

● *Original Contribution*

ACOUSTIC EMISSIONS DURING 3.1 MHz ULTRASOUND BULK ABLATION *IN VITRO*

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Abstract—Acoustic emissions associated with cavitation and other bubble activity have previously been observed during ultrasound (US) ablation experiments. Because detectable bubble activity may be related to temperature, tissue state and sonication characteristics, these acoustic emissions are potentially useful for monitoring and control of US ablation. To investigate these relationships, US ablation experiments were performed with simultaneous measurements of acoustic emissions, tissue echogenicity and tissue temperature on fresh bovine liver. *Ex vivo* tissue was exposed to 0.9–3.3-s bursts of unfocused, continuous-wave, 3.10-MHz US from a miniaturized 32-element array, which performed B-scan imaging with the same piezoelectric elements during brief quiescent periods. Exposures used pressure amplitudes of 0.8–1.4 MPa for exposure times of 6–20 min, sufficient to achieve significant thermal coagulation in all cases. Acoustic emissions received by a 1-MHz, unfocused passive cavitation detector, beamformed A-line signals acquired by the array, and tissue temperature detected by a needle thermocouple were sampled 0.3–1.1 times per second. Tissue echogenicity was quantified by the backscattered echo energy from a fixed region-of-interest within the treated zone. Acoustic emission levels were quantified from the spectra of signals measured by the passive cavitation detector, including subharmonic signal components at 1.55 MHz, broadband signal components within the band 0.3–1.1 MHz and low-frequency components within the band 10–30 kHz. Tissue ablation rates, defined as the thermally ablated volumes per unit time, were assessed by quantitative analysis of digitally imaged, macroscopic tissue sections. Correlation analysis was performed among the averaged and time-dependent acoustic emissions in each band considered, B-mode tissue echogenicity, tissue temperature and ablation rate. Ablation rate correlated significantly with broadband and low-frequency emissions, but was uncorrelated with subharmonic emissions. Subharmonic emissions were found to depend strongly on temperature in a nonlinear manner, with significant emissions occurring within different temperature ranges for each sonication amplitude. These results suggest potential roles for passive detection of acoustic emissions in guidance and control of bulk US ablation treatments. (E-mail: doug.mast@uc.edu) © 2008 World Federation for Ultrasound in Medicine & Biology.

Key Words: Ultrasound ablation, Therapy, Acoustic emissions, Passive cavitation detection.

INTRODUCTION

The objective of the experiments reported here was to gain understanding of the possible role of cavitation and other bubble activity during bulk thermal ablation of tissue by continuous-wave, unfocused ultrasound (US). This approach to US ablation, which has recently been developed and used by several investigators (Diederich et al. 1999; Chopra et al. 2001; Prat et al. 2002; Makin et al. 2005), has the potential to treat large tissue volumes at rates comparable to radiofrequency ablation and other

minimally-invasive bulk ablation modalities. As with other thermal ablation methods, noninvasive monitoring and control of energy delivery, tissue temperature and coagulation effects could improve the reliability of ablation, thus increasing the safety and efficacy of these minimally invasive treatments.

Cavitation and other bubble activity is known to occur during thermal treatments by therapeutic US at megahertz frequencies *in vivo* (ter Haar and Daniels 1981; Hynynen 1991; Fry 1995; Rabkin et al. 2005, 2006). Such activity can be exploited to visualize ablation effects (Sanghvi et al. 1995; Rabkin et al. 2005, 2006) or to enhance tissue absorption (Melodelima et al. 2001; Sokka et al. 2003; Umemura et al. 2005; Kaneko et al. 2005), but can also complicate US energy deposi-

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tion and the resulting spatial pattern of tissue coagulation (Watkin *et al.* 1996; Chen *et al.* 2003; Makin *et al.* 2005; Mast *et al.* 2005). Mechanisms for interactions between cavitation activity and US-induced heating have been clarified by several detailed numerical modeling studies (Hilgenfeldt *et al.* 2000; Chavrier *et al.* 2000; Yang *et al.* 2004) and phantom experiments (Holt and Roy 2001; Khokhlova *et al.* 2006). Cavitation activity, measured by passive detection of acoustic emissions, has also been found to correlate with cellular-level bioeffects (Edmonds and Ross 1986; Hallow *et al.* 2006) and with US enhancement of thrombolysis (Datta *et al.* 2006).

Recent experimental studies have used passive cavitation detection during high-intensity focused ultrasound (HIFU) exposures (Rabkin *et al.* 2005, 2006; Thomas *et al.* 2005; Farny *et al.* 2005; McLaughlan *et al.* 2006; Coussios *et al.* 2006). These studies have shown that cavitation causing both subharmonic emissions, consistent with stable bubble shape oscillations, and broadband emissions, consistent with inertial bubble collapse, can occur during HIFU treatments. Some correlation has been found between broadband acoustic emission levels and increased B-scan image brightness (Rabkin *et al.* 2005, 2006), as well as enhanced heating effects (Thomas *et al.* 2005; Coussios *et al.* 2006). However, it has also been shown that broadband and subharmonic emission levels do not correspond precisely with increases in tissue echogenicity (Rabkin *et al.* 2005; McLaughlan *et al.* 2006), and that broadband emissions can decrease in some cases as the tissue temperature rises (Farny *et al.* 2005; Coussios *et al.* 2006). Kilohertz-frequency emissions, consistent with tissue boiling (Osborne and Holland 1947; Ying 1973), have also been detected during HIFU exposures (McLaughlan *et al.* 2006; Sanghvi *et al.* 1995; Anand *et al.* 2004), and have been found to correlate with enhanced backscattering from tissue (Sanghvi *et al.* 1995; McLaughlan *et al.* 2006). These low-frequency emissions have also been used successfully to measure the onset time of tissue boiling, allowing estimation of heating rates as a result of the HIFU sonication (Anand *et al.* 2004).

However, these experimental studies of HIFU, with reported *in situ* US intensities of 200–2500 W/cm² for frequencies 1–4 MHz, do not indicate how cavitation activity interacts with US-induced heating for the unfocused US exposures used in minimally-invasive bulk thermal ablation (Diederich *et al.* 1999; Chopra *et al.* 2001; Prat *et al.* 2002; Makin *et al.* 2005; Mast *et al.* 2005). Ultrasound bulk ablation treatments cause tissue temperature elevation to occur more slowly, but in a larger tissue volume, than HIFU treatments. Resulting volumetric rates of tissue ablation are ~1–4 mL/min, comparable to radiofrequency ablations currently in clinical use. In these treatment regimes, *e.g.*, 60–80 W/cm²

spatial average intensity at the probe surface for a 3.1-MHz beam (Mast *et al.* 2005), cavitation behavior may be substantially different than in highly-focused beams. At the same time, thermal ablation performed at lower intensities may be more sensitive to heat losses caused by perfusion *in vivo* (Mast *et al.* 2005), so that potential methods for monitoring and control of US ablation are particularly important for these modalities. Thus, knowledge of cavitation dynamics during bulk US ablation is needed.

Here, acoustic emissions associated with cavitation and other bubble activity were passively detected during *in vitro* US ablation under exposure conditions similar to those used by Mast *et al.* (2005), with a miniaturized image-ablate US array device. These measurements are intended to clarify the possible roles of cavitation and other bubble activity in this treatment regime, including the relationships between cavitation, tissue echogenicity, tissue temperature and the progress of thermal ablation. Characterization of these phenomena is a step toward their practical application, including the possibilities of therapy monitoring and control using passive cavitation detection.

MATERIALS AND METHODS

Measurements

The experimental configuration used is shown in Fig. 1. Whole *ex vivo* bovine livers were acquired from a local slaughterhouse and used less than 12 hours *post mortem*. Tissue was kept chilled at 0°C in a thermally insulated container until cutting for use. Liver specimens were cut to dimensions 7 × 3.5 × 3 cm³, with the liver capsule comprising one of the 7 × 3.5-cm² surfaces. Immediately after cutting, the sample was placed in a latex condom (Probe Guard, Carter Products, New York, NY, USA) with a small amount of phosphate-buffered saline that had been degassed a minimum of 90 min, found sufficient to achieve about 36% dissolved oxygen saturation, and allowed to acclimate to room temperature (approximately 25°C). Care was taken to minimize gas entrainment during tissue handling. The sample was suspended in a water tank filled with deionized water, which had acclimated to room temperature and other ambient conditions for at least 12 h.

