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EVALUATION OF CORONARY BLOOD FLOW VELOCITY PROFILE BY LASER DOPPLER VELOCIMETER WITH OPTICAL FIBER

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Abstract

In order to measure a phasic arterial blood flow velocity accurately ina small sample volume, we have developed a Laser Doppler Velocimeter with an optical fiber. After the fundamental experiments to evaluate the accuracy of the present method, the coronary blood flow velocity was measured in five anesthetized mongrel dogs. The velocity waveform near the center line of the left circumflex coronary artery showed a diastolic dominant flow pattern, which is a characteristic of coronary arterial flow. During diastole two peaks in the flow velocity pattern were commonly observed in early and in late diastolic phase. The blood flow velocity decreased especially in late diastole with traversing the fiber tip toward the vessel wall and the velocity component in early diastole also decreased at sampling points very close to the vessel wall. From these investigations, we have found that the laser Doppler velocimeter using an optical fiber represents a promising method for the evaluation of the precise flow fields in the coronary artery.

INTRODUCTION

Measurement of blood flow velocity is fundamental to understand the pathophysiology in the coronary circulation, since the blood flow velocity closely relates to the pressure loss due to an arterial stenosis[1,2]. It is also well known that one of the velocity derivatives, wall shear rate, plays an important role in the pathogenesis of coronary arterial sclerosis[3]. Attempts have been made by several investigators to measure the blood flow velocity and the velocity

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profile in the coronary arteries using a hot-film anemometer[4] and an ultrasonic pulsed Doppler velocimeter[5]. It is difficult, however, to evaluate the precise velocity profile in the coronary artery because of the relatively large sample volume for the measurements.

In order to measure an instantaneous coronary blood flow velocity in a small sample volume, we have developed a laser Doppler velocimeter using a small optical fiber[6,7]. After the fundamental experiments to evaluate the accuracy of the present method, we attempted to obtain the detailed flow velocity profiles in the canine coronary arteries.

METHODS

1. System of laser Doppler velocimeter with an optical fiber.

The experimental set-up of the laser Doppler velocimeter with an optical fiber is shown in Fig. 1. The basic optical system is the "reference mode". The He-Ne laser beam (632.8 nm, 10 mW) is divided by a beam splitter. Half of the initial light passes the beam splitter and is focussed onto the entrance of an optical fiber with an objective glass and transmitted through the fiber into the blood stream. The optical fiber used in the present study is a

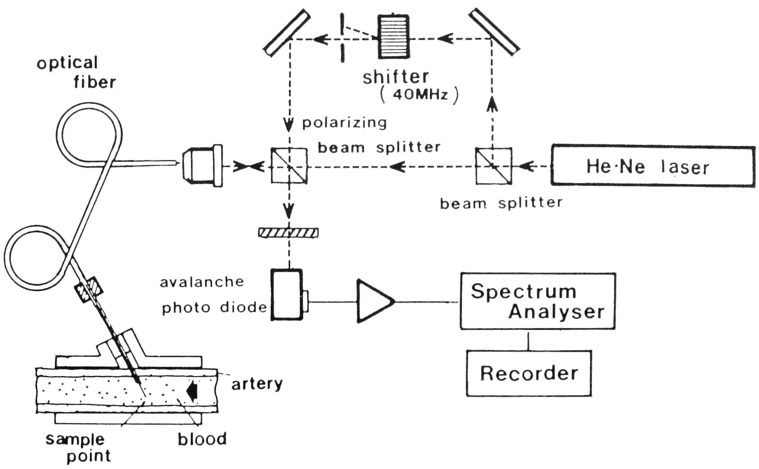

Fig. 1. Experimental set-up of a Laser Doppler Velocimeter.

