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Scanned Three-Dimensional Intracardiac ARFI and SWEI for Imaging Radiofrequency Ablation Lesions

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Abstract

Radiofrequency ablation (RFA) is used to locally disrupt electrical propagation in myocardium and treat arrhythmias, and direct visualization of ablation lesions by acoustic radiation force methods may benefit RFA procedures. This work compares four imaging modalities, B-Mode, ARFI, STL-SWEI and MTL-SWEI, in their ability to resolve RFA lesions in four *ex vivo* experiments. Ablation lesions are shown to be marked by at least a local halving of ARFI displacements and doubling of shear wave speeds. In a controlled ablation of *ex vivo* porcine and canine cardiac tissue, STL-SWEI and ARFI are shown to have similar CNR, better than MTL-SWEI and B-Mode. The SWEI modalities are demonstrated to have improved imaging of distal lesion boundaries. Gaps smaller than 5 mm are visualized in ablation lines made of discretely-spaced ablations, and complex structures are reconstructed through depth in an “x” ablation experiment. Scans of suspended atria show increased noise, but successfully visualize ablations in ARFI, MTL-SWEI and STL-SWEI.

I. INTRODUCTION

Atrial Fibrillation and other cardiac arrhythmias are often treated with Radiofrequency Ablation (RFA) [1]. Lines or loops of individually-created lesions are generated to eliminate the conductive pathways that cause arrhythmias. It has been noted that gaps in these lines can compromise the efficacy of the ablation procedure, [2], [3] and reconnection of conduction pathways at such sites has been identified as the primary source of AF recurrence [1]. Forming a lesion set extending through all layers from the endocardium through to the epicardium is critical for the ablation’s permanence, but ablating too much tissue can cause esophageal burns [4]. ICE is commonly used to confirm contact of the ablation catheter tip with the myocardium, but cannot reliably distinguish healthy tissue from ablated [5]. Instead, the duration, power, and temperature of the ablation are used to predict lesion size, and the electrical activity on the endocardium is used as confirmation of ablation. Because partially-treated tissue may become transiently electrically inactive, the ability to image the size, shape, and transmural of the generated lesions, which has been previously unavailable, could improve the efficacy of the procedure [2], [4].

Acoustic Radiation Force Impulse (ARFI) and Shear Wave Elasticity Imaging (SWEI) are two novel ultrasound-based imaging methods that show promise for estimating the local

mechanical compliance of the myocardium. ARFI is semiquantitative, with relative magnitude of the displacement response indicating local variations in elasticity, while SWEI directly measures the group velocity of a propagating shear wave, providing an absolute metric. Both ARFI and SWEI have been shown to be sensitive to myocardial stiffness in *in vivo* studies [6]–[14]. ARFI and SWEI have also been used to visualize RFA lesions, often using intracardiac echocardiography (ICE) catheter probes [15]–[19]. Intracardiac ARFI has furthermore been tested in clinical studies, providing potential guidance of RFA [20], [21]. ARFI has traditionally been thought to be higher resolution than SWEI (and thus more suitable for the resolution-centric task of lesion visualization), but recent work has shown that Single Track Location SWEI (STL-SWEI) may enable higher resolution systems than traditional, Multiple-Track-Location SWEI (MTL-SWEI) [22]. A diagram distinguishing the two is shown in figure 1. Our previous work comparing ARFI, MTL-SWEI and STL-SWEI found that STL-SWEI may even surpass ARFI's resolution performance [23]. This work compares B-Mode, ARFI, MTL-SWEI and STL-SWEI's abilities to resolve lesion geometry in controlled ablations of *ex vivo* porcine and canine myocardium.

II. METHODS

A. Experimental Setup

Ex Vivo samples of healthy porcine and canine myocardium were used with three different ablation geometries and scanning sequences to obtain calibrated images of tissue elasticity before and after ablation. While RFA procedures typically involve isolating the pulmonary veins in the right atrium, we image here sections of the right ventricle to give a clearer picture of the depth resolution of lesions. Sections of right ventricular tissue basal to the papillary muscles were selected for their relative smoothness and lack of trabeculae, providing a soft and pliable substrate to ablate. Samples were degassed in a Varian DS202 Vacuum degassing chamber for 30 minutes at -25 in Hg, before being mounted to anechoic rubber, either flat or on a 2.5 radius of curvature. Siemens Acuson AcuNav 10 French ICE catheters (Siemens Medical Systems, Mountain View, CA), connected to a Siemens Acuson SC2000 ultrasound scanner running custom software, were used to perform all imaging. The tissue samples were ablated in a saline bath with a speed of sound matched to tissue, and water temperature held at 37°C .

