Echocardiography in the Normal Neonate

By ROBERT SOLINGER, M.D., FRANCISCO EBL, M.D., AND KAREEM MINHAS, M.D.

SUMMARY

Utilizing the atrioventricular and semilunar valves as ultrasonic landmarks, a simple reproducible technic is described for the ultrasonic evaluation of the heart and its great vessels in the normal neonate. The importance of the clinical application of this method is discussed. Echocardiographic studies were performed on 240 normal newborns. Qualitative assessment was made of the interrelationships of the pulmonary, aortic, tricuspid, and mitral valves, and of interventricular septal motion. Quantitative norms were obtained for the following parameters: amplitude of motion of anterior leaflets of tricuspid and mitral valves, anteroposterior diameter of the ventricular and left atrial cavities, thickness of ventricular walls and interventricular septum, outside diameter of aortic and pulmonary roots, and interaortic and interpulmonary cusp distances.

Additional Indexing Words:
Aortic valve Echocardiographic profile
Left ventricular cavity Mitral valve
Tricuspid valve Ultrasoundcardiography

Echocardiography as a painless, atraumatic, and noninvasive technic is ideally suited to the study of normal and abnormal hearts. Since its introduction in 1954 by Edler and Hertz,1 pulsed reflected ultrasound has proved to be a useful tool in adults for the evaluation of a number of acquired2-7 and congenital8-11 lesions. It has also proved useful for assessment of chamber size,12-14 wall thickness,15, 16 and left ventricular function.17-18

Recent literature has described its use as an ancillary tool for the study of congenital heart disease in infants and children.19-23 Applications to date have incorporated technics acquired in the study of the adult patient. Examination of the right ventricle has been incomplete and detection of the pulmonary artery and valve inconsistent. Thus a satisfactory cardiac profile has not been offered.

The purpose of this paper is to describe a

standardized technic for the ultrasonic evaluation of the heart and its great vessels in neonates and infants and to present data obtained from a study of normal neonates.

Materials and Methods

Ultrasound examinations were performed on 240 neonates (table 1) who had normal physical examinations, electrocardiograms, and plain chest roentgenograms. The study group consisted of 123 males and 117 females divided into 10 half-pound groups ranging from 5 to 10 lb (2.27-4.54 kg). The majority were studied during the first 2 days of life, the earliest at 1½ hours of life, and the latest on the eighth day.

All cardiac echograms were recorded on Polaroid film using a Smith-Kline Ekoline 20 ultrasonoscope with a repetition rate of 1000 impulses/sec. A transducer with a center frequency of 9 MHz and an active area of 10 mm was used as a sound transmitter for 1 μsec and a sound receiver for 999 μsec. The principles of pulsed reflected ultrasound, including A-mode display and M-mode or "slow sweep" display have been reviewed in previous papers.12, 24, 25 Before beginning the study the controls were set for A-mode display and Polaroid prints for full scale deflections of 4 cm, 5 cm, and 6 cm were obtained for future accurate measurements of slow sweep displays.

The examinations were performed under an Air Shields Infant Warmer with a Servo Controller set to maintain the subject's skin temperature at 97.4°F. The head was rotated so that the facies were midline in order to minimize cardiac rotation. All examinations were performed without sedation with subject in supine position during normal respirations. The controls on the ultrasonoscope were set so that the depth compensation was not in use. The damping control setting was
minimized and the reject control was set at 0. The near and far gain controls were set at their maximum settings. In each case a Polaroid print was obtained after the direction of the sonic beam was adjusted to the maximal excursion of the structures under observation.

