obtained from pig experiments where coronary surgery had been performed, has
been used to compare the commonly used polynomial regression (PR) filter
with more advanced adaptive filtering techniques for clutter removal. More
specifically, three adaptive filtering techniques were used in the comparison. The
mean-frequency (MF) filter adapts to the tissue movement by down-mixing the
temporal signal with the mean Doppler frequency. The varying-frequency (VF)
filter adapts to the tissue movement by down-mixing the temporal signal with
the varying phase increments for each time sample. Both filters subsequently
apply a PR filter. The eigenvector regression (EV) filter spans the signal space
with an eigenvector basis, where the high-energy clutter signal can be extracted
by finding an appropriate basis for the clutter sub-space. The effectiveness
of the clutter filters was quantified by comparing the signal power before and
after filtering, from a region inside and outside a vessel. The procedure was
repeated for increasing filter basis size. Results showed that all three adaptive
filters outperformed the non-adaptive PR filter. A representative example from
a region with accelerated muscle movement and a filter basis size of two, yielded
a blood to clutter level of 11.2dB for the EV filter, 7.8dB for the VF filter, -
2.5dB for the MF filter, and -6.1dB for PR filter. As the filter basis size was
increased, the EV filter performance dropped to below that of all others in the
study. A reason for this may be that the basis vectors spanning the blood sub-
space is then included and removed by the filter. In conclusion, all three adaptive
filters ensured proper detection of blood, and a high reduction of clutter noise
artefacts. For a basis size of one to three the VF and EV filter were equally
the most effective. For a larger basis the VF filter prevailed. Also considering
computational demands, the VF filter should be the overall filter of choice.

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ELASTICITY
Chair: M. Insana
University of California-Davis

P2F-1

HYSTERESIS PARAMETER IMAGING OF SOFT TISSUE
UNDER QUASI-STATIC DEFORMATION

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The strain image can be influenced by the amount and rate of deformation
because the nonlinear elastic and viscoelastic properties cannot be neglected.
For stable mechanical assessment independently of such conditions, these prop-
erties must be assessed. On the other hand, these properties are capable of
characterizing tissue type and the degenerations. Therefore, we have been proposed the parameters to characterize the nonlinear elasticity and the hysteresis related to viscoelasticity. The hysteresis parameter (HP), which is focused in this study, is defined as the ratio (from 0 to 100%) of the area of hysteresis loop to that of the loading process. In the direct loading and unloading tests to the porcine muscle before and after formalin immersion under the deformation rates from 1.25mm/s to 6.25mm/s, the HPs were measured as the values of 55.2±3.0% and 23.6±0.8%, respectively. Obviously, the HP reflects tissue degeneration, and the variances to deformation rates are so small. Therefore, the HP is prospective to provide useful information to diagnosis independently of the deformation rates.

To make the local HP map in soft tissue, fundamental experiment with the porcine kidney embedded in a gel-based phantom was performed by employing a linear array probe with a center frequency of 7.5MHz. To generate local hysteresis loop, loading and unloading were applied to the phantom at the same deformation rates of 5mm/s. All 64 frames and the surface pressure for internal stress estimation by a pressure sensor were acquired in the both processes. The local incremental strains between the adjacent frames were estimated with the combined autocorrelation method and were accumulated after tracing. Subsequently, the HPs were estimated by using locally estimated stress-strain curves. Resultant HP image provided the different pattern from the conventional strain image. Moreover, the HP value of the cortex estimated by this procedure approximated that measured by direct mechanical test (error: 13.5%). Finally, we attempted to map the HP of the breast that suffers from the fibroadenoma with surface pressure data. Resultant HP image of the breast could clearly distinguish the fibroadenoma. Therefore, these results show the potentiality of the HP to tissue characterization.

