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Doppler two-dimensional echocardiographic determinations of right ventricular output and diastolic filling

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Summary

Two methods of measuring right ventricular cardiac output with pulsed Doppler two-dimensional echocardiography were developed in 29 patients who underwent cardiac catheterization and angiography. Using tricuspid inflow and main pulmonary artery outflow methods we determined cardiac output, and good correlations were observed between thermodilution and Doppler measurements ($r=0.93$ and 0.89, respectively). Results by the two methods correlated closely in patients without regurgitant lesions. In patients with tricuspid regurgitation, right ventricular inflow was always greater than right ventricular outflow volume while the reverse was true in those with pulmonary insufficiency. Furthermore, we investigated the right ventricular peak filling rate as the Doppler peak diastolic velocity × cross-sectional area of the tricuspid annulus and half filling right ventricular fraction derived from the time velocity integral of the Doppler-determined velocity curve. For the tricuspid valve morphologically, the Doppler-derived velocity profile in diastole resembled the first derivative of the angiographic right ventricular volume curve. A significant correlation was observed between the Doppler echocardiographic and angiographic peak filling rate ($r=0.84$).

The results of the present study validate the use of Doppler two-dimensional quantitative measurements of the right ventricular output, regurgitant fraction and indexes of diastolic function.

Key words

Doppler two-dimensional echocardiography Right ventricle Cardiac output Doppler peak filling rate

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Introduction

New generation two-dimensional echocardiographic scanners with quantitative spectral analysis output of the Doppler signal appear to provide a method for measuring cardiac output[1~11]. These measurements are based on the premise that the velocity of blood flow determined from the Doppler shifts of the reflected sound waves are uniformly distributed throughout the cross-section of the vessel, so that the product of the area under the velocity curve and the cross-sectional area of the vessel is equal to the volume of blood passing through the vessel. In this investigation we have developed and validated a new approach to measuring right ventricular flow, using the tricuspid valve in an apical four-chamber view. Furthermore, we calculated right ventricular output by Doppler estimates of transpulmonary arterial flow as described elsewhere[6,8]. Thus, it is possible noninvasively to quantitate tricuspid and pulmonary regurgitation.

Recently, Rokey et al.[9], using similar equipment, determined left ventricular diastolic filling as a product of instantaneous blood velocity and the cross-sectional area of the mitral annulus. We modified their method for the tricuspid valve orifice.

The purpose of the present study was therefore twofold: (1) to test the accuracy of pulsed Doppler echocardiographic estimates of the right ventricular stroke volume by validation of two methods sampling at the tricuspid orifice and the main pulmonary artery, and hence to grading the severity of tricuspid or pulmonary regurgitation, and (2) to determine the relationship between Doppler-derived early peak flow through the tricuspid annulus and angiographically-derived right ventricular filling rate, in order to evaluate, if possible, simplified indexes of right ventricular diastolic filling.

Methods

Clinical population

The clinical population consisted of 29 patients, 12 women and 17 men, whose ages ranged from 14 to 65 years, and who had undergone cardiac catheterization, angiography, and determinations of cardiac output by thermodilution. Mild tricuspid regurgitation diagnosed by Doppler echocardiography as a systolic wide frequency dispersion in the right atrium behind the tricuspid valve was present in four patients, and moderate pulmonary regurgitation detected as a wide frequency dispersion in the right ventricular outflow tract was recorded in five patients. Diagnoses and hemodynamic data of the patients are shown in **Table 1**. All echocardiographic studies were performed within 1 hr before the invasive investigations.

Equipment

Two new commercially available equipment systems were used. Ultrasonic pulsed Doppler flowmeter was incorporated in a real-time two-dimensional echocardiograph, Toshiba SSH 11A, with a phased array transducer, 2.5 MHz carrier frequency, and an Advanced Technology Laboratories 6001 apparatus with a mechanical wheel transducer having a 3.0 MHz carrier frequency. Each system has a movable Doppler cursor and an adjustable sample volume depth. Continuous video-recorded two-dimensional images (1/2 inch VHS) were played back through videocassette system equipment. The frozen image was recorded on glossy black-on-white paper at a paper speed of 50 mm/sec. Patients were examined in the left semilateral decubitus position and standard views from the apical and parasternal windows were recorded.