B. Beam Sequences

Three types of beam sequences were used to acquire B-Mode, ARFI, MTL-SWEI and STL-SWEI images. A diagram of each appears in figure 2:

1. *Linear-Translated Scan Sequences:* In the first set of sequences, the AcuNav was operated in linear mode to minimize the effect of steering angle. A diagram of the setup appears in figure 2(A). 90 Vpp, 300-cycle, 6 MHz push pulses were used to generate ARFI displacements and shear waves in the tissue. Each excitation was generated with a 32 element sub-aperture (3.54 mm), focused at 15 mm. To track displacements, 32 parallel lines were beamformed around the excitation, extending 2.25 mm to either side of the excitation. The tissue was imaged at 10,000 frames per second for 5 ms following each excitation. The

ensemble was electronically stepped across the aperture in 16 steps, with a push beam spacing of 0.15 mm, which matched the track beam spacing. The entire 64-element aperture was used in receive. To synthesize 3-D volumes, the tissue was translated with a Newport MM3000 translation stage (Newport, Irvine CA) in the lateral and elevational planes, such that the groups of 16 ensembles could be stitched together into total imaging grid measuring 28.8 mm laterally and 14.4 mm in elevation (with 0.3 mm increments in elevation).

2. *Phased-Translated Scan Sequences:* To test the performance of sequences that could be operated in an *in vivo* setting, a second set of sequences was constructed. A diagram of this setup appears in figure 2(B). These imaging sequences were designed to acquire ARFI, STL-SWEI and MTL-SWEI simultaneously. A 45° azimuthal viewing angle was interrogated with 32 excitations, each using a 300 cycle, 90 V_{pp}, 6 MHz excitation. The imaging sequences used diverging wave transmits and 32 parallel receive focused beams to track displacements at 16,000 fps, placed in line with the 32 push locations, and fixed regardless of which line was being pushed. To synthesize 3-D volumes, the tissue was translated in the elevation dimension with a translation stage.
3. *Phased-Rotation Scan Sequences:* For the final experiment, the sequence was changed to increase the push and track beam density by restricting the receive beams used to those that would image the shear wave propagation around each push. First, the number of pushes was increased from 32 to 50 to image the a 45° span with 0.9° push beam spacing. The diagram of this setup appears in figure 2(C). The parallel track beams were changed to be 21 beams centered around each push, so that the track beam spacing matched the push beam spacing of 0.9°. The response was tracked for 0.5 ms prior to the excitation and 2.5 ms after the excitation, at a frame rate of 16,000 fps. For these scans, to synthesize 3-D volumes, the catheter was rotated by hand, using an optical encoder to measure angle.

C. Ablation

Three different controlled *ex vivo* ablation procedures were performed to provide targets for 3-D reconstruction. Diagrams of the imaging setups appears each appear in figure 2.

1. *Ablation Pairs:* These scans were performed with the translated sequences. After the initial scan of ARFI and SWEI, a pair radiofrequency (RF) ablations were performed along the center lateral line using a BioSense Webster ThermoCool irrigated tip ablation catheter (Biosense Webster, Diamond Bar, CA). 22 W of power was applied for 60 seconds with 30 mL/min saline flow to create each ablation lesion. The distance between the centers of the lesions ranged from 10 to 12 mm, so that the gap between lesions was between 2 and 5 mm. After ablation, the tissue was scanned again with ARFI/SWEI. Following imaging, the tissue was frozen and stained with a triphenyltetrazolium chloride (TTC) protocol. After staining, the tissue slices were frozen in O.C.T Compound at -20°C , and sliced using a Micron HM 505 E cryotome (Thermo Fisher

Scientific, Waltham, MA) in 150 μm increments in the elevational direction to make images aligned with the axial-lateral planes of the ultrasound images. Photographs were taken of each slice from a mounted camera, and the green channel of the RGB color images was extracted to provide contrast between the stained (red) and unstained (white) regions of myocardium. The experiment was repeated for three lesion pairs, each in a separate *ex vivo* sample.

