Nuclear Angiocardiography in the Diagnosis of Congenital Heart Disease in Infants

By Hadwig Wesselhoeft, M.D., Peter J. Hurley, M.D., M.R.A.C.P., Henry N. Wagner, Jr., M.D., and Richard D. Rowe, M.D., F.R.C.P.

SUMMARY
Nuclear angiocardiography with a gamma camera, a pinhole collimator, and $^{99m}$Tc pertechnetate was performed on 43 children aged 3 years or less, including 10 neonates. Twenty-six children had congenital heart disease, which was confirmed at cardiac catheterization; the rest had no structural cardiac anomaly. Use of the pinhole collimator allowed magnification of cardiac images, with enhancement of resolution. Sensitivity was improved by positioning the pinhole 14 cm rather than 19 cm from the crystal of the gamma camera. Anterior and left lateral angiocardiograms were obtained with both 35-mm images at 0.3-sec intervals and cine-images at 18 frames/sec.

Abnormalities in origin, size, and position of the great arteries, in chamber configurations, and in the time and course of activity in right and left heart, lungs, and great vessels were used to assist in identification of anomalies such as transposition of the great arteries, pulmonary atresia with intact ventricular septum, truncus arteriosus, and aortic atresia. $^{99m}$Tc in a dose of 18.5 mCi/m$^2$ of body area was used and produced whole-body and gonadal radiation doses less than 1 rad. The low risk and simplicity of the technic make it promising as a screening procedure and as an adjunct to cardiac catheterization for cyanosed infants.

Additional Indexing Words:
- $^{99m}$Tc pertechnetate
- Pulmonary atresia
- Gamma camera
- Aortic atresia
- Pinhole collimator
- Truncus arteriosus
- Enhanced resolution
- Respiratory distress syndrome
- Transposition of great arteries
- Radiation dosimetry

Accurate diagnosis of the cause of cyanosis in the sick newborn infant is essential for adequate treatment. While cardiac catheterization is an important diagnostic tool in patients with congenital heart disease, it carries risks$^{1,2}$ and should be avoided in patients whose cyanosis is not cardiac in origin. When an infant with congenital heart disease presents in the first month of life with cyanosis or congestive heart failure or both, the heart disease is always serious$^3$ and prolonged heart catheterization may be tolerated badly. The use of an angiocardiographic contrast medium provides additional hazards.$^4,5$ A safe screening procedure is needed which could sort out those infants whose cyanosis is not primarily cardiac in origin, in whom cardiac catheterization is better avoided, and could also facilitate the planning and shortening of catheterization when serious heart disease is present. In this context the demonstration of normal cardiac anatomy in a cyanotic infant with congestive failure, as in respiratory distress syndrome or

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the syndrome of transient myocardial ischemia, could allow cardiac catheterization to be avoided. The demonstration of certain anatomic anomalies, such as aortic atresia, might also allow omission of catheterization. On the other hand, the demonstration of transposition of great arteries could expedite balloon septostomy, and the provisional diagnosis of complex positional malformations might greatly facilitate the programming of cardiac catheterizations.

Nuclear angiography has been investigated as a possible screening technic with the advantages of complete safety and ease of performance. In all series of nuclear angiocardiograms reported to date, a gamma camera with a multiple-parallel-hole collimator has been used: This type of collimator produced no magnification, and resolution of anatomic detail in the small infant heart on the few occasions it has been attempted was insufficient for clinical usefulness. We have used a different system, employing a pinhole collimator, which magnifies and thus enhances the resolution of small structures. This has allowed us to obtain nuclear angiocardiograms even in premature neonates.

![Diagram](image)

Figure 1

(A) Imaging with the pinhole collimator inserted conventionally. Object A is magnified \( \times 2 \) in the crystal, and object B \( \times 1.5 \). Note that for object B to be seen in its entirety, it must be placed further from the pinhole than the smaller object A.

