NONINVASIVE ESTIMATION OF RIGHT VENTRICULAR SYSTOLIC
PRESSURE IN VENTRICULAR SEPTAL DEFECT BY A
CONTINUOUS WAVE DOPPLER TECHNIQUE

YUJI MATSUOKA, M.D. AND KUNIO HAYAKAWA, M.D.

Noninvasive determination of right ventricular systolic pressure was attempted in 27 patients with ventricular septal defect based on the peak velocity of left-to-right shunt flow as measured in the right ventricle by a continuous wave Doppler technique. The systolic pressure gradient between the ventricles ($\Delta p$: mmHg) was calculated according to the simplified Bernoulli's formula, $\Delta p = 4 V^2$, where $V$ (m/sec) is the peak velocity of the left-to-right shunt flow. Right ventricular systolic pressure was determined by subtracting $\Delta p$ from the systolic blood pressure measured in the upper arm, which was regarded as the left ventricular systolic pressure. The peak velocity of left-to-right shunt flow could be measured in all patients except one with muscular ventricular septal defect, and values ranged from 0.6 to 4.8 m/sec. The peak velocity of left-to-right shunt flow decreased inversely with the increase in right ventricular systolic pressure. The values of right ventricular systolic pressure determined by the continuous wave Doppler technique correlated highly ($r = 0.820$) with those determined by cardiac catheterization. The peak velocity of left-to-right shunt flow also showed high negative correlations with the pulmonary to systemic pressure ratio ($r = -0.876$) and pulmonary to systemic resistance ratio ($r = -0.855$).

These results indicate that the continuous wave Doppler technique is clinically useful for determination of right ventricular systolic pressure as well as the pulmonary to systemic pressure ratio and pulmonary to systemic resistance ratio.

EVALUATION of right ventricular systolic pressure (RVSP) as well as left-to-right shunt volume in patients with ventricular septal defect (VSD) is important in determining the treatment and deciding time of surgery.

Noninvasive evaluation of RVSP and pulmonary arterial pressure has been attempted by measuring the right ventricular systolic time intervals by M-mode echocardiography, quantitative analysis of the interventricular septal configuration in two-dimensional echocardiograms, and analysis of the flow velocity curve of the right ventricular outflow tract or the main pulmonary artery by pulsed Doppler echocardiography. On the other hand, since the report by Halte et al. on patients with mitral stenosis, accurate assessment of the severity of various stenotic lesions of the heart and vessels has become possible by determining the downstream flow velocity by Doppler ultrasound technique and applying the values to the simplified Bernoulli's formula. If the systolic pressure gradient between the ventricles in patients with VSD can be similarly calculated from the peak
TABLE I  VALUES OF CARDIAC PARAMETERS DETERMINED BY CWD AND CARDIAC CATHETERIZATION

<table>
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<tr>
<th>Case</th>
<th>Age (yr)</th>
<th>Type of VSD</th>
<th>Qp/Qs</th>
<th>Pp/Ps</th>
<th>Rp/Rs</th>
<th>RVSP by Doppler (mmHg)</th>
<th>RVSP by cath (mmHg)</th>
<th>Systolic blood pressure (mmHg)</th>
<th>LVSP (mmHg)</th>
<th>Peak velocity of L-R shunt flow (m/s)</th>
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VSD = ventricular septal defect; Qp/Qs = pulmonary to systemic flow ratio; Pp/Ps = pulmonary to systemic pressure ratio; Rp/Rs = pulmonary to systemic resistance ratio; RVSP = right ventricular systolic pressure; cath = cardiac catheterization; LVSP = left ventricular systolic pressure; N.D. = not detectable.

velocity of left-to-right shunt flow (peak shunt velocity) through the defect, RVSP can be noninvasively determined by subtracting the systolic pressure gradient between the ventricles from the systolic blood pressure, which is regarded as the left ventricular systolic pressure (LVSP). In this study, RVSP was estimated from the peak shunt velocity in the right ventricle measured by a continuous wave Doppler (CWD) technique, and the values were compared with those measured by cardiac catheterization. We also examined the possibility of evaluating important hemodynamic parameters such as the pulmonary to systemic pressure ratio (Pp/Ps) and pulmonary to systemic resistance ratio (Rp/Rs) from the peak shunt velocity.

