Radiation Exposure to the Child During Cardiac Catheterization

J. D. WALDMAN, M.D., P. S. RUMMERFIELD, Sc.D., E. A. GILPIN, M.S., AND S. E. KIRKPATRICK, M.D.

SUMMARY Few data are available regarding radiation exposure to children during cardiac catheterization. Using lithium fluoride thermoluminescent dosimeters, radiation exposure was measured during precatheterization chest roentgenography, fluoroscopy (hemodynamic assessment phase of catheterization) and cineangiography in 30 infants and children, ages 3 days to 21 years. Dosimeters were placed over the eyes, thyroid, anterior chest, posterior chest, anterior abdomen, posterior abdomen and gonads.

Average absorbed chest doses were 24.5 mR during chest roentgenography, 5810 mR during catheterization fluoroscopy and 1592 mR during cineangiography. During the complete catheterization, average doses were 26 mR to the eyes, 431 mR to the thyroid area, 150 mR to the abdomen and 11 mR to the gonads.

Radiation exposure during pediatric cardiac catheterization is low to the eyes and gonads but high to the chest and thyroid area. To decrease radiation dosage we suggest (1) low pulse-rate fluoroscopy; (2) substitution of contrast echocardiography for cineangiography; (3) large-plate abdominal/gonadal shielding; (4) a selective shield for thyroid area; (5) a very small field during catheter manipulation. Minimum radiation consistent with accurate diagnosis is optimal; however, erroneous or incomplete diagnosis is more dangerous than radiation-related hazards.

THIS STUDY was intended to answer four questions relating to cardiac catheterization in children: How much radiation is the child exposed to during a routine study? What differences are there in exposure to various areas of the body? How much radiation is related to cineangiography compared with fluoroscopy? How might radiation exposure be reduced?

We know of no reports of thyroid carcinoma being associated with cardiac catheterization. Awareness of a potential association is desirable in all clinicians examining such patients.

References
7. Rowley KA: Patient exposure in cardiac catheterization and cinefluorography using the Eclair 16 mm camera at speeds up to 200 frames per second. Br J Radiol 47: 169, 1974

Materials and Methods

Thirty infants and children chosen randomly were evaluated during clinically indicated cardiac catheterization studies between April and July 1979. Age ranged from 3 days to 21 years (table 1). Fourteen had left-to-right shunts, 10 had cyanotic congenital heart disease, four had right- or left-heart obstruction, one had Ebstein's anomaly, and one child had no significant heart disease. Balloon septostomy was performed in two neonates.

Lithium fluoride thermoluminescent dosimeters (TLDs) were applied to the body during precatheterization chest roentgenography, during the hemodynamic assessment (fluoroscopy) phase of cardiac catheterization and during cineangiography. The TLDs, 0.3 × 0.3 × 0.09-mm chips of high-sensitivity...
TABLE 1. *Clinical and Dosimetry Data from 30 Children During Cardiac Catheterization*

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</tr>
</tbody>
</table>

Mean 14.4 | 4 y | 2 m | 71.8 | 15.8 | 5.1 | 41.6 | 24.5 | 5810 | 1592 | 25.9 | 431 | 150 | 11

± SD 11.9 | 4 y | 1 m | 33.2 | 5.9 | 1.7 | 37.8 | 20.8 | 5251 | 1340 | 14.5 | 244 | 110 | 10

Abbreviations: y = years; m = months; d = days; Cath = time from insertion to withdrawal of cardiac catheter; fluoro = fluoroscopy; angio = angiography; cine = cineangiography; NSHD = no significant heart disease; VSD = ventricular septal defect; TOF = tetralogy of Fallot; ASD = atrial septal defect; po = postoperative; PS = pulmonary stenosis; PDA = patent ductus arteriosus; TA = tricuspid atresia; CoA = coarctation of the aorta; BAS = balloon atrial septostomy; PAPVR = partial anomalous pulmonary venous return; RCA-RV = right coronary artery-to-right ventricle; SV = single ventricle; AS = aortic stenosis; D-Cor = dextrocardia; PA = pulmonary atresia; TGA = transposition of the great arteries. Arrows indicate combined dosage for cine and fluoro.

Lithium fluoride, were sealed in 5 × 3-mm plastic bags to avoid contamination. For chest roentgenography, the TLDs were placed over the left nipple and the left scapula; during fluoroscopy, TLDs were located on the glabella, sternal notch, left nipple, left scapula, umbilicus, sacral spine and on testicles (males) or inside the rectum (females) within an IVAC disposable plastic thermoprobe; during cineangiography, unexposed TLDs were added to those already present on the left nipple and left scapula and all of the other TLDs remained in place.

After irradiation, the TLDs were prepared and read
Cardiac catheterization was performed in the standard fashion; no change in technique was introduced. Angiograms were performed as clinically indicated using the Philips three-phase Rotax 350 biplane cineangiography system. Focal spot was 0.6 mm in each plane. The milliamperage was stabilized (maximum 300 mA) with variable kilovolts (maximum 125 kVp). Filming was performed at 60 frames/sec and measured to be 23 μR/frame.