2. **Ablation Lines:** A second set of scans was completed with the first phased imaging sequences, translated in elevation every 0.3 mm. In each scan, a series of ablations were performed in a line along the elevational field of view, centered within the lateral field of view. The same ablation protocol as for the pairs was used. This experiment was repeated three times at three different spacings between ablation sites: 6, 7, or 8 ablations were performed with 12, 10 or 8 mm between sites, respectively.
3. **“X” Ablation:** A third type of scan used a piece of right-ventricular free wall (RVFW) mounted on an arc in a water tank. The AcuNav was suspended in the tank through a US Digital HB6M optical encoder, so that a 3-D volume could be swept out only by rotating the transducer. This was designed to more closely simulate the type of imaging that would occur *in vivo*. The ablation, in this case, was designed to have a more characteristic three-dimensional shape than a single lesion. Three “x” shapes were ablated onto the tissue in a series of four ablations. The first “x” was ablated from the endocardial surface, using continuous motion of the ablation catheter over the course of the ablation rather than individual points. A second ablation was placed to the right of the first, also ablated on the endocardium. However, after the second lesion was created, the same locations were ablated from the epicardial surface, using pins through the tissue at the tips of the “x” to align the two shapes. A third ablation was placed to the right of the second, and ablated only from the epicardium. 240 images were collected along a 180° sweep after ablation.

D. Displacement and Shear Wave Speed Estimation

The axial tissue displacements between successive frames were estimated with a phase-root seeking algorithm [24] with a 5- λ kernel. For the linear scans, ARFI images were formed by averaging the integrated displacements at the center 4 imaging lines 0.2 ms after the excitation. For the phased scans, ARFI images were made from the estimated displacements 0.5 ms after excitation. For both scans, the displacement estimates away from the center were used to generate shear wave estimates. For each excitation, the progressive displacement curves were filtered with a 50 Hz – 1 kHz bandpass filter, and a directional filter [25]. The arrival time was estimated at each pixel as the time to peak velocity, using quadratic subsample peak estimation. To estimate MTL-SWEI shear wave speeds, the reciprocal of the time difference between adjacent receive locations was found for each push and filtered with a 1 mm $\times$ 1 mm median filter to provide spatial smoothing. The same process was used for STL-SWEI, but the difference was found between adjacent push locations for each track line. For MTL-SWEI, the overlapping estimates at each depth and tracking location were combined by taking the median across pushes, and for STL-SWEI,

the estimates at each depth and push location were combined by taking the median across the tracks.

For analysis, the displacements and shear wave speeds are used directly. For display, previous work has found that relative ARFI displacement has an inverse relationship with shear modulus, so for visual comparison, we display ARFI displacements as their inverse, in units of μm^{-1} , and for SWEI, we display the shear wave speed squared. In linear, isotropic, semi-infinite media, this would be the shear modulus in kPa. While these assumptions don't necessarily hold for the myocardium, it gives us a common scale on which to view the ARFI and SWEI images.

E. Region of Interest Analysis

The region of interest (ROI) for comparing the lesions to the background was defined in each lesion pair XY-plane image as a circle of 3 mm radius, surround around ($x = \pm 5$ mm, $y = 0$ mm), and the background was defined as everything greater than 7 mm from either lesion center. The values were compared inside and outside the lesions, and in the same ROIs prior to ablation (where the "inside" and "outside" regions should be no different). This method was selected to reduce the effects of high variability among a small number of pixels inside the lesions. For the "X" ablations, the ROIs were drawn manually for consensus between the elasticity imaging modalities. CNR was found using using a weighted sum of the standard deviations inside and outside of the lesions as the image noise:

$$\sigma = \sqrt{(1/N_{in} + N_{out}) (N_{in}\sigma_{in}^2 + N_{out}\sigma_{out}^2)} \quad (1)$$

III. RESULTS

A. Ablation Pairs

Figure 3 shows an example of the conventional lateral-depth (XZ) planes of one of the ablation lesions pairs before and after ablation. Each row shows a different imaging modality from the same dataset, along with the green channel values from the photograph of the stained tissue sliced approximately along the same axis as the ablations. Warping during the freezing and slicing process created misalignment and distortion between the stained photographs and the ultrasound volumes. ARFI images are shown as inverse displacement, and SWEI images are shown as square of shear wave speed. The images show low displacements and elevated shear velocities inside of the ablated regions, as well as increased echogenicity in the B-Modes. Animated versions of these datasets are available in the multimedia supplements available at <http://ieeexplore.ieee.org>.