Thermal ablation and B-scan imaging were performed using a miniaturized, 32-element image-ablate array (Mast *et al.* 2005) (THX 3N, Guided Therapy Systems, Mesa, AZ, USA) controlled by the Iris imaging and ablation system (Guided Therapy Systems). The Iris system provides user-programmable control of therapeutic US exposures for image-ablate arrays, as well as B-scan imaging with capabilities comparable to clinical diagnostic scanners (Barthe 2004; Makin 2005). The

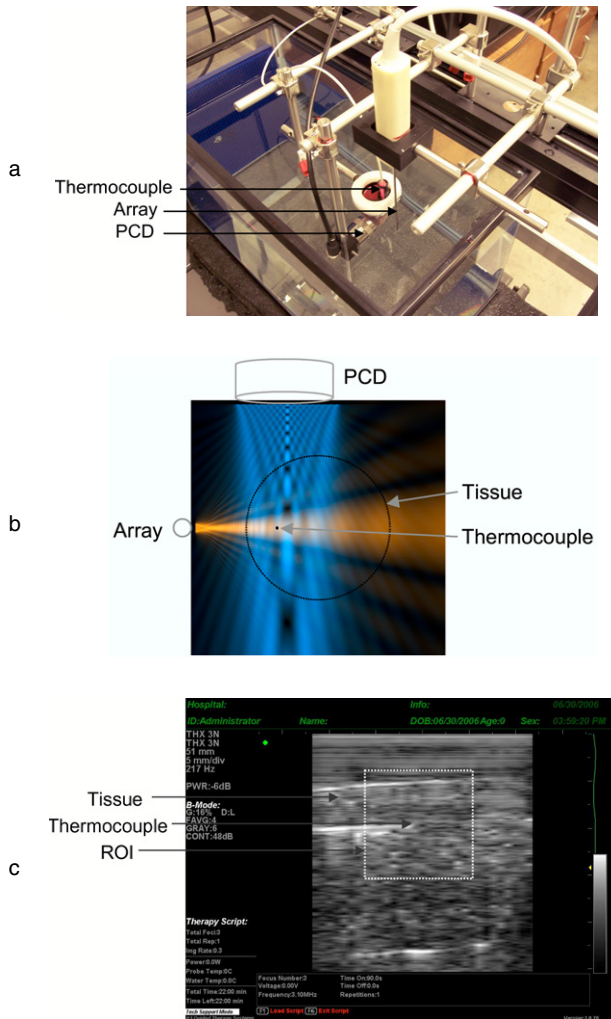


Fig. 1. Experiment configuration. (a) Experimental setup, showing a bovine liver sample with inserted thermocouple, image-ablate array and PCD. (b) Top view showing cross-sectional beam of image-ablate array (horizontal, red) (Mast et al. 2005), cross-sectional sensitivity beam pattern of detector at 1 MHz (vertical, blue) (Mast and Yu 2005) and relative positions of the transducers, thermocouple and tissue. The image-ablate array beam and PCD sensitivity pattern are shown on linear scales, with brightness proportional to amplitude. (c) B-scan of a bovine liver tissue sample from the image-treat array, showing the region-of-interest used for grayscale analysis. The thermocouple tip is seen at the region-of-interest center.

image-ablate array used has an active surface of $2.3 \times 49 \text{ mm}^2$ and individual element sizes of 2.3 mm in elevation and 1.5 mm in azimuth. The array was placed parallel to the liver capsule at a distance of $12.7 \pm 2.4 \text{ mm}$ (mean \pm standard deviation of distances measured from image-ablate array B-scans, $N = 18$), as illustrated in Fig. 1b. B-scan gain and time-gain compensation were adjusted to obtain signal levels appropriate for digitization, as well as uniform speckle brightness within the liver spec-

imen image. A representative tissue B-scan from the system is shown in Fig. 1c.

Passive cavitation detection was performed using a 25-mm circular diameter, unfocused, 1-MHz broadband receiver (C302, Panametrics, Waltham, MA, USA), placed perpendicular to the image-ablate array at a similar distance from the opposing tissue surface, as illustrated in Fig. 1a and 1b. This receiver was sensitive to acoustic emissions emanating from the entire tissue region significantly heated by the image-ablate array beam, as illustrated by the sensitivity beam pattern shown in Fig. 1b. Because acoustic emissions may originate at any point within the simultaneously sonicated and heated tissue region (volume $\sim 6 \text{ mL}$, based on observed ablation rates), this broad sensitivity pattern ensured that all significant emissions were recorded throughout each treatment. The resulting spatial averaging provides better characterization of overall cavitation activity for our bulk ablation experiments compared with the highly-focused detectors appropriate for HIFU ablation (Rabkin et al. 2005, 2006; Thomas et al. 2005; Farny et al. 2005; McLaughlan et al. 2006; Coussios et al. 2006).

A 0.4-mm diameter needle thermocouple (Type B, Ella CS, Hradec Králové, Czech Republic) was inserted at a depth of $7.7 \pm 2.3 \text{ mm}$ (measured from image-ablate array B-scans, $N = 18$) from the tissue surface facing the array, with the needle axis parallel to the array axis, as seen in Fig. 1b. Fig. 1c shows a representative B-scan image of the liver tissue sample with the inserted needle thermocouple. The thermocouple location corresponds approximately to the point of maximum tissue heating and the center of thermal lesions formed, so that temperature measurements at this location represent overall ablation progress throughout a given treatment. Because the therapeutic US beam used here was unfocused, temperature gradients near the center of the heated region are small, as seen from models of tissue heating from these image-ablate arrays (Mast et al. 2005). At other points throughout the heated region, the time-dependent temperature elevation is roughly proportional to the temperature elevation at the central thermocouple location. Thus, this single-point temperature measurement can be considered an indicator of the overall tissue heating throughout the treated region, consistent with our unfocused passive cavitation detector.

Ablation exposures, specified and controlled using the Iris system, were performed by firing the center 16 array elements at 3.1 MHz as an unfocused $2.3 \times 24.5 \text{ mm}^2$ aperture with amplitudes corresponding to calibrated acoustic power outputs of 16.2, 28.8 and 45.0 W. The resulting unfocused beam is collimated in the array direction (beam width similar to the 24.5-mm aperture width) and exhibits spreading in the elevation direction, as illustrated by the cross section shown in Fig. 1b.

Acoustic power calibration was performed by the probe manufacturer using a radiation force balance method (Makin *et al.* 2005). Stability of array performance was verified by regular measurements of element capacitance between experiments, as well as real-time display of delivered electrical power during each exposure. The measured acoustic powers were converted to *in situ* acoustic pressure levels by computing the diffracted acoustic field of this subaperture using a Fresnel approximation for transducer arrays with rectangular elements (Freedman 1960; Mast 2006), which has previously been shown to characterize array fields accurately (Makin *et al.* 2005). At a distance of 15 mm from the array, the acoustic pressure amplitudes used were thus estimated as 0.83, 1.10 and 1.38 MPa, corresponding to plane-wave acoustic intensities of 23, 41 and 64 W/cm², respectively.

A total of six exposures were performed for each of these three amplitude conditions, for a total of 18 experiments. Total exposure times used, found to ensure significant thermal coagulation in each case, were 20 min for the 0.8-MPa amplitude, 10 min for the 1.1-MPa amplitude and 5 min for the 1.4-MPa amplitude. Pulse lengths, chosen so that comparable tissue heating would occur from a pulse at each sonication amplitude, were 3.3 s for the 0.8-MPa exposures, 1.7 s for the 1.1-MPa exposures and 0.9 s for the 1.4-MPa exposures. The quiescent period between each pulse was the interval required for the Iris system to switch between therapy and imaging mode, acquire a single B-scan image frame and resume therapy mode, or about 30 ms. The resulting duty cycles were 97–99%.

Beamformed, radiofrequency A-line signals were recorded during each quiescent period using a 14-bit, PC-based A/D card (Compuscope CS 14200, Gage Applied, Montreal, Quebec, Canada) at a sampling rate of 33.3 MHz. During each quiescent period, 32 A-lines of 2,048-sample length were recorded, comprising an entire B-scan frame with dimensions 49 mm in the array direction and 47 mm in the depth direction.

Signals from the passive cavitation detector (PCD) were acquired at a 10-MHz sampling rate for 100-ms intervals synchronized to begin 100 ms after each image acquisition, ensuring that these signals were recorded only during continuous-wave exposure. The rate of acquisition for these signals, corresponding to the rate of acquisition for B-scan frames, was 0.3 Hz for the 0.8-MPa amplitude, 0.6 Hz for the 1.1-MPa amplitude and 1.1 Hz for the 1.4-MPa amplitude. PCD signals were recorded by a digital sampling oscilloscope (WaveRunner 6050A, LeCroy, Chestnut Ridge, NY, USA) after amplification by a low-noise preamplifier (SR 560, Stanford Research Systems, Sunnyvale, CA, USA). The preamplifier also acted as a low-pass filter (cutoff frequency 1.4 MHz, slope –6 dB/octave) to reduce fundamental

(3.1 MHz) signal components caused by diffraction and scattering of the high-amplitude incident wave. This filtering, in addition to the limited bandwidth of the PCD, reduced fundamental signal components to a level approximately 30 dB above background noise, comparable to the amplitude of subharmonic acoustic emissions in these experiments.

