Measurement of cyclic microdeformation of arterial wall with pulsatile flow

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ABSTRACT

The cyclic micro-deformation of the arterial wall with pulsatile flow was measured to get fundamental data for estimation of the mechanical stress in endothelial cells. The descending aorta (1-2 mm diameter) of an anesthetized rat was exposed under thoracotomy. The displacement measuring system was assembled with the charge coupled devise (CCD) of laser sensor. The movement of laser beam (670 nm wave length) reflected at the vessel wall was calibrated to the movement of the arterial wall. The fluctuating movement was also measured at four points marked on the vessel wall with CCD camera to distinguish the circumferential movement from the longitudinal one. The results showed that the present designed system has enough resolution to measure the arterial vessel wall cyclic-micro-fluctuation, which is 10 percent of diameter in the circumferential direction without deformation in the longitudinal direction with the cardiac beating *in vivo*.

Keywords: Biomeasurement, pulsating deformation, pulsatile flow, arterial wall, CCD laser sensor, mock circulation, diaphragm pump

1. INTRODUCTION

The blood flow causes mechanical shear and tensile stresses in a vessel wall. The inner surface of the vessel wall is covered with endothelial cells. The endothelial cells are secreting chemical agents and controlling thrombus formation[1]. Previous studies show that the endothelial cells are sensitive to mechanical stress[2-4]. The quantitative relation between mechanical and biological factors remains, however, under discussion. The pulsatile flow may cause different effects on the endothelial cells from the steady flow[5]. The present study shows the methodology to measure the cyclic micro-deformation of the arterial wall with a pulsatile flow to give fundamental data for estimation of stress in vessel walls.

2. METHODS

2.1 Measurement system with CCD laser

To measure the cyclic micro-deformation of the arterial wall with pulsatile flow, the displacement measuring system was assembled with the charge coupled device (CCD) of laser sensor (Figs. 1 & 2). The movement of laser beam of 670 nm wave length reflected at the vessel wall is computed and calibrated to the movement of the wall. The movement is calculated into the fluctuation of diameter of the vessel, which is fixed at the opposite side with the L bar. The measurement system distinguishes 0.02 mm fluctuation in the diameter of the vessel. In the experimental system, the simultaneous measurement of instantaneous flow rate enables to correlate the deformation of the wall with the phase of pulsatile flow.

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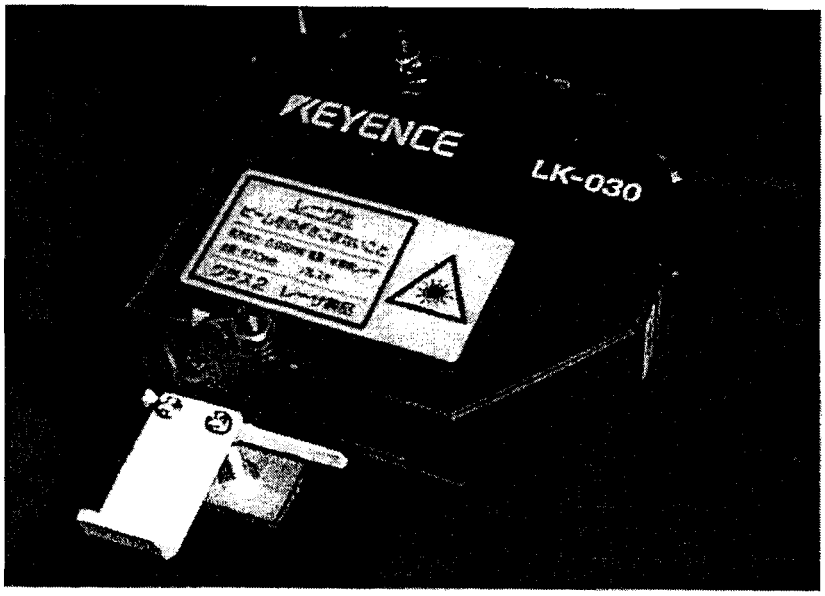

