THE ACCURACY AND PRECISION OF ESTIMATING TISSUE DISPLACEMENTS FROM ULTRASONIC IMAGES

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Abstract

In many medical ultrasound imaging systems, clinical data are often presented in the form of tissue displacement and tissue velocity maps. In this paper, we determine the accuracy of tissue displacement estimates obtained using a well established cross-correlation, speckle tracking technique. We evaluate the accuracy of the cross-correlation technique as a function of 3 parameters: 1) the magnitude of the tissue displacement, 2) the size of the region being tracked and 3) the host tissue type. Three different sample types: porcine liver, porcine muscle and woolen sea sponge samples were used to study the effect of different scattering media on displacement estimates. For identically sized target regions and displacements, liver samples produced estimates with the largest uncertainties. For all 3 sample types, the accuracy and precision of displacement estimates deteriorated with increasing sample displacements and decreasing target dimensions.

1. Introduction

Problem formulation

We consider the problem of tracking the position of a moving target in one or two dimensions, given a number of reflected echoes of the target received at different times. If the echoes are received at roughly equally spaced intervals and if the target is moving with constant velocity, then the movement of the target between the first and last echoes can be estimated in 2 ways. The direct approach, is to window out the portion of the first echo which corresponds the target and then apply a cross-correlation search to the first and last echoes [1-2]. The problem with this method is that the ultrasonic speckle signature of a target changes with increasing target translations [3-4].

The problem can be reduced by tracking the target over shorter distances. This is done by computing the target's displacement between successive echoes. By incrementally estimating the target's displacements and then summing the displacements (illustrated in Fig. 1), a good estimate of the target's net displacement can be obtained. The increased accuracy achieved using the incremental tracking strategy was experimentally verified and documented in a previous study [1]. Fig. 2. (taken from [1]) illustrates the improved performance of the incremental technique for tracking sponge targets.

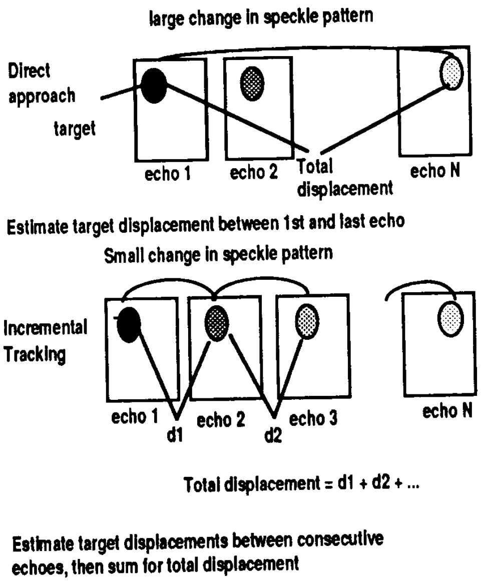

Fig. 1. Incremental estimation of target displacement.

Ultrasonic Time Domain Correlation Speckle Tracking Technique

To estimate target displacements the normalized correlation coefficient given in equation (1) is used to compute the best correlated position and thus displacement of the target between consecutive scans or echoes. Target displacements can thus be computed incrementally. A more complete description of the cross-correlation speckle tracking technique is given in [1,2].

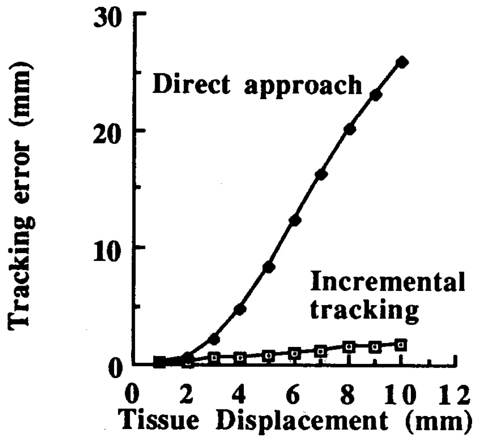

Fig. 2. Superior performance of the incremental tracking strategy. Tracking error was defined as the geometric distance between actual and estimated target displacements.

$$\rho_{xy}(k,l)=\frac{\sum_{i=0}^{M}\sum_{j=0}^{N}(x_{i,j}-\bar{x})(y_{i+k,j+l}-\bar{y})}{\sqrt{\sum_{i=0}^{M}\sum_{j=0}^{N}(x_{i,j}-\bar{x})^2\sum_{i=0}^{M}\sum_{j=0}^{N}(y_{i+k,j+l}-\bar{y})^2}} \qquad (1)$$

2. Experiments

Measurement of Tissue Displacement in Liver, Muscle and Sponge

Sections of porcine longissimus muscle and porcine liver were obtained from the Meat Science Laboratory, Department of Animal Sciences, at the University of Illinois. The porcine samples were obtained within 24 hours of death., and were vacuum sealed. All measurements were made at room temperature (20 degrees C). Samples of porcine liver, porcine muscle and woolen sea sponge were placed in a water tank and secured on top of sound absorbing (SOAB) slabs. Ultrasonic B-mode sector scans (video detected signals) were obtained using a 5 MHz ATL transducer and an ATL MK 500 Ultrasonic Imager.