Table 1

Survey of Material

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<tr>
<th>Weight (kg)</th>
<th>Total no.</th>
<th>Sex (no.)</th>
<th>Race (no.)</th>
<th>Day of life</th>
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<td></td>
<td></td>
<td>M</td>
<td>F</td>
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<td>11</td>
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<td>4.09 - 4.29</td>
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<td>17</td>
<td>6</td>
<td>13</td>
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<tr>
<td>4.32 - 4.51</td>
<td>14</td>
<td>10</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Totals</td>
<td>240</td>
<td>123</td>
<td>117</td>
<td>137</td>
</tr>
</tbody>
</table>

Figure 1

Frontal view of the heart of the newborn showing the precordial locations from which the semilunar and atrioventricular valves are recorded. (A) Represents an echogram obtained with the transducer directed from the second interspace through the pulmonary valve. (B) Echogram obtained with the sonic beam directed from the inferior border of the third rib at its junction with the sternum through the aortic valve. (C) Echogram obtained with the transducer directed from the left border of the sternum at the level of the third interspace through the tricuspid valve. (D) Echogram obtained with the sonic beam directed from the third interspace through the mitral valve.
Recording Techniques and Measurements

In figure 1, the frontal view of the newborn's heart has been drawn showing the precordial locations directly under which the atrioventricular and semilunar valves lie. Since the neonate's skeletal system is cartilagenous and there is no intervening lung tissue, all four valves can be recorded from directly overhead. Parallel lines can be seen leading to a typical echogram obtained from each precordial valve location. In these and all subsequent echograms "T" represents the transducer on the precordium. Movement toward T is an anterior movement. White represents appropriate boundaries from which echoes have returned. Black represents echo-free spaces such as the fluid-filled cavities and great vessels. An electrocardiographic lead (ECG) has been incorporated into each echogram.

The mitral valve (MV) was recorded from directly overhead by placing the transducer in the third left interspace just adjacent to the sternum and directing its beam inferiorly and posteriorly. The most anterior position of its anterior leaflet echotrace (figs. 1d & 2) was found at a depth of 22–32 mm and its pattern of movement was similar to that observed in adults. Various points on the mitral valve echotrace (fig. 1d) have been labeled according to the designation of Edler. In early ventricular systole (isovolumetric contraction) the trace moves posteriorly from B to C as the leaflet bows into the left atrium (LA). With the onset of ventricular ejection it gradually moves anteriorly from C to D as the ventricle empties. In early diastole the echotrace shows an abrupt anterior movement from D to E as the leaflet opens into the left ventricle (LV). With ventricular filling there is a steep posterior movement from E to F as the leaflet closes. If the transducer is angulated medially, the LA wall (recognized by its posterior movement during systole) is found to lie posterior to the mitral valve. If it is rotated laterally the posterior LV wall (recognized by its anterior movement during systole) is found posterior to the valve. Figure 2 demonstrates the method used to measure the motion and thickness of the interventricular septum (septum), thickness of the posterior LV wall, anteroposterior (AP) diameter of the LV cavity, and the mobility of the anterior MV leaflet. The sonic beam was directed from the MV recording position through the anterior right ventricular (RV) wall, RV cavity, septum, LV cavity, anterior MV leaflet, and posterior LV wall. Assessment of the motion of the septum was made utilizing the ECG. Measurement of...
the thickness of the septum (fig. 2 at 1) was made
between the endocardial echoes of the left and right
sides of the septum at end-diastole. Measurement of
the thickness of the posterior LV wall (at 2) was made
between the endocardial and epicardial echoes of the
posterior LV wall at end-diastole. Measurement of the
AP diameter of the LV cavity (at 3) was made
between the left septal echo and the endocardial echo
of the posterior LV wall at end-diastole. Measurement
of the mobility of the anterior MV leaflet was made
between the most anterior or open (E) point and the
most posterior or closed (C) point of the leaflet trace.
End-diastole was determined from the echocardiograph-
ic pattern in conjunction with the ECG and
electrocardiographically it occurred approximately at
the peak of the R wave. In the presence of normal sinus
rhythm the maximum mobility of the anterior MV
leaflet measured on the echogram was used for mobility,
while the average of two measurements was used for
wall thickness and cavity size.

The tricuspid valve (TV) was recorded from directly
overhead by placing the transducer over the left half of
the sternum at the level of the third interspace and
directing its beam posteriorly. The most anterior
position of its anterior leaflet echotrace (figs. 1c and 3)
was found at a depth of 13-19 mm and its pattern of
movement was similar to that of the mitral valve.