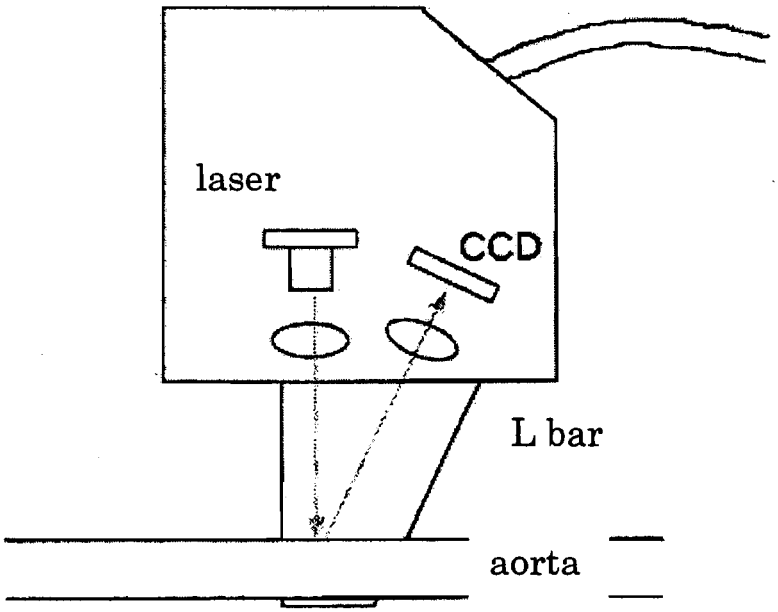

Fig. 1: Charge coupled devise (CCD) of laser sensor.

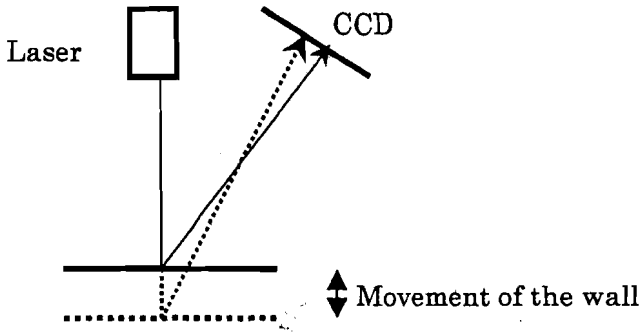

Fig. 2: Measurement on movement of the wall with CCD laser.

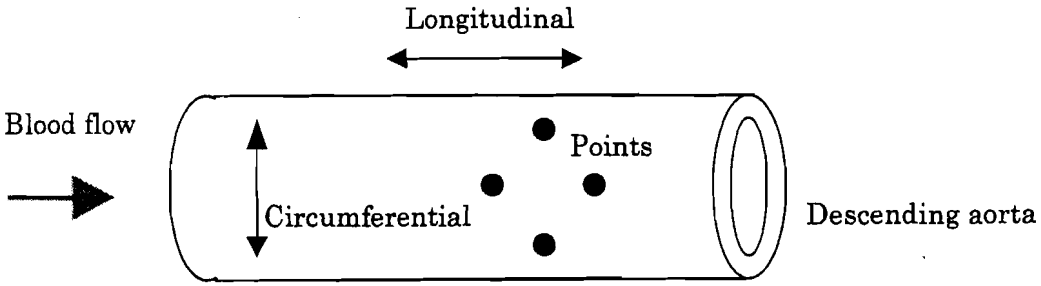

Fig. 3: Four points marked on the vessel wall.

Fig. 4: Measurement system with laser; electromagnetic flow meter, right; animal and laser device, center; respirator, left.

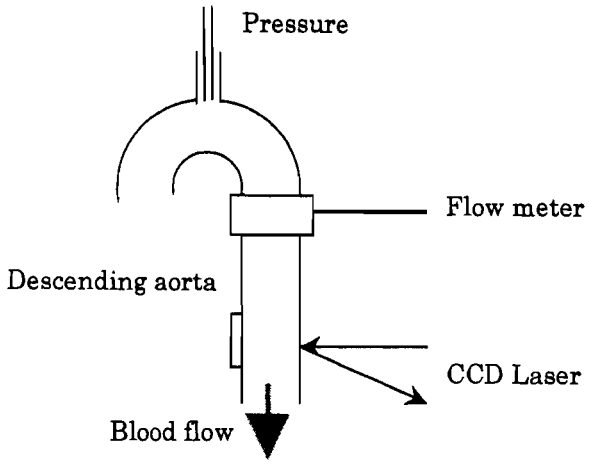

Fig. 5: Measurement procedure *in vivo*.