Each of the sample types was placed in contact with the imaging transducer and was positioned in the center of the transducer beamwidth. To simulate axial displacements the imaging transducer was translated along the beam axis using a Daedal motorized positioning system (precision of 1 micrometer for axial and lateral motions). Video/detected signals were digitized and saved using a Targa 16 frame grabbing system and a Compaq 386 computer. The displacement of 24 different target regions in porcine liver, porcine muscle and woolen sea sponge samples, with dimensions ranging from 1.0 mm (~ 3 wavelengths) to 5.0 cm (~ 160 wavelengths) were then computed on a Sun Sparc II workstation using the cross-correlation speckle tracking technique.

3. Results

Change in speckle patterns as a function of tissue translation

The tracking algorithms rely on a minimal distortion in speckle patterns after target translations [4]. Displacement estimates are therefore accurate only to the extent that speckle patterns remain stable or do not change significantly with tissue translations.

To measure the change in the speckle patterns as a function of sample displacements video detected data from porcine muscle, porcine liver and woolen sea sponge samples were recorded at known distances from the transducer. Next, the portions of each echo corresponding to a selected target were windowed out and then correlated with the first echo. The resulting correlations shown in Fig. 3. provide a measure of how much the acoustic signature of each of the samples changes with distance. The results are similar to those reported by Ramamurthy et al [4] for liver mimicking samples.

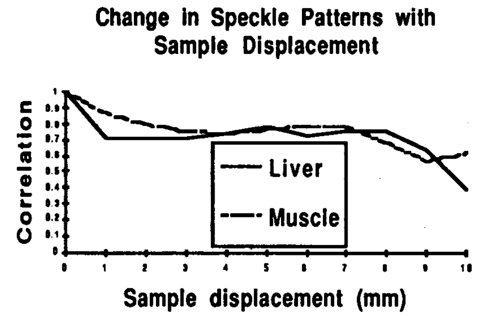

Fig. 3. Change in speckle patterns with sample displacements. Data points were averaged from five 2 cm target regions for each sample type.

Covariance curves for liver and muscle samples

The autocovariance functions for liver and muscle samples were generated by correlating video detected data received from each sample type, with shifted versions of itself (Fig. 4).

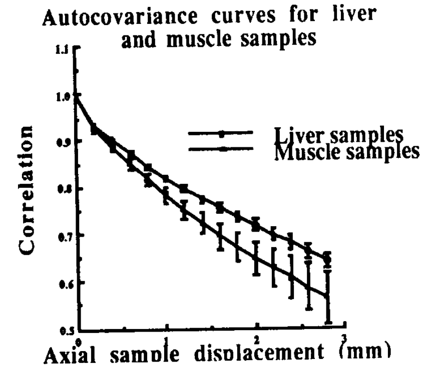

Fig. 4. Data points are the average of correlations from 10 independently acquired detected signals for each sample type. Error bars span 2 standard deviations.

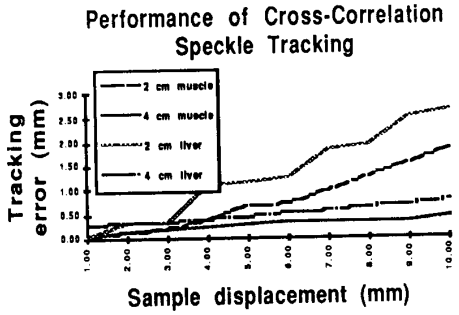

Fig. 5. Performance of cross-correlation speckle tracking for 4 of the 24 targets tested. For identically sized target regions and target translations muscle samples resulted in the smallest errors.

For video detected signals, a sharp and narrow sample covariance curve suggests that speckle tracking might produce sharp cross-correlation peaks with low sidelobes. This would reduce tracking errors due to false peaks and jitters as defined by Ramamurthy et al [4]. A broad autocovariance curve suggests that speckle tracking targets would result in correlation peaks consisting of a broad central lobe with higher sidelobes. This would increase tracking errors due to jitter and false peaks.

A narrow covariance curve also implies a small speckle cell size (using the full-width-half-max FWHM definition [3]). In the lateral dimension the speckle cell size is proportional to the frequency of interrogation. Thus, for the same sample types and target dimensions, target regions will likely contain more independent speckles and thus more information per unit area at higher frequencies.

Variation of Uncertainty with Tissue Displacements, Target Size and Tissue Type

For identically sized target regions and sample displacements, liver samples produced displacement estimates with the largest tracking errors (Fig. 5). Muscle targets produced the smallest errors while woolen sea sponge targets (not shown) were between liver and muscle errors. For all 24 targets tested the accuracy of displacement estimates deteriorated with increasing sample displacements and decreasing target dimensions. The increase in tracking errors for increasing sample displacements makes sense because target speckle patterns change with increasing sample displacements (Fig. 3). In particular we observe that liver speckle patterns decorrelated more rapidly than muscle speckle patterns.

