ARCHIVES OF ACOUSTICS
4, 4, 359-366 (1979)

SIMPLIFIED AUTOMATIC MEASUREMENTS OF BLOOD FLOW BY THE ULTRASONIC PULSE DOPPLER METHOD

ANDRZEJ NOWICKI

Institute of Fundamental Technological Research (00-049 Warsaw)

A new simplified method of measurement and recording of time averaged blood flow profiles in superficial arteries in man, using an ultrasonic pulse flowmeter UDP-30, is described.

The results of model investigations of flows in tubes, and subsequently preliminary results of measurements in carotid and femoral arteries are discussed.

1. Introduction

Of all noninvasive methods for diagnosis on the circulation system, the ultrasonic pulse Doppler method is particularly noteworthy. At present, four devices of this type are produced in the world: Mark I by ATL, United States, Mavis by GEC-Medical, Great Britain, Echovar Doppler Pulsée by Alvar Electronic, France, and UDP-30 by ZD "Techpan" in Poland. One should mention the large number of laboratory devices being developed in many renowned scientific and research centres. This requires development of practical — and convenient in clinical use — measuring and recording methods and their adequate and inambigous interpretation.

2. The principle of automatic measurement of flow profiles

The principle of the pulse Doppler blood flowmeter was described in [3] where it was shown that knowing the angle θ between the direction of an ultrasonic beam and a blood vessel, the diameter of the vessel investigated and the blood flow velocity profile can be determined. The diameter can be expressed by the formula

$$d = \frac{ct}{2} \sin\theta, \tag{1}$$

where t is the arrival time between the front and the rear walls of a blood vessel, c — the ultrasound propagation velocity in blood (≈ 1550 m/s). The blood flow velocity can be determined from the formula

$$V = \frac{f_d c}{2 f_n \cos\theta}, \tag{2}$$

where f_d is Doppler frequency equal to the difference between the frequency of a transmitted signal and that of a signal scattered by blood cells, and f_n is the transmitted signal frequency.

Both the vessel diameter and the flow velocity are a function of the angle θ which is usually unknown. It is relatively easy to determine the angle θ for vessels directly under the skin and parallel to the skin plane. With respect to the deeper vessels it is necessary to use a more complicated measurement technique, using a special double-transducer head permitting the angle θ to be determined by way of triangulation [1].

Most pulse Doppler blood flowmeters are equipped with an electronic analyzing gate with an adjustible delay time relative to the transmitted pulse [3]. Thus the measurement of the flow velocity profiles and the vessel diameter can be taken by a manual adjustment of the analyzing gate delay.

The technique for measurement of flow profiles, using the abovementioned devices, and the calculation of the blood flow rate from profiles obtained are time consuming, making complex clinical measurements difficult sometimes; in particular, during operations.

The automatic shift of the analyzing gate across the vessel investigated to a great extent accelerates the investigation and the recording of results [4].

With an automatic, directly adjustible delay of the analyzing gate B, the distribution of the curve for the blood flow velocity (averaged in time) from the velocity 0 at the front vessel wall through the maximum volocities in the center of the vessel to again the velocity 0 at the rear wall, is shown on the recorder paper tape (Fig. 1). Knowing the velocity u_1 of the automatic delay of the analyzing gate B, the speed u_2 of the paper tape shift, and lengths of the sections S_1 and S_2 between the zero flow values for the transducers P_1 and P_2, respectively, the vessel diameter can be determined from the formula

$$d = \frac{u_1}{u_2} S_1 \sin\theta, \tag{3}$$

where

$$\theta = \frac{\varphi}{2} + \tan^{-1}\left(\frac{S_2 - S_1}{S_2 + S_1} \tan\frac{\varphi}{2}\right), \tag{4}$$

φ being the angle between the transducers P_1 and P_2.