Figure 3 demonstrates the method used to measure
the thickness of the anterior RV wall, AP diameter of the
RV cavity, and the mobility of the anterior TV leaflet.

From the TV recording position the sonic beam was
directed through the sternum, anterior RV wall, RV
cavity, anterior TV leaflet, aortic root, LA cavity, and
LA wall. Measurement of the thickness of the anterior
RV wall (fig. 3 at 1) was made between the
endocardial and epicardial echoes of the anterior RV
wall at end-diastole. Measurement of the AP diameter
of the RV cavity (at 2) was made at end-diastole
between the endocardial echo of the anterior RV wall
and the most posterior boundary of the RV cavity
which was taken to be the most posterior point on the
anterior leaflet trace. Measurement of the mobility
of the anterior TV leaflet (at 3) was made between the
most anterior or open (E) point and the most posterior
or closed (C) point of the leaflet trace.

The aortic valve (AV) was recorded from directly
overhead by placing the transducer over the inferior
border of the third rib at its junction with the sternum
and directing its beam posteriorly and, because of the
thoracic curvature slightly medially and superiorly.
The echo pattern of movement of the aortic root and
AV cusps was similar to that observed in adults. The
aortic root consists of paired, undulating signals moving
anteriorly during systole and posteriorly during diastole.
Between the margins of the aortic root the echotracets
of the aortic valve cusps can be seen as they open toward
the margins of the root and close toward its center.

Figure 4 demonstrates the method used to measure the

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Method for RECORDING and MEASURING THICKNESS of ANTERIOR (RV) WALL, AP DIAMETER of RIGHT
VENTRICLE CAVITY, and MOBILITY of ANTERIOR LEAFLET of TRICUSPID VALVE. The transducer is placed
at the level of the third interspace over the left border of the sternum and directed inferiorly and posteriorly
through the right ventricle, aortic root and left atrium. Measurement of the (l) anterior ventricle wall thick-
ess and (2) AP diameter of the right ventricle are made at end diastole. Measurement of mobility of
anterior leaflet of tricuspid valve is made between the most open (E) and closed (C) points of the leaflet
trace. Scale in centimeters. MPA=main pulmonary artery; Ao=aorta; TV=anterior leaflet tricuspid valve;
MV=mitchal valve; AVW=anterior ventricle wall; and ECG=electrocardiogram.

**Figure 3**

Method for recording and measuring the thickness of the anterior right ventricular wall, AP diameter of
the right ventricular cavity, and mobility of the anterior leaflet of the tricuspid valve.
outside diameter of the aortic root and the AP diameter of the LA cavity. From the AV recording position the sonic beam was directed through the RV outflow tract, aortic root and valve cusps, LA cavity and LA wall. Measurement of the outside diameter of the aortic root (at 1) was made at end-systole between the outside signals of the aortic walls. Measurement of the AP diameter of the LA cavity (at 2) was made between the endocardial echo of the LA wall and the outside echo of the posterior wall of the aortic root at end-systole. End-systole was determined from the echocardiographic pattern in conjunction with the ECG and electrocardiographically occurred approximately at the end of the T wave. An average of two measurements was used for both parameters. Figure 5 focuses on the aortic valve and demonstrates the method described by Gramiak and Shah for recording, assessing, and measuring aortic valve cusp motion. In the diagram the anterior position of the right coronary cusp, posterior position of the posterior noncoronary cusp, and lateral position of the left coronary cusp are clearly exhibited. With systolic movement the left cusp does not alter the distance between it and the transducer, while the right and posterior cusps execute significant movements toward or away from the transducer and produce boxlike configurations as seen on the echogram. The distance between the inside edges of the open valve cusps (interaortic cusp distance) was measured in order to estimate the valve orifice.