Echocardiographic image acquisition

Calculation of cardiac output by Doppler technique requires knowledge of the cross-sectional area of the vessel or valve through which blood is flowing, and the linear velocity of flow. In this study the pulmonary blood flow was measured in the main pulmonary artery immediately distal to the pulmonary valve from a standard parasternal position (**Fig. 1**). Records of the tricuspid inflow velocity were made from an apical standard four-chamber view which provided good visualization of the right ventricular cavity and tricuspid valve leaflets. Calculation of the effective tricuspid valve flow area was

Table 1. Doppler two-dimensional echocardiographic and thermodilution data

No.	Age/Sex	Diagnosis	Doppler Tricuspid								Doppler Pulmonary				Thermo-dilution	
			HR	CSA	TVI	SV	CO	PFR	HFR	$T^1/_2$	CSA	TVI	SV	CO	SV	CO
1	65/M	CAD	62	4.1	14.2	58.2	3.6	152	0.52	38	3.5	18.8	65.8	4.1	75	5.2
2	63/M	CAD	71	3.9	20.5	79.1	5.6	135	0.62	59	4.1	20.1	82.4	5.8	80	5.5
3	48/W	CAD	59	2.9	6.0	17.4	1.0	185	0.62	100	2.8	6.5	18.2	1.1	24	1.7
4	62/M	CAD	80	4.3	6.5	27.9	2.2	140	0.49	75	3.1	15.0	46.0	3.7	3.7	2.8
5	52/M	CAD	73	3.5	12.1	42.0	3.6	171	0.56	65	3.1	13.2	40.9	2.9	36	2.6
6	57/M	CAD	74	4.0	8.2	32.8	2.4	216	0.63	87	3.5	12.1	42.3	3.1	31	2.2
7	39/M	CAD	59	6.2	13.3	82.4	4.8	102	0.63	120	3.8	20.5	77.4	4.5	84	4.9
8	62/F	CAD PR	65	3.2	10.8	34.5	2.2	115	0.70	94	3.7	12.5	46.2	3.0	40	2.6
9	57/M	CAD PR	73	6.5	11.1	72.1	5.2	140	0.49	85	8.2	12.8	104.1	7.6	78	5.6
10	59/M	CAD TR	64	3.7	12.2	45.1	2.9	535	0.40	250	2.7	10.0	27.0	1.7	38	2.4
11	62/F	CAD TR	67	6.1	18.6	111.6	7.4	623	0.70	240	5.8	12.5	72.5	4.8	70	4.6
12	64/F	CMI	69	1.5	13.2	19.8	1.3	187	0.45	340	2.5	7.8	19.5	1.3	22	1.5
13	56/M	CMI	65	2.8	8.0	22.4	1.6	135	0.39	272	2.8	7.5	21.0	1.4	25	1.6
14	60/M	CMI PR	80	2.5	8.8	19.3	1.5	173	0.50	236	3.6	10.8	38.8	3.1	28	1.8
15	59/M	CMI	67	4.3	12.5	52.5	3.5	120	0.60	82	3.7	14.0	51.8	3.4	56	3.7
16	15/F	MS PR	81	2.7	11.9	32.1	2.6	130	0.55	238	3.8	12.5	47.5	3.8	37	2.9
17	19/F	MR	65	5.0	8.4	42.0	2.7	284	0.52	65	4.5	8.7	39.4	2.6	33	2.1
18	21/M	MRMS	74	4.5	11.2	50.4	3.7	310	0.54	72	2.9	12.7	36.3	2.6	50	3.7
19	14/F	MR MS TR	63	4.0	13.2	52.8	3.3	805	0.42	160	2.8	10.5	29.4	1.8	29	1.8
20	17/F	MR	59	6.2	7.6	29.1	1.7	195	0.45	120	3.5	5.0	30.1	1.8	30	1.7
21	32/M	MR MS	75	3.2	12.1	38.7	2.9	226	0.58	105	2.8	18.1	50.6	3.8	32	2.4
22	20/M	MS	72	5.1	16.2	82.6	5.9	350	0.47	90	3.7	16.2	59.9	4.3	58	4.2
23	28/F	AR AS PR	70	5.0	12.0	60.0	4.2	270	0.38	85	6.9	21.1	145.6	11.1	80	5.6
24	37/F	AR AS TR	68	6.8	14.5	98.6	6.2	720	0.56	170	6.1	12.7	77.4	4.8	78	4.9
25	41/M	AS	71	3.7	9.9	36.6	2.6	145	0.40	130	3.8	13.0	49.4	3.5	39	2.7
26	30/F	CM	65	2.9	6.5	18.9	1.2	162	0.59	35	2.8	7.2	20.2	1.3	26	1.7
27	18/M	CM	69	3.2	8.9	28.4	1.9	168	0.45	85	3.1	10.5	32.5	2.2	36	2.4
28	42/M	CM	64	5.2	13.5	70.2	4.5	300	0.70	94	3.9	20.8	81.8	5.1	68	4.3
29	59/F	CM	59	4.7	6.9	32.4	1.9	205	0.38	80	2.8	12.5	35.0	2.0	30	1.8