P2F-2

ULTRASONIC MEASUREMENT OF MICRO-ORDER DISPLACEMENT OF PHANTOM ACTUATED BY ACOUSTIC RADIATION FORCE UNDER SAFETY GUIDELINES

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Background: Recently, several researchers have investigated the potential of the use of acoustic radiation force for imaging the mechanical properties of tissue. These methods, however, have some problems as to safety and/or the spatial resolution in depth direction. An alternative ultrasonic remote actuation and measurement method is proposed in this presentation, in which the intensity of the applied continuous ultrasonic wave is suppressed to be lower than the safety guideline (1 W/cm²) of the Japan Society of Ultrasonics in Medicine. Method: The radiation pressure was applied by the intersection of two continuous-wave
Ultrasonic beams with two slightly different frequencies around 5 MHz and the sound intensity less than 1 W/cm². To measure the resultant minute waveform of displacement with several micrometers in amplitude, the quadrature-demodulated signals of the RF echo data were A/D converted and then an ultrasonic correlation-based method (the phase tracking method) developed in our lab. (IEEE Trans. UFFC, 43:791-810;1996) was applied. In order to avoid the interference between the CW ultrasound for actuation and the pulsed ultrasound for displacement measurement, the radiation pressure was intermittently driven. Experimental Results: A silicone rubber (static elastic modulus=20 kPa, absorption coefficient=0.038 [1/m], thickness=10 mm) was placed in a water tank. Since the object was a totally absorbing material, the acoustic radiation pressure exerted on the interface of the object was calculated as 1.7 Pa. By integrating the difference in the measured velocity signals of the two points in the object, the change in thickness between these two points was successfully obtained as a waveform. The object was cyclically actuated at the frequency difference of 7 Hz with an amplitude of the order of 1.5 µm. For each actuated frequency from 5 to 20 Hz, the elastic modulus was calculated and it increases linearly with the frequency. By assuming the Voigt model, the viscosity coefficient was determined as 1.5 kPa s. Conclusions: A phantom was remotely actuated safety by the small acoustic radiation pressure and waveform of the resultant change in thickness in micrometer order was measured. From the frequency characteristics, the viscosity was determined without measurement of the pressure.

P2F-3

FAST BAYESIAN REGULARIZATION FOR VIBRATION ELASTOGRAPHY
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In this work we show that a novel application of Bayesian regularization can be applied as a fast, post-processing procedure to vibration elastography reconstructions to reduce artifacts. The technique allows for fast and simple algorithms to be applied during initial reconstruction provided that both an estimate and its uncertainty are obtained from the reconstruction. Bayesian methods work by incorporating prior information from the user. In this case, the operator-supplied a-priori knowledge is the expected feature size in the reconstruction. With this parameter, the algorithm creates a filtered image where each pixel is a weighted average of its neighbors in the initial reconstruction. The variance of these neighbors is also computed and stored. The final image is then a weighted average of the initial reconstruction and the filtered reconstruction with weights being the inverse of the respective variances. The effect is to use the initial reconstruction as the final result whenever its variance is low but when its variance is high to use an average of the surrounding pixels. The entire algorithm (including initial reconstruction using filter ratios) can be implemented in less than 100 lines of (Python) code and takes only a few seconds to run for a 256x256 image on 700
MHz Pentium III machines. We apply the algorithm to both simulated vibration elastography data and real data collected from 5%-20% graphite-laden bovine gels using 100Hz-600Hz vibrations detected with a 3.5MHz ultrasound transducer. The results show that reconstruction artifacts are significantly reduced especially those due to variability in the signal-to-noise ratio of the displacement measurements.

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P2F-4

AN EXPERIMENTAL CHARACTERIZATION OF SPATIAL RESOLUTION IN ELASTOGRAPHY: ANALYSIS OF THE TRADEOFFS BETWEEN SPATIAL RESOLUTION AND CONTRAST-TO-NOISE RATIO

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Theoretical and simulation studies on the spatial resolution of elastography have established lower bounds as well as practical limits on the achievable spatial resolution. In this work, we validate those theoretical and simulation results via an experimental study of the spatial resolution in elastography. Models that involved two cylindrical inclusions placed in the form of a wedge were used to characterize the axial and lateral resolution of the axial strain elastograms. A study of the dependence of the spatial resolution on several factors such as the algorithmic parameters, the applied strain, and the modulus contrast was performed. The axial resolution was found to show a linear dependence with respect to the algorithmic parameters, namely the window length and the window shift used for strain estimation. The lateral resolution showed a weak dependence on the algorithmic parameters. A weak dependence of the axial as well as lateral resolution on factors such as the modulus contrast and the applied strain was found.

The tradeoff between the spatial resolution and the elastographic contrast-to-noise ratio (CNRe) was then analyzed. A non-linear tradeoff between the CNRe and the axial resolution was shown for conventional strain estimation techniques, with the CNRe improving at a more than linear rate with respect to a linear degradation in the axial resolution. Similarly the CNRe showed a non-linear tradeoff with the lateral resolution. This study provided an experimental framework for characterizing the spatial resolution in elastography and facilitating a comparison of the CNRe with spatial resolution.