The pulmonary valve (PV) was recorded from directly overhead by placing the transducer in the second left interspace just adjacent to the sternum and directing its beam posteriorly and inferiorly. The echo pattern of movement of the pulmonary root and PV cusps was similar to that of the aortic. Figure 6 demonstrates the method used to measure the outside diameter of the pulmonary root and the pulmonary valve cusp motion. The sonic beam was directed from the PV recording position through the pulmonary root. Measurement of the outside diameter of the pulmonary root (at 1) was made at end-systole between the outside echoes of the anterior and posterior pulmonary walls. In the diagram the anterior position of the anterior cusp, posterior position of the left cusp, and lateral position of the right cusp are clearly exhibited. With systolic movement the right cusp does not alter the distance between it and the transducer, while the anterior and left cusps execute significant movements toward or away from the transducer and produce boxlike configurations as seen in the echogram. Estimation of the valve orifice was made by measuring the interpulmonary cusp distance (at 2).

Assessment of mitral-aortic valve continuity was made utilizing the same technic described in adults. Figure 7 demonstrates this procedure which is essentially a rapid, medial, and superior rotation of the sonic beam from the anterior MV leaflet onto the aortic root.

Handling of Data

All measurements were made to the nearest 0.5 mm. The measurements were separated into 10 half-pound
groups ranging from 5 to 10 lb (2.27-4.54 kg). Following a statistical analysis of the data, a graph was constructed for each parameter measured, relating the size of the parameter to the weight of the subject. From these graphs table 2 was constructed.

Results

Qualitative Findings of Septal Motion and Atrioventricular-Semilunar Valve and Great Vessel Relationships

The interventricular septal echoes moved anteriorly during ventricular diastole as the left ventricle filled and posteriorly during ventricular systole as the left ventricle emptied. Comparison of the septal and posterior LV wall echoes revealed them to move in opposition to each other (figs. 1d and 2).

The anterior wall of the aortic root at its most anterior position (end-systole) was found at a depth of 18-27 mm below the inferior border of the third rib at its junction with the sternum. The pulmonary root was located superiorly, anteriorly, and slightly to the left of this position under the second interspace (fig. 1). Its anterior wall at end-systole was found at a depth of 11-16 mm.

The echotrace of the anterior leaflet of the tricuspid valve in its most posterior (closed) position was continuous with the posterior wall of the aortic wall (fig. 7). In the vast majority of subjects studied it was at the same depth as the posterior wall of the aortic root. However, in some instances, it was found to lie as much as 3 mm below the wall.

Quantitative Results of Measurements of Cardiac Dimensions Related to Weight

Table 2 summarizes the relationships of the various cardiac dimensions measured to the weight of the subject. In this table it can be seen that the thickness of the interventricular septum is approximately equal to that of the posterior LV wall, and that the thickness of each of these structures is greater than the thickness of the anterior RV wall by about 0.7 mm for each weight group. A comparison of TV and MV mobilities reveals the TV to be about 0.5 mm greater than the MV mobility at 5 lb (2.27 kg) and 0.8 mm at 10 lb (4.54 kg). The outside diameter of the pulmonary artery is greater than that of the aorta by about 1.8 mm at 5 lb and 2 mm at 10 lb. The interpulmonary cusp distance is greater than the interaortic by about 2 mm at 5 lb and 3 mm at 10 lb.

Discussion

In the adult and older child a calcified sternum makes it necessary to angulate the ultrasonic beam.
Method for recording, assessing, and measuring pulmonary root and valve cusp motion. The transducer is placed in the second left interspace just adjacent to the sternum and directed inferiorty and posteriorly through the pulmonary root. The anterior position of the anterior cusp, posterior position of the left cusp, and lateral position of the right cusp are clearly exhibited. With systolic movement the right cusp does not alter the distance between it and the transducer while the anterior and left cusps execute significant movements toward or away from the transducer and produce boxlike configurations. (1) Measurement is made at end-systole of the outside diameter of the MPA. (2) Estimation of valve orifice can be made by measuring the distance between the opened valve cusps. MPA = main pulmonary artery; ECG = electrocardiogram.

Likewise, the presence of lung tissue over the pulmonary valve makes it difficult to record.