Figure 4 shows all seven ablation lesion pairs in each modality, along with the histology slices in the first column. The lesions are comparable in size to those indicated by the histology, with varying contrasts. The gap between the pairs of ablations is visible in each ARFI and SWEI image. Contrast varies between rows, with some rows (like the fourth) showing significantly lower contrast than others (like the third), but agree between ARFI, STL-SWEI and MTL-SWEI. The SWEI images appear to have higher contrast, but also

more noise, compared to the ARFI images. Some of the B-Mode images show contrast corresponding to the ablated areas, but others do not. Many of the SWEI are marked by artifacts in the center of the inclusions.

Figure 5 shows the box plots for each modality inside and outside of each pair of ablation lesions before and after ablation from each of the XY scans in figure 4. The background values are unaffected by ablation, while the ablated regions increase in value for all modes. ARFI shows a drop in the background values after ablation for some of the ablations. Table I shows the mean and standard deviation of the median values measured inside and outside of the lesion pairs. These are reported in their conventional forms, as μm and m/s for ARFI and SWEI, respectively. A small increase in stiffness was observed in the background following ablation, but a larger, significant change was seen at the lesion sites following ablation, as speeds more than doubled, displacements fell by more than half, and B-Mode brightness increased by 40%.

Figure 6 shows the values (scaled) across the entire ablation, before and after ablation. B-Mode shows almost no contrast, ARFI shows smooth profiles, and STL-SWEI and MTL-SWEI show sharper boundaries but higher variance and an artifact in the center of the left lesion.

B. Line Ablations

Figure 7 shows the phased-linear scans of the ablation line with 8 mm spacing before and after ablation. The red lines and dots indicate the targeted location and spacing of the ablations. The volume is sliced in the lateral dimension (shown in axial-elevation plane) in frames (A) and (B), and in the axial dimension (shown in the lateral-elevation plane) in frames (C) and (D). The gaps in the lesion line are visible in the XY scans, with higher contrast in the SWEI images than in the ARFI. The lateral edges of the ARFI image appear bright in the pre-ablation scan, corresponding to low displacements at the highest steering angles. The STL-SWEI images appear smoother in the lateral dimension than the MTL-SWEI images. The streaking artifact at the right side of the images is due to the translation stage reaching its maximum elevational extent.

Figures 8 and 9 shows the phased-linear scans of ablation lines with 10 and 12 mm spacing, respectively. As the spacing between lesions increases, the gaps become more apparent in the ARFI and SWEI images. The attenuation of ARFI displacements with depth makes the bottom of those images bright, and obfuscates distinction of the bottom of the lesions from the bottom of the tissue, as both are marked by low displacements.

C. “X” Ablation

Figure 10 slices the volumes from figure 11 at equal depths from the transducer face, moving deeper in to the tissue from top to bottom. The ARFI images have had the dynamic range shown at each depth scaled by the median displacement at that depth from the pre-ablation scans. In all three modalities, the center “x” is visible at depths up to 22 mm, after which its shape becomes obfuscated. The left “x” is preferentially visible shallow and the right “x” is more visible in the deeper slices. The epicardially-ablated “x” also appears slanted out-on plane, as the tissue does not form a perfect cylinder around the AcuNav.

Figure 11 renders each set of slices' raw data as a three-dimensional, semitransparent volume. The "x"s are most visible in the STL-SWEI and MTL-SWEI volumes. The B-Mode data has been used as a transparency mask for the other images, and the ARFI has been normalized by the mean value at each depth. A lowpass filter with a cutoff of 1 mm⁻¹ has been applied in three dimensions as well. Rotating animations appear in the supplemental multimedia available at <http://ieeexplore.ieee.org>.

Figure 12 shows the regions of interest used for comparing the four methods at a depth of 18 mm, superimposed on the STL-SWEI image. Figure 13 shows the distribution of pixel values within each of the left and center "X"s and within the background.

Figure 14 shows post-study photographs of the "X" ablations from both the endocardial and epicardial side. The ablation lines appear thinner and more well defined on the epicardial side.

IV. DISCUSSION

A. Ablation Pairs

In all cases, the ablation lesions were visible in each of the elasticity imaging modalities, with a clear gap visible between the lesions. The heightened echogenicity of the B-Mode at the center of the ablation lesions (column 2 of figure 4) is likely due to the transient formation of bubbles rather than to ablation of the tissue, as the size of the bright hyperechogenic area is focused around the catheter tip location. While we had degassed the tissue to try to limit bubble formation, and avoided steam "pops", these transient bubbles created distortions at the center of the ablations.