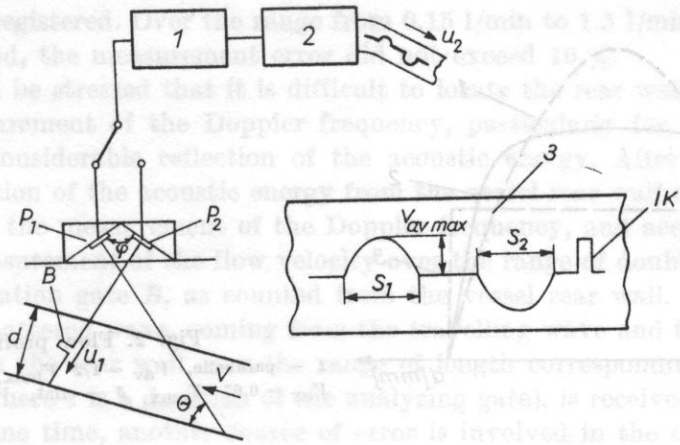

Fig. 1. The principle of automatic blood flow measurement

1 – ultrasonic pulse Doppler flowmeter, *2* – recorder, *P1*, *P2* – ultrasonic transducers, *B* – analyzing gate, u_1 – automatic delay velocity of analyzing gate, u_2 – shift velocity of recorder tape, *3* – recording of time averaged profiles of blood flow velocity obtained by means of an ultrasonic beam produced by transducers P_1 and P_2 respectively, *IK* – calibration impulse

In the case of operational investigations, the angle θ between the ultrasonic beam and the vessel is known, and for the heads used it equals 67°. For such an angle expression (3) takes the form

$$d = 0.91 \frac{u_1}{u_2} S_1. \tag{5}$$

The device is equipped with a system for recording a standard Doppler signal (the so-called calibration impulse *IK*), the amplitude of which corresponds to the Doppler frequency $f_{dK} = 1000$ Hz. For $\theta = 67°$ the calibration impulse amplitude corresponds to the standard calibration velocity $V_K = 30$ cm/s. Knowing the magnitude of the calibration impulse, the maximum mean (time averaged) velocity amplitude of blood flow, $\overline{V}_{max}$ can be read from the recorder paper tape. Accordingly, the blood flow rate is defined by the formula

$$Q = 0.67\, \overline{V}_{max} \frac{\pi d^2}{2}. \tag{6}$$

The numerical coefficient 0.67 in (6) has been obtained experimentally for carotid and femoral arteries by comparison of time averaged flow profiles measured using the above method with the distribution of instantaneous profiles. Introduction of this coefficient can also be justified physically, the blood flow profile in vessels usually being neither parabolic nor flat but lying between the two (Fig. 2). In the case of laminar flow (parabolic profile) the mean flow velocity is equal to half its maximum value. For turbulent flow the profile becomes considerably flattened so that the mean velocity value nears its maximum value.

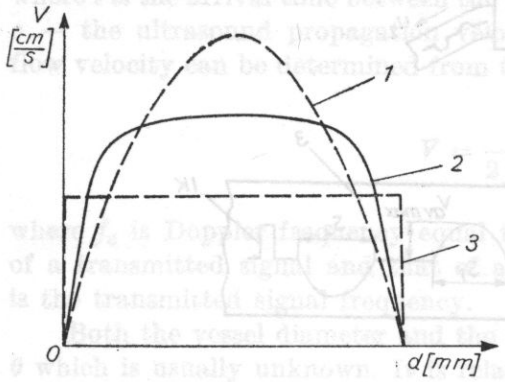

Fig. 2. Flow profiles
1 – parabolic, $V_{av} = 1/2\ V_{max}$, *2* – flattened, $V_{av} = 0.67\ V_{max}$, *3* – flat, $V_{av} = V_{max}$

Experimental investigations were carried out *in vitro* on a laboratory model, assuming a stationary liquid flow in a plexiglass tube with a diameter $d = 8$ mm and length $l = 100$ cm.

Starch suspension in a mixture of distilled water and glycerine at the ratio of 100 g starch to 10 l liquid was used. The kinematic viscosity of the mixture was equal to $2.2 \cdot 10^{-2}$ St. The flow in the velocity range corresponding to the Reynolds number of 200 to 1700, i.e. in the range of laminar flow, was inve stigated. Selected measurement results are shown in Fig. 3.