Temperature from the needle thermocouple probe was recorded using a digital data logger (Omegette HH306, Omega Engineering, Stamford, CT, USA) at a sampling rate of 1 Hz throughout each ablation experiment. For data analysis, recorded temperatures were temporally interpolated to correspond with the sampling times of the echo data and PCD signal acquisitions.

After each ablation treatment, tissue samples were frozen and sectioned into macroscopic slices of calibrated thickness for evaluation (Makin *et al.* 2005). A slice thickness of 2 mm was chosen as the smallest practical for consistent, damage-free tissue handling. Areas ablated in each tissue section were quantified by manual segmentation (ImageJ, National Institutes of Health, Bethesda, MD, USA) into regions of uniform discoloration associated with specific temperature or thermal dose thresholds (Mast *et al.* 2005). Based on pathologic analysis of *in vivo* thermal ablation studies, gross discoloration of tissue by thermal effects consistently indicates coagulative necrosis and tissue death (Thomsen 1999). The total volumes of tissue ablation (all coagulated tissue) were thus estimated and used to compute volumetric ablation rates (mL/min) for each experiment. Similarly, the total volumes of overtreatment (brown cores of some thermal lesions) were determined and used to compute volumetric overtreatment rates for each experiment. These overtreated regions, which correspond to the central island in the “island and moat” description of HIFU lesions (Warwick and Pond 1968), incurred temperature elevations and thermal doses significantly higher than those required for coagulative necrosis (Mast *et al.* 2005). The segmentation process is illustrated in Fig. 2, which shows segmented areas of ablated and overtreated regions for a representative tissue section from a 1.4-MPa, 5-min exposure as described in Materials and Methods. Ablation rates averaged 0.14, 0.66 and 1.15 mL/min for the 0.8, 1.1 and 1.4 MPa amplitudes, whereas overtreatment rates averaged $9.2 \cdot 10^{-4}$, $5.5 \cdot 10^{-3}$, and $9.2 \cdot 10^{-3}$ mL/min ($N = 6$ for each of the three amplitude conditions).

Data processing

Acoustic emissions, intended to signify cavitation and other bubble activity, were quantified by spectral analysis of PCD signals. For each 100-ms signal sampled at 10 MHz, a power spectrum density was estimated by the periodogram method (Bartlett 1950) using 1,000-

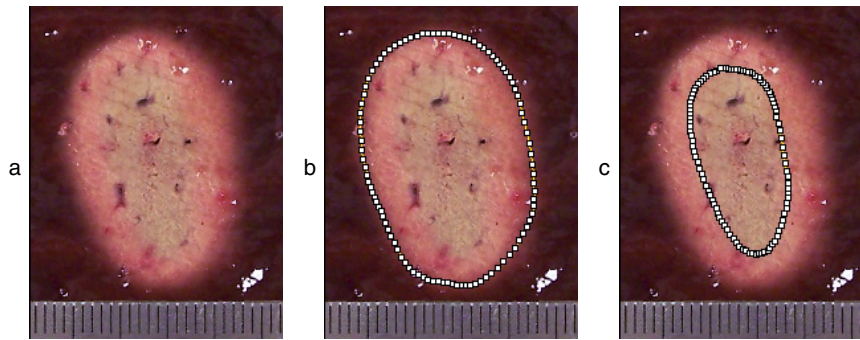


Fig. 2. Representative cross section of treated bovine liver tissue from one of the 1.4-MPa exposures, showing segmentation of ablated regions (all coagulated tissue) and overtreated regions (brown cores of some lesions). This cross section was taken parallel to the tissue surface (perpendicular to the image plane) at a depth of 8 mm. The ruler shown is scored at 1-mm intervals. (a) Treated cross section. (b) Segmented area of complete ablated region. (c) Segmented area of inner, overtreated region.

sample ($100 \mu\text{s}$) rectangular windows with no overlap, so that 1,000 periodograms (*i.e.*, magnitude-squared discrete Fourier transforms) were averaged to obtain power spectra with a frequency resolution of 10 kHz. To isolate different physical mechanisms of bubble activity, spectral energy was integrated within three frequency bands. The first band considered, consisting of the single frequency bin centered at the subharmonic frequency of 1.55 MHz, is sensitive to nonlinear bubble vibrations often associated with stable cavitation activity (Leighton 1994; Yang and Church 2005). Because of the highly narrow-band nature of the subharmonic oscillations and the high frequency resolution of the spectrum measurements, this single bin was sufficient to fully characterize the subharmonic emissions. The second band, covering frequencies 0.3–1.1 MHz, was chosen to characterize broadband emissions such as those resulting from inertial bubble collapse (Leighton 1994; Yang and Church 2005). This frequency band, well within the known range for acoustic emissions from inertial cavitation (Leighton 1994), was chosen for optimal detector sensitivity and convenience of data acquisition. The third band, ranging from 10–30 kHz (the three frequency bins of lowest nonzero center frequency), characterizes low-frequency emissions associated with tissue boiling (Osborne and Holland 1947; Ying 1973). Electronic noise levels within each band were quantified by performing the same data acquisition and analysis for signals acquired during sham exposures, in which the Iris system drove a 50Ω dummy load. The resulting spectra, which were nearly indistinguishable from spectra measured in the absence of any signal, were used as reference noise levels for scaling of the measured emissions. Instantaneous and time-average spectral energy in each band for the ablation experiments were quantified in decibels relative to this measured noise energy in the same band.

The time variation of tissue echogenicity was cal-

culated using the RF echo data recorded from the image-able array. For each measurement, echo energy was quantified as the mean-square value of the echo signals within a region-of-interest spanning 24.5 mm or 16 lines in azimuth (corresponding to the extent of the therapy beam), and from 8–32 mm in range (the region predominantly heated by the therapy beam, approximately centered on the active thermocouple element). Because the initial echogenicity varied from sample to sample depending on the tissue structure, mean grayscale values were computed in decibels relative to the mean value at the onset of treatment.

Possible artifacts in the measured acoustic emissions were minimized by several methods. First, it was confirmed that the 1-MHz PCD successfully recorded broadband emissions within the frequency range 0.3–1.1 MHz during acoustic destruction of an US contrast agent (Optison, Amersham Health, Amersham, United Kingdom), in a manner similar to the passive cavitation detection performed by Giesecke and Hynynen (2003). Passive cavitation detection over a similar frequency band was also performed by Rabkin et al. (2005, 2006) to characterize inertial cavitation. To confirm that detected acoustic emissions were not caused by cavitation in the deionized tank water outside the tissue sample, exposures identical to the tissue experiment conditions were performed in the empty tank and found to result in negligible emissions.

To control for possible influence of the thermocouple surface on cavitation seeding, two complete ablation exposures were performed at each of the three amplitude conditions, with identical conditions except for absence of the needle thermocouple. Possible thermocouple self-heating artifacts (Hynynen and Edwards 1989) were not compensated and may have resulted in small positive biases in the absolute temperatures measured. Measurements of thermocouple self-heating, performed under

exposure conditions identical to the present ablation experiments, indicate that any such temperature biases were no greater than 3°C.

Correlation analyses were performed among the time-averaged and instantaneous measured quantities. First, the volumetric ablation rate for each experiment, as well as the volumetric rate of overtreatment, as defined in Materials and Methods, were correlated with time-averaged subharmonic, broadband and low-frequency acoustic emission levels for each experiment ($N = 18$ for each pair). Correlation coefficients and corresponding p -values were computed to assess statistical significance based on the criterion $p < 0.01$ (two-tailed). Because the passive cavitation detector interrogated the entire volume significantly heated by the image-ablate array beam, the signals recorded include acoustic emissions originating from locations throughout the tissue volume undergoing ablation. Thus, these correlation analyses of time-averaged quantities provide an assessment of any correspondence between temporally consistent, detectable bubble activity and treatment effectiveness for the bulk ablation conditions used here.

In addition, to assess the temporal correspondence of detected acoustic emissions with simultaneous tissue properties, all time-dependent measured quantities were cross correlated for all epochs recorded ($N = 6179$ for all data points in the 18 experiments). The time-dependent quantities measured included acoustic emissions in the three bands considered, mean B-scan grayscale value within a region-of-interest and tissue temperature measured at a single point. The region-of-interest for computation of mean grayscale value, illustrated in Fig. 1, was chosen to cover the area of the image plane incurring significant tissue heating, within the volume interrogated by the PCD.

