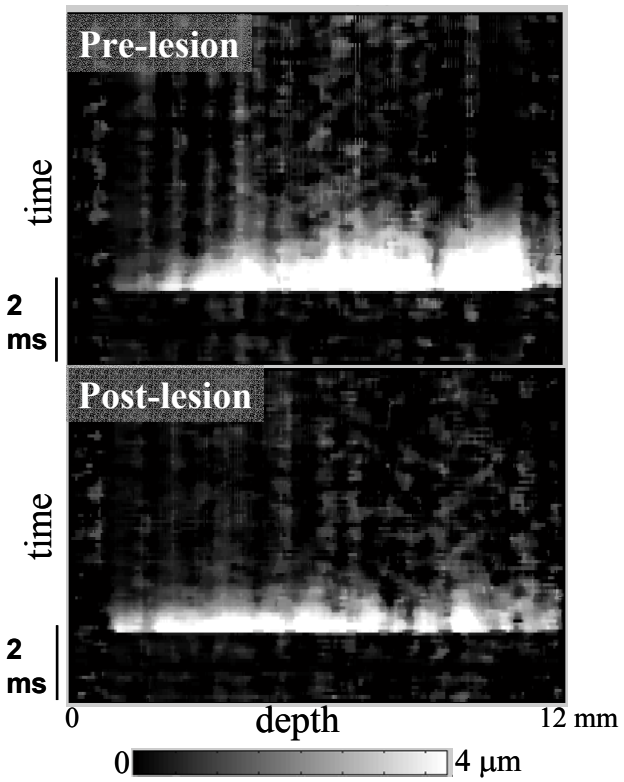

Figure 3: Induced displacements in *in-vitro* liver before (top) and after (lower) lesion.

resultant motion. This attenuation produces a "shadow" in the observed motion at deeper sites.

The spectrum analysis mode of operation was evaluated on the same liver specimen. The result was obtained by spectrum analysis of the "pre-push" RF data before and after lesion formation using a 1-mm sliding Hamming window. Local values of midband fit were computed as a function of range. At each range, the pre-lesion midband fit value was subtracted from the post-lesion value. A plot of this (Fig. 4) shows an elevated value in the anterior 6-mm depth, where the lesion was located. It also shows a reduced value, or shadow, immediately posterior to the lesion. (An artifact at the extreme right of displacement and midband fit plots is most likely due to a posterior fluid-filled space that was altered by HIFU exposure.)

This result indicates increased backscatter and increased attenuation within the lesion. The attenuation increase reduces the midband fit values posterior to the lesion. [2] Simple calculations indicate that the attenuation coefficient is increased by a factor of about two compared to normal liver.

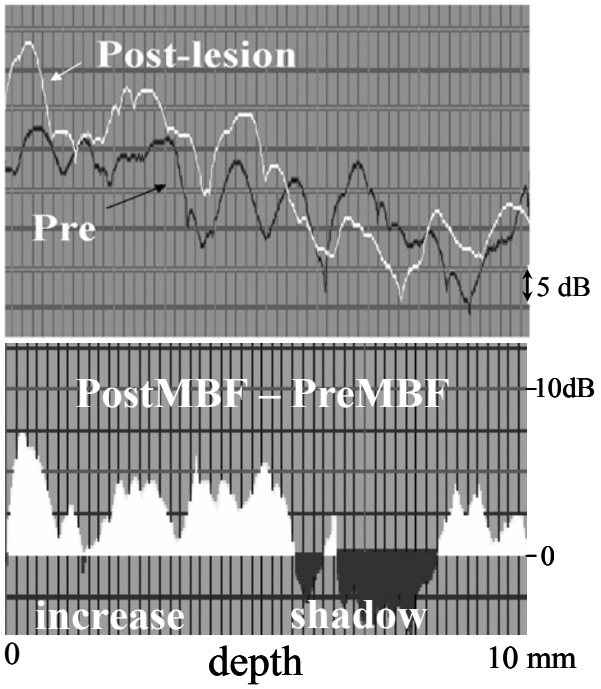

Figure 4: Spectral midband fit values vs. tissue depth (top) and difference (bottom).

IV. SUMMARY

The use of a dual-transducer configuration offers a flexible approach to obtaining information to help guide HIFU exposures and monitor their results. The harmonic imaging mode takes advantage of the large bandwidth of the diagnostic transducer to evaluate the harmonic content of the incident HIFU beam, which directly affects absorbed doses because tissue absorption coefficients increase with frequency. To verify beam positioning, we will superimpose images of the fundamental and harmonic beam patterns on B-mode images of target tissues. In post-exposure evaluations, this mode should readily detect harmonics in the backscatter from gas-filled bodies produced by, e.g., tissue vaporization. Such results have been reported by Ebbini and coworkers with a single transducer. [7]

The radiation-force technique provides sensitivity to lesions by virtue of their increased stiffness (Young's modulus) and attenuation parameters. These parameter changes can exert conflicting effects on induced motion. The spectrum analysis mode can help clarify these issues by providing direct information regarding lesion attenuation.

These initial investigations support the feasibility of these techniques and indicate their potential utility in HIFU procedures. These results have led us to incorporate and expand all of these techniques in a new digital system that employs HIFU arrays with central broadband diagnostic arrays.

V. ACKNOWLEDGEMENTS

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