1. Subjects and methods (Table I)

The subjects were 27 patients with VSD aged from 4 months to 10 years (mean: 3 years and 7 months), in whom diagnosis and evaluation of hemodynamic state had been made by cardiac catheterization and angiography. Two of the patients had a residual shunt after previous closure for VSD. The anatomical location of the VSD was expressed according to Kirklin's classi-
Patent ductus arteriosus and mitral regurgitation were each present in one patient. The RVSP measured by cardiac catheterization ranged from 33 to 115 mmHg with a mean ± SD of 68.4 ± 25.2 mmHg. Nineteen of 27 patients exhibited pulmonary hypertension with a mean pulmonary arterial pressure of 25 mmHg or higher; one of these patients was considered to exhibit Eisenmenger's complex.

An electric beam sector-scanning echocardiograph (Toshiba, SSH-40A) and a Doppler unit (SDS-21B) were combined as a system for flowmetry. The Doppler unit contained both pulsed Doppler and continuous wave Doppler apparatus, which can be alternated instantaneously with a mode selector switch. The carrier frequencies of the two-dimensional echocardiograph and the pulsed Doppler mode were 2.4 and 3.6 MHz respectively, and that of the continuous wave Doppler mode was 2.4 MHz. The pulsed Doppler apparatus allowed measurement at any desired site within the two-dimensional echocardiogram, but to the maximum velocity of 64 cm/sec with a maximum range of 10 cm at a carrier frequency of 3.6 MHz and a pulse repetition frequency of 6 kHz. It is noted that CWD lacks range resolution, but allows measurement of high velocity flow to a maximum of 7.6 m/sec. Since the probe for CWD was attached to the outside of the probe for two-dimensional echocardiography, the position of the CWD probe had to be adjusted by placing the beam marker at the measurement site. The examination was performed with patients in a quiet resting state and in the supine position in older children, but under mild sedation with trichloryl syrup in younger children.

Direct visualization of VSD was first attempted in a few two-dimensional echocardiographic views. Pulsed Doppler flowmetry was carried out in the right ventricle in front of the defect when the defect could be echocardiographically detected, but at various locations in the right ventricle to determine the sites of the shunt flow in those who showed no defect in echocardiograms. After confirming the site of left-to-right shunt flow by pulsed Doppler, the shunt flow curve was recorded by CWD with lead II electrocardio-
gram using a strip chart recorder at a paper speed of 50 mm/sec, and the peak flow velocity was determined on the strip chart. Accurate determination of the angle between the ultrasonic beam and the shunt flow is necessary for flowmetry but was impossible in this study. Therefore, we tried to minimize the error by carefully manipulating the direction of the beam to obtain the maximum flow velocity.

2. Data analysis
The peak of the Doppler flow velocity curve by CWD was regarded as the peak shunt velocity, and was measured manually. The peak shunt velocity was determined in 10 consecutive heart beats in each subject, and the maximum value was used for the pressure evaluation described below. The measurement was performed twice by one observer (intraobserver variability), and once by another observer (interobserver variability) in all patients. Peak shunt velocity correlated highly between intraobserver and interobserver determination, and mean absolute differences between the observations (expressed as a percentage of the first observer’s observation) were both within 3%.

3. Calculation of RVSP
The interventricular systolic pressure gradient was calculated by applying the peak value of the shunt flow velocity to a simplified Bernoulli’s formula ($\Delta p = 4V^2$), suggested by Halte et al.\(^5\)

$$\Delta p = 4V^2$$

where $\Delta p$ is the interventricular systolic pressure gradient in mmHg and $V$ is the peak shunt velocity in m/sec. The systolic blood pressure measured in the upper arm was regarded as the LVSP. The RVSP was determined by subtracting $\Delta p$ from the systolic blood pressure. Systolic blood pressure was expressed as the mean value of the 3 measurements at the time of the Doppler ultrasound examination.

4. Cardiac catheterization
Cardiac catheterization was performed in all patients by percutaneous technique within 3 days of the Doppler ultrasound examination. A fluid-filled catheter system was used for the pressure measurement at various sites in the heart. Oxygen saturation was determined with an oximeter OSM-II. From the values obtained, the pulmonary to systemic flow ratio ($Qp/Qs$), $Pp/Ps$, and $Rp/Rs$ were calculated. LVSP was determined by left heart catheterization in 14 patients, but systolic femoral arterial pressure, obtained by needle puncture, was used as LVSP in the remaining 13.

RESULTS

1. Determination of left-to-right shunt flow and peak velocity by CWD
Detection of left-to-right shunt flow and measurement of peak shunt velocity were performed mainly in the parasternal long axis view.