Shear wave estimation was challenging within the lesions, both due to reflection artifacts and a low displacement signal. Even with many overlapping estimates, spatial smoothing needed to be applied with the 1 mm kernels, so sub-millimeter imaging was not achieved with this setup. Inside the lesions, the finite differences in arrival times approached the noise floor, even when imaged at 10,000 fps, which corrupted high-resolution shear wave speed maps. Furthermore, artifacts appear at the center of the inclusions. This is consistent with the findings of [26] and [25], which indicate that internal reflections off of the lesion boundary create artifacts in the shear wave images.

ARFI, by contrast, does not require shear propagation, and the low displacement signal in lesions does not confound additional processing steps. The error bars on the ARFI data (figure 5) are much smaller than those on the SWEI estimates, although the contrasts are also lower. The profiles through the lesions shown in figure 6 show nearly equivalent performance between MTL-SWEI and STL-SWEI.

B. Ablation Lines

The phased-linear scans of ablation lines were able to resolve the individual ablations that made up each of the ablation lines in both the axial-elevational (ZY) and lateral-elevational (XY) planes. The ablations appear to have sizes between 5 mm and 1 cm in diameter, but the edges of the ablations appear as gradients in all three elasticity modes. Even so, gaps <5 mm

wide whose appearance in the ARFI and SWEI images showed values similar to the pre-ablation images were visible between the individual ablations. Only the 8 mm - spaced ablation line showed a contiguous section of lesion on the left side, but in the XY plane, it appears that the ablation line becomes quite thin (<5 mm) in the lateral dimension between the ablation centers. There are regions of less-elevated stiffness above and below the connected centers in the ZY plane, but without knowing what shear velocity or ARFI displacement corresponds to permanent electrical ablation, it is impossible to determine the hypothetical functional integrity of this line. A determination of the threshold imaging-derived mechanical properties as they pertain to transient and permanent disruption of electrical activity will be the focus of future work, and will require attention to geometric dispersion, viscoelasticity, or anisotropy.

The center lesions in figure 9 appear to be softer than those towards the edges. All three elasticity imaging modalities agree on this observation, and we therefore hypothesize that those lesions were indeed less-ablated than the others. It is possible that the contact of the catheter with the tissue was affected by hyperechoic layer seen in figure 9(A), or that this layer absorbed some of the RF energy intended for the target region.

The pronounced gradients visible in the ARFI images are due to variations in the applied acoustic radiation force amplitude. In the ZY planes (panels A and B of figures 7–9), the attenuation of ARFI displacements limits their ability to resolve the deep edge of the ablations, and in the XY plane (panels C and D), angular sensitivity decreases displacements at the lateral edges of the field of view. Because the images are displayed as inverse displacement, the deep parts of the tissue sample where the radiation force does not penetrate become white pixels, indicating displacements $<0.8 \mu\text{m}$; They would show an equivalent loss of contrast in their conventional, displacement magnitude form. These effects could be corrected with calibration by the pre-ablation image, or by using a model of expected transmit pressures and attenuation. Furthermore, atrial myocardium is thin (2–3 mm) relative to ARFI beam depth of fields (about 1 cm), so the axial gradients seen here may not be as bad *in vivo*. STL-SWEI and MTL-SWEI show a more clear delineation of the distal edges of the lesions but the B-Mode is the most useful means of assessing which parts of the image correspond to which anatomy.

While STL-SWEI is expected to suppress speckle noise to the point where it can operate at substantially higher resolution than MTL-SWEI, the benefits of STL-SWEI over MTL-SWEI are not seen in the elevation dimension, in which we have the gaps. By elimination of the speckle bias, lateral speckle texture is visibly suppressed in the STL-SWEI images, showing smoother lesion visualization without apparent bias in the shear wave speeds.

C. “X” Ablation

For the sequences used in the line-ablation experiment, we obtained every combination of push and track beam. While this provided easy distinction of ARFI, MTL-SWEI and STL-SWEI, many of the push-track combinations were too far apart to show significant shear wave propagation. For the “x” ablation experiment, we switched the beam configuration to pack the push and track beams more tightly, decreasing the beam spacing from 1.4° to 0.9° .

This provided more efficient use of the push and track beams, as all track beams could be used for all pushes.