(B) Imaging with pinhole collimator inserted to achieve \( \times 2 \) and \( \times 1.5 \) magnification, respectively; objects A and B are positioned much closer to the collimator than in figure 1A. \( \theta \), the angle of acceptance, is increased from 58° to 73°.

Methods

For our study imaging was performed with an Anger scintillation camera (Pho-Gamma/III, Nuclear Chicago), equipped with a pinhole collimator. The pinhole collimator magnified the representation of radioactivity distribution in the crystal of the gamma camera, thus enhancing resolution. The smaller the distance between patient and pinhole, compared to the distance between pinhole and crystal, the greater the magnification (and therefore the greater the resolution) (fig. 1A). On the other hand, a sufficient separation between patient and pinhole was necessary for visualization of the entire heart and adjacent structures. In the pinhole collimator supplied by the manufacturers, the pinhole is 19 cm from the crystal when the collimator is inserted conventionally. If the collimator is inverted, the pinhole is 14 cm from the crystal (fig. 1B), and the patient lies closer to the pinhole. The closer the patient is to the detector, the greater the sensitivity. Sensitivity is thus increased when the collimator is inverted. The pinhole is inset 5 cm from the collimator face in the inverted position. In children 1 to 2 years of age and younger, the entire heart and adjacent structures can be visualized with the inverted collimator face virtually touching the chest wall. In experiments simulating this situation, with a target-to-collimator distance of 4 cm, the gamma camera with inverted pinhole collimator could resolve two thin linear sources of \( ^{99m} \text{technetium} \) 0.75 cm apart; the resolution of the camera with
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4,000-holed collimator was 1.5 cm. The sensitivity of the inverted pinhole collimator was 1.8 times that of the conventionally inserted pinhole collimator for equivalent magnification, but was only 0.3 times that of the multiple-holed collimator.

**Group Studied**

Forty-four children, aged 3 years or younger, were studied. Thirty-one were under the age of 1 year, including 10 less than 28 days (table 1). In 32 children there was evidence of heart disease at the time of the tracer study, and the diagnosis was established by cardiac catheterization with contrast angiography. The other 12 children studied had no evidence of heart disease, but were given 99mTc pertechnetate for brain scanning. The nuclear angiogram was made during the course of injection of the dose for the brain study.

**Technic**

All subjects were studied as follows: Before the study was begun, an intravenous 21- to 23-gauge needle was inserted into an arm or scalp vein and kept open with an infusion of 5% dextrose solution. The child was sedated, if clinically allowable, with chloral hydrate. Oral or rectal potassium perchlorate, 235 mg/m², was given to block thyroidal uptake of radioactivity. The spectrometer of the gamma camera was calibrated to detect the gamma-ray emission of 99mTc (140 kev, with a 30% window). For an anterior view, the patient was positioned with chest beneath the pinhole collimator, as close as possible to it in neonates, and with up to 1- to 2-cm separation in older children. For the left lateral view the left arm was elevated, and the collimator brought as close as possible to the left lateral chest wall. Patient motion was rarely a problem. The dose of 99mTc pertechnetate was injected rapidly into the intravenous needle as a bolus and flushed through with 1 to 2 ml of 5% dextrose solution immediately after removal of a tourniquet. The dose of 99mTc used was 18.4 mCi/m² of body surface area, the latter computed from the nomogram of Shirkey and Barba.12 The volume of injectate was kept low, usually in the range of 0.3 to 0.5 ml. The radiation dosimetry from this quantity of radioactivity, based on calculations given in the "Appendix," is shown in table 2.

