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Estimation of Pulmonary Arterial Pressure in the Newborn: Study of the Repeatability of Four Doppler Echocardiographic Techniques

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Abstract. Despite the increasing use of Doppler echocardiographic (DE) techniques to determine pulmonary arterial pressure in the neonate undergoing intensive care, there have been no studies comparing their repeatability in this population. Our objective was to compare the repeatability of four such techniques in neonates. The study was conducted in two regional neonatal units serving the North East of England. Group A (repeatability between observers): Two experienced observers performed detailed DE examinations, one directly after the other. Group B (within observer repeatability/temporal variability): One observer performed two examinations 1 hour apart. Group A comprised 15 preterm babies (26–36 weeks' gestation, 975–2915 g), most with mild respiratory failure; 4 healthy term babies; and 7 with congenital heart disease, in whom tricuspid regurgitation (TR) only was measured. Their ages were 18 hours to 12 days. Group B comprised 11 babies aged 12–64 hours with moderate to severe respiratory failure; 10 were preterm (26–36 weeks, 785–2800 g). We recorded four measurements: (1) Peak velocity of TR in m/s; (2) peak left-to-right ductal flow velocity (PDAmax in m/s); (3) TPV/RVET ratio; and (4) PEP/RVET ratio, where TPV = time to peak velocity at the pulmonary valve, PEP = right ventricular preejection period, and RVET = right ventricular ejection time. The Bland-Altman analysis was used to produce the coefficient of repeatability (CR: 95% confidence limits of repeatability), also expressed as a repeatability index (CR/mean value) and as a number of "confidence steps"—a measure of sensitivity of the technique to hemodynamic change (range of values within the population/CR). Between-observer and within-observer repeatabilities were similar. Within-observer CR and index (%) results were for TR ± 0.26 m/s (9%); for PDAmax, ± 0.48 m/s (39%); TPV/RVET 0.1:1.0 (34%), PEP/RVET 0.12:1.00 (36%). TR and PDAmax had the largest number of confidence steps in the expected range of values (TR 8.5; PDA max 6.5; TPV/RVET 3.2; PEP/RVET 3.2). The most repeatable technique was TR, but PDAmax would also be useful for a serial study owing to the potential for large change. Systolic time interval ratios were less repeatable and likely to be less sensitive indicators of hemodynamic change.

Key words: Doppler — Echocardiography — Newborn — Pulmonary arterial pressure — Repeatability

There has recently been considerable interest in the noninvasive assessment of cardiopulmonary hemodynamics in the sick newborn with a structurally normal heart. Several methods to estimate pulmonary arterial pressure using Doppler echocardiography have been used in clinical studies of neonates, and all have strengths and weaknesses. Systolic pulmonary arterial pressure can be determined reliably by measuring the peak velocity of tricuspid regurgitation and applying the modified Bernoulli equation [22–24, 27], but tricuspid regurgitation is not always present, even in babies with pulmonary arterial pressure at systemic levels [19, 20]. It remains important therefore to evaluate the alternative methods. There are, to our knowledge, no published repeatability studies of any of the Doppler methods of pulmonary arterial pressure determination in the neonate. It is essential to appreciate the inherent error in any measurement technique before meaningful interpretation of derived values can be made, particularly when looking for evidence of hemodynamic benefit following therapeutic intervention.

Aims

The study aims to compare the repeatability of four Doppler methods of pulmonary arterial pressure estima-

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tion. We assess their likely value in the evaluation of serial change in pulmonary arterial pressure in the sick newborn with a structurally normal heart.

Methods

Two aspects of repeatability were studied: interobserver (between-observer) and intraobserver (within-observer) repeatability. The study of within-observer repeatability was designed to include a component of temporal variability because most potential studies using these techniques attempt to identify change over a specified period. This time period is frequently around 1 hour after instigation of a specific therapy designed to lower pulmonary arterial pressure. The analysis of within-observer repeatability is extended to include some Doppler measurements of blood flow, allowing comparison of this study with previous reports of repeatability of other Doppler measurements in the newborn.

Studies were performed in one of the two regional neonatal units or the cardiac unit in Newcastle upon Tyne using a Hewlett Packard ultrasound machine (either Sonos 100 or Sonos 1000). Parental consent was obtained in each case, and ethical approval was obtained from the district ethics committee.