CAD=coronary artery disease; PR=pulmonary regurgitation; TR=tricuspid regurgitation; CMI=chronic myocardial infarction; MS=mitral stenosis; MR=mitral regurgitation; AS=aortic stenosis; AR=aortic regurgitation; CM=cardiomyopathy; HR=heart rate (beats/min); CSA=cross-sectional area; TVI=time velocity integral; SV=stroke volume; CO=cardiac output; PFR=peak filling rate; HFR=half filling rate; $T^1/_2$=diastolic half time.

relatively complex due to the normal variation in size of the tricuspid orifice during diastole. Whenever possible, the tricuspid annulus was also imaged in the parasternal position (**Fig. 2**).

Doppler velocity recording

After good visualization of the main pulmonary artery, the Doppler cursor was positioned as nearly parallel to pulmonary flow as possible and the sample volume was placed immediately distal to the pulmonary valve. From this standard point, the system was switched to the Doppler mode and the beam scanned in a tight radial pattern with slight changes in the axial depth of sampling until the velocity profiles with the

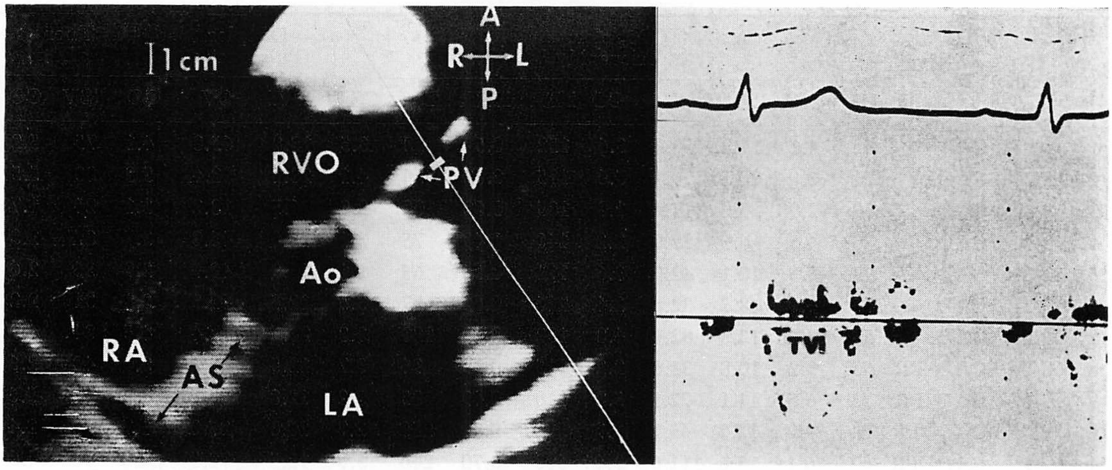

Fig. 1. Two-dimensional echocardiogram showing the right ventricular outflow tract and main pulmonary artery in the parasternal view illustrating the position of the sample volume immediately proximal to the pulmonary valve (left), **and the normal recording of the main pulmonary artery Doppler flow velocity** (right) (paper speed of 100 mm/sec).