The temperature measurements used in this correlation analysis were obtained at a single point near the center of the region-of-interest at the depth of maximum tissue heating, as described previously. Because of the relatively broad heating pattern of the unfocused image-ablate array (Makin *et al.* 2005, Mast *et al.* 2005), this single-point temperature measurement provides an estimate of the tissue temperature throughout the center of the heated region. The relative homogeneity of heating in this region is illustrated in Fig. 2, which shows a treated tissue cross section taken near the thermocouple position at a depth of 8.0 mm. Thus, for the purpose of correlating tissue heating with changes in tissue backscatter and acoustic emissions, this single-point measured temperature can be considered an indicator of the overall progress of a given ablation treatment.

Correlation coefficients were computed for each possible pair of temporal variables for the entire set of measured epochs across the 18 experiments ($N = 6179$),

providing a measure of correspondence between time-dependent acoustic emissions, simultaneous tissue echogenicity and the temporal progress of tissue ablation. Statistical significance for these correlations was assessed using the criterion $p < 0.01$ (two-tailed). In interpretation of these correlations, it is important to recognize that the correlated measurements of acoustic emissions, mean grayscale values and tissue temperatures did not interrogate identical sample volumes. Thus, although these analyses provide insight about relationships between these measured quantities within the heated region, they should not be considered definitive tests of local correlation between tissue temperature, backscatter and acoustic emissions.

RESULTS

Representative time-frequency surface plots of the measured PCD spectra for each exposure condition are shown in Fig. 3. These plots illustrate the three distinct acoustic emission phenomena considered here. Subharmonic emissions at 1.55 MHz occur sporadically in all three cases. Broadband emissions are seen within the 0.3–1.1-MHz band in all cases, with increasing amplitude at the higher sonication levels. Strong low-frequency emissions within the 10–30-kHz band, associated with tissue boiling, are seen only in the highest-amplitude case (1.4 MPa, Fig. 3c) late in the treatment cycle.

Mean and standard deviation values for the time-averaged acoustic emission levels, based on measured spectra for all 18 experiments analyzed, are shown in Fig. 4 for the three frequency bands considered. Emissions at the subharmonic frequency are seen to vary among experiments at each amplitude, consistent with the large standard deviations shown (comparable to the mean emission level in each case). Broadband emissions were much more consistent, with time-averaged levels predictably increasing with the exposure pressure amplitude and relatively small deviations between experiments. Low-frequency emissions were generally small for the 0.8-MPa and 1.1-MPa amplitudes, but larger and more variable for the 1.4-MPa amplitude. This is consistent with the expectation that tissue boiling is more likely to occur at higher acoustic intensities. Emission levels are not directly comparable among the three frequency bands because of frequency-dependent variations in the detector sensitivity.

Also shown in Fig. 4 are the mean time-averaged acoustic emissions levels for two control experiments performed without the needle thermocouple at each exposure condition. Measured emission levels in each band show similar trends with or without the thermocouple present, with no substantial discrepancies except for

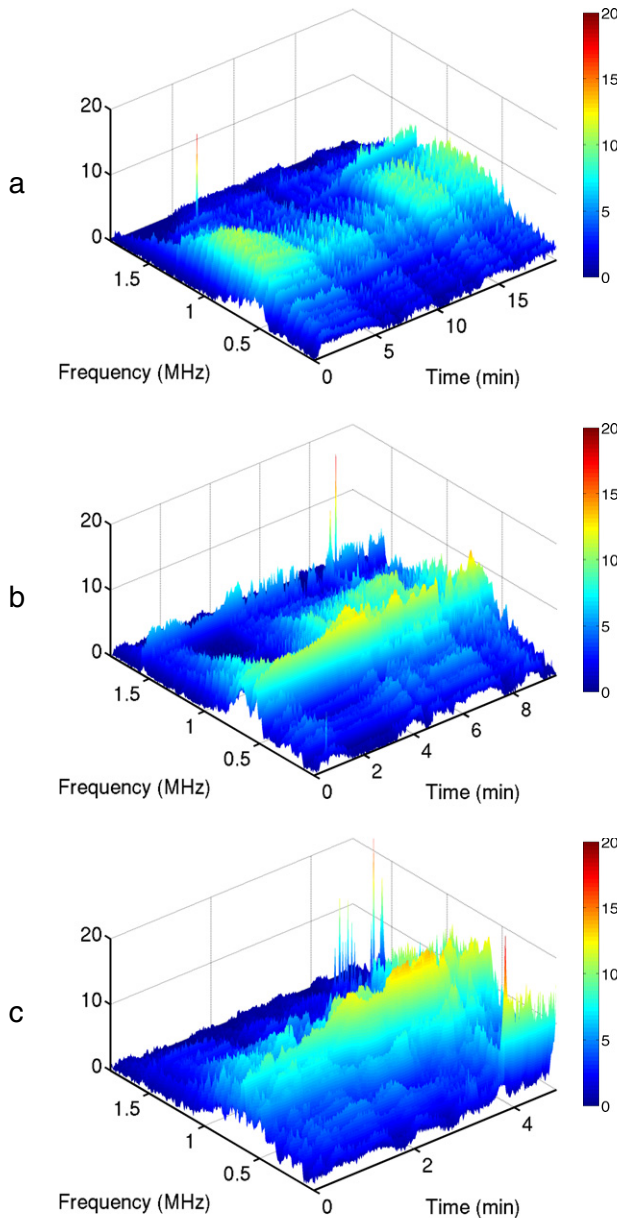


Fig. 3. Time-frequency plots for representative PCD spectra at the three exposure conditions used. Spectra are shown in decibels relative to a measured noise level. All panels show narrow-band subharmonic emissions at 1.55 MHz and broadband emissions throughout the depicted frequency range. Panel (c) also shows low-frequency emissions in the kHz range for times ≥ 4 min. (a) 0.8-MPa nominal sonication amplitude. (b) 1.1 MPa. (c) 1.4 MPa.

broadband emissions at the 0.8-MPa amplitude. This discrepancy suggests that the hydrophobic thermocouple surface may have decreased the pressure threshold for inertial cavitation, causing increased broadband emissions to occur at lower pressures when the thermocouple was present. However, this phenomenon did not change the general trend of increasing broadband emissions with

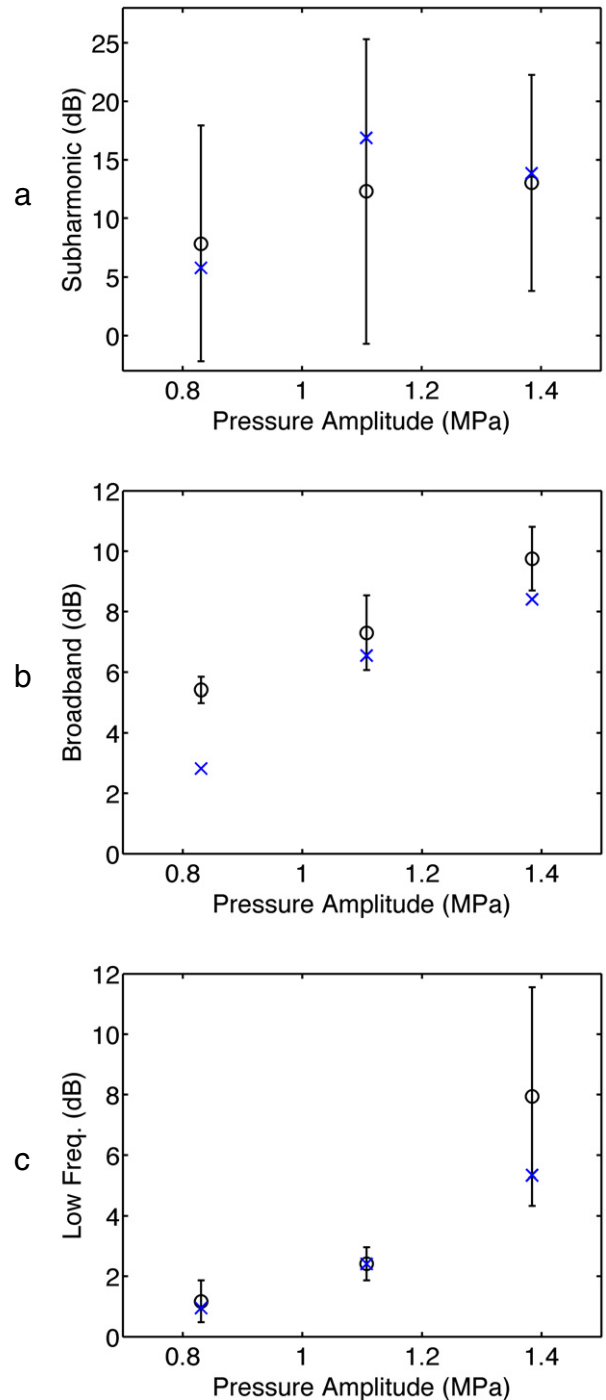


Fig. 4. Average levels for PCD-measured acoustic emissions within subharmonic, broadband and low-frequency intervals at the three exposure conditions used. Plotted as circles with error bars are the mean and standard deviation of the average emission level for each pressure amplitude ($N = 6$ for each). The plotted "x" symbols show average acoustic emission levels in each band for two experiments without the needle thermocouple at each exposure condition.