Simultaneously with injection of the radiopharmaceutical, data recording was begun. Rapid-sequence images were obtained from the display oscilloscope of the gamma camera with a 35-mm photographic camera equipped with a motorized film-advance mechanism. Each exposure was of 0.4 sec, with a "dead time" during film advancement of 0.3 sec. At the same time, cineangiograms were obtained, with the use of a super 8-mm cine camera directed at the "persistance" oscilloscope of the gamma camera. After

<table>
<thead>
<tr>
<th>Diagnosis and Age Distribution in 44 Children</th>
<th>1 mo</th>
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<th>6-12 mo</th>
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<td>3</td>
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<td>Normal heart (heart disease excluded at catheterization)</td>
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<td>1</td>
<td>6</td>
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<td>Transposition great arteries</td>
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<td>9</td>
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<td>1</td>
<td>4</td>
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<td>3</td>
<td></td>
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<tr>
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<td>2</td>
<td>3</td>
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<td></td>
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<tr>
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<td>1</td>
<td>2</td>
<td>3</td>
<td></td>
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<tr>
<td>Complex heart disease</td>
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<td></td>
<td>1</td>
<td></td>
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<td>13</td>
<td>8</td>
<td>6</td>
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*From nomogram of Shirkey and Barba.12

<table>
<thead>
<tr>
<th>Body mass (kg)</th>
<th>Surface area (m²)*</th>
<th>Dose of pertechnetate (mCi)</th>
<th>Absorbed dose (rad)</th>
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<tr>
<td>10</td>
<td>0.46</td>
<td>8.31</td>
<td>0.66</td>
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</tbody>
</table>

Table 1

Table 2

Gonadal and Whole-Body Absorbed Radiation Doses from Nuclear Angiocardiography. Using 99mTc-pertechnetate, 18.5 mCi/m² of Surface Area
Figure 2

B.J. (JHH No. 1372700), age 9 months, weight 8.2 kg. Normal study, anterior view, 35-mm frames. In this and all subsequent figures, numbers in upper left-hand corner express time in seconds after injection; SVC = superior vena cava; RA = right atrium; RV = right ventricle; PA = pulmonary artery; RPA = right pulmonary artery; LA = left atrium; LV = left ventricle; Ao = aorta.

Data had been collected in both of these imaging modes for about 30 sec, the dynamic recording was stopped. Before the patient was moved, a final 350,000-count image of all the structures in the gamma-camera's field of view was obtained for orientation purposes; this generally required 30 to 60 sec. The patient could then be returned to the incubator if necessary. The time required

Figure 3

R.S. (JHH No. 1357438), age 15 months, weight 10.7 kg. Normal study, lateral view, 35-mm frames. PA arises anteriorly, from RV, and Ao arises posteriorly, from LA (table 3).
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for any baby to be out of an incubator was less than 4 min for the entire study. For sick children, heating lamps were used to maintain body warmth during this 4-min period.

Most subjects had only a single anterior study, but seven had both anterior and left lateral views on successive injections. The residual activity from the first injection did not preclude interpretation of the second, but sometimes made it more difficult. Even studies of overall indifferent quality sometimes proved useful because characteristic appearances in certain key regions could be used to supplement the rest of the available clinical data in making a diagnosis. The appearances in the patients with and without evidence of heart disease were used to establish criteria for the interpretation of these studies, and representative examples are described below. The superior resolution of the 35-mm frames, and the lack of “dead time” and graphic dynamic display of the cine, made each of these imaging modalities useful, and both have been used in the cases illustrated.

Results

Normal Heart

Figure 2 shows the series of images in a normal 9-month-old (8.2-kg) infant. The superior vena cava (SVC), right atrium (RA), right ventricle (RV), and pulmonary artery (PA) can be clearly distinguished. There is a clear space between the main PA and the SVC. The left atrium (LA), left ventricle (LV), and ascending and descending aorta are then progressively outlined. LA may be difficult to visualize in the anterior view because of activity in overlying structures. Details in these structures are often better appreciated by examining several successive frames.

The same sequence in the left lateral view in another normal child, aged 15 months (10.7 kg) is shown in figure 3: The PA arises from

![Figure 4](https://example.com/figure4.png)

G.M. (JHH No. 1397118), age 7 months, weight 5.3 kg. Transposition of the great arteries with septal defect, anterior view; cine frames. Ao arises from RV, filling the space beside the SVC; right-to-left interventricular shunt; faint visualization of PA and lung after LV (table 3).
Figure 5

(A) Same patient as figure 4. Transposition of the great arteries with ventricular septal defect, left lateral view, cine frames. Ao arises anteriorly from RV.

