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On the Potential for High Framerate ARFI Variance of Acceleration (VoA) Imaging

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***Abstract*—A significant risk factor in ischemic strokes is carotid atherosclerotic plaque that is susceptible to rupture, with rupture potential conveyed by plaque composition and structure. Prior work has shown that Variance of Acceleration (VOA), derived from Acoustic Radiation Force Impulse (ARFI) imaging, is capable of delineating plaque components. However, the method relies on focused ARF excitations at each lateral location, limiting framerate. To increase framerate, it is hypothesized that VoA imaging may be implemented using fast plane wave imaging techniques. In this work, VoA's ability to discriminate materials based on signal decorrelation and SNR is compared for conventional focused wave versus plane wave tracking methods. Relative to focused wave tracking, plane wave tracking yields comparable discrimination. This study suggests that a plane wave implementation of ARFI VoA analysis could be feasible for increased frame rate in atherosclerosis imaging.**

Keywords—Variance of Acceleration, Plane Wave, ARFI

I. Introduction

With over 140,323 deaths from strokes every year, preventative diagnostic tools are needed [1]. Techniques such as B-mode ultrasound suffer from poor tissue specificity and atherosclerotic plaque delineation, so developing a new imaging technique and validating its ability to distinguish between plaques components will enable clinicians to better track plaque progression and determine if surgical intervention is required.

A. Plaque Discrimination with Acoustic Radiation Force

Degree stenosis has often been treated as a measure of atherosclerotic plaque rupture risk [2]. However, highly stenotic plaques may be stable, while minimally stenotic plaques may be rupture-prone, depending on the plaque composition and structure [3, 4]. Therefore, there is a vital need for noninvasive methods for identifying the compositional and structural features that undermine plaque integrity. Hallmarks of plaque rupture including thin fibrous cap, intraplaque hemorrhage (IPH), lipid-rich necrotic core (LRNC), and calcium, are difficult to delineate using standard imaging methods [4]. In order to differentiate these components, recent methods such as Acoustic Radiation Force Impulse (ARFI) ultrasound imaging have been used to measure peak induced tissue displacement, which reflects tissue stiffness [5]. However, the method exhibited low sensitivity and specificity for differentiating stiff collagen from stiff calcium or soft LRNC from soft IPH. To improve discrimination between plaque features with similar stiffness, our group developed a new higher-order ARFI-derived parameter that considers echogenicity and elastic recovery behavior, Variance of Acceleration (VoA) [6].

B. Variance of Acceleration Imaging

Variance of Acceleration (VoA) imaging exploits decorrelation from scatterer motion and signal-to-noise (SNR) differences due to local variations in echogenicity to identify plaque features [6]. More specifically, as the Cramer Rao Lower Bound (CRLB) [7] predicts, displacement measurement variance, or jitter magnitude, increases with decreasing correlation and SNR. Therefore, plaque features that exhibit different amounts of displacement in response to an ARF excitation and/or have different echogenic properties may be differentiated by evaluating jitter magnitude. To highlight jitter, a high-pass filter, in the form of two time-derivative operations, is applied to ARFI displacement profiles, yielding profiles of acceleration versus time. Then, jitter magnitude is parameterized as the decadic log of the variance of acceleration (log(VoA)), as in equation (1):

$$logVoA(x,y) = \log_{10}\frac{1}{N-1}\sum_{t=1}^{N}\left|\left(A(x,y,t+\Delta)-\mu(x,y)\right)^2\right| \quad (1)$$

Here N is the calculation kernel length delayed in time by Δ after the occurrence of peak displacement, A is acceleration, and μ is the mean acceleration across the kernel. This allows for independent calculation of log(VoA) for each pixel in the image. After empirical testing, N and Δ were chosen to be 5 and 20 temporal samples, respectively, corresponding to 0.5 and 2.0 ms. By evaluating log(VoA) images obtained in the carotid plaques of 25 human volunteers, *in vivo*, Torres *et al* demonstrated that VoA improved discrimination of collagen from calcium, and of intra-plaque hemorrhage from lipid-rich necrotic core, relative to ARFI PD [6].

