Blood Flow Measurements in Studies of Macro- and Microcirculation

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Ultrasound blood flow transducers were tested by using pulsating flows in a dynamic test system with Pito tube. Simultaneous studies of rat ascending aorta with a Doppler strip detector (13 MHz) and ultrasound catheter (33 MHz) produced a 10% discrepancy of the results. Here we describe a computing unit to estimate the volume flow rate in biomicroscopic studies. The value of blood flow rate estimated with a 38.5-MHz Doppler probe and diameter of the microscopically examined vessel were inputted into a computer for real-time processing. Blood flow rate in microvessels of rat mesentery and cremaster muscle was 10-700 nl/sec.

Key Words: *Pito tube; ultrasound; blood flow probe; microcirculation*

Blood flow velocity, volume flow rate, and pulsating blood flow waveform are the major characteristics of blood circulation. Industrial blood flow probes are usually calibrated in units of blood flow rate and used to study blood supply to organs and various parts of the cardiovascular system and evaluate the performance of the left and right cardiac ventricles.

Studies of circulation usually involve methods for estimation of blood flow velocity. Blood flow velocity in magistral vessels is characterized by a narrower range of changes compared to flow rate. This parameter varies from units to several tens of cm/sec. The value of blood flow velocity reflects the type of blood flow. The blood flow waveform is recorded to study phases of cardiac activity and expressed in units of flow velocity. Acceleration of cardiac output is recorded in investigating blood flow in the ascending aorta with flow velocity probes. It serves as an important criterion for evaluation of contractile activity of the myocardium. Blood flow velocity can be determined from blood flow rate at a known diameter of the vessel. The accuracy of measurements depends on the mean velocity in the flow profile. A complex shape of the flow profile is characteristic of the arterial system (particularly in the aorta) [12].

A dynamic test system was constructed at the Bioengineering Laboratory (Institute of General Pathology and Pathophysiology) to analyze the recording of pulsating flows with blood flow probes [9]. Pulsating flows were produced by opposite movements of a piston in the Pito tube. The piston was moved by a slider-crank mechanism with a DC motor drive. The frequency of movements was brought to 10-15 Hz. A differential manometer served as the major measuring element of the Pito tube, which recorded the signals from receiving tubes of static and dynamic pressure. The flow profile was determined with a movable receiver of dynamic pressure. The vector of the mean velocity in the parabolic profile was localized at a distance of $R\sqrt{3}$ from the axis. Since the piston had a known diameter and limited range of movements, the probes were calibrated in units of the volume flow rate using a dynamic test system. Piezoelectric cells of ultrasound tubes from the system to estimate the difference between the time of ultrasound distribution along and against the flow were mounted in an enclosing case of the Pito tube. The tube also included a Doppler-effect system.

Ultrasound tubes of the system for estimating the difference between the time of distribution of short

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ultrasound pulses along and against the flow integrate the speed profile. Therefore, volume characteristics can be calculated from the linear speed. The error in input measurements of the volume flow rate did not exceed 5%. Strip detectors of this system were calibrated on animals using an artificial circulation device.

The performance of an ultrasound catheter was studied in the Pito tube. Accurate reproduction of the pulsating flow waveform and high noise immunity of the pulse method allowed us to construct an intravascular probe for estimating blood flow rate, which was extensively used for the diagnostics of heart defects [3].

Single- and dual-element Doppler probes were subjected to bench trials. Milk served as the test fluid. The study of dual-elements probes with separate functions of emission and detection yielded a significant spread of the results (25%), which depended on ultrasound frequency, size and sensitivity of piezoelectric cells, and other factors. Blood flow velocity estimated by the device was similar to a maximum value of the flow profile. Ultrasound frequency was increased to improve the device performance. The Doppler signal was processed on a device to estimate the Doppler spectrum density. This approach allowed us to decrease the error in measurement and perform high-accuracy recording of the pulsating flow waveform. The error in measurement by a dual-element Doppler probe at 8 MHz was 10-12%. Further correction of the results was performed in a simultaneous study with pulse detectors fixed on dog abdominal aorta.

Dual-element Doppler probes were tested with various objects. In experiments of O. S. Medvedev, detectors of an ultrasound device and Nicotron electromagnetic blood flow meter were placed on the carotid artery in cats. Blood flow was produced by a flow meter pump localized proximal to detectors. The discrepancy of results was 12-15%. Previous studies compared the results of cardiac output measurement in rats with strip detectors (operating frequency 8 MHz) and isotope-labeled microspheres [8]. A similar discrepancy was revealed in indications of the devices.