Results

Catheterization time (from insertion to withdrawal of catheter) ranged from 23–149 minutes (mean 71.8 minutes) (Table 1) and mean fluoroscopy time (the sum of the anteroposterior and lateral planes) was 15.8 minutes (range 5–27 minutes). Volume of contrast administered varied with patient size; when indexed to weight (ml/kg body weight) the average was 3.16 ml/kg (range 1.33–4.76 ml/kg). The number of angiograms performed varied with the complexity of the lesion. The number of angiograms was tabulated as the number of planes of cineangiography performed; one biplane cineangiogram was tabulated as two angiograms (table 1). Most children had two or three biplane cineangiograms.

Precatheterization chest roentgenography was performed in all children; dosimetry was measured in 20. Average absorbed dose to the chest was 24.5 ± 20.8 mR. Absorbed dose was defined as the difference between entrance and exit doses. Absorbed chest dose during fluoroscopy (hemodynamic assessment) was an average of 5810 ± 5251 mR (table 1) and during cineangiography was 1592 ± 1340 mR.

As a means of comparison, radiation exposure was expressed as chest x-ray equivalents, defined as ratio of total catheterization dose to chest roentgenogram dose. When so expressed (table 2), the fluoroscopy phase of the study was equal to an average of 428.2 chest x-rays and the cineangiography was equivalent to an average of 99.9 chest x-rays (fig. 1). From the complete cardiac catheterization, the average thyroid dose was equivalent to 35 chest x-rays.

Average target doses during the complete catheterization study (fluoroscopy plus cineangiography) were: nose (25.9 mR) thyroid (431 mR) and gonads (11 mR); absorbed dose to the abdomen averaged 150 ± 110 mR. Even though the TLDs were placed internally in females and externally in males, there was no significant difference in gonadal dose between males and females. Thyroid dose did not correlate significantly with age, weight or body surface area.

Chest dose did not correlate well with fluoroscopy time (r = 0.52) but did correlate with body surface area when controlling for fluoroscopy time (partial correlation, r = 0.84). A regression equation (r = 0.92, see ± 2.54) was developed, based on fluoroscopy time (fluoro time) (minutes) and body surface area (BSA) (cm²): chest dose (R) = 0.3 (fluoro time) + 13.5 (BSA) – 7.2.

Discussion

In 1906, Bergonie and Tribondeau reported that younger, more immature organisms have greater sensitivity to radiation effects. Experience with childhood irradiation of the head and neck has confirmed this. Extrapolating from California Children’s Services data, over 37,000 cardiac catheterizations were performed in children in the United States in 1978. Despite the extensive use of cardiac catheterization and the demonstrated sensitivity of children, data are fragmentary regarding radiation exposure to the patient during cardiac catheterization.

Adams et al. emphasized the importance of radiation exposure data. Evaluating blood samples taken

![CHEST X-RAY](24 mR)

![CARDIAC CATHETERIZATION](7402 mR)

**Table 2. Chest X-ray Equivalents of Cardiac Catheterization**

<table>
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<th>Absorbed by chest during</th>
<th>Average dose (mR)</th>
<th>Equivalent # of chest x-rays</th>
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<td>Cardiac fluoroscopy</td>
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<td>428</td>
</tr>
<tr>
<td>Cineangiography</td>
<td>1592</td>
<td>100</td>
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</table>

**Figure 1. Pediatric radiation exposure to the thorax — chest roentgenogram vs cardiac catheterization. Area in circles reflects relative absorbed dosage to the chest. Relative contributions of the fluoroscopy (F) and angiography (A) phases of catheterization are indicated.**
before and after catheterization with cineangiography in 20 children, chromosomal damage was found in all post-study specimens. In a subsequent study, the dose effect was shown to be enhanced by the use of contrast agent for angiography. Differences between pediatric and adult cardiac catheterization are relevant: average volume of contrast administered in children was 3.16 ml/kg body weight; in adults, the average volume was 2.08 ml/kg body weight (unpublished data).

In adults, Gough et al., Aradan et al., and Malsky et al. estimated exposure based on radiologic equipment settings and field size. Calculation of total exposure ranged from 3–100R. Malsky suggested that the ideal setting would be to obtain dosimetry information of the performance of the actual procedure.

Thermoluminescent dosimetry has been applied to adults and children during cardiac catheterization, usually to measure gonadal or thyroidal dosage. Mean exposure to the pubic region was 12.1 mR in adults, a figure almost identical to ours, and ranged from 9–300 mrad in children, apparently reduced in the presence of gonadal shielding, according to Kaude and Svahn. A wide diversity of thyroidal dosage has been reported. Martin and Olson reported an exceedingly high thyroidal exposure (average of 7.7 rad) in a catheterization laboratory in which the serial film changer technique was used in all studies. In children from early infancy to 13 years of age, Gustaffson and Mortensson reported a total median absorbed thyroidal dose of 261–369 mrad, based on a soft-tissue conversion factor of 0.92 rad R. Reuter, in 12 adults, reported a similar level of exposure (243–278 mR).