Time velocity integral (TVI) is derived by digitizing the velocity curve.

RVO=right ventricular outflow tract; PV=pulmonary valve; Ao=aorta; RA=right atrium; LA=left atrium.

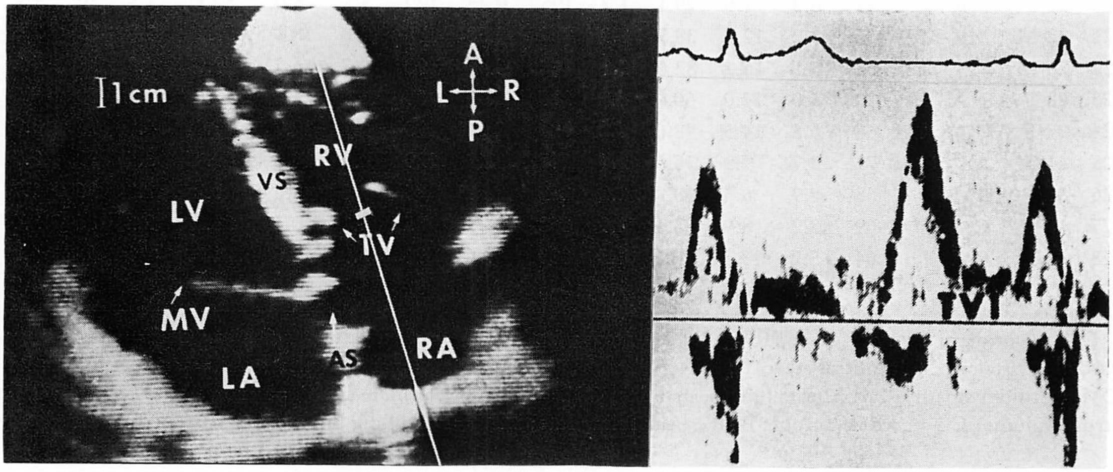

Fig. 2. Four-chamber view of the heart obtained from the parasternal view with the sample volume positioned at the plane of the tricuspid annulus, in which the Doppler cursor is aligned parallel to the tricuspid flow (left), **and the normal recording of tricuspid Doppler velocity is obtained** (right) (paper speed of 100 mm/sec).

TV=tricuspid valve; MV=mitral valve; RV=right ventricle. Other abbreviations as in Fig. 1.

largest Doppler shifts were recorded (**Fig. 1**). Tricuspid inflow velocity recordings were obtained from the standard apical four-chamber view. The Doppler cursor was initially aligned parallel to the apparent direction of the flow, and the sample volume was positioned at the level of the tricuspid annulus in diastole. In the Doppler mode, the flow profile with the highest apparent velocities was searched for in a manner analogous to that described for the pulmonary valve (**Fig. 2**). At the end of each flow recording, a careful search was made to exclude " native " tricuspid and pulmonary valvular insufficiency.