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PERFORMANCE ANALYSIS OF A REGULARIZED ALGORITHM FOR ELASTICITY IMAGING
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Elasticity images computed from ultrasonic RF data are degraded by decorrelation noise whenever tissue deformation reduces echo coherence. We have shown previously that noise is reduced through application of a regularized optical flow (ROF) algorithm, where strain is computed from dense displacement fields estimated by regularizing the optical flow constraint of echo amplitude conservation. The ROF algorithm determines local motion through a multi-scale optimization process that minimizes a difference energy constrained by a displacement roughness penalty.

In this study, we investigate image quality features of ROF for strain imaging - noise, contrast and spatial resolution. ROF features were compared to those obtained using a standard multi-resolution cross-correlation (MRCC) algorithm under equivalent conditions. Comparisons were made quantitatively using resolution phantom data and qualitatively using flow phantom and in vivo breast data. The axial resolution phantom consisted of two stiff graphite-in-agar blocks with adjacent planar surfaces oriented normal to the beam axis. Sandwiched between the surfaces was a 1-mm layer of graphite-in-agar slurry. When compressed, all the strain was concentrated in the soft slurry layer, thus simulating a step displacement and strain impulse.

We compared the Full-Width-Half-Maximum (FWHM), strain, and standard deviation of the noise (SDN) for strain measured at the layer. At low compression, the FWHM, strain and SDN were respectively 1.95mm, 0.86%, 0.06% (ROF) and 1.90mm, 0.80%, 0.90% (MRCC). At high compression, the FWHM, strain and SDN were respectively 1.18mm, 9.0% and 0.9% (ROF) and 1.14mm, 8.5% and 3.4% (MRCC). These results and MTF curves show that ROF provides up to an order of magnitude reduction in image noise with comparable contrast, spatial resolution and computational time. Flow phantoms with large dynamic range of stiffness also showed that ROF effectively eliminates decorrelation noise without a significant reduction in contrast or resolution. A comparable qualitative improvement was found on breast elastograms.

AN IN-VIVO VALIDATION STUDY OF ULTRASONIC STRAIN IMAGING - A COMPARISON OF STRAIN DERIVED BY ULTRASONIC STRAIN RATE IMAGING, GREY-SCALE M-MODE AND MRI
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Introduction: Strain Rate Imaging (SRI), a Doppler-based method to quantify regional myocardial deformation, has been validated against other techniques. However, these studies have been limited to validating peak strain values. As the temporal evolution of the strain curve is believed to contain important information on the functional consequences of regional pathology, we compared the complete strain curve as measured by SRI with the curves obtained by ultrasound M-mode and Magnetic Resonance Imaging (MRI).

Methods: Colour Doppler data from the posterior wall of the left ventricle were obtained at high frame rate (≥150 fps) in 10 normals (28±4y) and in 20 patients (63±9y) with ischemia (≥60% stenosis in a. circumflex). Data were taken in a parasternal short axis view using a 2.5MHz transducer (GE Vingmed Vivid7). Data were post-processed with custom made software enabling extraction of the strain curve and timing of global cardiac events. The strain curve of the same region could be extracted by manual delineation of the endo- and epicardial borders on an ultrasound M-mode and a cine MRI loop from the same subject. For the comparison of the three strain curves throughout the cardiac cycle, 10 strain values were extracted during systole and diastole (20 values in total). These values were used for an analysis of variance appropriate for repeated measures. Agreement was expressed using an intra-class correlation coefficient (0≤ICC≤1).

Results: The ICC for the normals was higher than for the patients (0.69 vs. 0.36). Moreover, the ICC was higher for systole than for diastole (0.58 vs. 0.47). ICC values were highest between SRI and ultrasound M-mode (0.67) and worst between MRI and ultrasound M-mode (0.42).

Conclusions: In normals, deformation measured by SRI correlated well in all parts of the cardiac cycle with MRI and ultrasound M-mode. In patients, this agreement decreased when comparing to MRI. This could be attributed to the lower temporal resolution of MRI and the more heterogeneous strain distribution in a diseased ventricle. Overall, differences were within acceptable limits. Ultrasound SRI thus provides a good new approach to the non-invasive assessment of regional myocardial function.