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Experimental study on the pressure wave propagation in tubes mimicking stenosed vessels

血管模擬狭窄チューブ内の圧力波伝搬に関する実験的検討

Shimpei ONO[1†], Mami MATSUKAWA[1], Pierre-Yves LAGREE[2] ([1]Doshisha Univ.; [2] Université Pierre et Marie Curie)
小野　慎平 [1†], 松川　真美 [1], ピエール-イヴ・ラグレー[2] ([1] 同志社大学, [2] ピエール・マリー・キュリー大学)

1. Introduction

The cardiovascular disease (CVD) is a major cause of death in the world [1]. One of the initial symptoms of the CVD is arteriosclerosis and it is very important to detect arteriosclerosis in its early stages. We have then focused on the measurement of the pulse wave at the carotid artery to evaluate the arterial elasticity. The pulse wave is a local displacement of the surface skin and has similar characteristics to the intravascular pressure wave. We have studied the pulse wave using an artificial tube mimicking a real artery [2]. As arteriosclerosis progresses, plaques often form on the arterial wall. Their growth can trigger blood vessel obstruction and even obliteration [3].

In this study, we fabricated transparent tubes with artificial stenosis and examined the effects of the stenosis on the flow motion using the PIV (Particle Image Velocimetry) method and an ultrasonic Doppler system, and compared these results with the measured pressure wave.

2. Viscoelastic tube

2.1. Normal and transparent tubes

We fabricated several normal tubes and short transparent and normal tubes made of polyurethane gel (Normal: Asker-C 5, Exseal Corp, Transparent: Gummy Cast Clear, Nissin resin Corp). The diameter and thickness of these tubes were 8 mm and 2 mm, respectively. The measured Young's moduli of the normal tubes were 200 kPa and those of short transparent tubes were 320 kPa by the tensile test.

2.2. Stenosis tube

Fig. 1 shows the cross-sectional image of the fabricated stenosis tubes and an ultrasonography (Hitachi aloka medical, Prosound α7) image of the tube.

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mmatsuka@mail.doshisha.ac.jp

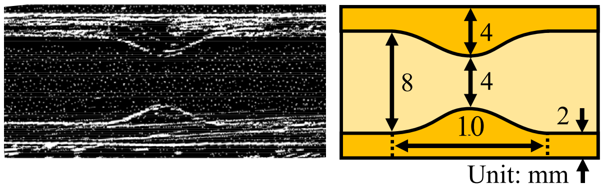


Fig.1 Cross-sectional image of the stenosis tube.

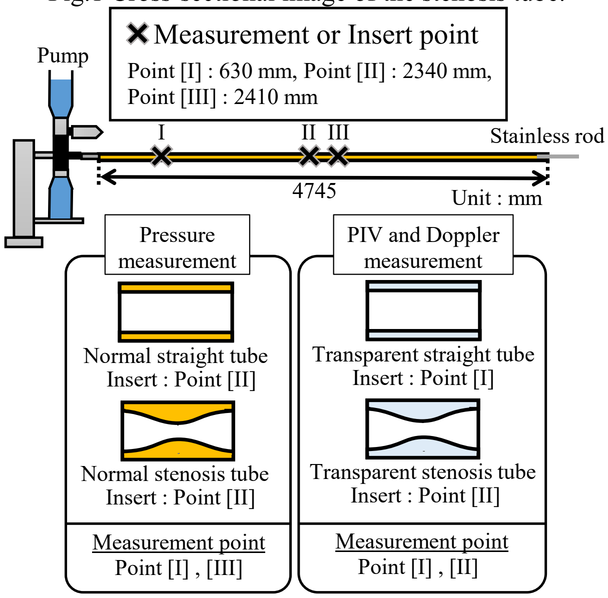


Fig. 2 Experimental systems.

The shape of the stenosis part is a squared cosine waveform. We fabricated normal stenosis and transparent stenosis tubes. The stenosis ratio is considered as an index to evaluate the stenosis condition. The estimated stenosis ratio was 75 % by area-stenosis method (percentage of plaque in the blood vessel cross-sectional area) [4].

3. Pressure and flow motion measurement

For the pressure measurement, we at first inserted two normal tubes (stenosis or straight) at Point [II] as shown in Fig.2. A piston pump (Tomita engineering) ejected water into the tubes. The inlet flow velocity waveform was a half cycle of a sinusoidal wave. The inlet flow period and ejection volume were set to 0.3 s and 4.5 ml respectively. A stainless rod imitating a vascular bed was placed at the tube end. The inner pressure of the tubes was measured by a pressure sensor (Keyence AP-10S). The pressure measurement points were point [I]: 630 mm and point [III]: 2410 mm (before and just after the stenosis) from the input point. For the flow measurements (PIV and Ultrasonic Doppler), we inserted the transparent straight tube and the stenosis tube at Points [I] and [II] as shown in Fig.2. The flow motion of at these points were observed by a high-speed camera (Photron, Fastcam MC-2.1, 1000 fps) and Ultrasonography (Hitachi aloka medical, Prosound α7, 30 fps). The diameter and the density of the tracer particle (ORGASOL®) used for PIV were 50 μm and 1.03 g/cm^3 respectively. The wave length and output of the laser beam were 532 nm and 18 mW, respectively.