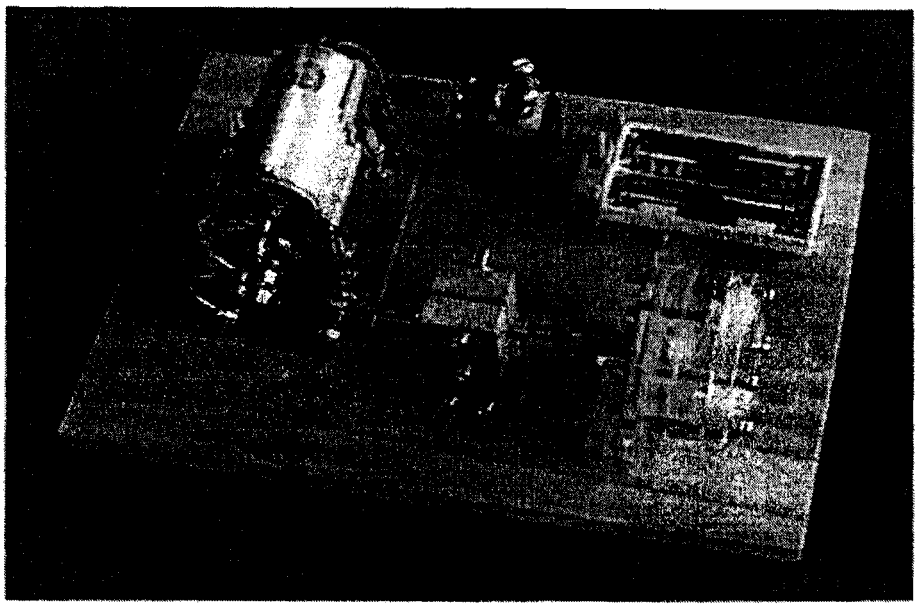

Figure 6: Reciprocating-micro-diaphragm pump system.

2.2 Measurement system with CCD camera

The fluctuating movement was also measured at four points marked on the vessel wall with the charge coupled devise (CCD) camera to distinguish the circumferential movement from the longitudinal one. The four points are located to make a square of 1 mm. Each diagonal line of the square coincides with the circumferential or longitudinal direction of the vessel (Fig. 3).

2.3 Measurement procedure *in vivo*

Rats were chosen for the animal to be handled in a large number (thirty-two rats) of tests. The descending aorta of an anesthetized rat was exposed and exfoliated from surrounding tissue under thoracotomy with respirator of 60 beat per minute (Fig. 4). The measurements of cyclic deformation of arterial wall were performed at the descending aorta. The

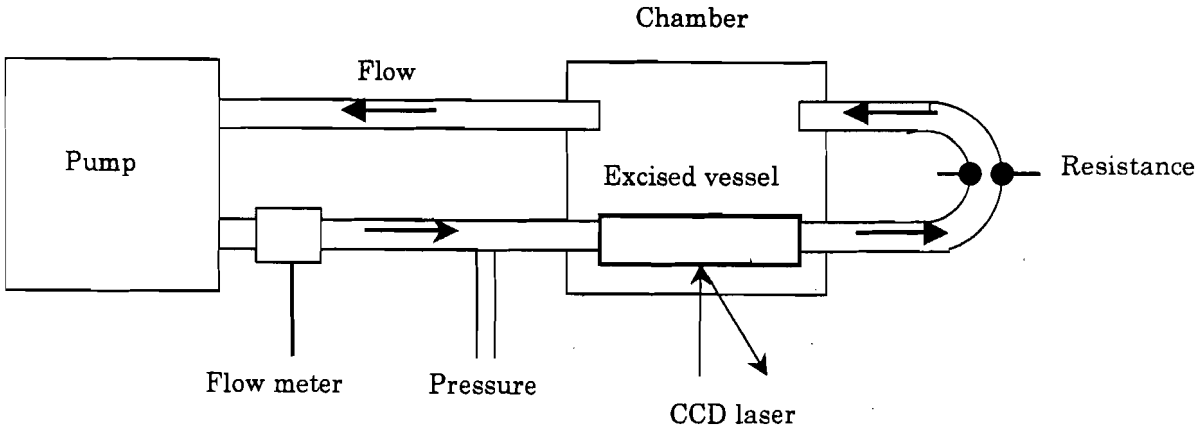

Figure 7: Mock circulation circuit.