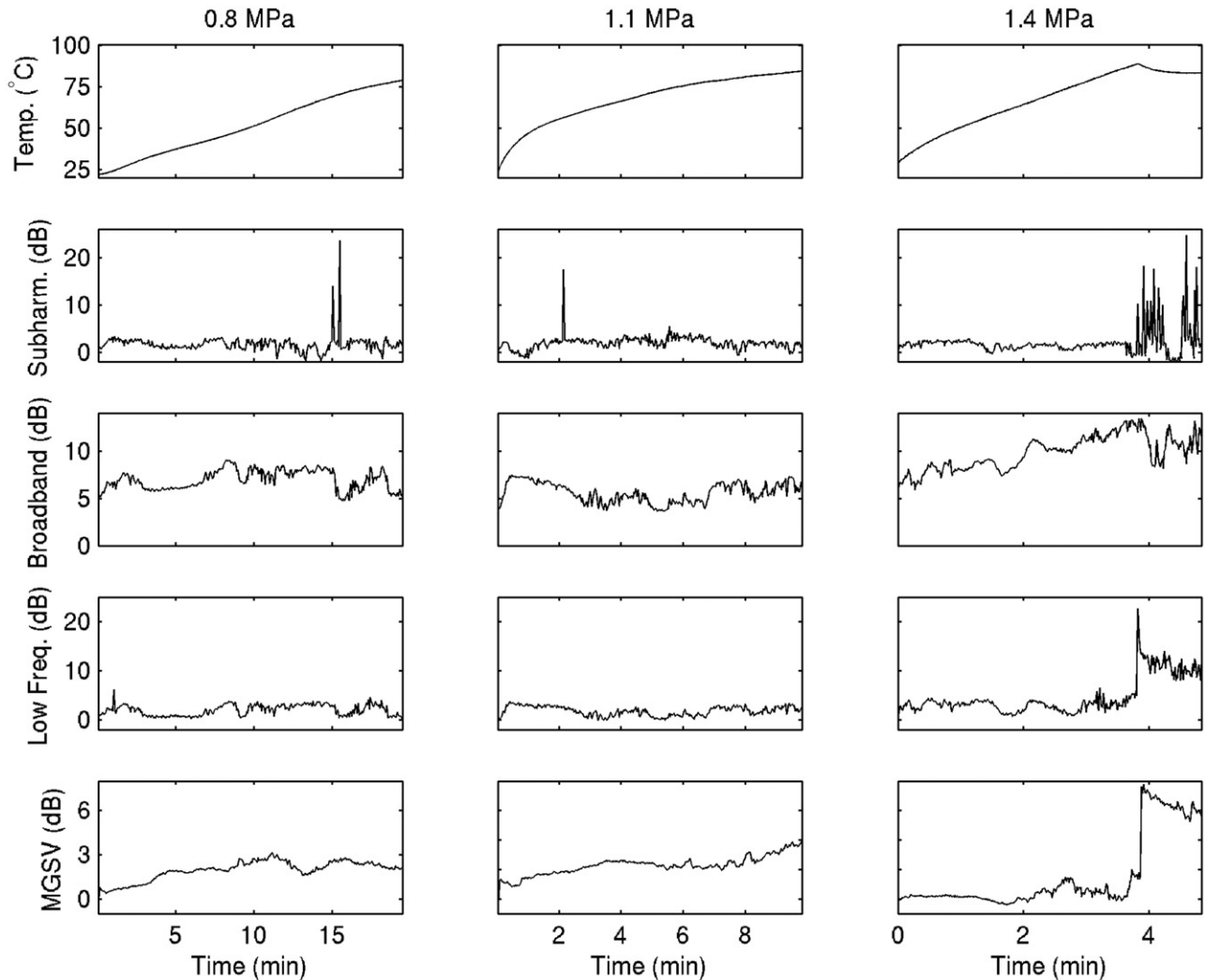


Fig. 5. Representative plots of the measured time-dependent temperature, acoustic emission levels and B-scan mean grayscale value for one ablation experiment at each of the three exposure conditions used.

increased sonication amplitude, and is thus not expected to substantially affect the correlation results presented later. In general, these control experiments indicate that any influence of the needle thermocouple on cavitation activity was of secondary importance in these experiments.

Representative time series for experiments at each exposure condition are shown in Fig. 5, for the same experiments illustrated in Fig. 3. The temperature time history shows a significant rise over the course of each experiment to temperatures $>75^{\circ}\text{C}$ associated with significant thermal ablation, with higher heating rates at higher acoustic amplitude as expected. A local decline in temperature, seen about 4 min into the highest-amplitude (1.4 MPa) treatment, is consistent with acoustic shadowing caused by tissue or water vaporization proximal to the thermocouple (Makin *et al.* 2005). Acoustic emissions are shown in decibels relative

to the measured noise floor, as described in Materials and Methods, so that the measured emission level was near 0 dB in each band immediately before and after the US exposure. Subharmonic emissions occurred in each case shown, appearing sporadically at the two lower amplitudes (0.8 and 1.1 MPa) but late in the highest-amplitude (1.4 MPa) treatment, after the apparent vaporization. Broadband emissions were largest in the highest-amplitude case, and also appear to increase with the treatment time in this case. Low-frequency emissions were small except in the highest-amplitude case after the apparent vaporization. Tissue echogenicity rose with temperature to a limited extent, except in the highest-amplitude case where a rapid increase occurred at the time of apparent vaporization, coincident with the rise in low-frequency emissions. Notably, the passive cavitation detector was sensitive to acoustic emissions originating within a broad region. Thus, bubble activity from multiple

tissue regions, possibly varying because of local differences in temperature and pressure amplitude, may have contributed to received emission spectra.

Table 1 shows correlation coefficients among average acoustic emission levels in the three bands considered and the measured volumetric rates of ablation and overtreatment, as defined in Materials and Methods and illustrated in Fig. 2. Volumetric rates of ablation and overtreatment showed significant correlation with time-averaged broadband and low-frequency emission levels across the 18 experiments analyzed, as illustrated in Fig. 6, but they did not correlate significantly with subharmonic emission levels. Notable is that the ablation rate correlated more highly with broadband emissions ($r = 0.848$) than with low-frequency emissions ($r = 0.747$), whereas the rate of overtreatment correlated more highly with low-frequency emissions ($r = 0.754$) than with broadband emissions ($r = 0.682$). These statistically significant correlations suggest that for the experiments reported here, increases in average broadband and low-frequency emission levels corresponded with increased bulk ablation effects, but average subharmonic emission levels were not measurably related to ablation effects.

The scatter plot for ablation rate vs. average acoustic emission levels, shown in Fig. 6, suggests that the volumetric ablation rate was correlated approximately linearly with broadband emissions but nonlinearly with low-frequency emissions. The correspondence between measured broadband emissions and bulk ablation rate may result from increased number or amplitude of inertial cavitation events with increased intensity of the therapeutic US beam, which in turn is proportional to the rate of heat deposition. The observation of nonlinear correspondence between low-frequency emissions and volumetric ablation rate suggests a consistency between vaporization and rapid tissue ablation, both of which were associated with rapid temperature rises in the experiments considered. The corresponding scatter plot for the overtreatment rate, shown in Fig. 7, instead shows an approximately linear correlation, suggesting that overtreatment effects (defined here by tissue browning, as illustrated in Fig. 2) and low-frequency emissions both occurred at similar temperature elevations.

Table 1. Correlation matrix for time-averaged quantities over all measured epochs ($N = 18$ for the 18 experiments)

	Subharmonic	Broadband	Low-frequency	Overtreatment	
0.144	0.848	0.747	0.663		Ablation
	0.172	0.250	0.225		Subharmonic
		0.697	0.682		Broadband
			0.754		Low-frequency

Correlation coefficients in bold type are statistically significant ($p < 10^{-2}$ in all cases).