The reconstruction successfully shows depth-varying “x” ablations (figure 11), particularly with STL-SWEI, highlighted by figure 11. The center “x”, ablated from both the inside and outside is very visible on the SWEI renders. The endocardial and epicardial “x”s are visible in the volume, although harder to appreciate in still 3-D renders. ARFI is significantly less effective at visualizing the structure because of the depth-dependence displacement. While the ARFI images have reasonable image quality at shallow depths, the size of the “x” is too large relative to the ARFI depth to be imaged with any uniformity. The slices through the MTL-SWEI and STL-SWEI volumes (figure 10(C–D)), however, show clear visualization of the “x” shapes. The axis of ablations appears positioned at an angle relative to the scan, which is why the left, endocardial “x” appears centered near the bottom of the images and the right, epicardial “x” near the top. Additionally, the tissue didn’t wrap to form a perfect cylinder, so the epicardial “x” appears at an angle through depth, with the left side appearing at more shallow depths than the right side. The endocardial ablation appears to have line widths on the order of 0.5 cm to 1.0 cm, similar to what we saw in the previous section with the line ablations, but now with clear contiguity. Comparison to the photographs (figure 14) shows similar dimensions for the left ablation. The ambiguity of the top junction of the center “x” also corresponds to the photograph. The endocardial ablations appeared significantly thicker in the photographs, possibly due to the corrugated surface, which may have conducted heat away from the tip, compared to the smooth epicardial surface. The left side of the epicardial “x” is very clearly visible at 18 and 20 mm in the STL-SWEI images, and does show thinner dimensions than the epicardial ablations. At 22 mm and beyond, however, the penetration of the radiation force has diminished, and noise starts to take over, preventing clear resolution of the fine “x”s placed on the epicardium. A second scan from the epicardial side may have elucidated this point further, and more generally, imaging targets in multiple orthogonal directions is likely to be further elucidate the differences in axial, lateral and elevational resolution.

D. Study Limitations

1. *Scan configuration:* Because of the misalignment between the histology and the imaging frames, we couldn’t simply use the histology as ground-truth for the lesion locations. Some automatic registration and warping scheme may provide better alignment, so that the volumetric means and standard deviations can be extracted from inside and outside the lesions, and limit the depths to those inside the tissue. The crude ROIs analyzed here serve only to quantify what we see in the pictures, while a more detailed and controlled analysis of contrast and CNR among these elasticity imaging techniques can be found in [23]. Furthermore, as noted earlier, the lines and pairs of ablations had their gaps defined in the elevation dimension of the scan. While STL-SWEI’s speckle-reducing features improve the CNR by suppressing noise, the resolution improvement is not present in the direction of primary interest, as it only affects the lateral dimension. The elevation dimension is dictated by the elevational beamwidth, which, owing to the shape of the phased array, is much larger than the lateral

focused beamwidth. This may be, however, somewhat realistic, as the electrophysiologist using these methods to map out an ablated region may not know in which direction the gaps will be oriented. Secondly, the study is limited by the fact that the samples were imaged *ex vivo*. Cardiac tissue is in constant motion *in vivo*, which creates the challenge of separating the ARFI-induced displacements from the physiologic motion of the heart [27]. Physiological motion challenges ARFI differently than SWEI, and the effect of residual physiologic motion on reconstructed volume resolution is left to other work.

2. *Beamforming*: The sequences that we designed collected B-Mode, ARFI, STL-SWEI, and MTL-SWEI simultaneously. Because the sequence acquired all four modes, it was optimized for none of them. ARFI performs best with tightly focused track beams co-aligned with the push beams, whereas our sequences used broad transmits to detect shear wave propagation. STL-SWEI may also benefit from tightly focused tracking beams for improved displacement SNR, but there is a tradeoff, as parallel track beams can be averaged together to suppress noise. The effect of broad speckle is expected to increase speckle-bias noise in MTL-SWEI, which is not present in STL-SWEI [22], which may account for the increased noise in MTL-SWEI, which are otherwise formed from the same arrival time data as STL-SWEI. Future work will explore using coherent compounding [28] to provide pseudo-two-way focusing at every beamformed pixel. This will likely improve ARFI and STL-SWEI estimates, as it improved MTL-SWEI.
3. *Mechanical Model*: The chief limitation is the uncertain relationship between the TTC stain, derived and actual mechanical properties, and electrical permanence of the ablation. To our knowledge, no “cutoff” elastic or shear modulus has been established to distinguish unablated from ablated tissue, or furthermore, electrically “stunned” from ablated tissue. An extensive study will need to be conducted *in vivo* to establish these parameters and requirements. Nonetheless, because such realistic sources of noise would limit the head-to-head comparison of modalities, this work provides a look at performance and spatial consistency without those confounding, if realistic, effects.

