METHODS

An Experimental Study of the Determination of Volumes of Turbulent Blood Flows by Doppler Echocardiography

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Translated from *Byulleten' Eksperimental'noi Biologii i Meditsiny*, Vol. 121, No. 4, pp. 477-480, April, 1996
Original article submitted December 5, 1995

An experimental model is used to reproduce high-speed unsteady turbulent flows of small diameter (3 to 5 mm). The spectra of the simulated flows were recorded by the continuous Doppler method and their volumes were estimated as the product of the velocity-time integrals times the cross-sectional area of the tubes. The flow volumes were too high in comparison with the specified values in all cases, necessitating the use of correction factors. The factors were inversely proportional to the flow velocities, and thus to the turbulence (as is evident from the Reynolds turbulence equation). For the range of maximum velocities of turbulent intracardiac flows most frequently occurring in practice (140 to 500 cm/sec) the correction factors were 0.76-0.87. The method may be very helpful in developing noninvasive criteria of the severity of regurgitations, in differentiating these, and in determining the prognosis, particularly for borderline states and combined heart defects.

Key Words: *Doppler echocardiography; turbulent flow*

Doppler echocardiography (DEchoCG) is widely used to determine the stroke volume of heart ventricles; it involves the assessment of intracardiac flows of low velocity or of blood flows in the major vessels [3-11,14].

Quantifying the intensity of intracardiac turbulent flows (TF) is no less important, notably for valvular regurgitation (including asymptomatic subclinical forms), whose detection has greatly increased in recent years due to the introduction of color mapping of flows in echocardiography [3,13]. Regurgitation flows have to be differentiated by their intensity, this often being a difficult task, particularly in cases with combined heart defects. Determining the regurgitation volume would help solve this problem.

We studied the possibility of using continuous DEchoCG for the quantitative assessment of high-speed intracardiac TF.

To do this, we devised an experimental model reproducing high-speed flows similar to valvular regurgitations and intracardiac shunts of small diame-

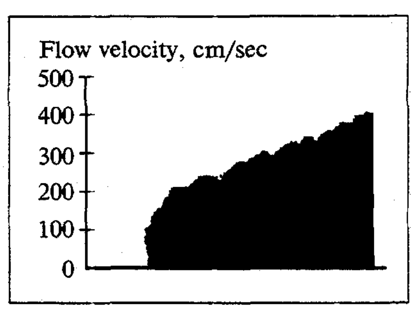

Fig. 1. Spectrum of a simulated flow recorded in the continuous Doppler range, during 1 sec.

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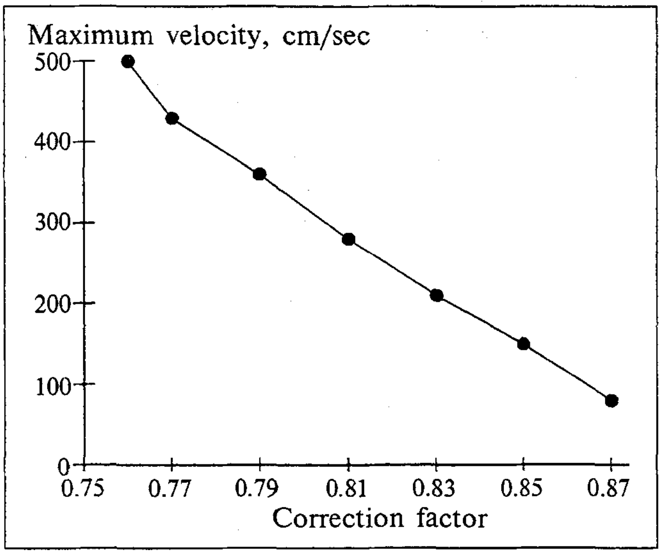

Fig. 2. Relationship between the maximum velocity of flow and the correction factors for experiments with a 4 – mm tube, which most fully reflects the range of maximum velocities of actual turbulent flows. An identical relationship was observed with 3 – and 5 – mm tubes for the same velocities.

ter and we compared the specified TF volumes with the values estimated by DEchoCG in experiments. Correction factors for calculating the volumes of high-speed flows using continuous DEchoCG were determined as the need arose.

MATERIALS AND METHODS

An automated dose injector from a Siemens angiographic device was used in the study; it was connected to tubes of different diameters through which the liquid was delivered in a dosed amount into a plastic 200-ml tank filled halfway. In addition, a Hewlett-Packard Sonos-1000 echocardiograph was used, which can operate in any Doppler range, including color mapping and semiautomatic computer processing of data.