Method for RECORDING and ASSESSING MITRAL-AORTIC VALVE CONTINUITY. The transducer is placed in the third left interspace just adjacent to the sternum and directed inferiorty, laterally and posteriorly through the right ventricle, interventricular septum, anterior leaflet of mitral valve, and left ventricle (position 1). The transducer is then rotated superiorly and medially through the aortic root (position 2). The posterior aortic wall lies at the same depth as the anterior leaflet of the mitral valve in systole. LA = left atrium; LV = left ventricle.

Figure 7
Method for recording and assessing mitral-aortic continuity.
Table 2

Relationship between Weight of the Subject and Magnitude of Various Echocardiographic Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Predicted normal</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.27</td>
<td>2.73</td>
</tr>
<tr>
<td>TV mobility (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± 2 SD = ± 1.6</td>
<td>10.4</td>
<td>10.8</td>
</tr>
<tr>
<td>AP diameter RV cavity</td>
<td>8.8-12.0</td>
<td>9.2-12.4</td>
</tr>
<tr>
<td>at end-diastole (mm)</td>
<td>12.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Thickness ant (RV) wall</td>
<td>10.4-14.6</td>
<td>11.0-15.2</td>
</tr>
<tr>
<td>at end-diastole (mm)</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Outside diameter MPA</td>
<td>1.1-2.9</td>
<td>1.3-3.1</td>
</tr>
<tr>
<td>at end-diastole (mm)</td>
<td>12.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Interpulm cusp distance</td>
<td>10.7-13.3</td>
<td>11.2-13.8</td>
</tr>
<tr>
<td>(mm)</td>
<td>Mean ± 2 SD = ± 1.3</td>
<td>6.6</td>
</tr>
<tr>
<td>AP diameter LA cavity</td>
<td>5.8-7.4</td>
<td>6.3-7.9</td>
</tr>
<tr>
<td>at end-systole (mm)</td>
<td>Mean ± 2 SD = ± 0.8</td>
<td>8.7</td>
</tr>
<tr>
<td>MV mobility</td>
<td>6.8-10.5</td>
<td>7.4-11.1</td>
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<tr>
<td>Mean ± 2 SD = ± 1.8</td>
<td>9.8</td>
<td>10.2</td>
</tr>
<tr>
<td>AP diameter LV cavity</td>
<td>8.5-11.1</td>
<td>8.9-11.5</td>
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<tr>
<td>at end-diastole (mm)</td>
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<td>18.9</td>
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<tr>
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<tr>
<td>Mean ± 2 SD = ± 0.6</td>
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<td>2.4-3.6</td>
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<tr>
<td>at end-diastole (mm)</td>
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<td>Thickness post (LV) wall</td>
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<td>2.3-3.7</td>
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<tr>
<td>Mean ± 2 SD = ± 0.7</td>
<td>10.3</td>
<td>10.7</td>
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<tr>
<td>at end-diastole (mm)</td>
<td>9.3-11.3</td>
<td>9.7-11.7</td>
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<tr>
<td>Outside diameter aorta</td>
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<td>4.3-5.7</td>
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<tr>
<td>at end-systole (mm)</td>
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</tr>
<tr>
<td>Interventric cusp distance</td>
<td>Mean ± 2 SD = ± 0.7</td>
<td>5.7</td>
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</table>

Graimiak et al. have developed a technic utilizing a focused transducer in which they angulate the beam in a lateral and cephalic direction from a high left parasternal location. Using this technic they were able to detect the pulmonary valve in 95% of the adults and 60% of the older children studied. In contrast, the neonate and infant possess a cartilagenous skeletal system and a minimum of intervening lung tissue allowing direct overhead or antero-posterior recordings. Using a high-frequency transducer a satisfactory cardiac profile, including an adequate assessment of the right ventricle and pulmonary artery, can uniformly be obtained.