Doppler echocardiographic measurements

Measurements were made from a minimum of four cardiac cycles. The indices of pulmonary arterial pressure were as follows.

1. Application of the modified Bernoulli equation to the *peak velocity of tricuspid regurgitation:* $p = 4v^2$, where p = peak pressure drop from the right ventricle to the right atrium (mmHg) and v = peak velocity of tricuspid regurgitation (m/s). The maximal value was recorded (Fig. 1). Results were analyzed both in meters per second and millimeters of mercury. No allowance was made for the right atrial pressure, and the derived values are therefore the right ventricle to right atrial (RV-RA) pressure drop, which is *directly* related to pulmonary arterial pressure.
2. *TPV/RVET ratio* (time to peak velocity/right ventricular ejection time) [3, 5, 12].
3. *PEP/RVET ratio* (preejection period/RVET) [7, 9, 12]. Measurements of both of these systolic time interval ratios (TPV/RVET and PEP/RVET) were obtained with the pulsed Doppler sample at the pulmonary valve (Fig. 2). TPV/RVET is *inversely* related to pulmonary arterial pressure, and PEP/RVET is *directly* related to pulmonary arterial pressure. The mean value for each was recorded.
4. Maximal and mean *left-to-right flow velocity across the arterial duct* (in meters per second). These velocities are related to the pressure gradient between the aorta and pulmonary artery [8, 10, 16], and the velocities increase when pulmonary arterial pressure falls in relation to systemic arterial pressure. They were measured using stand-alone 1.9 MHz continuous-wave Doppler at the upper left sternal edge. The highest recordable velocity was taken from over four cardiac cycles (Fig. 3). These measurements are *inversely* related to pulmonary arterial pressure.

Indices of blood flow were as follows.

1. *Aortic stroke distance and minute distance* (stroke distance × heart rate) [1, 4, 6]. These measurements are analogues of left ventricular stroke volume and left ventricular output, respectively, avoiding the inaccuracy induced by repeated measurement of the cross-sectional area of the aorta. In the absence of significant interatrial shunting, these indices reflect pulmonary venous return.

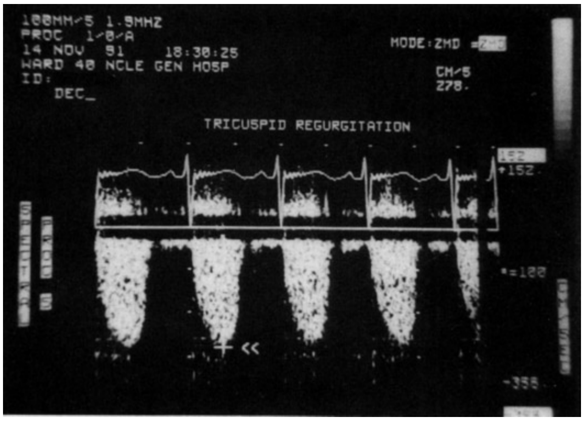

Fig. 1. Tricuspid regurgitation: Doppler recording. The peak velocity is 2.78 m/s.

2. *Pulmonary stroke distance and minute distance.* These measurements similarly are analogues of right ventricular stroke volume and output. They therefore reflect systemic venous return.

Statistical Analysis

The method to calculate repeatability coefficient was described in detail by Bland and Altman [2]. Repeatability coefficient represents the limits of disagreement between two measured variables expected from observer error alone 95% of the time. The coefficients for each method were calculated (as shown in Tables 3 and 6, below), as were the confidence intervals for the coefficient.

Comparison of repeatability between Doppler techniques is difficult, as they all use different units. A *repeatability index* was therefore designed to allow comparison of repeatability. It was calculated by expressing the repeatability coefficient for each Doppler technique as a percentage of its average value. A *high* repeatability index indicates *poor* repeatability. Taking maximal left-to-right ductal flow velocity (PDAmax) as an example, the average velocity was 1.98 m/s. The coefficient of repeatability in the between observer study was 0.56: 0.56/1.98 = 0.28. Therefore the repeatability index is 28%.