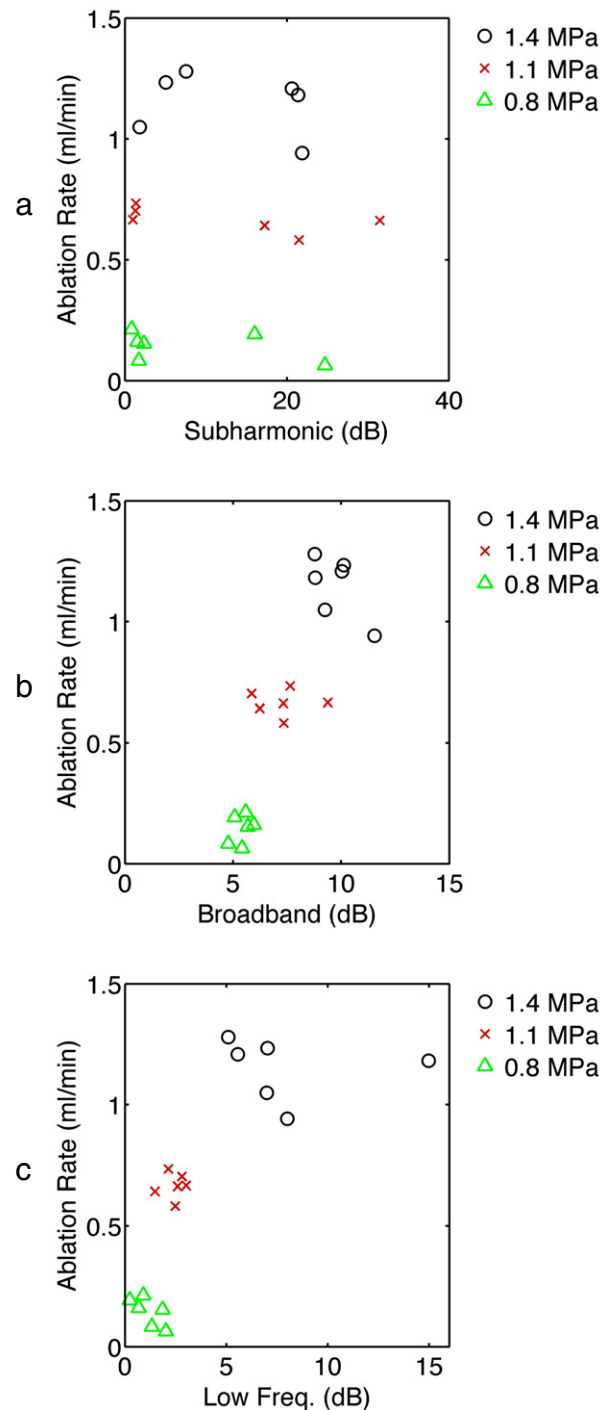


Fig. 6. Scatter plots of ablation rate vs. time-averaged acoustic emission levels for the three frequency bands considered: (a) subharmonic, (b) broadband and (c) low-frequency emissions. Points are shown for all 18 experiments performed at the three exposure conditions used.

Correlation coefficients for the time-dependent measured temperature, acoustic emission levels and B-scan mean grayscale value are shown in Table 2, with statistically significant correlations indicated in bold

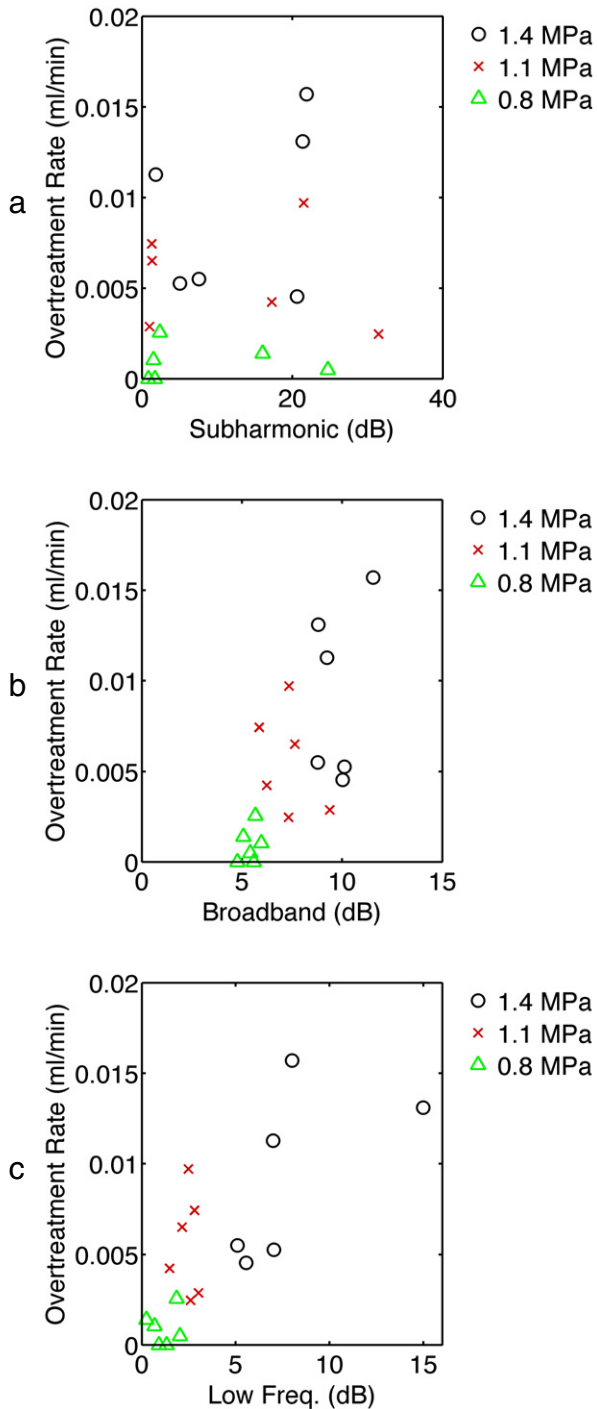


Fig. 7. Scatter plots of overtreatment rate vs. time-averaged acoustic emission levels for the three frequency bands considered: (a) subharmonic, (b) broadband and (c) low-frequency emissions. Points are shown for all 18 experiments performed at the three exposure conditions used.

type. These correlation values indicate temporal correspondence among simultaneously measured acoustic emissions, tissue echogenicity and the progress of tissue heating throughout an US ablation procedure. Measured

temperature is seen to correlate significantly ($p < 10^{-25}$ for $N = 6179$ epochs from 18 ablation experiments) with low-frequency emissions, broadband emissions and relative tissue echogenicity (mean grayscale value), with low-frequency emissions showing the strongest correlation. However, measured subharmonic emissions were uncorrelated with simultaneously measured tissue temperature. The relative grayscale value correlated significantly with low-frequency and subharmonic emissions, although the measured correlation coefficients are relatively weak ($r < 0.25$). Tissue echogenicity was not significantly correlated with broadband emissions in these experiments. These temporal correlations suggest that overall tissue heating and ablation progress may correspond with measurable broadband and low-frequency emissions as well as tissue echogenicity for the ablation conditions studied here. Although the temporal correlations observed are not close to unity, their statistical significance suggests potential for use in treatment monitoring, as discussed later.

Corresponding scatter plots for the time-dependent variables are shown in Figs. 8 and 9. Although these plots are somewhat complicated because of the large number of data points ($N = 6179$), some observations can be made. In Fig. 8a, the scatter plot for subharmonic emissions shows definite structure, although no significant linear correlation was found. Except for one outlier point, no subharmonic emissions exceeded 10 dB above background for measured tissue temperatures below 45°C. The nature of subharmonic emissions also varied with the intensity of sonication. For the lowest intensity used (nominal pressure amplitude 0.8 MPa), subharmonic emissions corresponded consistently with measured temperatures in the range 47–49°C. Within this temperature range, 70% of the measured subharmonic emission levels were greater than 10 dB above background for the 0.8-MPa sonications. Subharmonic emissions are concentrated at higher temperatures for the two higher sonication intensities used.

The scatter plot for broadband emissions shown in Fig. 8b shows a general rise in emission level with the nominal sonication intensity, consistent with the average emission levels shown in Fig. 4. Some broadband emis-

Table 2. Correlation matrix for time-dependent quantities over all measured epochs ($N = 6179$ for the 18 experiments)

Subharmonic	Broadband	Low-frequency	Grayscale	
$-6.47 \cdot 10^{-4}$	0.419	0.527	0.455	Temperature
	$1.02 \cdot 10^{-4}$	$3.54 \cdot 10^{-3}$	0.123	Subharmonic
		0.651	$2.32 \cdot 10^{-3}$	Broadband
			0.218	Low-frequency

Correlation coefficients in bold type are statistically significant ($p < 10^{-25}$ in all cases).