graded-index multimode fiber with a diameter of 0.1 mm. The back-scattered light by flowing erythrocytes is collected partly by the same fiber and transmitted back to its entrance. The other half of the beam divided at the beam splitter is used as reference beam. A frequency shifter is interposed in the path of the reference beam to differentiate the reverse flow from the forward. The optical heterodyning is made by mixing this reference beam with the Doppler shifted beam by the moving erythrocytes. An avalanche photodiode (APD) is employed as a photodetector to obtain a high signal/noise ratio. The photocurrent from the APD is fed into a spectrum analyser to detect the Doppler shift frequency. Theoretically, the Doppler shift frequency Δf of the system can be written as :

$$\Delta f = 2\ nv\ \cos\theta\ /\ \lambda \quad \cdots\cdots\cdots\cdots \quad (1)$$

where v is the blood flow velocity, n the refractive index of blood, θ the angle of incident beam to the blood stream and λ the wave length of the laser beam.

2. Blood flow velocity measurement in coronary circulation of dogs.

Five adult mongrel dogs were used for the experiment. The dogs were anesthetized with sodium pentobarbital (30 mg/Kg) which was administered intravenously with heparin (500 units/Kg) to prevent coagulation. The chest was opened in the left fifth intercostal space and the lungs were ventilated with room air through an endotracheal cannula by means of a Harvard respirator pump. The left circumflex coronary artery (1.8–2.8 mm outer diameter) was exposed, after which fat and connective tissue were removed. Then a small plastic tube sustainer (1.8–3.0 mm inner diameter, 0.5 mm thick and 5.0 mm length) was placed around the vessel to fix the fiber tip at an appropriate position in the blood vessel (Fig. 2). The optical fiber was inserted into the vessel through the sustainer with the aid of a small needle. The incident angle of the laser beam was held at 60° to the longitudinal axis of the vessel. The

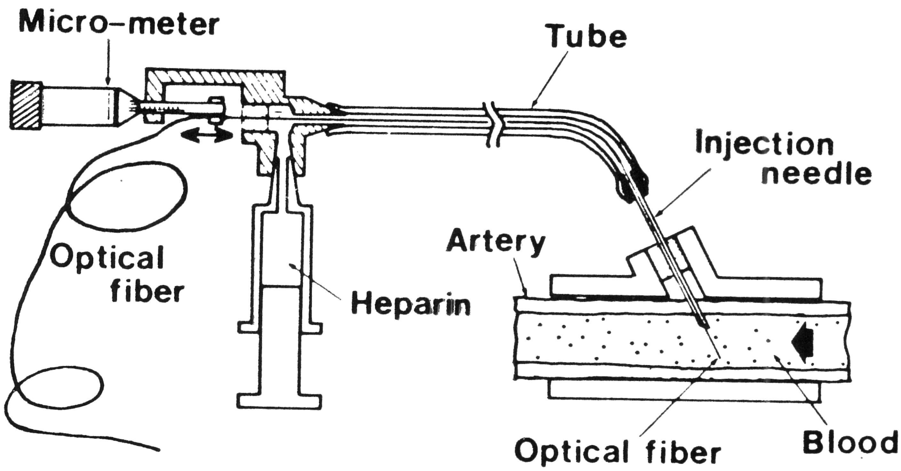

Fig. 2. Illustration of a small sustainer to fix the fiber tip to the coronary artery and a micrometer to control the position of the fiber in the vessel

position of the fiber tip to the vessel wall was determined by the disappearance of the Doppler shift signals. The needle was pulled back to the near wall of the vessel to make fiber tip free within the vascular lumen. Then the fiber tip was traversed stepwise across the vessel under the control of a micro-manipulator and the blood flow velocity was measured at each sampling point. The left ventricular and the aortic pressures were measured by using Statham P37 transducers through stiff vinyl catheters. Then, the velocity waveform at each sampling point was digitized by tracing with a sonic digitizer and was stored on magnetic tapes. By keying on the electrocardiogram, the velocity profiles were sequentially reconstructed during one cardiac cycle.