(B) L.M. (JHH No. 1364515), age 11 months, weight 6.7 kg. Transposition of the great arteries with intact ventricular septum, left lateral view; 35-mm frames. Ao arises anteriorly from RV (table 3).

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Figure 6

A.M.H. (JHH No. 1409361), age 2 days, weight 3.3 kg. Truncus arteriosus, anterior view; cine frames. Truncus fills beside the SVC only after LV outlines (table 3). Tr = truncus arteriosus; RDAO = right descending aorta.

the anterior ventricle and immediately perfuses the lungs. After the lung phase the aorta is seen arising posteriorly from the LV.

Transposition of Great Arteries

Figure 4 shows the cine frames (anterior view) from a 7-month-old (5.3-kg) infant with transposition of the great arteries and ventricular septal defect. The SVC, RA, and RV outline normally, but no PA is seen in its normal position. Instead, the clear space which normally exists between the SVC and the PA fills immediately after the RV, representing the aorta. A few frames later the LV is outlined because of a right-to-left shunt at the ventricular level. Subsequently, faint filling of the PA and some lung activity are visualized. In the lateral view of the same infant (fig. 5A), obtained a few minutes after the first injection, some background radioactivity is present. In contrast to the normal arrangement, the great vessel arising from the anterior ventricle passes down into the abdomen and is therefore the aorta. This finding is diagnostic of transposition of the great arteries. The left lateral view in figure 5B was obtained from an 11-month-old infant, weighing 6.7 kg, with transposition of the great arteries and intact ventricular septum.

Truncus Arteriosus

The cine frames in figure 6 were obtained from a 2-day-old (3.3-kg) infant with mild persistent cyanosis, congestive heart failure, and a grade III/VI to-and-fro murmur audible over the entire chest, loudest in the aortic area. The chest X-rays showed a large heart and increased pulmonary vascularity, and the
ECG demonstrated biventricular hypertrophy, without Q waves. Clinically, truncus arteriosus with insufficiency of the truncal valve was difficult to distinguish from absence of the pulmonary valve. In the figure, the SVC, RA, and RV appear normal (not the appearance of pulmonary atresia), but the PA is not seen. The space beside the SVC fills as a broad trunk from the LV, which in turn fills immediately after the RV. This trunk appears broader than a normal aorta, and this observation is evidence against transposition of the great arteries. Tetralogy of Fallot might have given this appearance, but this condition had been excluded on clinical grounds. At the time of filling of the trunk, activity appears below the heart in the abdominal aorta, which lies on the right side of the abdomen. This is characteristic of a truncus arteriosus (type 1), with a right aortic arch. This diagnosis was confirmed at catheterization and at autopsy, since the infant died 1 day after a Blalock-Taussig procedure and PA banding.

**Pulmonary Atresia with Intact Ventricular Septum**

Figure 7 demonstrates the findings in a 6-month-old (6.2-kg) infant with pulmonic atresia and a hypoplastic RV with intact septum. The diagnosis had been established at the age of 2 days, and at age 3 days a successful Pott's procedure was carried out. In figure 7 the RA is very prominent, and retrograde flow into the interior vena cava can be seen in subsequent frames. A clear distinction between the RA and the RV cannot be made. Neither pulmonary outflow tract nor PA is outlined; instead there is immediate visualization of LA and LV. A space persists between RA and left heart, suggesting that RV is small, unlike the situation in transposition of the great arteries or tetralogy of Fallot. Similar appearances might be found in...
tricuspid atresia or Ebstein's anomaly, but these could be excluded on clinical grounds, particularly electrocardiography. There is no definite aortic filling, but moderate lung activity, attributable to the functioning Pott’s anastomosis, is seen later. In the lateral view (fig. 8), obtained first, no vessel is seen arising from the anterior ventricle; the anterior angle between SVC and right heart is empty. This is a point of distinction from the normal situation in which the angle is filled by PA (fig. 3), and also from transposition of the great arteries in which the angle is filled by aorta (fig. 5A and B). Subsequently the LV is outlined, and abdominal and lung activity are seen; this sequence is due to the right-to-left shunt at ventricular level.