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of the right ventricular outflow tract (Fig. 1, left). Although the shunt flow could be detected in all 27 patients by the pulsed Doppler technique, the peak shunt velocities could be obtained only in Patient 19 since the other 26 exceeded the measurement range of the pulsed Doppler velocimeter and produced wide band velocity spectrograms due to aliasing (Fig. 1, lower right). By CWD, recognizable left-to-right shunt flow velocity curves were obtained in 25 patients except (excluding Patient 12), and peak shunt velocity could be readily determined (Fig. 1, upper right).

In Patient 12 with VSD of the muscular portion, the defect could be detected in a subcostal four-chamber view, but measurement of peak shunt velocity was impossible since the CWD beam marker could not be placed in line with the shunt flow in this view.

2. Comparison between systolic blood pressure during Doppler ultrasound examination and LVSP measured by cardiac catheterization (Fig. 2)

As the two examinations were not performed simultaneously, the condition of the patients at the examinations may have differed. Therefore, it is important to examine the differences between the systolic blood pressure and LVSP for comparison between the RVSP estimated by CWD and that measured by cardiac catheterization. The difference between the systolic blood pressure and LVSP ranged widely from -37 to +42 mmHg (mean ± SD, 5.4 ± 12.7 mmHg), but the RVSP/LVSP ratio as estimated by CWD and that determined by cardiac catheterization showed an extremely high positive correlation indicated by the regression equation \( y = 0.95 x + 0.02 \) (\( r = 0.862, p < 0.01 \)). This result suggests that the systolic blood pressure measured during Doppler ultrasound examination can be regarded as closely reflecting true LVSP, despite its difference from the LVSP value measured by cardiac catheterization due to the differences in the conditions of measurement.

**Fig. 4.** Relationship between RVSP determined by CWD and RVSP measured by cardiac catheterization.

**Fig. 5-A.** Relationship between the peak velocity of left-to-right shunt flow and \( Pp/Ps \).

**Fig. 5-B** Mean ± SD of the peak velocity of left-to-right shunt flow in three groups classified according to \( Pp/Ps \).

\( *, p < 0.01, ***, p < 0.001 \)

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3. Peak velocity of left-to-right shunt flow and RVSP measured by cardiac catheterization (Fig. 3)

As RVSP increased, peak shunt velocity decreased almost linearly. The relationship between the two parameters was expressed by a linear regression equation, \( y = -0.17x + 0.772 \) (\( r = -0.777 \), \( p < 0.01 \)), indicating a negative correlation.

4. RVSP determined by CWD and RVSP measured by cardiac catheterization (Fig. 4)

The relationship between these values was expressed as a linear regression equation, \( y = 0.90x + 6.76 \) (\( r = 0.820 \), \( p < 0.01 \), SEE = 1.5). However, the values estimated by CWD were 20 mmHg or greater than those measured by cardiac catheterization in 3 patients (12%).

5. Peak velocity of left-to-right shunt flow and pulmonary to systemic pressure ratio

The peak shunt velocity decreased almost linearly with an increase in Pp/Ps. The relationship between the two parameters was expressed as \( y = -0.23x + 1.13 \) (\( r = -0.876 \), \( p < 0.01 \)), indicating a negative correlation (Fig. 5-A). When the patients were classified according to three ranges of Pp/Ps values, namely Pp/Ps < 0.45, 0.45 \( \leq \) Pp/Ps < 0.75, and 0.75 \( \leq \) Pp/Ps, the means of the peak shunt velocity showed significant differences among the three groups (3.6 \( \pm \) 0.8, 2.1 \( \pm \) 0.2, and 1.5 \( \pm \) 0.5 m/sec, respectively), but the ranges of the peak shunt velocity of the group with 0.45 \( \leq \) Pp/Ps < 0.75 and the group with 0.75 \( \leq \) Pp/Ps partially overlapped. When the patients were divided at a peak shunt velocity of 2.4 m/sec, however, Pp/Ps ranges of the two groups did not overlap, i.e. patients showing peak shunt velocities of over 2.4 m/sec were considered to have Pp/Ps values under 0.45 (Fig. 5-B).