E. Insights for In Vivo Translation

These data demonstrate that radiation-force based elasticity imaging methods are capable of visualizing the gaps between radiofrequency ablations with enough contrast and resolution to identify gaps as small as a few millimeters. Clinical testing will need to determine if this is sufficient enough to add useful information to the procedures, or if more technical development is needed to improve the robustness and resolution of the images. Another issue to be address in *in vivo* translation will be the scan times. Because these experiments were performed in a water tank with a translation stage, acquisition time was irrelevant, but *in vivo*, the diastolic window is quite short (100–200 ms). For ARFI and STL-SWEI, whose acquisition times are proportional to the line density and field of view, there is only time for a single image acquisition. For MTL-SWEI, when implemented with parallel beamforming, the acquisition time can be quite low (just 5 ms per push) as an image can be made from just

a few excitations. MTL-SWEI could perhaps be used in a “scanning” mode to visualize ablations in real-time, with ECG-triggered ARFI or STL-SWEI used in a “zoom” mode to create high resolution maps of potential gaps. Any of the imaging modes will need to be combined with some sort of registration system to build up the out-of-plane dimensions, as we have demonstrated in [29]. With robust reconstruction algorithms, three-dimensional tracking of the catheter tip, and rapid acquisition tools, these elasticity methods hold promise for providing a useful suite of tools for analyzing RFA lesions.

V. CONCLUSION

B-Mode, ARFI, STL-SWEI, and MTL-SWEI were used to image ablations in *ex vivo* porcine and canine myocardium. Three different imaging scans (linear-translation, phased-translation, phased-rotation) were used to image increasingly complicated ablation scenarios. The pairs of ablation lesions indicated performance in line with our predictions, with STL-SWEI and ARFI having similarly high CNR, followed by MTL-SWEI. Ablations were shown to be marked by at least a halving of displacements and a doubling of shear wave speeds. The lines of ablations were individually visualized by ARFI, STL-SWEI and MTL-SWEI. All three modes could resolve <5 mm gaps in lines 0.5 – 1 cm ablations at spacings between 8 and 12 mm, although the SWEI methods could better visualize the lesions through depth. Finally, the “x” ablation showed that with rotation of the catheter, as would be done in an *in vivo* setting with rapid image acquisition and position tracking, high quality volumes can be stitched together from a series of images that show not just regions of ablation, but actual three-dimensional structure and geometry with consistent results in the elevation dimensions. The consistency of the images in the elevational plane lends confidence to *in vivo* results using individual slices, and with advances in catheter tracking and real-time processing, these scanned 3-D techniques could be applied *in vivo* for mapping large segments of the heart wall.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

In both MTL-SWEI and STL-SWEI, the wave speed at each depth is calculated by dividing the known distance x by the difference in shear wave arrival time. The tracking beams illustrated show random speckle bias through depth. The interrogated region is shaded. (A) MTL-SWEI configuration. A single shear wave generated at x_{p1} is tracked at multiple locations spaced laterally $\Delta x = x_{t2} - x_{t1}$ apart. (B) STL-SWEI configuration. Two push beams separated by $\Delta x = x_{p2} - x_{p1}$ produce shear waves recorded at a single tracking location x_{t1} .

Fig. 2.

Three ablation and imaging scenarios used to test 3-D imaging of ablation lesions. (A) Lesion pairs. The spacing between the ablation sites was controlled by a translation stage. The AcuNav (blue cylinder) imaged directly forward, and the tissue sample was translated laterally and in elevation to scan the volume (the “linear-translated” scan). (B) Lesion line. The spacing between lesions was controlled. The AcuNav had a 45° lateral field of view, and was translated in the elevation plane (the “phased-translated” scan). (C) “X” ablation. One ablation was created from the endocardial surface, one from the epicardial surface, and one from both. The AcuNav had a 45° lateral field of view, and was rotated to cover a 180° elevational field of view (the “phased-rotated” scan).

Fig. 3.

The left two columns are from a pre-ablation section of tissue. The right two columns are after ablation. The first and third columns show conventional axial-lateral cross sections of the scanned volume, while the second and fourth show lateral-elevational cross sections. The top row is stained slides of histology photographs (post-ablation only), followed by B-Mode, ARFI, STL-SWEI and MTL-SWEI. The final row shows the post ablation photographs, stacked as a 3-D volume, with the cut plane superimposed as a teal plane. The lesion pair is clearly visible in all modalities as regions of elevated contrast, although the contrast and resolution vary substantially between images. Animated versions of these datasets are available in the multimedia supplements available at <http://ieeexplore.ieee.org>.