Single-element Doppler probes for ultrasound emission and detection were constructed to study blood circulation in vessels with a diameter <1 mm. These probes operate in the continuous and impulse regimen. Such studies also involve an ultrasound device equipped with volume flow rate probes, which estimates the difference between the time of ultrasound distribution along and against the flow. Doppler probes have smaller size, include a highly elastic connecting wire, and are more sensitive in studying blood flow velocity [4]. Bench trials showed that single-element Doppler probes provide a less accurate measurement than dual-element Doppler probes. Emission and detection in single-element probes are realized via the same ultrasound beam. There is no angular dispersion between piezoelectric cells. These characteristics explain maximum sensitivity of single-element probes in recording the echo signal. Blood flow in compact single-element strip detectors is determined by the minimum divergence zone of the ultrasound beam (Frenel zone), which corresponds to the maximum concentration. These data provided the basis for construction of strip, contact, and intravascular single-element blood flow detectors. High sensitivity of these detectors was achieved by the increase in ultrasound frequency. The use of high-frequency ultrasound (27 MHz) allowed us to construct strip microdetectors for estimating blood flow rate in vessels with a diameter of 200 μ [7].

A Doppler strip detector and intravascular catheter were simultaneously studied in rats [5]. A strip detector operating at 13 MHz was calibrated in units of blood flow rate and placed on the ascending aortic arch. An intravascular ultrasound catheter (33 MHz) was inserted into the ascending aorta through the left carotid artery. We compared the maximum rate of cardiac output, mean flow rate in the ascending aorta equivalent to minute volume, and stroke volume estimated by integration of the cardiac output curve area. The scatter of data estimated by various systems did not exceed 10%. It was concluded that an intravascular ultrasound probe can be used to determine variations in cardiac output under closed chest conditions.

Contact detectors were used to study coronary [7] and cerebral circulation in rats [10].

Ultrasound devices were successfully used to study microcirculation. Special devices and biomicroscopic probe were constructed for this purpose [6]. The bio-

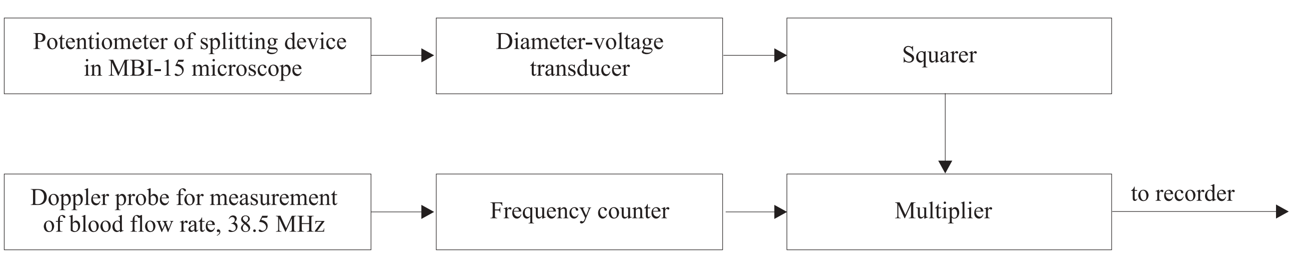

Fig. 1. Flow diagram of a device for measurement of blood flow rate in microvessels.

microscopic probe operated at a frequency of 38.5 MHz, and its electronic module provided a measurement of blood flow velocity in mm/sec.

A flow rate probe for the microcirculatory bed was equipped with an ultrasound beam-focusing acoustic lens to increase the selectivity and accuracy of measurements. We studied blood flow velocity and diameter and lumen of the microvessel (MBI-15 microscope, image-splitting technique) [1]. Measurement of blood flow velocity in the microvessel and study of its diameter allowed us to calculate blood flow rate:

$$Q=V\times\frac{\pi D^2}{4}\times10^{-3},$$

where Q is blood flow rate (nl/sec), V is blood flow velocity (mm/sec), and D is diameter of the microvessel (μ).

Microcirculation was studied in vessels of the mesentery (standard object), *cremaster* muscle, and brain cortex of rats [2]. When blood flow velocity varied from units to several tens of mm/sec, the volume flow rate corresponded to 100-1000 nl/sec.

The study of vasomotions showed that changes in blood flow coincide with or are inconsistent with variations in the diameter of microvessels [11]. An analog computing device was constructed at the Bioengineering Laboratory (Institute of General Pathology and Pathophysiology) to perform on-line processing of changes in blood flow rate in the microcirculatory bed (Fig. 1). The device had several elements of analog computers. The calculating module included an analog multiplier and squarer. The signal from the electric circuit of the image splitter (MBI-15 microscope) was inputted to a squarer and multiplied by the signal generated in a frequency detector of the Doppler device. A calculating module was constructed from microcircuits of series 140 UD 6 and 525 PS2. The instrumental error did not exceed 2%.

Flow rate measurements were calibrated by introduction of the calibration signal for microvessel size (object micrometer, scale interval 10 μ) and signal of a Doppler frequency counter in a calculating module. The frequency of input voltage in a Doppler frequency counter corresponded to a speed of 10 mm/sec.

The studies of microcirculation demonstrated high effectiveness of the complex method to investigate microhemodynamics. This method allows simultaneous measurements of blood flow velocity, volume flow rate, and size of the microvessel (Fig. 2). On-line recording of blood flow allowed us to estimate changes in the ratio between blood flow velocity, volume flow rate, and diameter of the microscopically examined vessel (Fig. 3).