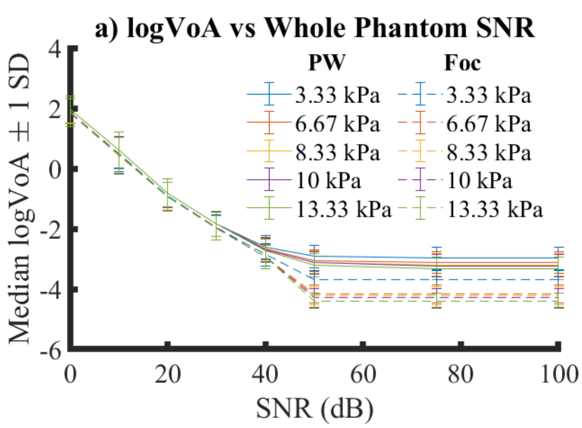
While VoA has been shown to be effective for delineating the structure and composition of atherosclerotic plaques, the associated tracking data are acquired in ensemble form in several different lateral locations, which is time consuming when using conventional focused transmit-receive beam forming methods. The purpose of this work is to evaluate the potential for plane wave tracking to expedite VoA data acquisitions.

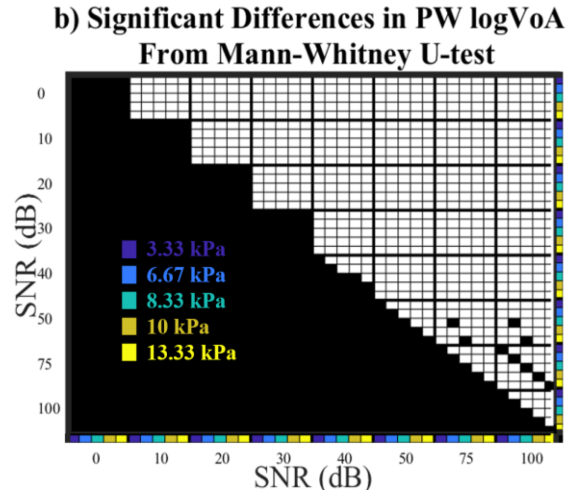
II. Methods

To simulate the effects of a 300-cycle acoustic radiation force (ARF) excitation focused at 25 mm in depth from a VF7-3 transducer, point loads representative of the excitation were modeled in LS-Dyna (Livermore, CA) and projected onto nodes in homogenous phantoms with varying shear moduli (3.33, 6.67, 8.33, 10, and 13.33 kPa) [8-10]. Displacements were then projected onto scatterers in Field II ultrasound simulation software and tracked using focused transmit and receive (f_c: 4.21 MHz, f/#: 1.5) at 10 MHz PRF. In order to induce a shear wave that disturbed tissue across a larger field of view and cause decorrelation, a single 500 cycle ARF excitation was also implemented with plane wave receive. Five heterogeneous phantoms were simulated, containing inclusions of varying shear moduli (1.67, 3.33, 6.67, 10, and 13.33 kPa) in an 8.33 kPa background to evaluate the sensitivity of log(VoA) to detecting changes due to elasticity alone. To test the effect of SNR on log(VoA), homogenous and heterogeneous phantoms were simulated with various signal-to-noise ratios (0, 10, 20, 30, 40, 50, 75, 100 dB). Differences in log(VoA) in a region of interest (ROI) due to these parameters were assessed with Mann-Whitney U-tests ($\propto = 0.01$).

III. Results

Increasing the SNR of the received RF data resulted in the expected decrease in log(VoA), indicative of less variance in the displacement estimate (Fig. 1a). However, this trend was more pronounced at SNR values below 50 dB. Figs. 1b and 1c indicate cases, represented by a white box, where differences in median log(VoA) are significant between combinations of SNR and elasticity (Wilcoxon rank-sum, $p<0.01$). Generally, below 50 dB, changes in elasticity of the phantom had no significant effects on log(VoA). However, above 50 dB, changes in SNR had no significant effects on log(VoA); any significant effects were due to elasticity or tracking method.