RESULTS

1. Evaluation of the accuracy of the present measurement.

To evaluate the accuracy of the blood flow velocity measurement by the present method, known blood velocities in a circular groove on a rotating turn table were measured at various revolution speeds. The frequency intervals ΔF between 40 MHz and the cut-off frequencies Fcut were plotted against the known blood velocities (Fig. 3). Note that the ΔF showed an excellent linear relationship with the known blood velocity both for the forward and the reverse flow ($r = 0.998$). The ΔF values also showed good agreement with the value of the frequency shift calculated from the known blood flow velocity using Eq(1). This indicates that the blood flow velocity can be measured accurately from the ΔF. In practice, the ΔF was read automatically every 5 msec and it was recorded as time sequential data.

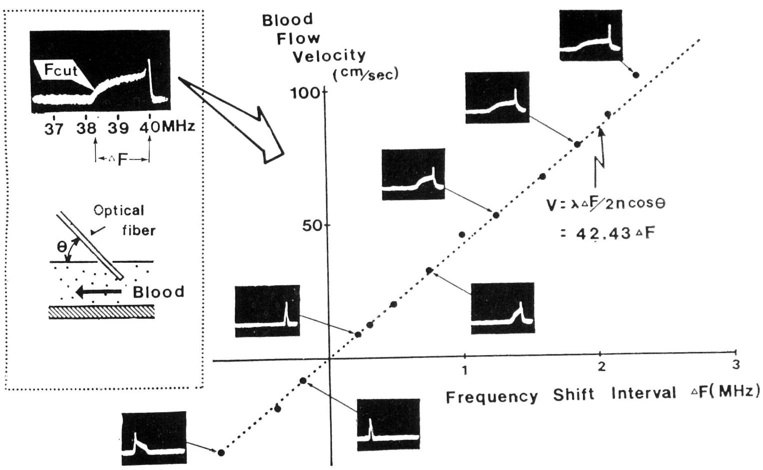

Fig. 3. Linear relation between the known blood velocities and the Doppler shift frequencies.

2. Coronary blood flow velocity.

The blood flow velocity measured near the center line in the coronary artery showed a diastolic dominant pattern which is a characteristic of the coronary arterial flow[8]. A typical example is shown in Fig. 4. Usually two peaks were observed on the flow velocity pattern in early and in late diastole. The early diastolic peak of blood flow velocity appeared during the period of isovolumic relaxation of the left ventricle in which the myocardial compressive force decreases significantly. The late diastolic peak was observed at a time just prior to isovolumic contraction of the left ventricle. This late diastolic peak disappeared when ventricular pacing was performed under the atrial arrest

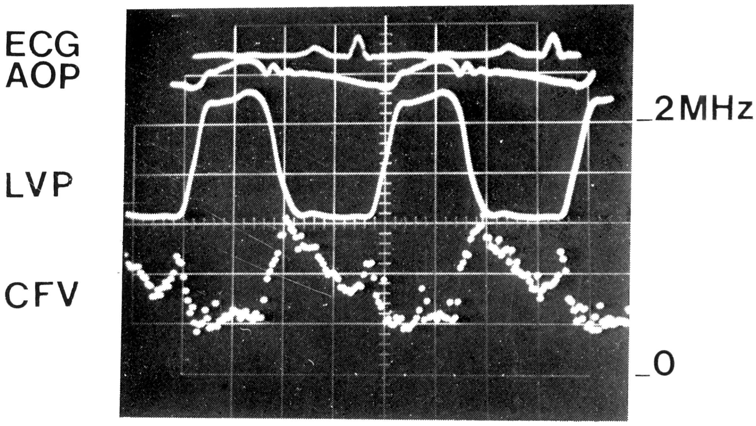

Fig. 4. Blood velocity pattern (CFV) obtained in the left circumflex coronary artery of a dog.