To test the value of each of these Doppler measurements further, *confidence step* analysis was employed. The repeatability coefficient was divided by the total range of values that are likely to be seen in the sick neonate. It shows how many ‘‘confidence steps’’ there are from lowest to highest values and is an indication of the likely sensitivity of the method for detecting hemodynamic change. The more confidence steps in the expected range, the more sensitive is the technique. The figures for the expected range in neonates were derived from a longitudinal study of healthy term and preterm babies and those with respiratory distress [19, 20]. For example, most RV-RA pressure drop values encountered in the neonatal population lie between approximately 12 and 65 mmHg, a range of 53 mmHg. The within-observer repeatability coefficient was 6.5 mmHg. The number of ‘‘confidence steps’’ over this range is 53/6.5 = 8.2.

Patients and Methods

Part 1: Repeatability Between Observers. Two experienced neonatal Doppler echocardiographers performed detailed studies on 26 neonates. There were 15 preterm babies and 4 term babies with structurally

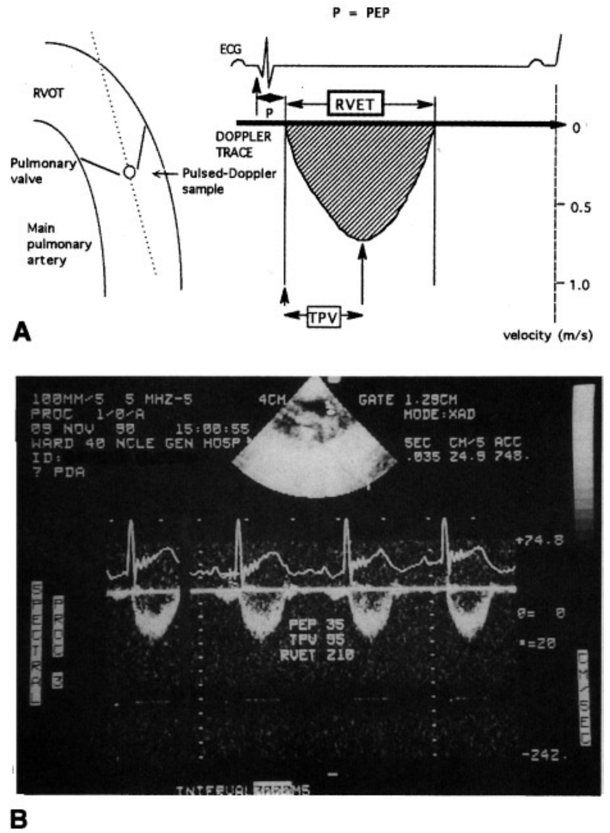

Fig. 2. Systolic time intervals. (**A**)Measurement of right ventricular systolic time intervals. The pulsed Doppler sample is placed at the pulmonary valve (*RVOT*, right ventricular outflow tract). On the right is a Doppler trace, illustrating the preejection period (*P*), from the first deflection of the QRS complex to the onset of flow at the pulmonary valve, and time to peak velocity (*TPV*), from the onset of flow to the peak, and the right ventricular ejection time (*RVET*). (**B**) Pulsed Doppler recording showing a short preejection period (35 ms) and a longer time to peak velocity (95 ms) in a patient with low pulmonary arterial pressure.

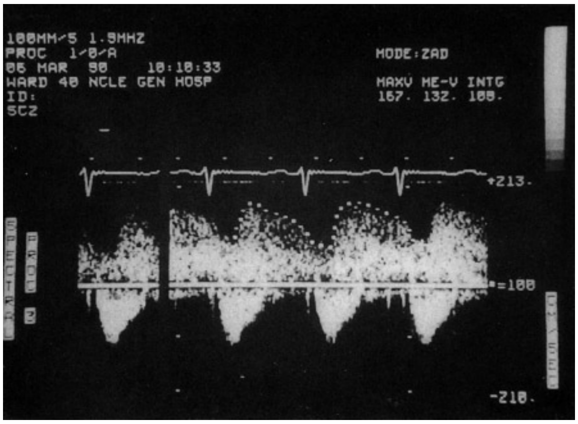

Fig. 3. Left-to-right ductal flow velocity. Continuous-wave Doppler recording, taken from the upper left border of the sternum with the probe pointing posteriorly. The flow above the line indicates continuous left-to-right ductal flow (maximal left-to-right velocity was 1.67 m/s). The position of the Doppler probe was adjusted to achieve highest upward deflection on the tracing.

normal hearts, all of whom were clinically stable. Of these 19 babies, 12 had a patent duct. There were seven term babies with congenital heart anomalies (Table 1). The second examination was done immediately after the first. An attempt was made to record all of the Doppler measurements outlined above, although it was not always possible (Table 2). Left-to-right ductal flow velocities were obviously recordable only when the duct was patent. In the seven babies with congenital heart anomalies only TR was measured. Electrocardiograms (ECGs) were not recorded in the well babies, so the preejection period (PEP) was not measured in them.

