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Removal of beam directional displacement caused by blood vessel pulsation for ultrasonic roughness measurement on luminal surface of carotid artery

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1. Introduction

In the experiment on rabbits, it has been reported that the luminal surface of the arterial wall became rough in tens of micrometers after one week of exposure to high blood pressure [1]. We have been studying a method to estimate the surface roughness of the carotid artery wall using that the phase of the reflected signal is shifted by the surface roughness when the carotid artery wall is displaced in the lateral direction by blood vessel pulsation [2]. However, the radial displacement of the arterial wall is caused by not only the surface roughness but also the blood vessel pulsation. Thus, the latter has to be removed. The present study proposes a method to remove the radial displacement due to the blood vessel pulsation by the high-pass filter (HPF).

2. Methods

In the previous study [2], to estimate the radial displacement due to the blood vessel pulsation, $z_{\mathrm{g}}(n;m)$, the radial displacements $z(n;m)$ measured at each beam m are averaged by all M beams at each frame n. This is based on the assumption that the radial displacement due to the blood vessel pulsation is constant in the lateral direction within all M beams.

However, the radial displacement due to the blood vessel pulsation was not completely constant in the lateral direction. Therefore, we consider estimating it by the spatial moving-average filter (low-pass filtering). Since the posterior wall of the carotid artery moves reciprocally with the non-constant velocity in the lateral direction during the heartbeat, the following process is applied.

With limiting the time range in analysis in which the posterior wall of the carotid artery displaces monotonically and maximally in the lateral direction (**Figs. 1**(a) and 1(b), black dots), the radial displacement $z(k;m)$ (Fig. 1(a)) and lateral displacement $x(k)$ (Fig. 1(b)) are interpolated with a factor of 100 by the reconstruction interpolation, and combined by the interpolated frame sample k to obtain $z(x(k);m)$ (Fig. 1(c)). Then, the non-constant sample intervals of $z(x(k);m)$ in the lateral direction are adjusted by the linear interpolation to obtain $z(x;m)$ (Fig. 1(d)) with a constant interval of 1 μm. The displacement due to the blood vessel pulsation, $z_{\mathrm{g}}(x;m)$, is estimated by applying the moving-average filter to $z(x;m)$ as

$$z_{\mathrm{g}}(x;m)=\frac{1}{N}\sum_{i=-(N-1)/2}^{(N-1)/2} z(x+i;m). \qquad (1)$$

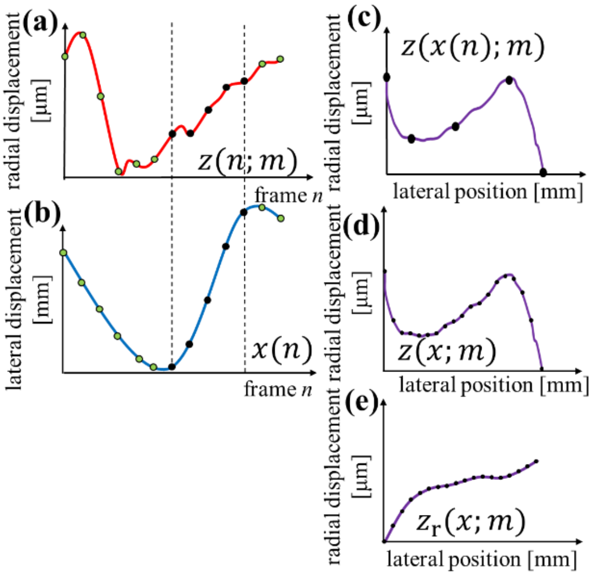

Fig. 1. Concept of removal of the radial displacement caused by the blood vessel pulsation, (a) radial displacement $z(n;m)$, (b) lateral displacement $x(k)$, (c) $z(x(n);m)$ obtained by combining (a) and (b), (d) $z(x;m)$ which has the constant sample intervals of 1 μm, (e) the surface profile $z_{\mathrm{r}}(x;m)$ estimated by removing the blood vessel pulsation $z_{\mathrm{g}}(x;m)$ from (d).

The window width N of the moving average filter is determined based on the cut-off spatial frequency which is set between the spatial frequency of the blood vessel pulsation and that of the surface roughness. The surface profile $z_{\mathrm{r}}(x;m)$ (Fig. 1(e)) is estimated by removing $z_{\mathrm{g}}(x;m)$ from $z(x;m)$ (high-pass filtering) as

$$z_{\mathrm{r}}(x;m)=z(x;m)-z_{\mathrm{g}}(x;m). \qquad (2)$$

The surface roughness $z(x)$ is estimated by combining [2] the surface profiles $z_{\mathrm{r}}(x;m)$ with all M beams.