4. Experimental results and discussion

Figure 3 shows the observed pressure waveforms measured at 2 points ([I]: 630 mm, [III]: 2410 mm). In the case of measurement point [I], we could observe small waves around 0.7 s and 1.7 s. The admittance of the tube was proportional to the radius. As shown in Fig.1, the radius gradually decreases the stenosis part. Thus positive reflection of the pressure wave was measured at the measurement point [I] (before the stenosis part) due to the decreasing of admittance of the stenosis tube. The result [D] shows pressure waveforms observed just after the stenosis. The first peak of the result [D] was smaller than that of the result [C]. As shown in Fig.1, behind the stenosis part, the radius gradually increases, thus the negative reflection was measured at the measurement point [III] (after the stenosis part) due to the increasing of admittance at the stenosis.

Next we focused on two peaks of the pressure wave (first and second peaks) to examine the effect of the stenosis on the flow. We measured propagation time of these peaks from the initial rise to compare the flow motion results. We measured flow at propagation time of these peaks using the PIV method and an ultrasonic Doppler.

Figures 4 (a) and (b) show the flow motion images of the transparent tube using PIV and ultrasonic Doppler. We could observe the straight trajectories of the particles in Fig.4 (a) at 159 ms. Reflected wave from the stenosis in Fig.4 (a) at 683 ms, however, we could not measure flow motion using the ultrasonic Doppler. By contrast, we could see the deviation of the particle trajectories and acceleration of the flow due to the presence of the stenosis in Fig.4 (b). By the PIV, we could observe vortex after the stenosis more clearly than by the ultrasonic Doppler.

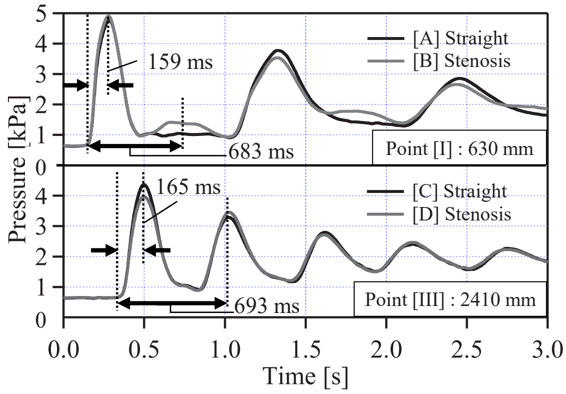
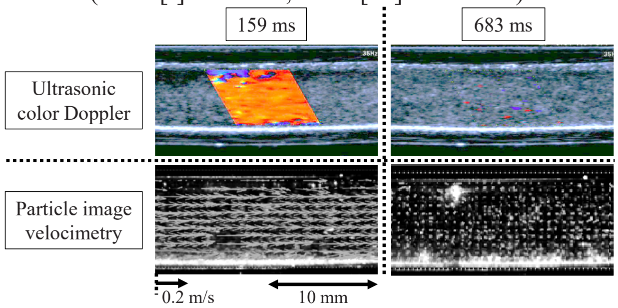
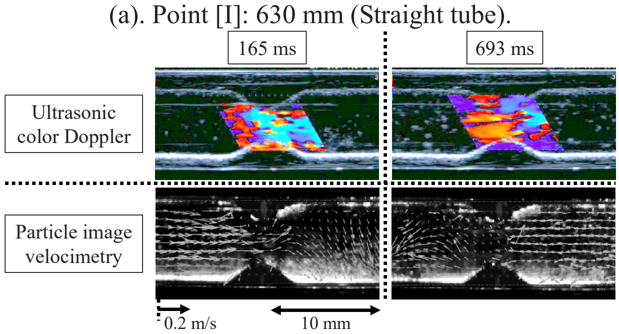


Fig.3 Pressure wave propagation through the stenosis (Point [I]: 630 mm, Point [III]: 2410 mm).



(a). Point [I]: 630 mm (Straight tube).



(b). Point [II]: 2340 mm (Stenosis tube).

Fig. 4 Flow motion image of the tubes measured by PIV and Ultrasonic Doppler at the observed time of peak.

5. Conclusion

We fabricated transparent tubes mimicking stenosis and measured pressure and flow motion before or after the stenosis. We could observe the deviation of the particle trajectories and acceleration of the flow due to the presence of the stenosis using PIV method. It was difficult to detect the vortex of the flow by the ultrasonic Doppler. Plaque may also change the flow motion and flow velocity after the stenosis in *vivo*.

References

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