Part 2: Within-Observer Repeatability/Temporal Variability. Eleven babies receiving intensive care underwent two detailed Doppler echocardiographic examinations separated by approximately 1 hour. The infants were aged between 12 and 64 hours. The first 12 hours were avoided because of the potential for rapid hemodynamic change over this time and to avoid excessive handling during this critical period. Five babies were receiving 100% oxygen. Birth weight was between 785 and 3545 g (mean 1840 g), and gestational age was between 26 and 40 weeks (mean 32.3 weeks). Additional clinical details are given in Table 3.

Each examination was performed by the same observer, recording the first and second scans on separate tapes to be analyzed subsequently on different occasions. The study was extended to include indices of blood flow, including aortic stroke distance and pulmonary stroke distance. Systolic blood pressure and heart rate were also recorded as easily recognizable clinical parameters of hemodynamic temporal variability.

Care was taken to include only babies who were clinically stable and, in particular, not having large swings in oximetry readings. Pulse oximetry was used in all babies, and readings at the second examination were always within 3% of the first. Systemic arterial pressure was recorded with oscillometry (Dynamap) to avoid the handling necessary for Doppler sphygmomanometry. The ratio of the RV-RA pressure drop/systemic arterial pressure (RV-RA/BP ratio), was also calculated.

The measured values were analyzed by an independent statistician (R.J.B.).

Results

Between-Observer Repeatability

The subjects and the measured Doppler values are listed in Table 2. There were 16 paired measurements each of tricuspid regurgitation (TR) and TPV/RVET values, and 12 each of PEP/RVET and both PDA velocity measurements. The repeatability coefficients and repeatability index for each technique are shown in Table 4.

The RV-RA pressure drops determined by the TR technique are remarkably similar when comparing the results of the first two observers (repeatability index 8%). The largest difference was in subject 20 (6.6 mmHg).

Most of the paired values for the TPV/RVET ratio fall within 0.06 of each other, but there were four examples where the difference exceeded 0.08. This poor

Table 1. Details of subjects of between-observer repeatability study

Pt. no.	Gestation (weeks)	Weight (g)	FiO_2 (%)	Age (hours)	Diagnosis
1	26	1040	21	175	HMD
2	27	975	33	72	HMD
3	27	1075	37	86	HMD
4	28	1258	55	38	HMD
5	28	985	45	96	HMD
6	28	1115	37	98	HMD
7	29	1375	40	62	HMD
8	30	1495	27	99	HMD
9	30	1385	21	63	Well
10	30	1476	21	64	Well
11	31	1503	27	210	HMD
12	31	2160	65	44	HMD
13	31	2220	21	80	HMD
14	33	2650	21	49	Well
15	36	2915	35	70	HMD
16	40	3200	21	35	Well
17	40	3629	21	18	Well
18	40	3545	21	23	Well
19	40	3555	21	38	Well
20	40	4480	21	255	Arterial trunk
21	40	3720	30	210	Hypoplastic left heart
22	40	3560	35	94	Interrupted arch
23	40	3600	21	235	Myocardial ischemia
24	40	3415	21	273	VSD
25	40	2990	35	185	Hypoplastic left heart
26	38	3250	21	212	Coarctation (postop)

HMD, hyaline membrane disease (all receiving positive-pressure ventilation); FiO_2, inspired oxygen fraction.
Subjects 1–19 had structurally normal hearts.

agreement between observers is reflected in the high repeatability index (36%). In general, there is close agreement for paired observations of the PEP/RVET ratio: to within 0.05. On two occasions, however, the discrepancy was large. In case 11 the second value was almost half the first value, and with case 9 the second value was almost double the first. The repeatability index was 45%.