Aortic Atresia

Figure 9 is taken from the study of a 6-day-old (2.24-kg) infant with hypoplastic left heart syndrome with mitral stenosis, aortic atresia, and hypoplastic ascending aorta, proved at cardiac catheterization and autopsy. In this study, after some waxing and waning of its contained activity, the right heart remains densely outlined up to 20 sec after injection, due to a huge left-to-right shunt. There is subsequent lung activity, but never an outline of the left heart. Early abdominal activity suggests a right-to-left shunt through the ductus arteriosus.

Respiratory Distress Syndrome

Figure 10 presents a study performed on a 1-day-old (1-kg) premature infant, with severe respiratory distress, deep cyanosis, a changing, at times pansystolic, murmur, and a split second heart sound. In the chest X-rays the lungs had a ground-glass appearance,
attributable either to alveolar opacification or pulmonary edema. The heart appeared moderately enlarged. The ECG showed an axis of +90°, and RA and LV hypertrophy. Since cyanotic congenital heart disease could not be excluded, a nuclear angiocardiogram was performed. It demonstrated a right-to-left shunt at the atrial level, almost completely bypassing the lungs. At 2.2 and 2.4 sec after injection, LA filled immediately after the right heart, and LV followed; both filled before there was any evidence of great-vessel activity. No structural abnormality of the heart was evident, and the tracer study was interpreted as possibly showing right-to-left shunting through a patent foramen ovale, secondary to a marked increase in pulmonary vascular resistance because of a lung disorder. The infant died a few hours later. Autopsy revealed severe hyaline membrane disease and no structural cardiac anomaly.

Possible Transient Myocardial Ischemia

Figure 11 demonstrates the findings in a 1-day-old (2.9-kg) infant, with slight cyanosis from birth and increasing heart failure. A grade III/VI, pansystolic, late crescendo murmur was audible at the left lower sternal border with normal heart sounds. The pulses were present and equal. Chest X-rays showed an enlarged heart and possible pulmonary edema. There was right predominance in the ECG. In the tracer study, performed before contrast angiography, the sequence of events was normal; particularly in the left heart phase. There was no evidence of right-to-left nor of left-to-right shunt. The study was interpreted as indicating a normal heart, but since there was a strong family history of congenital heart disease, cardiac catheterization was performed. This demonstrated no structural cardiac anomaly; the ductus was still patent, with bilateral shunting and pulmonary artery pressure slightly above systemic levels. Ten days later, the cyanosis, murmur, and heart failure had disappeared completely.

The salient features of the studies described above are summarized in table 3.

Discussion

With the technic of nuclear angiocardiography using the pinhole collimator, we were able to characterize a number of important
Figure 10

B.B.R. (JHH No. 1409889), age 1 day, weight 1 kg. Respiratory distress syndrome, anterior view; cine frames. Right-to-left shunt at atrial level.

Figure 11

B.B.K. (JHH No. 1414156), age 1 day, weight 2.9 kg. Possible transient myocardial ischemia, anterior view; 35-mm frames. Normal right and left heart phases.