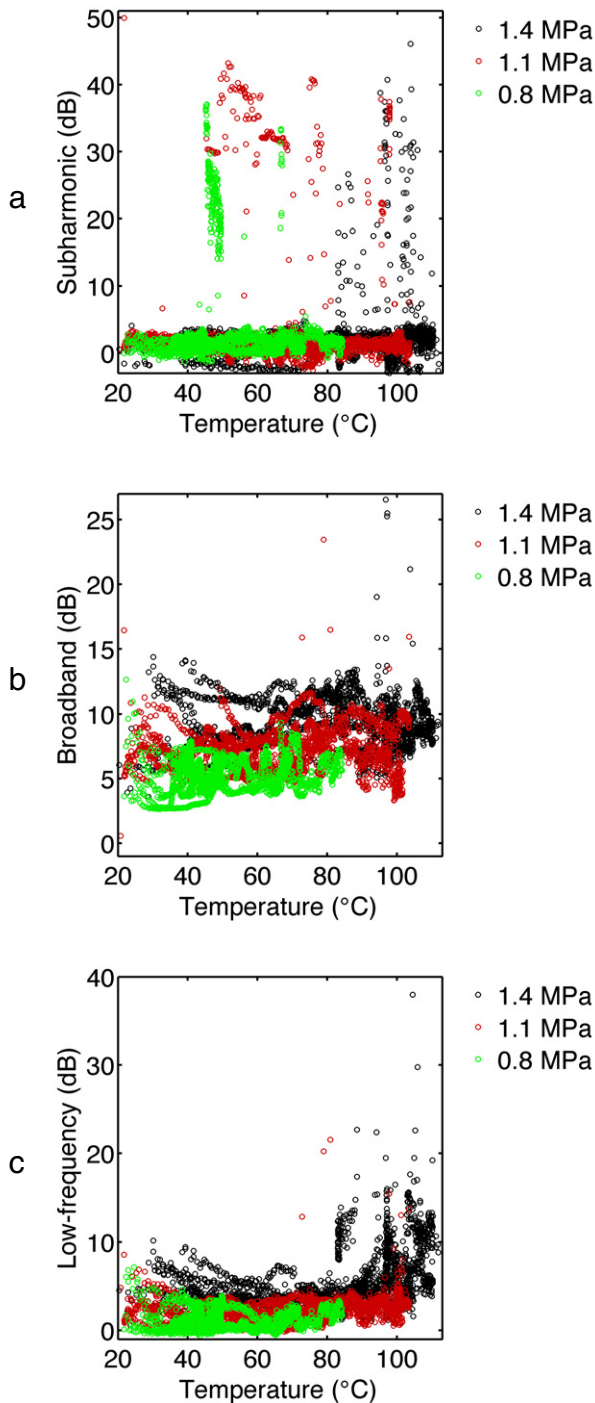


Fig. 8. Scatter plots of instantaneous measured tissue temperature vs. acoustic emission levels for the three frequency bands considered: (a) subharmonic, (b) broadband and (c) low-frequency emissions. Points are shown for all 6,179 epochs within 18 experiments at the three exposure conditions used.

sions of much higher amplitude are also seen for higher temperatures at the two higher pressure levels (nominal amplitudes 1.1 and 1.4 MPa). Low-frequency emissions, illustrated in Fig. 8c, appear to scale with sonication

amplitude at low temperatures, similar to the broadband emissions measured in a higher-frequency range. However, low-frequency emissions far above background occurred preferentially at high temperatures, suggesting tissue boiling. For epochs with thermocouple-measured temperature greater than 100°C, 75% showed measured low-frequency emissions >5 dB above background. For epochs with thermocouple-measured temperature less than 80°C, 80% showed measured low-frequency emissions <5 dB above background. Discrepancies may occur in part because temperatures measured at the thermocouple tip did not necessarily correspond to the maximum tissue temperature.

Fig. 9 shows scatter plots of the relative echo brightness or mean grayscale value (MGSV) within the heated region-of-interest, plotted as a function of the instantaneous thermocouple-measured temperature and the subharmonic, broadband and low-frequency acoustic emission levels. The plot of MGSV vs. temperature in Fig. 9a shows a general trend of increasing echo brightness with tissue temperature. The highest grayscale values (relative MGSV >5 dB) occurred only for temperatures >80°C at the thermocouple tip, suggesting the likelihood of tissue or water vaporization. The plots of temperature vs. the three measured acoustic emission levels in Fig. 9b–d show considerable scatter. Fig. 9b and 9d suggest a weak dependence of MGSV on acoustic emission level for the subharmonic and low-frequency bands measured, although the corresponding correlation coefficients in Table 2 show statistical significance. In Fig. 9c, broadband emission levels appear to be nearly independent of the echo brightness, consistent with the small correlation between grayscale value and broadband emissions seen in Table 2. Thus, in these experiments, bubble activity observable by increased echo brightness did not consistently cause subharmonic or broadband acoustic emissions. Although low-frequency emissions and echo brightness both increase at high temperatures, the largest low-frequency emissions (>15 dB above background) did not coincide with high MGSV. This discrepancy suggests that echo brightness within portions of the region-of-interest can be significantly reduced by acoustic shadowing, caused by widespread tissue or water vaporization at high temperatures (Makin et al. 2005; Mast et al. 2005).

DISCUSSION

The measurements reported here provide insight on bubble activity detected acoustically during US ablation performed with unfocused, high-intensity beams. Because the PCD used employed has a similarly unfocused sensitivity pattern, the acoustic emissions recorded emanated from a fairly broad region, as depicted in Fig. 1b.

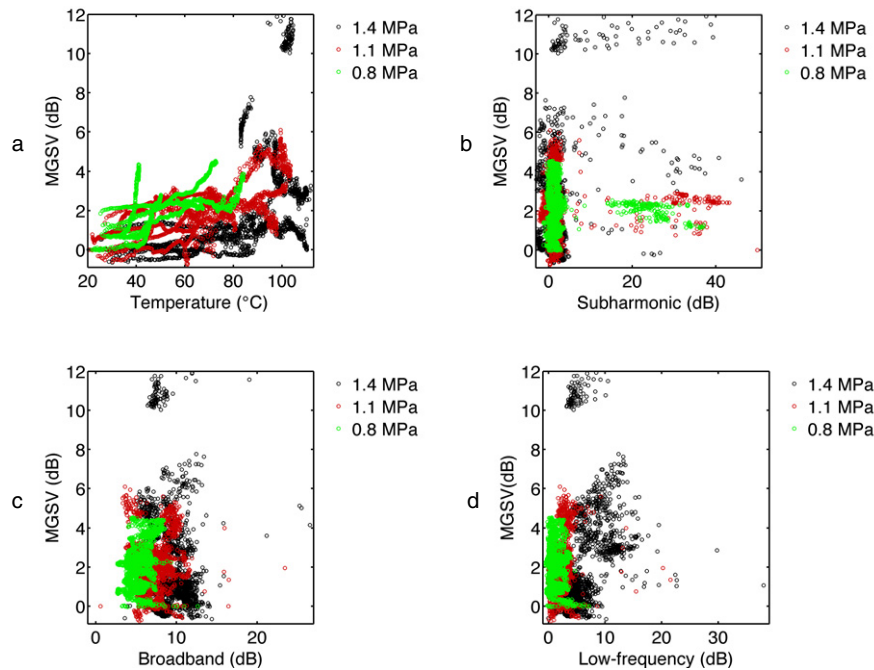


Fig. 9. Scatter plots of instantaneous measured MGSV in the heated region-of-interest vs. acoustic emission levels for the three frequency bands considered: (a) subharmonic, (b) broadband and (c) low-frequency emissions. Points are shown for all 6,179 epochs within 18 experiments at the three exposure conditions used.

This configuration has several pertinent advantages, including sensitive emission detection as a result of spatial integration, as well as insensitivity to small misalignments and localized artifacts. Because the recorded acoustic emissions are caused by cavitation activity throughout the significantly heated tissue volume, this approach also provides a useful measure of overall bubble activity in the treated tissue. However, this experimental configuration provides no detailed information on the precise spatial location of the cavitation events detected. Thus, received acoustic emissions detected at a given instant may contain components caused by bubble activity in multiple tissue regions subject to different temperatures and acoustic pressures.