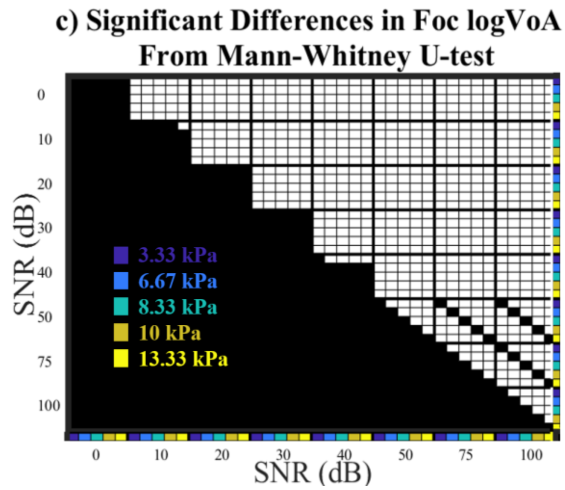


Fig. 1. Log(VoA) versus signal SNR for focused (Foc) and plane wave (PW) tracking methods. As many comparisons between combinations on SNR and elasticity can be made, significance of Mann-Whitney U tests for difference in median log(VoA) are represented as a grid for PW (b) and Foc (c) tracking methods. White boxes represent statistically significant differences ($p<0.01$), whereas black indicate insufficient evidence to reject null hypothesis. Due to symmetry in comparisonss, only the upper triangular region is shown. Below 50 dB SNR differences in logVoA are driven by SNR, whereas at and above 50 dB, differences in logVoA are driven by elasticity or tracking method.

In heterogeneous phantoms, where 5 mm diameter inclusions were positioned at a depth of 25 mm, SNR of the inclusion was modulated, while the background was fixed at 8.33 kPa and 40 dB SNR. Increasing the inclusion SNR from 0 to 40 dB decreased its CNR in log(VoA) images by both PW and Foc tracking (Fig. 2). However, with Foc tracking, CNR increased as inclusion SNR increased from 40 to 100 dB, while this trend was not as strong for PW tracking. For inclusion SNRs above 50 dB, stiffer inclusions yielded higher log(VoA) contrast because the lower amount of decorrelation, as well as the higher SNR, collectively drove inclusion log(VoA) down relative to the background. This behavior is depicted through representative parametric log(VoA) images of a heterogeneous digital phantom with a 10 kPa inclusion (Fig. 3).

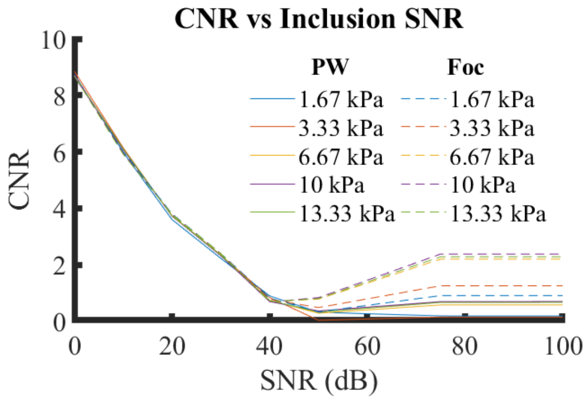


Fig. 2. CNR derived from parametric log(VoA) images of digital inclusion phantoms using PW and Foc displacement tracking versus inclusion SNR for varying inclusion stiffnesses. The digital phantom background was fixed at 40 dB SNR and 8.33 kPa.