Echocardiographic-Doppler analysis

The systolic diameter of the main pulmonary artery was measured at a point just beyond the pulmonary valve in the field immediately following valve opening from inner edge to inner edge, one or two video frames after maximal systolic leaflet separation. The cross-sectional area was calculated as $\pi \times r^2$, where r represents the annular radius (average of five cardiac cycles). The tricuspid valve area was measured in the apical four-chamber view from the mid-diastolic transverse diameter utilizing the second or third video frame after the initial maximal opening position. Measurements were taken from the inner edge of the lateral bright corner of the annulus to the inner edge of the medial corner just below the insertions of the tricuspid leaflets. Measurements from a minimum of five cardiac cycles were averaged and the cross-sectional area of the annulus was derived as $\pi \times r^2$. This method assumes a circular shape of the tricuspid annulus and a constant cross-sectional area throughout diastole. In normal subjects we performed a two-dimensional echocardiographic reconstruction of the tricuspid annulus from multiple calibrated views and found the shape of the annulus to be nearly circular during diastole. An 11% gradual increase in cross-sectional area was observed from early to end-diastole. In half of the patients, the cross-sectional area of the tricuspid annulus was also derived by combining the annular diameter from the four-chamber apical and parasternal views as $\pi \times (r_1^2 + r_2^2)/2$. The results were nearly identical to those derived from the apical four-chamber view alone, and therefore the single measurement method was selected for the investigation in order to increase the clinical applicability of the method.

Doppler and two-dimensional echocardiographic calculations

1. Pulmonary $SV = P\text{-}CSA \times TVI$ and
2. Tricuspid $SV = T\text{-}CSA \times TVI$,

where SV = stroke volume in m*l*, P-CSA = main pulmonary artery cross-sectional area in cm^2, T-CSA = tricuspid cross-sectional area in cm^2 and TVI = time velocity integral (cm/sec) or area under the velocity curve for the entire systolic period for pulmonary SV and for the entire diastolic period for tricuspid SV, respectively. TVI was derived by digitizing the contour of the darkest portion of the corresponding curves (**Fig. 1 & 2**). The angle (θ) of the incidence between the ultrasonic beam and blood flow was assumed to be zero in these computations ($\cos \theta = 1$). However, within the plane of the two-dimensional image, this angle may be estimated and a correction of the above equation can be made if desired ($SV \times \cos \theta$). Cardiac output was calculated as SV × heart rate.

3. Regurgitant volume and regurgitant fraction of the tricuspid and pulmonary valves were calculated using classical methods.
4. Right ventricular peak filling rate (m*l*/sec) was computed as the early peak Doppler diastolic velocity × two-dimensional cross-sectional area of the tricuspid annulus. This index represents the peak early diastolic velocity times the cross-sectional area of the tricuspid annulus.
5. Half-filling fraction was determined as TVI at one-half diastolic filling period divided by the total diastolic TVI.
6. Diastolic half time of the tricuspid inflow, reflecting the time takes for the initial pressure gradient to drop by 1/2, was derived by modified final Bernoulli equation:

$$V_t = Vo/\sqrt{2} \text{ or } Vo/1.4$$

where V_t is the velocity at one-half the initial pressure gradient and Vo is the initial maximum velocity. The time required for Vo to drop to V_t is the diastolic half time[11] ($T^1/_2$) (Fig. 3).

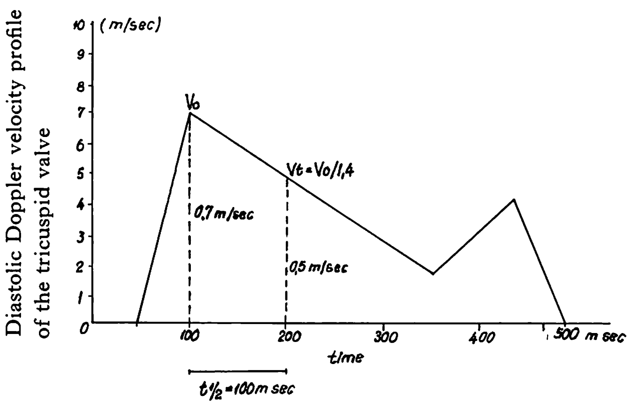

Fig. 3. Schematic diagram of a typical tricuspid flow pattern during diastole demonstrating the calculation of the diastolic half time ($T^1/_2$).

The initial peak velocity (Vo) is 0.7 m/sec. Vo is divided by 1.4 to yield a V_t of 0.5 m/sec. The diastolic half time is the time from Vo to V_t, which is 100 msec.