In contrast to the broad spatial region sampled by the PCD, temperature measurements were obtained only at a single point near the thermocouple tip. Because the unfocused beam emitted by the image-ablate US array results in a broad heating pattern with relatively low temperature gradients (Mast *et al.* 2005), this single temperature measurement provides an estimate of tissue temperature for points near the center of the heated volume, and also can be regarded as an indicator for the overall progress of each ablation treatment. However, this local temperature measurement does not correspond to the local tissue temperature at the originating sites of all detectable acoustic emissions. In particular, after the onset of tissue boiling, the tissue heating pattern is com-

plicated by acoustic shadowing from large vapor bubbles, which can reduce the tissue heating occurring at the thermocouple tip. Such acoustic shadowing may also attenuate the propagation of high-frequency acoustic emissions.

For these reasons, the reported correlations between acoustic emissions and tissue temperature show the dependence of overall detectable bubble activity on overall tissue heating in these ablation experiments, but do not test the precise correspondence between local temperature and bubble activity at any single spatial point. Thus, it is possible that acoustic emissions detected with higher spatial resolution would show stronger correlations with local tissue temperature or backscatter. Resolution of this issue will require further study of passive cavitation detection in tissue with higher spatial resolution.

Another limitation of the experiments reported here was the use of fresh *ex vivo* tissue, which may be expected to have different properties compared with living tissue. In particular, living tissue should contain smaller amounts of free gas before sonication, so that initial cavitation levels may be smaller *in vivo*. Perfusion effects will also vary the initial heating rate, leading to differences in treatment effects between *in vivo* and *in vitro* ablation procedures (Mast *et al.* 2005). However, once tissue temperature is raised 10°C or more by the sonication, differences between *ex vivo* tissue and heated, nonviable *in vivo* tissue, including both free gas

and perfusion characteristics, should be much less. After coagulative necrosis, tissue should also behave similarly with respect to US induced bubble activity, both *in vivo* and *in vitro*. Thus, for *in vivo* ablation, it is possible that acoustic emissions will be correlated more highly with ablation effects and tissue temperature than in the experiments reported here, particularly if bubble activity is detected with higher spatial resolution.

The low-frequency emissions observed here are known to be associated with vaporization and boiling for US ablation at 3.5 MHz, comparable to the sonication frequency used here (Anand et al. 2004; Khokhlova et al. 2006). However, physical mechanisms for the bubble activity causing measurable high-frequency acoustic emissions are not yet fully understood. One characteristic of all the present experiments was measurable broadband emissions that were roughly proportional to the sonication amplitude (Fig. 4b) and significantly correlated with the simultaneously measured temperature ($r = 0.419$). These broadband emissions were relatively long-lived over significant fractions of the treatment duration, except for distinct transitions presumably caused by phase changes such as tissue coagulation and boiling. One possible physical scenario consistent with such broadband emissions is the process of widespread, continual bubble seeding and growth by rectified diffusion (Crum and Hansen 1982) until inertial collapse. Based on computations by Church (1988) for air bubbles in water, the peak-negative pressure threshold for rectified diffusion is less than 0.7 MPa for 3-MHz sonication and initial bubble radii of 0.1–2 μm , with much lower thresholds near the bubble resonant size of about 1 μm , and only weak dependence on gas concentration. Thus, the pressure levels used here were likely all sufficient for widespread rectified diffusion leading to inertial collapse events.

Stable, noninertial cavitation with enduring subharmonic emissions was observed rarely in these experiments except under special conditions, including the 47–49°C temperature range for the 0.8-MPa sonication amplitude. These subharmonic emissions may be caused by shape oscillations of gas or vapor bubbles generated at specific favorable temperatures or tissue conditions. Under most conditions within these experiments, it appears that any preexisting bubbles of resonant size were destroyed by the continuous-wave sound fields, except under special circumstances.

Both of these observations, persistent broadband emissions and short-lived subharmonic emissions, are consistent with typical acoustic emissions during stable cavitation, as defined by Neppiras (1980). Neppiras (1980) also states that persistent broadband emissions in this cavitation regime can contain distinct spectral lines unrelated to sonication frequency, possibly associated

with resonance frequencies of predominant bubble sizes. Such spectral lines were also observed here, seen as multiple narrow ridges in time-frequency surface plots of emission spectra (Fig. 3) for all three sonication amplitudes.

These observations on bubble activity during the present US ablation experiments can be compared with observations drawn from several recent studies using passive cavitation detection (Madanshetty et al. 1991) during HIFU exposures at higher sonication amplitudes. Consistent with a number of other experiments is the sudden onset of increased low-frequency emissions and echo brightness at temperature thresholds, suggesting tissue boiling (Khokhlova et al. 2006, McLaughlan et al. 2006). Both of these effects are likely because of large vapor bubbles, which act as US reflectors and undergo violent low-frequency oscillation.

Observations of high-frequency emissions are less consistent in previous experiments. Some HIFU studies have observed a large increase in subharmonic and broadband emissions simultaneous to, or slightly preceding, apparent vaporization (Bailey et al. 2003; Rabkin et al. 2005, 2006), whereas others have also observed significant high-frequency acoustic emissions, indicating cavitation, in the absence of tissue boiling (Khokhlova et al. 2006; McLaughlan et al. 2006). A possible explanation for this apparent inconsistency is the strong dependence of acoustic emissions on the sonication amplitude, as seen here for the subharmonic emissions depicted in Fig. 8a. In the present experiments, strong subharmonic emissions were seen only within distinct measured temperature ranges, but those ranges were different for each of the sonication amplitudes used. This behavior may also depend on the sonication frequency. Another reason for strong dependence of acoustic emissions on sonication characteristics are strongly nonlinear effects that can occur in HIFU beams (Bailey et al. 2003; Khokhlova et al. 2006). Thus, although high-frequency, cavitation acoustic emissions may show a consistent relationship with tissue temperature for a particular US ablation scenario, such relationships may not be applicable if the sonication amplitude or other acoustic conditions are modified significantly.

In the experiments reported here, B-scan echo brightness was typically observed to increase with increasing treatment time throughout an ablation experiment. Among the measured temporal variables ($N = 6179$), the highest observed correlation coefficient was between tissue echogenicity and the simultaneously measured temperature ($r = 0.455$). Correlations between tissue echogenicity and simultaneous acoustic emissions were weaker, with $r = 0.218$ for low-frequency emissions, $r = 0.123$ for subharmonic emissions and $r < 0.01$ (statistically insignificant) for broadband emissions. Al-

though the largest observed increases in echo brightness occurred at high tissue temperatures, suggesting vaporization and boiling, tissue or water vaporization also causes acoustic shadowing that can reduce echo brightness in portions of the region-of-interest analyzed. As seen in Fig. 9a, significant increases of tissue echogenicity also occurred at lower measured temperature elevations, particularly for the lowest sonication amplitude used. This observation is consistent with those of Khokhlova *et al.* (2006), who observed gradual increases in echo brightness as temperature increased in HIFU exposures of a polyacrylamide/gel phantom, even in the absence of passively-detected cavitation. Such increases in tissue echogenicity may be the result of bubbles liberated by the decreasing solubility of gas in tissue with increasing temperature.

For the bulk US ablation experiments reported here, relationships between simultaneously measured acoustic emissions, tissue echogenicity and temperature are illustrated by Figs. 8 and 9, as well as Table 2. Use of such relationships for ablation monitoring and control may be possible, as indicated by preliminary models predicting local tissue temperature based on measured acoustic emissions and tissue echogenicity (Salgaonkar *et al.* 2007). However, effective exploitation of these relationships for therapy guidance will require further study to clarify the interrelated effect of sonication parameters and tissue temperature on stable cavitation.

CONCLUSIONS

Measurements of acoustic emissions, temperature and tissue echogenicity have allowed the role of detectable bubble activity to be assessed for a series of *in vitro* bulk US ablation experiments at 3.1 MHz. For the exposure and measurement conditions studied, broadband emissions increased with the acoustic pressure amplitude and ablation rate, whereas low-frequency emissions were strongly associated with vaporization and boiling. Detectable subharmonic emissions, suggesting stable cavitation, were not directly related to tissue temperature or ablation efficacy. However, increased subharmonic emissions were observed to coincide temporally with specific ranges of thermocouple-measured temperatures, dependent on sonication conditions.

These results suggest that broadband and low-frequency emissions from tissue, together with tissue echogenicity and other image-based measurements, may be useful for noninvasive monitoring and control of energy delivery and tissue state during US ablation treatments. Subharmonic emissions may also provide useful information for treatment guidance, possibly including indications of local tissue temperature. However, exploitation of this information will require further elucidation of

cavitation behavior in heated tissue, as well as measurement of local cavitation activity with higher spatial resolution.

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