6. Peak velocity of left-to-right shunt flow and pulmonary to systemic pressure ratio

The peak shunt velocity decreased with an increase in Rp/Rs. The relationship between the two parameters was expressed as \( y = -0.17x + 0.77 \) (\( r = -0.777 \), \( p < 0.01 \)), showing a negative correlation (Fig. 6-A). However, since the two parameters formed a curve resembling a logarithmic function rather than a straight line, the relationship between the peak shunt velocity and \( \log_{10}(Rp/Rs) \) was studied. The regression equation was \( \log_{10}(Rp/Rs) = -0.559x + 0.024 \) and the correlation coefficient was -0.855. When the patients were divided at a Rp/Rs of 0.5, mean of the peak shunt velocity of the group with Rp/Rs < 0.5 was 3.0 \( \pm \) 1.0 m/sec and that of the group with 0.5 \( \leq \) Rp/Rs was 1.2 \( \pm \) 0.3 m/sec, thus the two values were significantly different (\( p < 0.001 \)). The ranges of the peak shunt velocity of the two groups did not overlap, and these groups could be differentiated at a peak
Fig. 7. Right ventricular shunt flow curve obtained by the pulsed Doppler technique in Patient 19 showing VSD with Eisenmenger's complex. Left to right shunt flow (arrows) are observed during early systole, but right to left shunt flow (stars) occurs during mid-systole to early diastole.

SV: sample volume, RV: right ventricle.

shunt velocity of 1.8 m/sec, i.e. a peak shunt velocity over 1.8 m/sec was always associated with an Rp/Rs value under 0.5 (Fig. 6-B).

**DISCUSSION**

Some authors have suggested the usefulness of the Doppler ultrasound technique in evaluation of the pressure gradient across the site of stenosis in stenotic heart disease. However, only Halte et al. and Otterstad et al. reported on the use of Doppler ultrasound techniques for estimating ΔP in VSD patients. The first two authors employed CWD, and the last the pulsed Doppler method to determine peak shunt velocity. The pulsed Doppler technique, however, allows measurement of velocities up to 3.2 m/sec and evaluation of RVSP is impossible in patients with low RVSP and a peak shunt velocity exceeding this measurement range. The CWD apparatus used in our study lacked range resolution but allowed measurement of high velocities. The peak shunt velocity was within the range of measurement in all patients, and RVSP could be determined in those with mild VSD. Our results (Figs. 2-6) showed that determination of the peak shunt velocity makes possible the evaluation of not only RVSP but also Pp/Ps and Rp/Rs.

Determination of the peak shunt velocity by Doppler ultrasound and calculation of RVSP by applying the values obtained to the simplified Bernoulli's formula have inherent problems. The findings of Doppler ultrasound velocimetry are largely dependent on the angle between the ultrasonic beam and the flow. In our study, this may have resulted in underestimation of peak shunt velocity, and thus, overestimation of RVSP. Since precise determination of the direction of the shunt flow is difficult even by the simultaneous use of two-dimensional echocardiography, we tried to measure peak shunt velocity at its greatest by carefully adjusting the direction of the ultrasonic beam.

In the studies of Halte et al. and Otterstad et al., accurate evaluation of ΔP was possible in only 55% and 46% of the subjects, respectively. These large errors may be due to measuring peak shunt velocity without simultaneously performing echocardiography and in patients with small shunts, to the difficulty in locating the jet and reduced velocity caused by viscosity. Tomita et al. corrected the angle between the shunt flow and the ultrasonic beam using a system for real-time two-dimensional Doppler echocardiography. They found that, although the direction of the shunt flow was perpendicular to the ventricular septum in a majority of their patients, correction of the angle was necessary in 20%. In 3 of our patients (Patients 10, 20, and 21), the RVSP estimated by CWD exceeded that measured by cardiac catheterization by 20 mmHg or more. In Patient 10 with supraventricular VSD, the left-to-right shunt flow was found angiographically to be directed toward the pulmonary valve, and peak shunt velocity was considered to have been underestimated by CWD. Patient 20 had mitral regurgitation and congestive heart failure accompanied by marked left ventricular enlargement. In this patient, counterclockwise rotation of the heart due to the marked left ventricular enlargement may have diverted the left-to-right shunt flow to the right in relation to the chest wall, resulting in underestimation of peak shunt velocity. Patient 21 also had supraventricular VSD, and angiographically the left-to-right shunt flow was shown to be directed nearly vertical to the ventricular septum. In this patient, the systolic blood pressure during CWD examination exceeded LVSP at cardiac catheterization by about 40 mmHg, leading to overestimation of RVSP. Angle correction by the use of real-time two-dimensional Doppler echocardiography is considered to be necessary for more accurate estimation of RVSP by CWD.