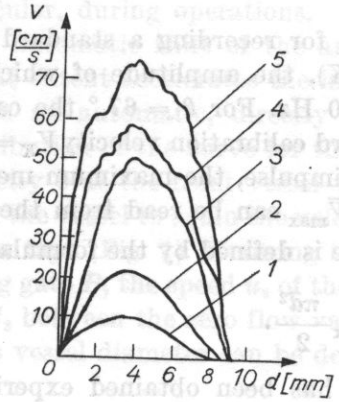

Fig. 3. Flow profiles recorded for various rates Q
1 – $Q = 0.15$ l/min., *2* – $Q = 0.4$ l/min., *3* – $Q = 1$ l/min., *4* – $Q = 1.2$ l/min., *5* – $Q = 1.4$ l/min.

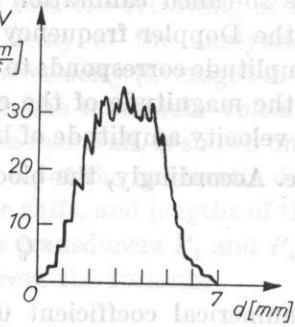

Fig. 4. An example of time averaged flow profile recorded for the external carotid artery

The results obtained were verified against the actual flows in the tube, comparing the flow rates determined by measuring the volume of a liquid flowing out of the tube in a time unit with the flow rates calculated from the

flow profiles registered. Over the range from 0.15 l/min to 1.5 l/min of the flow rates measured, the measurement error did not exceed 10 %.

It should be stressed that it is difficult to locate the rear wall of the tube by the measurement of the Doppler frequency, particularly for tubes whose walls cause considerable reflection of the acoustic energy. After JORGENSEN [2] the reflection of the acoustic energy from the vessel rear wall can influence the results of the measurement of the Doppler frequency, and accordingly the results of measurement of the flow velocity over the range of double the length of the observation gate B, as counted from the vessel rear wall. Because the energy of a scattered wave, coming from the travelling wave and from the one reflected from the rear wall over the range of length corresponding to a time interval 2τ (where τ is a duration of the analyzing gate), is received by a receiver at the same time, another source of error is involved in the measurement of the Doppler frequency. In the case of blood vessels, the effect is usually very small, because the reflection of the acoustic energy from the boundary of the vessel wall and tissue is slight due to close values of respective acoustic impedances.

3. Measurements of blood flow in carotid and femoral arteries in man

Preliminary investigations of the method were carried out, measuring the flow in the external carotid artery in seven healthy young men. The diameters of vessels measured ranged from 6 to 7 mm and flow rates calculated from formula (6) ranged from 0.2 l/min to 0.25 l/min. These results also agree with the generally accepted values of physiological flows. They also agree with the results of measurement of blood flow in a common carotid artery, ranging from 0.35 l/min to 0.5 l/min under the assumption of twice as much blood flowing in the artery, compared to the internal or external carotid arteries [1,4].

Figs. 5a and 5b show examples of flows recorded in the common carotid and superficial femoral arteries in a healthy man (J.K., aged 57). The vessel diameters measured were 6 mm for the carotid artery and 6.5 mm for the femoral artery, and the flow rates calculated were 0.38 l/min. and 0.24 l/min. respectively. The recordings in Figs. 5a, b — *1*, *2* show curves for instantaneous and mean velocities, respectively, measured in the vessel center (fixed analyzing gate).

The recordings in Figs. 5a, b — *3*, *4* show distributions of instantaneous and mean velocities across the vessel with an automatically shifting analyzing gate. The shape of recordings obtained for the mean velocity distribution (Fig. 5, a, b — *4*) is irregular, particularly for the femoral artery where the flow pulsation effect was not sufficiently filtered This would suggest insufficient efficiency of the filter which averages the signal proportional to the blood flow velocity However, an increase in the filter time constant would greatly distort