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Table 3

**Summary of Nuclear Angiocardiographic Findings in Differential Diagnoses of Certain Cardiac Malformations**

<table>
<thead>
<tr>
<th></th>
<th>RA</th>
<th>RV</th>
<th>PA</th>
<th>Lung</th>
<th>LA, LV</th>
<th>Ao</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal heart</td>
<td>Normal size</td>
<td>Outline of body &amp; pulmonary outflow tract</td>
<td>Origin from RV. Empty space beside SVC</td>
<td>Visualization after RV and PA</td>
<td>Outline after lung phase</td>
</tr>
<tr>
<td></td>
<td>Transposition of great arteries</td>
<td>Normal size</td>
<td>RV body normal size. No pulmonary outflow tract</td>
<td>Not visualized after RV filling. Faint outline after LV filling</td>
<td>Faint activity after LV and PA</td>
<td>Outline before lung phase via intracardiac R → L shunt</td>
</tr>
<tr>
<td></td>
<td>Truncus arteriosus</td>
<td>Normal size</td>
<td>RV body normal size. No pulmonary outflow tract</td>
<td>Not visualized after RV filling</td>
<td>Visualization after filling of truncus</td>
<td>Outline before lung phase via interventricular R → L shunt</td>
</tr>
<tr>
<td></td>
<td>Pulmonary atresia with intact ventricular septum, hypoplastic RV</td>
<td>Large, with reflux into IVC</td>
<td>Small</td>
<td>No visualization</td>
<td>Visualization after aortic filling via PDA</td>
<td>Outline before lung phase via interstitial R → L shunt</td>
</tr>
<tr>
<td></td>
<td>Aortic atresia</td>
<td>Normal appearance</td>
<td>Normal appearance</td>
<td>Normal appearance</td>
<td>Normal appearance</td>
<td>No visualization</td>
</tr>
</tbody>
</table>

Abnormal persistence of activity due to large L → R shunt

Abbreviations: Same as in text and figures; PDA = patent ductus arteriosus.
cardiac malformations in infants as young as 1 day old. Anterior and lateral views, usually only the former, were adequate to characterize and distinguish transposition of the great arteries, truncus arteriosus, pulmonary atresia with intact ventricular septum, and aortic atresia. In several infants suspected of serious heart disease, the tracer study correctly demonstrated normal anatomy. An example was the baby illustrated in figure 11, in whom our study showed a normal heart. This was confirmed at catheterization and by the subsequent clinical course. If right-to-left shunting is observed in an otherwise normal study, this may represent a patent foramen ovale. It has been reported that neonates with lung disease, high pulmonary vascular resistance, and elevated RA pressure may have large right-to-left shunts through the foramen ovale. This was probably so in the case shown in figure 10.

Although revealing far less anatomic detail than contrast angiography, nuclear angiocardiology is of no danger to the patient. The simple ionic substances used in trace quantities have no pharmacologic effect. Others who have used nuclear angiocardiology have been concerned mainly with studies in adults. Graham and associates described their experience in children, but all except one of their patients were more than 5 years old, and they did not attempt to differentiate between the various forms of cyanotic congenital heart disease. A problem in imaging the infant heart has been its small size, which taxes the inherent resolution capability of the scintillation camera unless special technics are used. The use of the pinhole collimator, which allows magnification of the structures, helps solve this problem. Sensitivity is decreased compared to the conventional parallel-hole collimator, however, because of the increased distance between the patient and the scintillation crystal (fig. 1). We have offset this to a degree by inverting the collimator, thereby reducing this distance. Distortion of anatomic detail by the pinhole collimator has not been a practical problem.

A dose of $^{99m}$Tc of 18.5 mCi/m² of body surface area was required for adequate visualization, especially in the later phases of the study. This dose cannot be significantly reduced if useful information is to be obtained. Whole-body and gonadal radiation doses were less than 1 rad in newborn infants, even if no biologic excretion of the tracer were assumed. Since there is renal excretion, the absorbed whole-body dose is in fact considerably lower. The International Commission on Radiological Protection has recommended that a whole-body or gonadal dose for radiation workers can be up to 5 rad/year, and for the general adult populace 0.5 rad/year. It has also stated that, although all radiation to embryos or fetuses is undesirable, accidental doses of 1 rad, even in the first 2 months of gestation, may be accepted. (See table 4.)