flow rate was measured at aorta with the electromagnetic flow meter. The blood pressure was measured at the branch of aorta with the catheter and diaphragm method (Fig. 5). Temperature of the rectum is maintained at thirty-seven centigrade with a lagging pack. To control the mean diameter of the descending aorta and the compliance of the vessel wall, following liquids were introduced through the venous; the saline solution, the vasodilatation agent (nitroglycerin), or the vasoconstriction agent (dopamine).

2.4 Measurement procedure *in vitro*

The descending aorta, of which branches were ligated, as long as 10 mm was excised from a rat and connected to the mock circulation circuit. The excised aorta segment was sunk in a saline solution contained in a chamber. Pulsatile saline-solution-flow powered by the reciprocating-micro-diaphragm pump (Fig. 6) was applied to the excised descending aorta, and measured the fluctuating movement of the vessel wall (Fig. 7). The pump system consists of a battery, a DC motor, a crank, a diaphragm chamber, and leaflet one-way valves. The flow condition was controlled to simulate that with the natural heart of rats; beating rate of 300 per minute, stroke volume of 0.06 ml with the diaphragm pump. Variations were made in the distal resistance with constricting the silicone tube, which was connected at the downstream of the mock circulation. The flow rate and the pressure were measured with the electromagnetic flow meter and with the catheter-diaphragm method, respectively. After the test, the diameter and the wall thickness of the vessel were measured with a scale.

3. RESULTS

Fig. 8 exemplifies the tracings of the deformation of the arterial wall and the blood flow rate with the pulsatile flow *in vivo*. The tracing shows 0.2 mm cyclic sinusoidal fluctuation of the vessel diameter with the cardiac beating. The pulsating value is estimated to ten percent of the mean diameter of the descending aorta. The movement observed with the CCD camera indicates that the vessel wall deforms at circumferential direction, and that the wall deforms below one percent of the mean diameter at longitudinal direction. The results of thirty-two animal tests show that the rate of deformation at circumferential direction with cardiac beating is from 5 to 10 percent of the mean diameter.

When the vasodilation agent (nitroglycerin) is introduced into the circulation in the tests *in vivo*, the blood volume moves to the peripheral circulation by telangiectasia. This decreased the mean diameter of aorta, and increased the rate of fluctuation of its diameter with cardiac beating (Table 1). When the saline solution is introduced into the circulation, the circulating blood volume expansion increases the mean diameter of aorta. Infusion of dopamine also expands the mean diameter of aorta, because of the movement of blood from peripheral circulation by the effect of vasoconstriction.