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3. Phantom experiment

The proposed method was verified in the experiment using a phantom that has 10 saw-teeth with 10-μm height and 500-μm width on the surface. For simulating the blood vessel pulsation, the phantom was moved reciprocally 1.0 mm at 1.4 mm/s in the lateral direction and 0.5 mm at 0.7 mm/s in the radial direction by the automated stage. Ultrasonic measurements were performed using an ultrasound diagnostic apparatus (ProSound F75; Hitachi-Aloka-Medical Ltd., Tokyo, Japan) with a linear array probe (UST-5415; Hitachi-Aloka-Medical Ltd., Tokyo, Japan). The transmitted and sampling frequencies were 7.5 MHz and 40 MHz, respectively, and a longitudinal cross-section of the phantom was measured with $M = 61$ ultrasonic beams. The distance between neighboring beams was 150 μm and the frame rate was 187 Hz. The window width of the moving average filter was set to 460 μm (*i.e.*, cutoff spatial frequency is 1.3 mm^{-1}). The reference surface profile of the phantom was measured using a laser displacement meter (LT9010; Keyence Corp., Osaka, Japan) in the same experimental configuration.

4. Results

Figure 2 shows the results of the phantom experiment. Figures 2(a) and 2(b) correspond to the black dots in Figs. 1(a) and 1(b), although it is interpolated with a factor of 100. Figures 2(c) and 2(d) correspond to Figs. 1(d) and 1(e) for beam number 31. As shown in Figures 2(d), the saw-tooth shape with a width of 500-μm was estimated by the proposed method.

Figure 2(e) shows the B-mode image of the phantom surface. Figure 2(f) shows the surface roughness $z(x)$ estimated by combining the surface profile $z(x;m)$ with all 61 beams. Figure 2(g) shows the surface roughness measured by the laser displacement meter. The surface roughness measured by the proposed method (Fig. 2(f)) corresponded to the brightness pattern in the B-mode image of the phantom surface (Fig. 2(e)). This may be because the ultrasonic wave is scattered at the top point of the saw-tooth but reflected at the other positions of the surface. The surface roughness measured by the proposed method showed 10 saw-teeth with approximately 8 μm in height and 500 μm in width, which was similar to the result by the laser displacement meter.

5. Conclusion

In the surface roughness measurement, we proposed the method to remove the radial displacement due to the blood vessel pulsation by convolving the spatial HPF in the lateral directions.

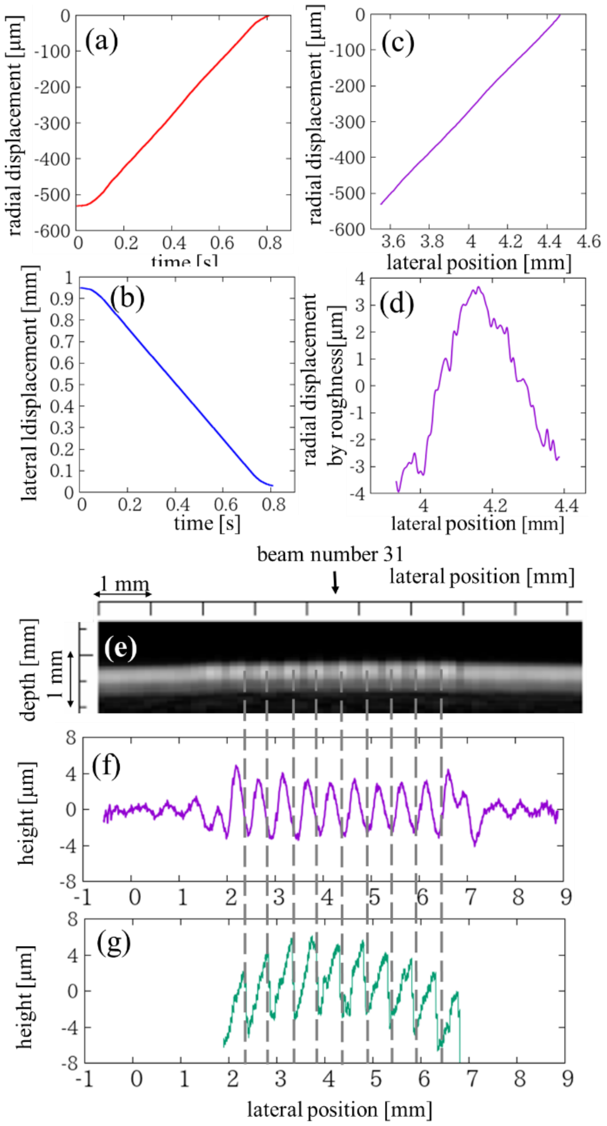

Fig. 2. The results of phantom experiment, (a) radial displacement $z(k;31)$, (b) lateral displacement $x(k)$, (c) $z(x;m)$ obtained by combining (a) and (b), (d) surface roughness $z(x;31)$ obtained by removing $z_g(x;m)$ from (c), (e) B-mode image of phantom surface, (f) estimated surface roughness $z(x)$ by ultrasound, and (g) surface roughness measured by laser displacement meter.

In the future work, we will apply the proposed method to the *in vivo* measurement to investigate the luminal surface roughness of the carotid artery.

References

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