Fig. 4.

C-Scans of the seven ablation lesion pairs, spaced between 1 and 1.2 cm apart. Each row is a different lesion pair, and each column is a different modality. Gaps between the lesions are visible in the elasticity images (right three columns). The lesion pairs are visible in all modalities, with particularly high contrast in STL-SWEI, and particularly poor contrast in B-Mode. Some mis-registration is visible between the histological data (column 1) and the ultrasound data.

Fig. 5. Boxplots of the ablations and background, before and after ablation. B-Mode values rise, ARFI displacements are suppressed, and STL-SWEI and MTL-SWEI values rise greatly following ablation.

Fig. 6.

Median profile across the entire ablation for the second ablation pair. ARFI appears to show gradients and lower resolution, while the SWEI methods show an artifact in the left lesion at the ablation tip site.

Fig. 7. Phased-linear scan of the 8 mm- spaced lesion line. (A) Axial-Elevational slice, pre-ablation. (B) Axial-Elevational slice, post-ablation. (C) Lateral-Elevational slice, pre-ablation. (D) Lateral-Elevational slice, post-ablation. The red lines and dots mark the ablation sites.

Fig. 8.

Phased-linear scan of the 10 mm- spaced lesion line. (A) Axial-Elevational slice, pre-ablation. (B) Axial-Elevational slice, post-ablation. (C) Lateral-Elevational slice, pre-ablation. (D) Lateral-Elevational slice, post-ablation. The red lines and dots mark the ablation sites.

Fig. 9.

Phased-linear scan of the 12 mm- spaced lesion line. (A) Axial-Elevational slice, pre-ablation. (B) Axial-Elevational slice, post-ablation. (C) Lateral-Elevational slice, pre-ablation. (D) Lateral-Elevational slice, post-ablation. The red lines and dots mark the ablation sites.

Fig. 10.

Images of the “x” ablation volume sliced at different axial depths, with the endocardial surface in the top row and the epicardial surface in the bottom. Note that the dynamic range of the colorbar changes with depth in the ARFI images. The “x” on the left was ablated from the endocardium, the “x” in the middle from the endocardium and epicardium, and the “x” on the right from the epicardium only.

Fig. 11.

Renders of the 3-D reconstructed volumes of canine RVFW following the “x” ablation. The “x” structures are clearly visible in the SWEI images, but harder to resolve in the ARFI images due to the steering and depth dependence of the signal. See the supplemental multimedia for animated versions.

Fig. 12.

Boxplot distribution of the pixel values in each of the background ("BG"), left ("X1") and center ("X2") ablations at $r = 18$ mm. ARFI shows less contrast and CNR in the left ablation than the SWEI methods. STL-SWEI shows the tightest distributions and the highest CNR.

Fig. 13.

Regions of interest for the $r = 18$ mm slice of the “X” ablation volume, superimposed on the STL-SWEI image. The orange “X”s are compared against the blue background shapes.

Fig. 14.

Post-scan photographs of the “X” Ablations, showing that the left “x” was ablated from the endocardial side, the right “x” from the epicardial side, and the center “x” from both sides. The boundaries of the surface discoloration have been outlined in green.

TABLE I

Average estimated values (echogenicity or elasticity) in the lesion pairs and background, before and after ablation.

	Background			Lesion Site		
	Baseline	Post-RFA	<i>p</i>	Baseline	Post-RFA	<i>p</i>
BMODE	0.46 ± 0.1	0.46 ± 0.1	NS	0.48 ± 0.1	0.61 ± 0.1	0.0124779
ARFI	5.04 ± 1.2	4.31 ± 1.1	NS	5.21 ± 1.3	2.48 ± 0.7	<.001
STL-SWEI	3.62 ± 0.7	4.02 ± 0.7	NS	3.75 ± 0.8	8.49 ± 2.4	<.001
MTL-SWEI	3.55 ± 0.7	3.93 ± 0.7	NS	3.60 ± 0.9	8.23 ± 2.6	<.001

NS = Not Significant. values represent a two-tailed, unpaired Welch's t-test over the mean values from the seven pairs of lesions at the $\alpha = 5\%$ significance level. B-Mode, STL-SWEI, and MTL-SWEI show statistically significant differences in the lesion values.