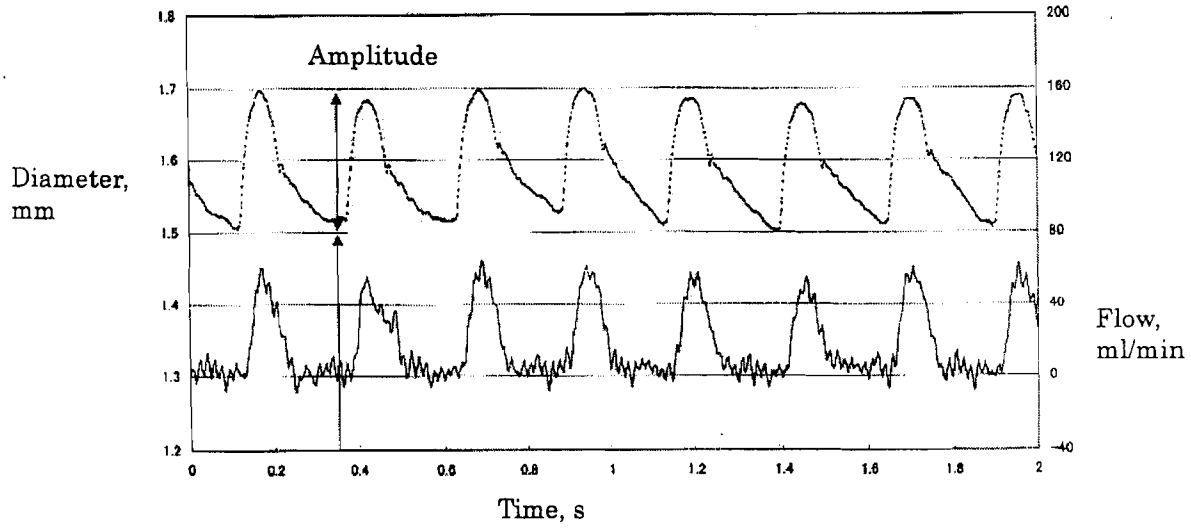

Figure 8: Tracings of the deformation of the arterial wall and blood flow rate with the pulsatile flow.

Table 1: The mean vessel diameter and the rate of its fluctuation.

	Before infusion		After infusion	
Infused liquid	Vessel diameter	Rate of fluctuation	Vessel diameter	Rate of fluctuation
Saline solution	1.40 mm	5.5%	1.60 mm	7.8%
Dopamine	1.70 mm	4.2%	1.75 mm	5.5%
Nitroglycerin	1.78 mm	4.2%	1.56 mm	10.6%

The result *in vitro* shows that the rate of fluctuation depends on the mean diameter, which reflects tensile stress in the wall at the neutral in the cardiac cycle. When the vessel wall is strongly stretched at neutral, it becomes hard. This decreases the rate of fluctuation of the vessel wall with the phase of pulsatile flow. When the vessel wall is softly stretched at the natural, on the other hand, it becomes flexible. This increases the rate of fluctuation of the vessel wall with the beating of the pulsatile pump. The mean values of outer diameter and of the wall thickness of the vessel were 2 mm and 0.15 mm, respectively.

4. DISCUSSION

The microdeformation of the vessel wall should be measured with the sensor out of contact, because the vessel wall is compliant. Both the ultrasound and light beams are generally used for the media to measure the distance between the sensor and the surface without contact each other. The resolution of measurement depends on the wavelength of the reflected beam.

Ultrasonograph is widely used in the medical measurement. It enables measurement of movement of the interface in the body non-invasively. The normal level device distinguishes the distance of 0.1 mm[6].

The CCD camera is useful to get the moving image of the surface. The advantage of laser (light amplification by stimulated emission of radiation) beams is its uniformity about both phase and frequency. The CCD laser sensor consists of the semiconductor laser and the CCD element. The laser beam reflected at the surface focuses on the CCD element. As the movement of the surface, the angle of the reflected beam varies. The variation of the angle corresponds to that of the focused position on the CCD element.

Being compared with the ultrasonograph or the charge coupled devise (CCD) camera systems, the present measuring system with the CCD of laser sensor has the advantage about the dynamic resolution to distinguish the fluctuating micro-deformation of arterial walls with the cardiac beating. For example, the measuring system is preferable to apply to an artery of small diameter.

The results should be applied to simulate compliance of arterial vessel wall[7]. The cyclic variation of diameter is useful to estimate fluctuating stress in vessel wall with pulsatile flow. The effects of pulsatile flow on mechanical stress in endothelial cells of arteries have not been quantified[8-10].

In the present tests *in vivo*, surrounding tissue around the descending aorta is exfoliated. The surrounding tissue may have some minor effects to the compliance of the vessel wall.

The surrounding pressure in the thorax also affects the deformation of the vessel wall of the descending aorta before thoracotomy. The pressure periodically fluctuates with respiration. The negative surrounding pressure increases the mean diameter of the vessel, which decreases the compliance of the vessel wall.

The pulsatile flow modifies the stress in the vessel wall. Both the shear stress on the wall and tensile stress in the wall fluctuate periodically. The present study shows that tensile stress generates mainly in the circumferential direction of the vessel wall. The stress may cause various effects in endothelial cells[10]. The pulsatile flow also may play an important role to control clot formation [5].

5. CONCLUSION

The present study showed that the designed system has enough resolution to measure the arterial vessel wall micro-fluctuation, which is 10 percent of diameter in the circumferential direction without deformation in the longitudinal direction with pulsatile flows.

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