The transducer is the most important component of the instrument. In general, higher frequencies result in less beam spread and greater resolution, however, tissue penetration is diminished. In addition, the divergence of the beam is inversely proportional to the diameter of the crystal, thus, the larger the diameter the less beam spread. Following the early investigations of Edler and Hertz1 in which they showed that echo signals were best obtained from the deeper parts of the thorax in the average adult using a transducer with a center frequency of around 2.5 MHz, transducers with a center frequency of 2.25 MHz became commercially available. They also showed that a transducer with a center frequency of 5 MHz had good results in thin adults, and particularly in children. Despite this finding, to our knowledge, all the published studies to date in infants and children have been made using a commercially available 2.25 MHz transducer of 0.75 in (19 mm) diameter. While this transducer has given fairly satisfactory results as far as the more distant left ventricular and aortic echoes have been concerned, the echoes returning from the more anterior structures such as the anterior right ventricular wall have been "fuzzy" and unacceptable for quantitative measurement. Spectrum and real-time analysis was performed on the transducer used in this study by Aerotec Laboratories and it was found to have a center frequency of about 9 MHz and to be capable of resolving two structures 0.5 mm apart.

The movement of the interventricular septal echoes was the same as that originally described in the adult by Popp et al. and later confirmed in the child by Chesler et al. The relationships of the anterior leaflet of the tricuspid valve to the anterior wall of the aortic root and the anterior leaflet of the mitral valve to the posterior wall of the aortic root were the same as these originally described in the adult by Graimiak and Shah and later confirmed in the child by Chesler et al.
Gramiak et al., 24-26 using selective injections of indocyanine green dye to produce intracardiac echoes, have clearly shown that the various cardiac chambers, the interventricular septum, the atrioventricular valves, the aortic root and valve, and the pulmonary root and valve can be identified ultrasonically. Using this technic we have confirmed their work in the neonate and we have also proved that ultrasonic tracings obtained from the second left interspace just adjacent to the sternum represent the pulmonary root and valve (Fig. 8).

Studies performed in adults have demonstrated an excellent correlation between cardiac measurements by ultrasound and by other established methods. 14-16, 18 The thickness of the LV wall has been compared to surgical and autopsy estimations and to angiocardiographic measurements. 16 The AP diameters of the LA and LV cavities have been compared with those calculated by angiocardiography. 14, 18

Measurements have been made on normal newborn hearts at autopsy of the thickness of the walls of the right and left ventricles and the circumferences of the atrioventricular and semilunar valve orifices. Variations in fixation procedures and technics of measurements have resulted in conflicting data. Studies performed in the 1950's 27, 28 showed the thickness of the right ventricle to be greater than that of the left ventricle. Studies performed in the 1960's 29-32 showed the thickness of the right ventricular wall to be less than that of the left ventricular wall. The mean thickness reported in the latter studies for the right ventricular wall ranged from a low of 2.4 mm to a high of 3.2 mm. The mean thicknesses reported for the left ventricle ranged from a low of 4 mm to a high of approximately 5 mm. All the studies were in

Figure 8

Indocyanine green dye injection into main pulmonary artery. The resulting cloud of echoes is confined by the margins of the pulmonary root.
agreement on the size of the valve orifices. The tricuspid valve circumference and diameter were greater than the mitral, and the pulmonary valve circumference and diameter were greater than the aortic.

Utilizing the unique physical characteristics of the neonate and infant a simple reproducible technic has been developed which can be used in the nursery with a minimum of equipment. A minimum of five echograms are required for an "echocardiographic profile" of the heart and its great vessels. The profile consists of the quantitative parameters summarized in Table 2, plus the assessment of the qualitative features of pulmonary artery-aorta, tricuspid valve-great vessel, and mitral valve-semilunar valve relationships as well as septal motion. The clinical application of this "echocardiographic profile" in our institution has been very helpful in the differential diagnosis of newborns presenting in cardiorespiratory distress and/or cyanosis, rapidly separating those neonates with normal hearts from those with cardiac malformations. Its use in the abnormal hearts promises to make echocardiography a valuable tool for a fast and accurate clinical diagnosis of congenital heart disease in the critical neonatal period.33, 34

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