There was mostly close agreement between observers for peak left-to-right ductal flow velocity (PDAmax). The largest difference was 0.62 m/s (subject 10); all the others were less than 0.4 m/s. The two measured velocities were 1.45 and 2.07 m/s. If the modified Bernoulli equation is applied to these velocities, it represents a difference of the two estimates of pressure drop across the duct of only 8.8 mmHg: ($1.45^2 \times 4$) = 8.4 mmHg; ($2.07^2 \times 4$) = 17.2 mmHg; 17.2 − 8.4 = 8.2 mmHg). However, there was a high repeatability index (28%).

Results were similar for mean left-to-right ductal flow velocity (PDAmean).

Within-Observer/Temporal Variability

The paired measurements are shown in Table 5. Results for repeatability coefficient and repeatability index are presented in Table 6. The wide confidence intervals reflect the small numbers, but the repeatability indices are strikingly similar to those of the between-observer study. Measurement of the velocity of tricuspid regurgitation was highly repeatable, with little temporal variability (under these stable conditions). The TPV/RVET and PEP/RVET ratios had repeatability indices similar to those of the between-observer study (34% and 36% respectively).

Aortic stroke distance had a low repeatability index (10%), of the same order as for the heart rate (11%). Aortic minute distance had a repeatability index of 17%, but pulmonary stroke distance had a higher repeatability index (26%).

The repeatability coefficients were then divided into

Table 2. Between-observer repeatability study: Doppler values from two observers on the same babies

Pt. no.	RV-RA (mmHg)		TPV/RVET		PEP/RVET		PDAmax (m/s)		PDAmean (m/s)	
	1	2	1	2	1	2	1	2	1	2
1			0.45	0.40	0.19	0.22				
2	23.0	24.4	0.46	0.53	0.35	0.30	1.62	1.70	1.37	1.41
3			0.32	0.25	0.31	0.29	1.32	1.66	1.05	1.34
4	46.8	42.2	0.24	0.20	0.36	0.39	1.21	1.15	0.76	0.41
5	30.2	31.1	0.32	0.41	0.25	0.25				
6	23.0	24.0	0.45	0.45	0.18	0.19				
7	29.6	28.5								
8			0.38	0.43	0.27	0.25	2.77	3.03	2.17	2.49
9			0.29	0.37	0.20	0.37	1.65	1.72	1.01	1.04
10			0.44	0.33	0.32	0.30	1.45	2.07	1.07	1.76
11			0.34	0.31	0.18	0.10	0.60	0.48	0.35	0.22
12	36.5	40.0	0.27	0.32			1.36	1.12	1.23	0.97
13	28.5	31.8								
14	19.2	21.9	0.50	0.39						
15	28.1	24.0								
16			0.38	0.32	0.38	0.32	3.45	3.10	3.06	2.93
17			0.36	0.31	0.29	0.29	2.73	2.60	2.36	2.32
18			0.34	0.29			2.40	2.67	2.13	2.23
19			0.41	0.41			2.49	2.73	2.17	2.49
20	80.3	86.9								
21	55.6	57.8								
22	59.9	56.0								
23	29.6	31.4								
24	56.8	59.0								
25	100.4	101.6								
26	31.8	28.3								

RV-RA, right ventricle to right atrial peak pressure drop during systole, determined from tricuspid regurgitation; TPV, time to peak velocity at the pulmonary valve; PEP, right ventricular preejection period; RVET, right ventricular ejection time; PDAmax/PDAmean, respectively, maximal and mean left-to-right velocity through the arterial duct.

the total range of values for each method seen in this population. The number of ''confidence steps'' within the expected range are presented in Table 7. A large number of confidence steps (more than six, indicating more sensitive techniques) were found for aortic stroke distance, tricuspid regurgitation, and ductal flow velocities, whereas systolic time interval ratios had fewer (fewer than four).

Discussion

When any new measurement technique is introduced into clinical practice, the error inherent in the technique must be evaluated. The ''acceptable'' error for a technique to be clinically useful alters according to the degree of change that can occur in a given variable. A technique confidently detecting a 20% change is of little value if the parameter never varies by more than 20%, but it is useful if variation of 100% occurs. In the present study, ductal flow velocities and systolic time intervals had similar percentage indices of repeatability, but ductal flow velocities are likely to be more sensitive to hemodynamic change because the range of potential change is larger in relation to the error of the measurement. This point was demonstrated using the ''confidence step'' technique; the two methods with the smallest coefficient of repeatability in relation to the expected range (the largest number of confidence steps in the range) were peak velocity of tricuspid regurgitation and velocity of ductal flow. Systolic time intervals fared much less well.