The skin dose during typical fluoroscopy using image intensification in a patient weighing 10 kg at Johns Hopkins Hospital is 3 rad/10 min; the gonadal dose is a minimum of 0.05 rad/10 min, with efficient collimation, but may be as high as 3 rad/10 min. Gonadal or whole-body doses of the order of 1 rad, as imposed by our technic, are many times less than a level at which permanent genetic or somatic damage is a significant risk. Such a small risk seems warranted in light of the seriousness of the patient’s problem. A tracer

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**Table 4**

<table>
<thead>
<tr>
<th>Body mass (kg)</th>
<th>Nonpenetrating radiation</th>
<th>X-rays</th>
<th>Gamma rays</th>
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study may spare an infant the radiation and other risks attendant on prolonged catheterization. It is likely that the radiation dose will be lowered and image quality improved by development of new radiopharmaceuticals and data-processing techniques, such as those using computers. Since the study is completed within a few minutes, the 6-hour half-life of \(^{99m}\)Tc is unnecessarily long. As radionuclides with shorter half-lives become available, the radiation dose may be considerably reduced. Even now, for properly selected patients, the procedure appears to be of considerable value.

**APPENDIX**

**Radiation Dosimetry Calculations**

The general equation\(^1\) for the absorbed radiation dose from an internally administered radionuclide is:

\[
D = \hat{C} \Sigma \Delta i \phi_i
\]

where: \(D\) = total absorbed dose (rads)  
\(\hat{C}\) = cumulative concentration  
(mCi ⋅ hr/kg)  
\(\Delta i\) = the equilibrium absorbed dose constant for the \(i\)-th emission of the radionuclide  
\(\phi_i\) = is the absorbed fraction for the \(i\)-th emission, i.e., the fraction of the \(i\)-th type of emission absorbed by the tissue under consideration.

This can be expanded:

\[
\hat{C} = \frac{A_0 \cdot 1.44 \cdot \%\text{eff}}{m} \quad (\text{mCi} \cdot \text{hr/kg})
\]

where: \(A_0\) = activity administered (mCi)  
\(\%\text{eff}\) = effective half-life of the radionuclide (hr) and \(m\) = mass of tissue under consideration (kg).

Thus, substituting in equation 1:

\[
D = \frac{A_0 \cdot 1.44 \cdot \%\text{eff}}{m} \Sigma \Delta i \phi_i \quad (\text{mCi} \cdot \text{hr/kg})
\]

These formulae were used to calculate absorbed doses for gonads and whole body in infants weighing 2, 6, and 10 kg (table 4). Values of \(\Delta i\) for \(^{99m}\)Tc (simplified from Dillman, 1969)\(^2\) are:

- Nonpenetrating radiation: 0.0363 kg ⋅ rad/mCi ⋅ hr  
- X-ray: 0.0031 kg ⋅ rad/mCi ⋅ hr  
- Gamma-ray: 0.2643 kg ⋅ rad/mCi ⋅ hr

For all calculations, the effective half-life of \(^{99m}\)Tc pertechnetate was taken as the physical half-life of \(^{99m}\)Tc, or 6 hours. Thus no excretion of pertechnetate was assumed, and the calculations if anything overestimated the absorbed dose in this respect.

Values of \(\phi_i\) were obtained from the tables of Brownell and associates.\(^3\) The body was assumed to approximate an ellipsoid with principal axes in the ratio of 1/1.8/9.27; the gonads were assumed to occupy a central point location in this ellipsoid. Values of \(\phi_i\) for \(^{99m}\)Tc for whole body and for gonads are almost identical under these circumstances. Values for \(\Sigma \Delta i \phi_i\) are shown in table 4. Using these values, substituting in equation 3, the absorbed doses to gonads are:

For a 2-kg infant:

\[
D = \frac{1 \times 1.44 \times 6 \times 0.0675}{2} = 0.29 \text{ rad/mCi}
\]

For a 6-kg infant:

\[
D = \frac{1 \times 1.44 \times 6 \times 0.0820}{6} = 0.12 \text{ rad/mCi}
\]

For a 10-kg infant:

\[
D = \frac{1 \times 1.44 \times 6 \times 0.0891}{10} = 0.077 \text{ rad/mCi}
\]

Results for whole-body dose are identical. Gonadal and whole-body doses based on the calculations in this "Appendix" are listed in table 2 in the main body of the text.

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