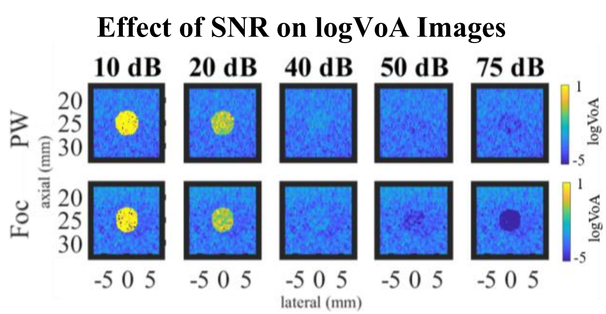


Fig. 3. Parametric log(VoA) images from PW and Foc tracking in digital a phantom with a 10 kPa inclusion in a 8.33 kPa and 40 dB background. The inclusion SNR was increased from 10 to 75 dB. PW tracking performs similarly to Foc for low SNR cases, but Foc produces better contrast for high SNR cases.

IV. DISCUSSION

Figure 1 shows that at low SNR values (<40 dB), variance in the displacement estimate is dominated by signal noise, and differences in degrees of decorrelation in response to an ARF excitation in softer versus stiffer materials have negligible impact on log(VoA) whether PW or Foc tracking is implemented. However, as SNR increases above 40 dB, the effects of decorrelation result in statistically significant log(VoA) differences between materials with different elasticities. In softer materials, ARF-induced deformation, nd thus scatterer decorrelation, is greater than in stiffer materials. Thus, softer materials are more readily differenetiated by log(VoA) than stiffer materials whether PW or Foc tracking is implemented. However, while both PW and Foc tracking better discriminate softer materials, it is important to consider that PW tracking implements a broader tracking pulse realizing a wider swath of scatterers under the tracking point spread function and therefore more signal decorrelation. Therefore, log(VoA) measured by PW tracking is higher than that measured by Foc tracking.

In regard to contrasting a feature, it is important to consider that overall contrast in a log(VoA) image is related to both the SNR and the decorrelation of the inclusion and backgrond (Fig. 2). If the inclusion SNR is lower than the that of the background (as in regions of lipid rich necrotic core), SNR will dominate the log(VoA) contrast, and PW and Foc tracking will yield similar CNR results. When the inclussion SNR is greater than that of the background, competing interations between decorrelation and SNR emerge. The effect of the higher SNR is to decrease log(VoA) relative to the background, and if the inclusion is also stiffer (as in a calcium deposit), then log(VoA) will be further reduced relative to the background for high CNR. However, if the high SNR feature is soft, the higher feature decorrelation will increase log(VoA), making it closer to the background value and decreasing feature CNR. Because decorrelation effects are amplified by PW tracking, as described above, PW tracking achieves overall lower CNR than foc tracking, particularly in soft materials.

There are some important limitations to this study. First, due to the computational burden of the FEM and Field II simulations, statistical analyses were conducted using log(VoA) measures across a region of interest from a single scatterer realization. Future work will incorporate more scatter realizations. Second, materials were modeled as being linearly elastic; however, some atherosclerotic plaque components, such as lipid-rich necrotic core and intraplaque hemorrhage, may not exhibit elastic recovery following ARF excitation. Incorporating analyses of non-elastic behavior is a topic of on-going work. Despite these limitations, the results support that log(VoA) evaluated using PW or Foc tracking discriminates materials by their SNR and decorrelation in response to ARF excitations. Importantly, the decorrelation effects are more pronounced when PW tracking is employed.

V. CONCLUSIONS

The findings suggest that the balance of SNR and decorrelation effects must be considered when applying log(VoA) analyses, whether PW or Foc tracking is employed. In application to delineating the structure and composition of atherosclerotic plaque by ARFI ultrasond, the results suggest that log(VoA) contrast of hypoechoic features like lipid-rich necrotic core and intraplaque hemorrhage is dominated by SNR, whereby PW and Foc tracking perform comparably. The results also suggest that in hyperechoeic plaque features like calcium, stiffer quality (resulting in less decorrelation) achieves higher contrast by log(VoA). In the latter case, PW tracking results in more signal decorrelation and achieves lower log(VoA) contrast. Overall, these results suggest that PW tracking may offer faster ARFI frame rates when imaging carotid atherosclerotic plaque, but at the expense of elasticity contrast in hyperechoic features.

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