However, an index of pulmonary arterial pressure is often needed when there is neither a measurable TR jet nor a patent arterial duct; systolic time intervals can be used for serial measurement by the same observer, provided the limits of repeatability are borne in mind. The observation that systolic time interval ratios are unreliable for detecting change in pulmonary arterial pressure in babies with large intracardiac shunts [25] need not necessarily imply that they are useless in babies with a structurally normal heart. For example, both TPV/RVET and PEP/RVET have been shown to reflect the normal postnatal fall in pulmonary arterial pressure [5, 7]. It should be stressed, however, that this is only a study of

Table 3. Subjects for temporal/within-observer variability study

Pt. no.	Gestation (weeks)	Birth weight (g)	Diagnosis	Age (hours)	FIO_2 (%)	Oximetry (%)
1	33	1640	HMD (surf)	64	24	85
2	36	2800	HMD (surf)	28	65	85
3	29	1250	Immaturity	58	21	89
4	26	785	HMD (surf)	64	35	88
5	36	2250	HMD, PTC	22	80	90
6	36	2535	HMD, PTC	17	100	89
7	32	1610	Pulm h'age	29	100	81
8	40	3545	Asphyxia, PTC.	19	100	76
9	28	935	HMD (surf)	49	60	85
10	31	2000	HMD	12	100	85
11	28	890	HMD, asphyxia	14	100	81

Immaturity, baby was ventilated because of respiratory center immaturity (recurrent apnoea) and wet lungs; Pulm h'age, pulmonary hemorrhage; surf, baby has received surfactant therapy; PTC, persistent transitional circulation.

Table 4. Between-observer repeatability study: coefficient of repeatability and repeatability index for Doppler measurements of pulmonary arterial pressure

Measurement	No. pairs	Repeatability coefficient	95% Confidence limits[a]	Repeatability index (%)	95% confidence limits[a] (%)
TR velocity (m/s)	16	0.24	0.18–0.37	8	6–12
RV-RA (mmHg)	16	6.3	4.7–9.5	15	11–22
TPV/RVET	16	0.13	0.10–0.20	36	26–54
PEP/RVET	12	0.12	0.09–0.20	45	32–74
PDA max (m/s)	12	0.56	0.40–0.92	28	20–47
PDA mean (m/s)	12	0.58	0.41–0.95	36	26–60

Abbreviations: see Table 2.
[a] 95% Confidence limits of the repeatability coefficient and repeatability index, respectively.

repeatability, and the relation of any of these variables to ''true'' pulmonary arterial pressure has not been assessed here.

The repeatability index is lower for the TR velocity when it is expressed in meters per second (8%) than when it is expressed in millimeters of mercury (15%). This difference can only be due to transformation from velocity to pressure and therefore presumably is due to the multiplication factor, $4v^2$. The largest difference between observers is 7 mmHg (87 – 80 mmHg) for subject 20, but the difference in velocity is 0.2 m/s (4.7 – 4.5 m/s). The percentage error in millimeters of mercury for this subject is (7/83.5) × 100 = 8%, and in meters per second it is (0.2/4.6) × 100 = 4%. Therefore larger percentage errors can be expected at higher pulmonary arterial pressures, when the results are expressed as a pressure, rather than as a velocity. Because subjects with pulmonary hypertension are likely to have higher temporal variability anyway owing to the nature of this condition, it would seem especially prudent in these subjects to express the velocity in meters per second rather than millimeters of mercury.

Why is the reproducibility of the systolic time interval ratios so poor? When the difference between the PEP, TPV, and RVET measurements of the two observers are expressed as percentage error, the average mean error (mean interobserver error) was highest for TPV (17%). Mean error was 9% for RVET and 13% for PEP. Therefore it is the determination of TPV which, on average, caused the most difficulty. Because the principal effect of movement of the pulsed Doppler sample around the pulmonary artery is to alter TPV [17], it may be that subtle differences in positioning of the sample around these small main pulmonary arteries are to blame for this error. Turbulence within the pulmonary artery sometimes disturbs the contour of the pulmonary waveform, making accurate location of the point of peak velocity, as well as the end of the ejection time, difficult and prone to subjective variability.