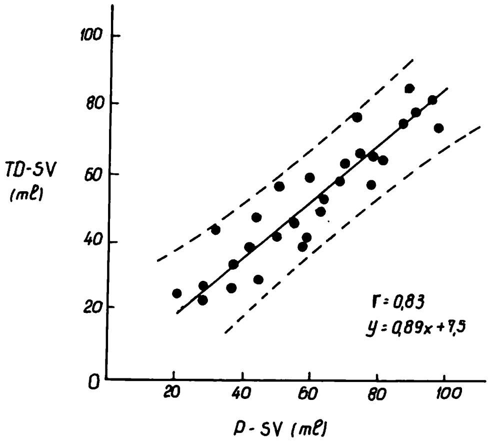

Fig. 4. Correlation between thermodilution (TD) and Doppler measurements of stroke volume (SV) using the pulmonary artery (P) method.

The broken lines indicate the 95% cofidence limit of the regression.

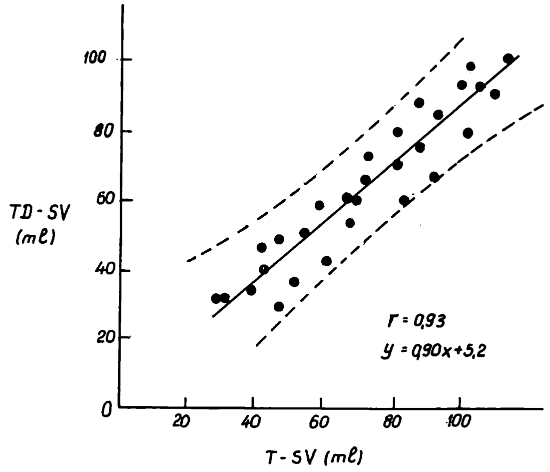

Fig. 5. Correlation between thermodilution (TD) and Doppler measurements of stroke volume (SV) using the tricuspid (T) inflow method.

The broken lines indicate the 90% confidence limit of the regression.

Results

Table 1 shows the data obtained for each of the patients studied concerning stroke volume and cardiac output as determined by pulsed Doppler two-dimensional echocardiography and by thermodilution. We found a close correlation between the thermodilution technique and the Doppler method sampling at the right ventricular outflow (r=0.93) (**Fig. 4**) and sampling at the tricuspid inflow (r=0.89) (**Fig. 5**). There was no consistent over- or underestimation of thermodilution cardiac output by the Doppler tech-

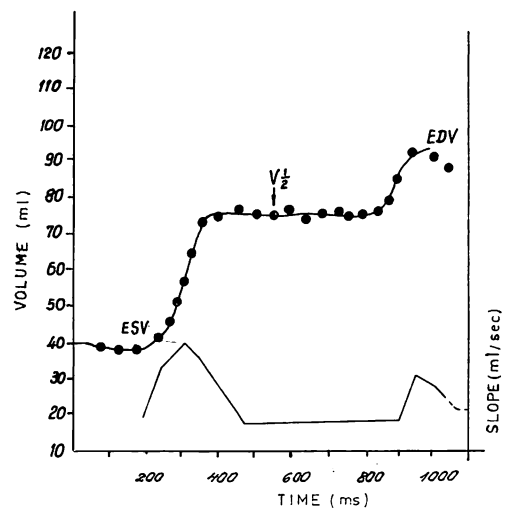

Fig. 6. Graphic display of an angiographic frame-by-frame right ventricular volume curve during diastole (top), **and an instantaneous slope or first derivative of the volume curve** (bottom).

ESV=end-systolic volume; EDV=end-diastolic volume; $V^1/_2$=absolute volume of the right ventricle at one half diastolic filling period.

niques as shown in regression equations. Neither method appeared to yield results higher or lower than the other. In four patients with tricuspid insufficiency the regurgitant volume ranged from 0.3 to 1.6 *l*/min and the regurgitant fraction from 24 to 38%, respectively. In five patients with pulmonary insufficiency the regurgitant volume ranged from 0.3 to 1.7 *l*/min and the regurgitant fraction from 29 to 40%, respectively.