The study with blood flow probes of various systems reflects high informativeness of the ultrasound method. This method provides blood flow measurement through the wall of blood vessels and stable operation of intravascular probes. The use of high-frequency ultrasound increases the instrument sensitivity, decreases the size of probes, and allows us to estimate microcirculatory characteristics in several tens of nl/sec (in combination with optical systems).

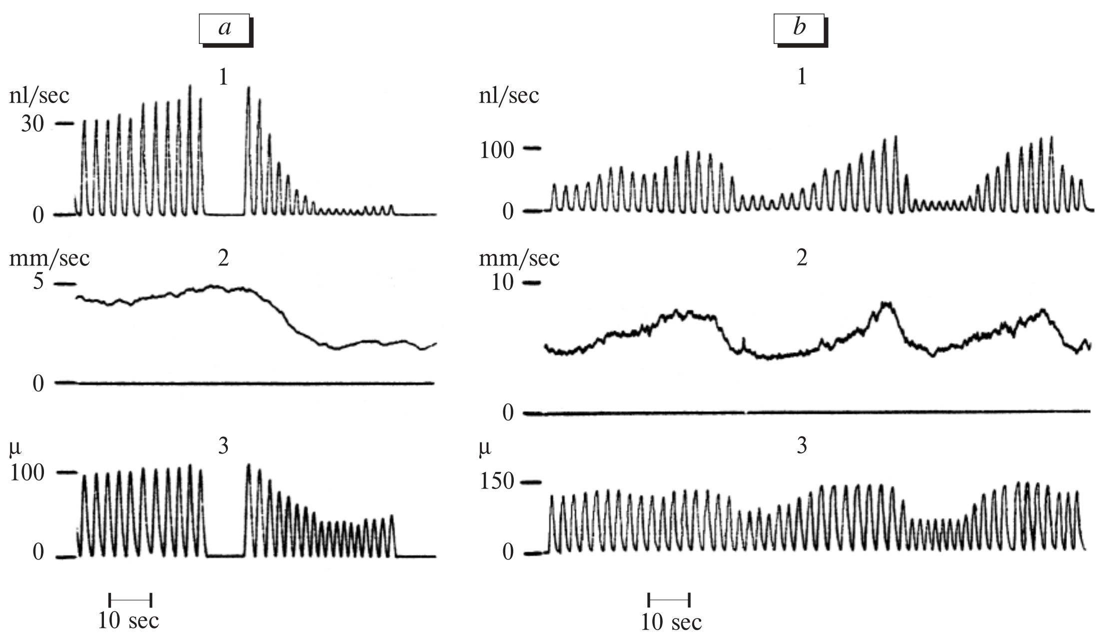

Fig. 2. Simultaneous measurement of blood flow velocity, volume flow rate, and diameter of rat mesenteric arteriole. Reaction to application of 0.8 μg epinephrine (*a*). Reaction of microvessel and changes in microcirculation produced by hyperthermia (*b*). Here and in Fig. 3: blood flow velocity (*1*), volume flow rate (*2*), and diameter of microvessel (*3*).

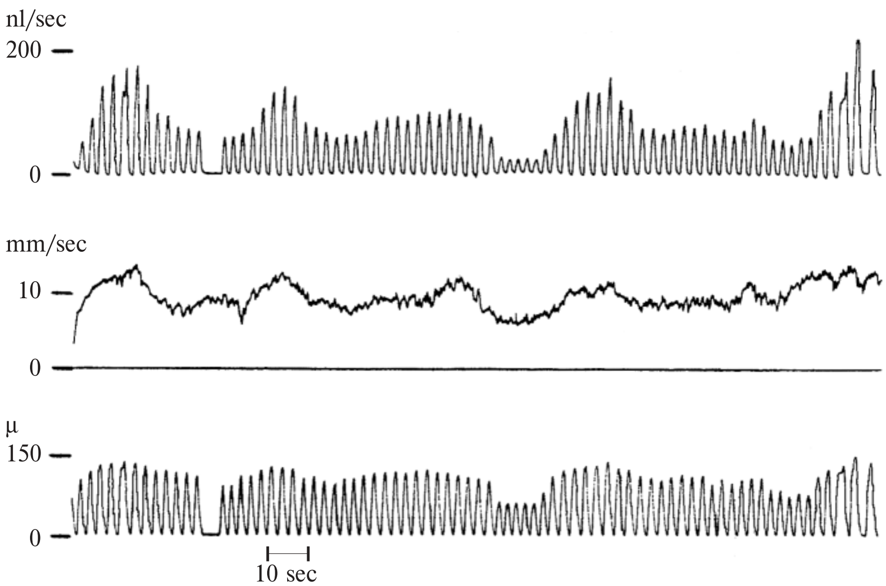

Fig. 3. Volume flow rate and blood flow velocity in the microcirculatory bed during vasomotions of rat mesenteric artery.

Our results indicate that ultrasound devices are highly effective in studies of systemic and organ circulation and microcirculation.

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