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Evaluation of reliability in measured local displacement inside carotid plaque to improve elasticity measurement accuracy

弾性率計測の精度向上を目指した頸動脈粥腫内部の局所変位計測結果の信頼性評価

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1. Introduction

We have aimed to characterize plaque in atherosclerosis by measuring the local elastic modulus of the vessel wall [1]. The change in local thickness inside the plaque caused by pulsation is measured from the displacements at the two different depths of the plaque, and the local elastic modulus is estimated from the change in local thickness when the vessel diameters are maximum and minimum during one heartbeat.

In our previous study [2], there were cases that the measured thickness change becomes thicker, which is contrary to the fact that the thickness becomes thinner with the dilatation of the blood vessels. In the present study, we proposed a method to evaluate the reliability in the measurement of the displacement inside the plaque by quantifying the change in the RF signal waveforms during one cardiac cycle using the normalized cross-correlation.

2. Methods

A plaque in the right carotid sinus of a dyslipidemic patient in his 60s was measured with a linear probe with a transmitted center frequency of 7.5 MHz, sampling frequency of 40 MHz, and frame rate of 286 Hz.

By pulsation, the internal tissue of the plaque deforms not only in the beam direction but also in the lateral and elevational directions. Therefore, in some cases, the speckle pattern in the ultrasound B-mode image largely changes as shown in **Fig. 1**. As the structure of the plaque is heterogeneous, the speckle pattern may locally change at the depth where the tissue is locally deformed in the lateral and/or elevational directions. At this depth, the waveform of the radiofrequency (RF) signal would change.

Instantaneous displacement is measured under the assumption that only the phase of the RF signal changes and the RF signal does not change between the frames [1]. Thus, the displacement at the depth where the RF signal largely changes by the local deformation in the lateral and/or elevational directions cannot be correctly measured. To quantitatively detect the depth where the RF signal waveform changes, we propose a method based on the normalized cross-correlation as follows:

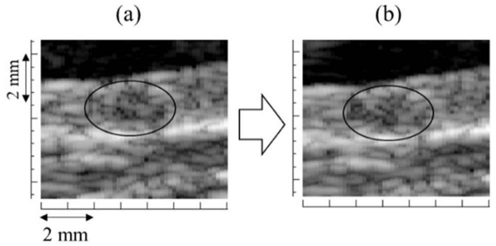

Fig. 1. Example of change of speckle pattern in the B-mode image of a plaque due to vessel dilatation. (a) Before dilatation and (b) during dilatation.

A correlation window of 385-μm width in the depth direction was set with changing the center position of the window along with the local displacements inside the plaque measured by the phased tracking method [1]. The correlation $r(n)$ between the succeeding nth and $(n+1)$th frames, and the correlation $r'(n)$ between the 0th (initial) and the nth frames were obtained at each depth by Eqs. (1) and (2), respectively.

$$r(n) = \frac{\frac{1}{N}\sum_{l=-\frac{L}{2}}^{\frac{L}{2}}(s_n(d_n+l)-\overline{s_n})(s_{n+1}(d_{n+1}+l)-\overline{s_{n+1}})}{\sigma_n\sigma_{n+1}}, \quad (1)$$

$$r'(n) = \frac{\frac{1}{N}\sum_{l=-\frac{L}{2}}^{\frac{L}{2}}(s_0(d_0+l)-\overline{s_0})(s_n(d_n+l)-\overline{s_n})}{\sigma_0\sigma_n}, \quad (2)$$

where d_n is the tracked target depth at the nth frame, L is the correlation window width (385 μm in the present study), and N is the number of samples in the correlation window. $s_n(d)$ is the RF signal at the depth d of the nth frame, and $\overline{s_n}$ and σ_n are the average and the standard deviation of the RF signals in the correlation window of the nth frame, respectively.

To prevent the decrease of the correlation due to the displacement being smaller than the sampling interval, the reconstructive method [3] was applied to interpolate the sampling interval of the RF signal

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10 times, and the normalized cross-correlation was calculated for the interpolated sampling interval.

3. Result and Discussion

Figures 2(a) and 2(b) show the changes in the RF signals at the depths where the correlation $r'(n)$ between the 0th and the nth frames were kept high or low, respectively. These results show that the RF signal waveform significantly changes at the depth where the correlation was low.