Morphologically, the first derivative of the angiographic right ventricular volume curve resembled the Doppler-determined diastolic velocity profile of the tricuspid valve (**Fig. 6**). Tricuspid diastolic half time ranged from 25 to 165 msec and tended to be augmented in patients with tricuspid regurgitation. There were no significant differences in the mean values for right ventricular peak filling rates obtained by Doppler echocardiography and those by angiography (peak filling rate 195±85 m*l*/sec vs 205±95 m*l*/sec). The mean value for half filling fraction as determined by the Doppler method was 0.52, and by angiography 0.58. The correlation coefficient between these two methods for the half filling rate was significant ($p<0.001$), but the r value was low (0.53), compared with those for the peak filling rate. Patients with tricuspid insufficiency had higher values for peak filling rate (>550 m*l*/sec) by invasive and noninvasive methods than the other patients. In contrast, low values for the peak filling rate (<300 m*l*/sec) were observed in all patients with primary cardiomyopathy and ischemic heart disease. A wider range of values was seen among the other patients.

Discussion

Doppler echocardiography is uniquely capable of noninvasively measuring volumetric flow at multiple locations within the heart and great vessels. In the normal flow state, this capability permits the determination of forward cardiac output from flow data derived from each of the four cardiac valves. When flow is distributed as a result of valvular regurgitation or a shunt, quantitation of the disturbance should theoretically also be possible by comparison with flow volumes at serial points along the path of normal blood flow through the heart.

The accuracy of the Doppler method in defining cardiac output with effects of sampling sites on these measurements[1~9] and its accuracy in shunt and regurgitant flow[6,9] has been extensively studied. Less attention, however, has been given to the use of this technique for quantifying right ventricular output and tricuspid flow.

This investigation clinically validates the use of Doppler-determined flow velocity through the tricuspid annulus or right ventricular outflow to calculate stroke volume and cardiac output. Both methods used in this study assumed uniform velocities within the tricuspid or pulmonary annulus. At low velocities, flow is usually laminar[10]. In addition, the velocity profile tends to flatten as blood converges into the inlet of a conduit and during rapid acceleration, e.g. during early ejection through the pulmonary annulus[10]. In this study we did not observe significant changes in velocity as we moved the sample volume laterally within the area of the tricuspid or pulmonary annulus, and the dispersion of velocities was minimal. Thus, it appears that the velocity profiles within the normal tricuspid and pulmonary annulus were appropriate for determining blood flow by Doppler echocardiography.

In this investigation we assumed that flow through the tricuspid annulus was dependent mostly on the cross-sectional area of the orifice and less on the mobility of the valve leaflets. In fact, we frequently observed an increase in flow velocity as the sample volume was passed through the valve orifice into the body of the right ventricle, and the magnitude of this increase was greater in patients with low cardiac output, suggesting that this assumption was correct. Although an increase in annular area averaging 11%, this represents a relatively small change in diameter since it is related to the square root of the area.

An additional advantage of estimating cardiac output sampling at the tricuspid valve and main pulmonary artery is the potential for calculating regurgitant volumes by comparing one with the other in patients with isolated tricuspid or pulmonic insufficiency. As shown in **Table 1** tricuspid flow volumes were greater than the right ventricular outflow volumes in all patients with tricuspid regurgitation, while the inverse was true in patients with pulmonary regurgitation. A regurgitant fraction could therefore be calculated as a difference between the results of the two Doppler methods divided by the volume derived from the representative regurgitant volume.

A significant correlation was observed between peak early diastolic velocity and the angiographic measurement of the peak filling rate of the right ventricle. However, the low correlation coefficient precluded close estimations of filling rates. Right half filling fraction is an index of ventricular filling that may be depressed in primary myocardial disease and coronary artery disease. Furthermore, this index incorporates the relative contributions to filling by early versus late diastole[12]. The index $T^1/_2$ appeared to be related with the area of the tricuspid valve.

In conclusion, the increased clinical yield provided by present methods should expand the applicability of Doppler echocardiography for measuring right ventricular output and filling in routine clinical practice.

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