The liquid used was an aqueous solution of glycerol at 37°C, whose viscosity corresponded to the mean viscosity of blood (3-5 rel. units) and was monitored by a viscosimeter. Known amounts of fluid (from 5 to 35 ml) were dosed into the tank in one second through 3-, 4-, and 5-mm tubes at different volumetric velocities. The maximum linear flow rates, recorded by DEchoCG, ranged from 51 to 980 cm/sec, and the majority of the flows simulated (15 out of 21) had maximum velocities from 140 to 505 cm/sec, corresponding to the velocities of intracardiac TF. An acceleration of 1 ml/sec^2 was conferred to the flows, making them unsteady. Since the tank had an outlet, a constant pressure could be maintained in it, and there were no pressure changes to affect the flow velocity characteristics.

In view of the small depth of scanning, a 5 MHz pick-up was used to record the flows. It was so fixed that the ultrasonic beam would be exactly parallel to the flow. The flow spectra were recorded in a constant Doppler range (Fig. 1).

The volumes of the modeled TF were calculated, assuming that the volumetric flow rate V_v (cm^3/sec or liters/min) is equal to the product of the area of the outlet through which it runs A (cm^2) times the mean linear velocity of this flow V_{Lm} (cm/sec): $V_v = V_{Lm} \times A$. As applied to the operating conditions of the

TABLE 1. Calculated Doppler Echocardiographic Parameters of Simulated Flows

Parameters	Series	Experiment						
		1	2	3	4	5	6	7
Specified volume, ml		5	10	15	20	25	30	35
Calculated volume, ml	1	5.8	12.2	19.2	26.3	34.2	42.9	51.5
	2	5.7	11.8	18.1	24.7	31.6	39.0	46.0
	3	5.6	11.4	17.6	23.8	30.1	37.0	44.0
VTI, cm	1	82	172	270	371	482	604	725
Mean flow velocity, cm/sec	2	46	93	143	196	251	309	365
	3	28	57	88	119	151	185	219
Maximum velocity, cm/sec	1	137	268	398	510	678	838	980
	2	76	146	211	280	354	429	501
	3	51	92	135	172	221	264	313
Correction factor	1	0.86	0.82	0.78	0.76	0.73	0.7	0.68
	2	0.87	0.85	0.83	0.81	0.79	0.77	0.76
	3	0.9	0.88	0.85	0.84	0.83	0.8	0.8

Note. Mean values are presented. The experimental series was determined by the diameter of the tube: 1) 3 mm, 2) 4 mm, 3) 5 mm. The number of the experiment in each series was determined by the specified fluid volume.

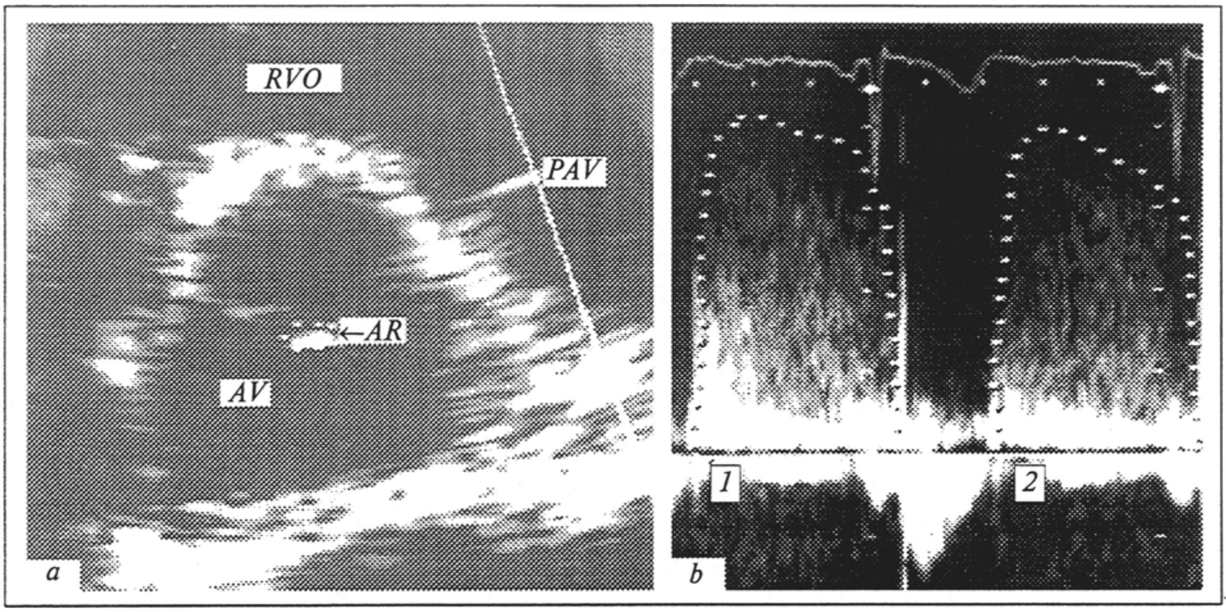

Fig. 3. Doppler echocardiograms of the aortic regurgitation stream. *a*) location of aortic valve along the short axis using the fragment amplification method. *AV*: aortic valve; *PAV*: pulmonary artery valve; *RVO*: right ventricular outlet; *AR*: aortic regurgitation. *b*) spectra of aortic regurgitation flow recorded in the continuous Doppler range with velocity—time integral 255 cm (*1*) and 238 cm (*2*).