The improved performance of the cross-correlation technique for large target regions can be attributed to the uniqueness of the target regions. Larger target regions actually produce lower correlations because they are generally more unique than smaller regions and it is more difficult to find an exact match. Conversely, smaller target regions are generally less unique than larger target regions and are thus more suceptible to false matches. This is in agreement with the findings of previous studies [1,2].

The cross-correlation values generated by estimating the 1.0 mm displacement of two rectangular targets with axial dimensions equal to 30 times the system wavelength and 3 times the system wavelength is shown in Figure 6. For the 1 cm target the location of the best correlated match is well defined by the brightness peak in Fig. 6a.

For the 1 mm target the true peak has been completely lost (Fig. 6b). These plots illustrate that by selecting smaller target regions the number of areas matching the target region increases. This produces an increasing number of ambiguous secondary correlation peaks until the actual *correct* peak is lost.

As target dimensions approach the order of the system wavelength, the target becomes comparable to the dimension of individual speckle cells. At these dimensions, the speckle patterns from separate targets become indistinguishable from one another. For most tissues with large speckle cells, the number of independent speckles contained in a target region may be reduced [3]. A broad autocovariance curve and large speckle cell size may contribute to less information being available per unit area for target regions. This is in agreement with the theory for object structures that are correlated [3].

4. Conclusion

Target regions in porcine muscle produced displacement estimates with the highest precision and smallest tracking errors. Liver tissue, which is largely homogeneous in structure, produced displacement estimates with the largest tracking errors. This may be because liver speckle patterns decorrelated more rapidly than muscle speckle patterns. Application of correlation speckle tracking techniques at high frequencies should result in a narrower lateral autocovariance curve and may reduce tracking errors due to false peaks and jitter in that direction. A broad autocovariance curve suggests that the number of independent speckles and hence usable information per unit area may be reduced. Quantitative estimates of tissue displacement estimated using the cross-correlation speckle tracking technique, may be limited by uncertainties on the order of 19% for tissues with muscle like composition (on the order of 27% for targets in liver media) for targets with dimensions in the range of 1 to 200 wavelengths and for target displacements in the range of .1 to 30 wavelengths. Selection of large target dimensions and implementation of an incremental tracking strategy has the potential of reducing uncertainties in displacement estimates.

Acknowledgment

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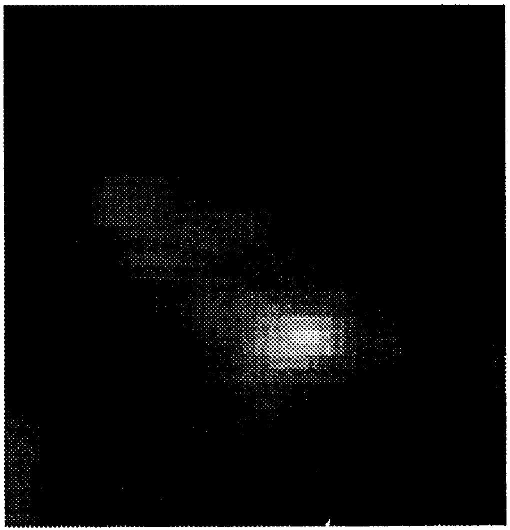

Fig. 6a. Cross-correlations produced by a 1 cm (axial dimension) target

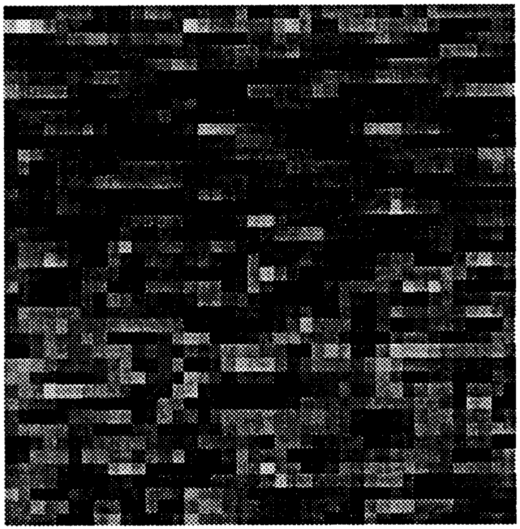

Fig. 6b. Cross-correlations produced by a 1 mm (axial dimension) target.

Fig. 6. Result of cross correlation speckle tracking 1 cm and 1 mm target regions (in sponge samples) undergoing a 1 mm displacement. Bright areas indicate positive correlation, dark areas indicate negative correlations. Horizontal axis corresponds to lateral position, vertical axis corresponds to axial position. Cross correlation peak is clearly defined for 1 cm target. For the 1 mm target the peak has been completely obscured by secondary correlation peaks resulting from false matches.