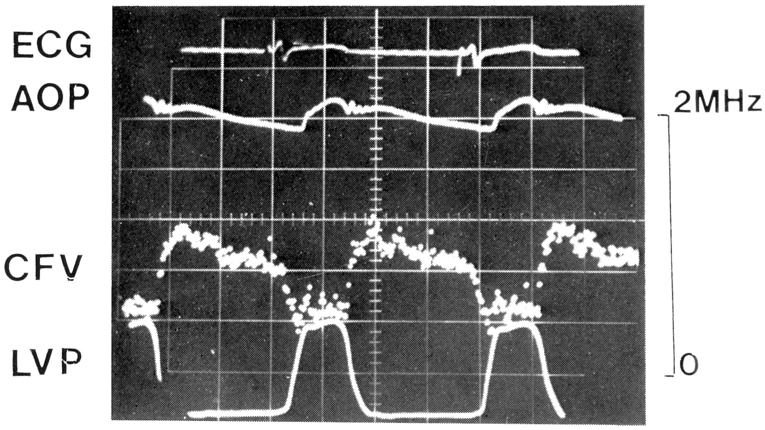

Fig. 5. Blood velocity pattern obtained under the ventricular pacing during the atrial arrest.

induced by the vagal stimulation (Fig. 5). In general, a small peak in early systole was observed near the center line of the coronary artery. As the fiber tip was traversed toward the vessel wall, the flow velocity decreased especially in late diastole (Fig. 6) and the velocity component in early diastole also decreased at sampling points very close to the vessel wall.

The flow conditions near the center line of the left circumflex coronary arteries were characterized by peak Raynolds numbers of 280–420 and unsteadiness parameters of 1.6–2.4, since the overall ranges of peak blood flow velocity and heart rate ran from 49 to 61 cm/sec, and from 86 to 190/min, respectively.

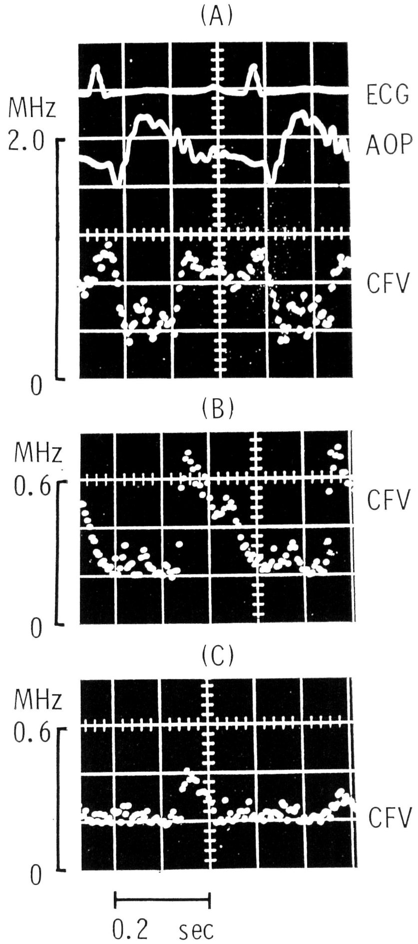

Fig. 6. Blood velocity patterns obtained in the left circumflex coronary artery. A) is obtained in the vicinity of the center line of the coronary artery : B) and C) near the vascular wall. Notice difference in calibrations.

A set of velocity profiles in the proximal portion of the left circumflex coronary artery was shown in Fig. 7. For convenience, the sequence of the profiles was initiated from 80 msec after the peak of the R wave in the electrocardiogram. It is easier to understand the characteristics of coronary blood flow velocity profiles by introducing the three dimentional display. Note that there exist three peaks in early systole, in early and in late diastole. In this case the velocity profile at each sampling time showed a parabolic type configuration, while in some other cases, blunter velocity profiles were observed.