All time intervals were therefore difficult to repeat accurately. Are these results consistent with results from other studies of repeatability in older children? Most publications validating the TPV/RVET ratio against direct measurement do not report variability between ob-

Table 5. Temporal/within-observer variability: Doppler values from the start of the study (1) to 1 hour later (2)

Pt. no.	TR (m/s)		RV-RA (mmHg)		TPV/RVET		PEP/RVET		Heart rate (bpm)		PDA max (m/s)		PDA mean (m/s)		AoSD (cm)		PaSD (cm)		BP sys (mmHg)	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.85	1.72	13.7	11.8	0.35	0.29	0.35	0.42	160	154	2.02	2.15	1.74	1.96	6.1	6.9	5.50	5.30	53	54
2	2.86	2.72	32.7	29.6	0.34	0.26			141	135	1.33	1.47	1.15	1.30	16.3	16.0	8.20	8.35	43	44
3					0.29	0.33	0.20	0.28	136	150	1.65	2.05	1.01	1.30	10.3	10.6	7.50	7.90	51	49
4					0.35	0.37	0.27	0.24	156	165	2.10	2.00	1.58	1.58	13.7	14.3	11.70	13.50	60	58
5	3.90	3.70	60.8	54.8							1.00	1.20	0.50	0.69	12.1	12.4			48	48
6	3.60	3.50	51.8	49.0	0.22	0.26	0.25	0.31	158	156	0.80	0.70	0.10	0.27	16.0	15.8	8.00	8.60	52	49
7					0.36	0.28	0.33	0.39	143	158	0.60	0.80	0.69	0.48	11.7	11.8	6.60	6.30	80	71
8	3.80	3.85	57.8	59.3	0.28	0.26			170	176					7.4	7.7	2.10	2.90	65	55
9	2.75	2.65	30.3	28.1	0.27	0.27	0.39	0.33	145	152					6.0	6.5	5.89	5.61	52	54
10	3.40	3.52	46.2	49.6	0.33	0.30	0.43	0.49	140	142	0.80	0.70	0.07	0.21	7.8	9.0	7.20	5.30	51	53
11	2.10	2.25	17.6	20.3	0.25	0.32	0.30	0.27	140	147	0.20	0.70	0.06	0.30	8.6	8.7	8.20	7.50	30	35

TR, peak velocity of tricuspid regurgitation; RV-RA, pressure drop from right ventricle to right atrium during systole; TPV, time to peak velocity at the pulmonary valve; PEP, right ventricular preejection period; RVET, right ventricular ejection time; AoSD, aortic stroke distance; PaSD, pulmonary stroke distance; BPSYS, systolic systemic arterial pressure; PDA max, PDA mean, maximal and mean left-to-right ductal flow velocity, respectively.

Table 6. Temporal/within-observer variability: coefficient of repeatability and repeatability index for Doppler measurements of pulmonary arterial pressure and blood flow

Measurement	No. pairs	Repeatability coefficient	95% confidence limits	Repeatability index (%)	95% confidence limits (%)
TR velocity (m/s)	8	0.26	0.18–0.50	9	6–17
RV-RA drop (mmHg)	8	6.45	4.4–12.3	17	11–32
TPV/RVET	10	0.10	0.07–0.18	34	24–60
PEP/RVET	8	0.12	0.08–0.22	36	24–68
PDA max (m/s)	9	0.48	0.33–0.88	39	27–71
PDA mean (m/s)	9	0.39	0.27–0.71	47	32–85
Aortic stroke distance (cm)	11	1.1	0.8–1.8	10	7–17
Aortic minute distance (cm)	11	281	200–478	17	12–30
Pulmonary stroke distance (cm)	10	1.9	1.3–3.3	26	18–46
Systolic BP (mmHg)	11	9	7–16	18	12–30
Heart rate (bpm)	11	17	12–30	11	8–20
RV-RA/BP ratio	8	0.18	0.12–0.35	23	16–45

Abbreviations: see Table 5. RV-RA/BP ratio, ratio of the peak RV-RA pressure drop/systolic systemic arterial pressure.