heart, the flow is characterized not only by its mean velocity, but also by the duration in a certain phase of the cardiac cycle. This parameter is called the velocity-time integral (*VTI*) (cm) of the flow; it is measured by its DEchoCG curve and reflects the distance covered by the red cells during a given time.

Hence, the blood flow volume (cm^3) was calculated as the product $VTI \times A$ [2,3,7,12,13]. In the experiments the *VTI* of the resultant flows were measured planimetrically. The diameters, and thus the areas, of the tubes employed were determined echocardiographically and corresponded to those specified. The volumes of the flows were calculated automatically according to the above formula. Their mean values (of the three calculated for each flow) were compared with the specified values in three experimental series with tubes 3, 4, and 5 mm in diameter.

RESULTS

The results of the measurements are presented in Table 1. We see that the estimated TF parameters are higher than the specified values for all cases, the correction factors in each of the three experimental series being 0.68-0.86, 0.76-0.87, and 0.8-0.9 for the tubes 3, 4, and 5 mm in diameter, respectively. This distribution of the factors was due to the differences in the velocities of the resultant flows, an inverse relationship indicating that the higher the flow velocity, the greater will be the distortion of the Doppler signal. In turn, higher flow rates indicate a greater degree of flow turbulence, which is confirmed by the Reynolds turbulence equation: $R=V\times d$, where R is the Reynolds number, d is the tube diameter (for flows in tubes), and V is the kinematic viscosity of the fluid. A flow is considered turbulent if the critical value of the Reynolds number is over 2300 [2,7,11].

We explain the high calculated values by the fact that, using the continuous Doppler method, the velocity is recorded not at a single monitoring point of the flow, as in the pulsed method, but rather along the entire flow; the mechanism of TF implies the existence of a so-called "velocity pulsation" [1], whereby particles of fluid, moving through a constricted outlet in the main axial direction of the flow, move transversely as well. The recording of these transverse movements distorts the resultant velocity parameters, the distortion being the greater the greater is turbulence.

Hence, when assessing the volume of TF, we should take into account the correction factor, which depends on the flow velocity (Fig. 2).

For the most frequently occurring maximum velocities of regurgitating flows the factors are 0.76 to 0.87.

It is noteworthy that, proceeding from the same Reynolds equation, the flow turbulence varies inversely as the fluid viscosity [1,2,7]. In our experiments the viscosity was equal to the mean viscosity of blood. Fluctuations of this parameter within the range of values common for blood to a certain measure affect the magnitude of turbulence of intracardiac flows, but deviations from their estimated volumes are usually so insignificant as to be negligible. Changes in the diameter or area of the regurgitating stream at the site of its formation deserve much more serious attention, for inaccurate measurements may appreciably alter the results.

The volume of intracardiac flows of small diameter can be calculated on the basis of continuous DEchoCG as the product of the flow *VTI* times the area of the outlet in which it forms, the correction factor depending on the velocity. The same conditions as for laminar flows should be adhered to [2,3, 12], but, in addition to these, the flow should be colored for a more precise determination of its area at the formation site.

As an example, let us calculate the volume of a narrow but extensive (2-3+) aortic regurgitation flow in a 53-year-old coronary patient with postinfarction cardiosclerosis (Fig. 3). The area of the flow was measured using amplification of a fragment and the color Doppler method, for ranging from the parasternal access along the short axis directly under the cusps of the aortic valve. Its size is 0.076 cm^2. *VTI* of the regurgitating flow is 247 cm. It was recorded using the continuous Doppler method for ranging from the apical access and five-chamber position. The maximum flow velocity is 406 cm/sec, to which a correction factor of 0.78 corresponds. The volume of the flow of aortic regurgitation is 0.78×247 cm$\times$ 0.076 cm^2=15 ml (cm^3), classifying it as of moderate intensity.

The proposed method of using continuous DEchoCG to determine the volumes of intracardiac TF of small diameters may help develop noninvasive criteria of the intensity of regurgitations, aid in their differentiation, and facilitate a prognosis, particularly in borderline (subclinical) states and combined heart defects.

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