Figures 3(c) and 3(d) show the results of $r(n)$ and $r'(n)$, respectively. The correlations $r'(n)$ between the 0th and the nth frames lowered in time direction at several depths, whereas the correlations $r(n)$ between succeeding frames kept high values regardless of the depth and time. These results suggest that the change of the RF signal waveform due to the local deformation inside the plaque occurs not rapidly but gradually.

Thus, it is difficult to detect this gradual change of the RF signal waveform only from the change of RF signals between succeeding frames. To evaluate the reliability in the measurement of the displacement results, it is essential to use $r'(n)$, which evaluates the change in the RF signal waveform from the initial (0th) frame.

In Figs. 3(d) and 3(e), there was a tendency for the correlation $r'(n)$ to decrease as the artery dilatated by pulsation and then increase as the artery returned to its initial form. This may show the movement of the internal plaque as it is pushed by the pulse pressure and locally deformed in the lateral and/or elevational directions, and then returns to its original shape. The depth dependence of the correlation values in Fig. 3(d) shows that the local deformation occurred inside the plaque due to the heterogeneity in the structure of the plaque.

Since the keeping of high correlation $r'(n)$ in the time direction confirms the high reliability in the measurement of the displacement results, it may be possible to measure the correct thickness change inside the plaque only by focusing at the depth where the correlation $r'(n)$ keeps high.

4. Conclusion

In the present study, we proposed a correlation-based method for evaluating the reliability in the measurement of the displacement results inside the plaque used in the elasticity estimation. Using only displacement measurement results evaluated as reliable by the proposed method, it would be possible to measure the correct thickness change inside the plaque.

In the future, we will focus only on the depths where the displacement measurement results are reliable, and establish a method to correctly characterize the plaque based on the accurate measurement of the internal movement of the plaque.

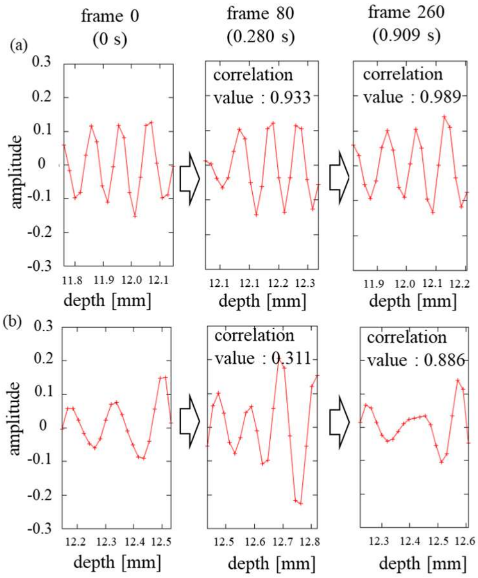

Fig. 2. Change of RF signal waveform at the depth (a) where the correlation remained high (initial depth in Fig. 3(d): 11.74 mm) and (b) where the correlation lowered (initial depth in Fig. 3(d): 12.24 mm).

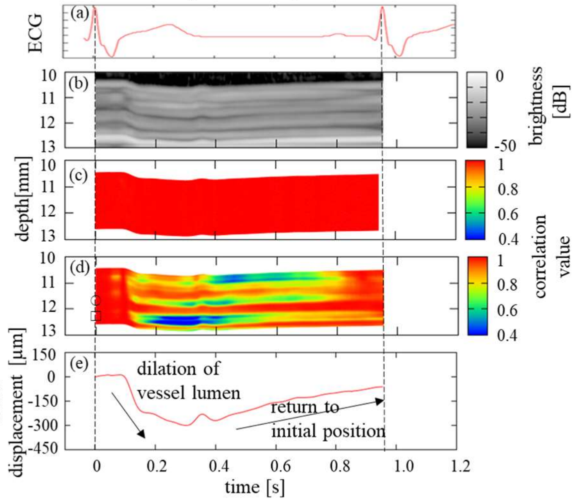

Fig. 3. (a) Electrocardiogram (ECG), (b) M-mode image of the plaque on the posterior wall, (c) distribution of normalized cross-correlation between succeeding frames, (d) distribution of normalized cross-correlation between the 0th (initial) and the nth frames, and (e) measured displacement of the vessel wall in the radial direction (i.e., depth direction).

Acknowledgment

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References

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