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Besides the beam angle, the difference in the time of measurement between the CWD and cardiac catheterization and the use of systolic blood pressure values as LVSP values are considered to be other causes of the discrepancy between the RVSP values obtained by the two methods. Both RVSP and LVSP tend to fluctuate, and independent determinations would result in varying degrees of errors. Nevertheless, there was a high correlation ($r = 0.862, p < 0.01$) between the RVSP/LVSP values determined by CWD and those determined by cardiac catheterization, justifying the general use of systolic blood pressure values as LVSP values.

In patients with VSD showing markedly elevated RVSP, the left ventricular pressure is higher than the right ventricular pressure during early systole, but this pressure gradient reverses from the mid- to end-systole. These changes in the interventricular systolic pressure gradient have been shown by Levin et al.\textsuperscript{13} and Tomita et al.\textsuperscript{12} by simultaneous pressure measurement in both ventricles as well as by determination of the timing and direction of the shunt using cineangiography by the former investigators and a pulsed Doppler technique by the latter. In such instances, evaluation of RVSP from the peak shunt velocity during the early systole cannot be justified. Of our 27 patients, only one patient exhibiting Eisenmenger’s complex showed a reversal of the shunt direction at mid-systole (Fig. 7).

Tomita’s patients, in whom alteration of the flow direction was noted by pulsed Doppler examination, showed RVSP equal to, or greater than, LVSP. RVSP determined by cardiac catheterization exceeded LVSP by about 5 mmHg in the above mentioned patient. Under these conditions, therefore, RVSP determined by Doppler ultrasound techniques may not be accurate, but it is at least considered to be equal to, or greater than, LVSP. Moreover, even when the direction of the shunt flow remains left to right throughout systole, the values and the timing of the maximal instantaneous pressure gradient between the ventricles estimated from the peak shunt velocity may not be consistent with the values and the timing of the gradient between LVSP and RVSP measured by cardiac catheterization. This discrepancy may be adequately explained only by simultaneous recording of the pressure of the both ventricles and the velocity curve of the left-to-right shunt flow. However, the differences between these values are considered to be minor\textsuperscript{12}

Bernouilli’s formula is valid in stenotic cardiac diseases on the condition that upstream velocity is negligibly small compared to the downstream velocity. The measurement of the peak shunt velocity by the pulsed Doppler technique on both the left ventricular and right ventricular sides of the VSD\textsuperscript{12} at times detected left-to-right shunt flow within the left ventricle with an already considerable velocity. In such cases, evaluation of RVSP based on the peak shunt velocity in the right ventricle alone would lead to underestimation. This possibility of underestimation must be considered in VSD patients when estimating RVSP by CWD without range resolution. This problem could not be resolved in this study, because pulsed Doppler velocimetry was not carried out in the left ventricle. However, the RVSP values estimated by CWD were lower than those measured by cardiac catheterization in a few patients although LVSP values determined by the two methods were highly comparable.

It is of considerable clinical significance to be able to calculate not only RVSP but also more important hemodynamic parameters such as $Pp/\text{Ps}$ and $Rp/Rs$ from a simple measurement of the peak shunt velocity. As is clear from the simplified Bernouilli’s formula, $\Delta p$ is directly related with peak shunt velocity. $Pp/\text{Ps}$ is calculated as mean pulmonary arterial pressure - mean left atrial pressure/mean aortic pressure - mean right atrial pressure and is considered to be indirectly related to not only $\Delta p$ but also to peak shunt velocity. In this study, there was a high correlation between peak shunt velocity and $Pp/\text{Ps}$ ($r = -0.876$).

$Rp/Rs$ is calculated as $\frac{Pp}{Qp/Qs}$, but its relationship to $\Delta p$ or peak shunt velocity is less consistent due to the involvement of the flow volume ($Qp/Qs$). In our study, there were relatively high correlations between peak shunt velocity and $Rp/Rs$ and between $\Delta p$ and $Rp/Rs$ ($r = -0.855$ and $-0.675$, respectively). However, $Pp/\text{Ps}$ values may vary even if $\Delta p$ and peak shunt velocity are the same, and $Rp/Rs$ may differ more widely depending on $Qp/Qs$. Although these values showed high correlations in this study with a limited number of patients, the accuracy of the estimation of $Pp/\text{Ps}$ and $Rp/Rs$ values from peak shunt velocity must be evaluated more closely in a larger series of children with VSD.

The area of clinical application of CWD is expected to broaden since the determination of RVSP by this method contains fewer factors that
may cause errors than the method involving flow volumetry and is simple enough to allow repeated performance.

REFERENCES