Table 7. ‘‘Confidence steps’’ for six Doppler echocardiographic measurement techniques in the newborn

Doppler measurement	Lowest expected value	Highest expected value	Expected range[a]	Repeatability coefficient	No. of ‘‘confidence steps’’[b]
TR velocity (m/s)	1.8	4.0	2.2	0.26	8.5
TPV/RVET	0.18	0.50	0.32	0.10	3.2
PEP/RVET	0.12	0.50	0.38	0.12	3.2
PDA max (m/s)	0.40	3.50	3.10	0.48	6.5
Ao stroke dist	5.0	16.0	11.0	1.1	10.0
Pa stroke dist	2.5	14.0	11.5	1.9	6.1

Abbreviations: see Table 5.
[a] Approximate range of values seen in the neonatal population, based on a longitudinal Doppler echocardiographic study of healthy newborns and those requiring intensive care [19–21].
[b] Confidence steps, number of repeatability coefficients within the expected neonatal range (see text).

servers, but Dabestani et al. [3] reported a *mean* interobserver error for TPV of 8.8% among 39 adults, which is half the mean error in the present study. This difference could be due to a number of factors. Adults usually lie still and have much larger pulmonary arteries. Babies tend not to lie motionless; they have narrow pulmonary arteries, and turbulence from ductal flow can disturb the signal. Furthermore, there may also be more genuine temporal variability occurring between examinations, particularly in the ventilated babies. Nevertheless, if we assume that Dabestani et al. had a mean error for RVET similar to that for TPV (9%), the expected error for the TPV/RVET ratio can be estimated from these figures. Thus when a TPV of 70 ms and an RVET of 200 ms are measured by the first observer, and TPV is overestimated by 9% and RVET underestimated by 9% by the second observer, the TPV/RVET ratio changes from 70/200 = 0.35 to 76.3/182 = 0.42, representing an increase of 20%. Therefore even when applying these more modest margins of error, differences greater than 20% can occur owing to interobserver error alone. This analysis suggests that our results are broadly consistent with those of Dabestani et al.; high interobserver error for the TPV/RVET ratio is to be expected.

Aortic stroke distance is a reproducible measure of blood flow, with the same average percent variability (approximately 10%) over 1 hour as heart rate and the velocity of tricuspid regurgitation under stable conditions. There have been other reports of repeatability of this measurement. Mellander et al., in a study of 10 children 6 weeks to 13 years of age [15], found a mean coefficient of repeatability for aortic velocity measurements of between 2.5% and 10.9% (each patient underwent six consecutive examinations), similar to the present study. However, Robson et al. [18] in a study of eight healthy adults, showed a lower repeatability coefficient for both aortic stroke distance (6.4%) and left ventricular output (9%). The figure of 9% compares rather favorably with that of 17% for aortic minute distance in the present study. However, it is hardly surprising that sick preterm babies should have a greater degree of temporal hemodynamic variability than healthy adults; and the fact that left ventricular output can vary so much (by more than 200% in premature babies with a patent duct) [14, 21, 26] suggests that the repeatability index of 17% is satisfactory when assessing change. The most thorough evaluation of repeatability of left ventricular output measurements in neonates was done by Hudson et al. in 1990 [11]. They studied 12 healthy neonates with the same method as for the present study (using continuous-wave Doppler from the suprasternal notch) and found within-observer variance of 16.5% for aortic minute distance—remarkably similar to our figure of 17%.

Pulmonary stroke distance showed greater variability, which may be due to genuine temporal variation, but a measurement error might result from the phenomenon described by Lighty et al. [13], where the velocity measured by pulsed Doppler varies considerably with the position of the Doppler sample in the main pulmonary artery. Care was taken to minimize this effect, but, as discussed with regard to the measurement of TPV, small movements can produce big changes in the relative position of the sample within the small pulmonary artery.

In summary, a simple statistical method has been described for evaluating the sensitivity of a measurement technique for detecting hemodynamic change. The number of repeatability coefficients within the expected range of values of the population are calculated, producing a number of ''confidence steps.'' A large number of steps indicates a technique that is likely to be useful for detecting change. With respect to serial Doppler echocardiographic measurements, it is most important that each echocardiographer should establish his or her own limits of repeatability with their own ultrasound equipment. Our results for the repeatability of measurement of aortic stroke and minute distance were similar to previous studies in the newborn, suggesting that the technical aspects are comparable with these studies. In our hands the Doppler echocardiographic techniques that are the most sensitive and repeatable indices of pulmonary arterial pressure in the newborn were velocity of tricuspid regurgitation and velocity of ductal flow.

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