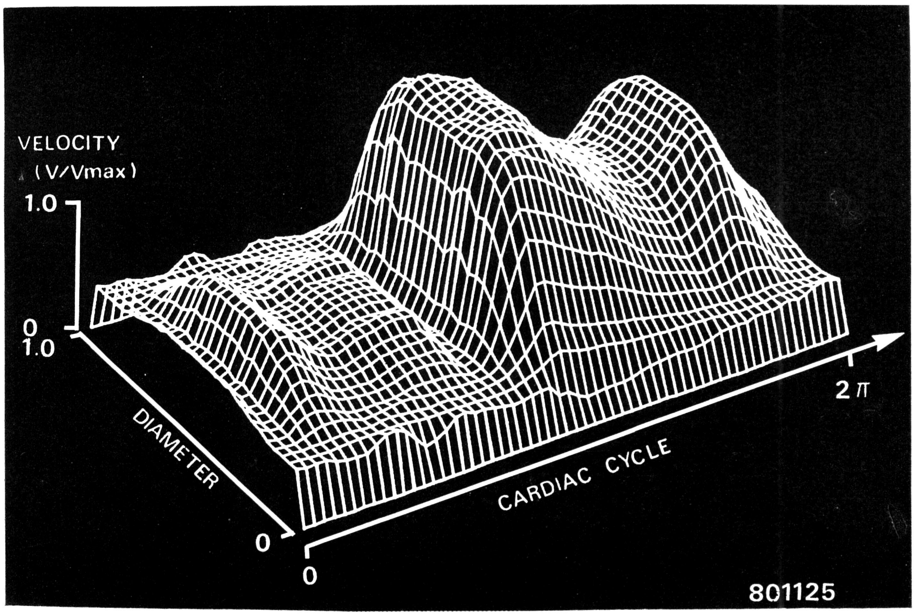

Fig. 7. A set of velocity profiles in the proximal portion of the left circumflex coronary artery of a dog.

DISCUSSION

Tanaka and Benedek[9] demonstrated the feasibility of using an optical fiber as a laser guide into the blood vessel with a non or low-transparent wall. They succeeded in measuring the average blood flow velocity of a rabbit femoral vein in a relatively large sample volume. In the present study, our efforts have been directed toward developing the laser Doppler velocimeter with an optical fiber to be able to measure instantaneous arterial blood flow velocity in a small sample volume[10].

The laser light transmitted into the blood, is attenuated by absorption and multiple scatter on the path to and from the flowing erythrocytes. In our system, the maximal distance detectable by the back-scattered light amounted to about 0.25 mm from the fiber tip in the blood. This value is compatible with the data reported by Anderson[11]. Since the blood velocity components in the vicinity of the fiber tip were eliminated by taking the ΔF, the axial sampling point will be in less 0.25 mm from the fiber tip. The cross-sectional area for projected volume can be considered to be almost equivalent to that of the core of fiber ($\pi \times 0.0025$ mm^2).

So far as we aware, this is the first report on detailed measurement of blood flow velocity in the left circumflex coronary artery of the dog. The waveform of the blood flow velocity near the center line of the artery showed a good agreement with the results of the theoretical calculations for the dog coronary artery by Atabek et al.[12]. The two peaks at the early and the late diastole were observed in the waveform of the blood flow velocity. Since the period of the early diastolic peak coincides with the isovolumic relaxation of the left ventricle, it is probably related to the abrupt decrease in the intramyocardial compressive force. Although it is difficult to explain explicitly the cause of the presence of the late diastolic peak, the atrial contraction will be concerned with the peak formation, since this peak vanished when the ventricular pacing was performed.

Nerem et al.[4] measured the coronary blood flow velocity of the horse by a hot-film anemometer. They also observed the presence of these oscillatory velocity components in the early and the late diastolic phase, while the systolic component of the horse coronary artery was much larger than that of the dog. These peaks, however, were not attributed to random oscillations of velocity waveform, since the occurrence of peaks in our experiment was consistent through different cardiac cycles. Their paper is apparently the only report on the in vivo measurement of the velocity profile in the coronary artery. Comparing the velocity profiles shown in the present study with those in the horse coronary artery, the latter showed high kurtosis in the curvature and lower velocity gradient at the vicinity of the vascular wall. This may be attributed to the species differences of the experiments. It should be also emphasized that our measurements of the velocity profiles were made at several decade sample points in the vascular lumen, whereas the velocity measurements were carried out at six to eight points in the entire lumen in Nerem's report.

In conclusion, we have found that the laser Doppler velocimeter using an optical fiber represents a promising method for the measurement of the pulsatile flow velocity in a small sample volume, and especially for the analysis of the precise flow fields in the coronary artery.

Acknowledgment

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