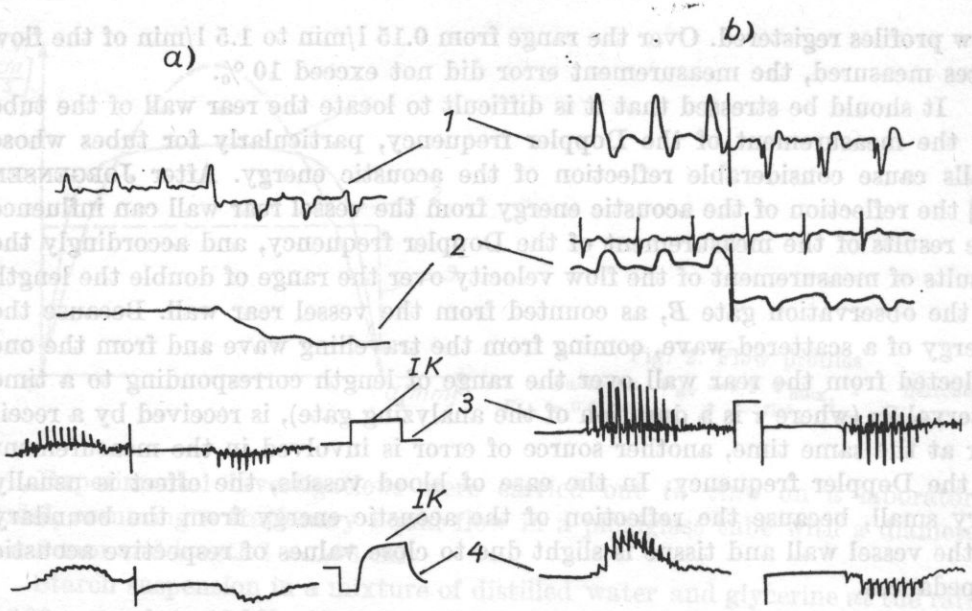

Fig. 5. Flow velocities recorded for (a) carotid artery and (b) femoral artery
1 – instantaneous flow velocities in the vessel centre, *2* – mean flow velocities in the vessel centre, *3* – instantaneous flow velocity profiles, *IK* – calibration pulses

the registered profile, particularly for the vessel front and back walls (long rise and drop times for a flitered signal). Expressed in the asymmetry of the profile relative to the vessel center, this effect is already visible in the currently used filter with a time constant of 3 s. The effect of the filter is also seen in the fuzzy profile contour, particularly at the real wall. Therefore, a more exact measurement of the vessel diameter is obtained, taking into consideration the recording lengths (S_1 and S_2 in Fig. 1) for the instantaneous velocity distribution (Figs. 5a, b – *3*).

4. Conclusions

The present method, although it accelerates the recording and interpretation of measurements of the blood volume flow, in the case of measurements in vivo can introduce the measurement error of about 30 %, which results from the shape of the time averaged flow profile (cf. Fig. 2), accepted under a simplified assumption. This error seems small for large vessels with a diameter larger than 5 mm. For small vessels with diameters of 2 to 3 mm, the flow profile is usually very much flattened, and accordingly the blood flow rates calculated from formula (6) will be underrated. It seems that the main advantage of the method is a direct recording of the vessel diameter on the recorder paper tape, permitting an easy estimation of the obstruction degree and a direct comparison of the vessel diameters before and after removal of the obstruction.

References

[1] K. Borodziński, L. Filipczyński, A. Nowicki, T. Powałowski, *Quantitative transcutaneous measurements of blood flow in carotid artery by means of pulse and continuous wave Doppler methods*, Ultrasound in Medicine and Biology **2**, 189-193 (1976).

[2] J. E. Jorgensen, D. N. Campau, D. W. Baker, *Physical characteristic and mathematical modelling of pulse ultrasonic flowmeter*, Med. and Biol. Engng. **12**, 4, 404-420 (1973).

[3] A. Nowicki, *Ultrasonic pulse Doppler method in blood flow measurement*, Archives of Acoustics **2**, 4, 305-323 (1977).

[4] A. Nowicki, *Automatic simplified measurement of blood flow by means of ultrasonic pulse Doppler method*, Digest of papers of 1st Mediterranean Conf. on Med. and Biol. Engng., Vol. 1, 4-17, September 12-17, Sorrento 1977.

Received on December 19, 1978