While it is preferable to discuss human dosimetry in radiation-absorbed dose (rad), the conversion factor from roentgen (a unit of exposure) to rad is based primarily on size, location and mass density of various tissues, derived from phantom studies. Such studies have not been reported in children of various ages and sizes. Because of the wide range of patient size in our series and the likelihood of introducing error using a single roentgen-to-rad conversion factor, our dosimetry data are reported in roentgens.

Our results indicate a very low radiation exposure to patients' eye region; the level found is consistent with the forehead exposure to the physician found by Wold et al. and is probably related to scatter. The average gonadal dose we found, 11 mR (equivalent to less than one-half of the exposure to the chest from a chest roentgenogram), is reassuring, especially considering the work of Adams et al. The application of commercially available gonadal shields would be of little use in cardiac catheterization because the radiation source is posterior and the device is applied anteriorly.

Our data indicate an average exposure of 431 mR to the thyroid region. Gustaffson and Mortensson felt that absorbed dose to the thyroid comes almost exclusively from scattered radiation. Martin and Olson stated that thyroid exposure is directly related to the degree of collimation, at least during serial radiography. We believe that both scatter and collimation are significant factors. Collimation close to the heart is critical to prevent directing the primary beam on incidental structures, e.g., the thyroid. However, in small infants, it may be difficult to "cone" the field so as to completely avoid thyroid exposure and still visualize the aortic arch.

Childhood irradiation of the thyroid gland has been associated with the induction of thyroid tumors and hypothyroidism. In thyroid carcinoma, tumor incidence is proportional to thyroidal dose. A latent period of longer than 40 years has been found between irradiation and clinical presentation. It is difficult to compare our thyroid dosage with head-and-neck radiation given to children in the 1950s because the early dosage data were estimated rather than measured, and the 1950s exposure was repetitive, whereas cardiac catheterization is a single-dose event. The data of Beach and Dolphin and Silverman and Hoffman citing doses of 6–1225 rads is several orders of magnitude different from our measured thyroid exposure of 431 mR. However, both from recent and early reports, children are clearly more radiosensitive than adults. The optimal dose is the lowest possible dose that produces complete, clinically relevant information.

While some abdominal structures are not highly radiosensitive, the gastrointestinal tract may be damaged by ionizing radiation. The abdominal exposure found during cardiac catheterization is high enough (average 150 mR) to merit efforts at reduction. Placement of a lead shield (0.5 mm or thicker) under the buttocks should be standard; the shield should be positioned so that its most cephalad edge is just below the level of the diaphragm.

Radiosensitivity is proportional to cell reproduction rate and thus, the hematopoietic bone marrow areas are highly radiosensitive. In a 1974 study, Seidlitz and Margulis estimated x-ray dosimetry to the vertebral bone marrow based on measured skin entrance dose and phantom experiments to correlate entrance dose with intravertebral exposure. Although the internal mass relationships found in the adult human differ significantly from those in the child, we have applied our skin entrance dosimetry to the formula developed by Seidlitz to calculate an average abdominal vertebral bone marrow exposure of 40.5 ± 20.4 mR during the complete cardiac catheterization. Dose to the thoracic vertebral bone marrow as an average of 460 ± 267 mR for the complete cardiac catheterization study. Until long-term (20–40 years) studies indicate the absence of increased incidence of leukemia in patients who had cardiac catheterizations in childhood, continued vigilance and periodic check-ups must be applied.

The target organ of cardiac catheterization is, of course, the heart. The resultant x-ray dosage to the chest is large, an average of 7.4 R, expressed as the difference between entrance and exit exposures. (If
one considers only the entrance readings, the mean chest exposure was 8.1 R.) There is no accepted limit for maximum diagnostic radiation dosage to the thorax. The guidelines for maximum radiation to the whole body ("occupational dose") for those under 18 years of age limit the yearly exposure to 500 mrem.20

Certainly, occupational repetitive incremental exposure is physiologically different from single-event irradiation. Nonetheless, it is of concern that an average pediatric cardiac catheterization produces an absorbed thoracic x-ray dosage 14.8 times the yearly allowable whole body occupational dosage.

Damage to thoracic organs has been well documented after therapeutic levels of radiation, including cardiac inflammation,21-24 constrictive pericarditis25 and myocardial fibrosis.26 Though therapeutic dosage is in rads and diagnostic exposure is usually in mrad, a single average pediatric cardiac catheterization produces an absorbed thoracic dosage of 7.4 rads (fig. 1). Many children require multiple cardiac catheterizations, with resulting accumulation of radiation effects,24 and subclinical damage may become evident only after years or decades.17, 18 In view of the potentially longer life span of children, it seems imperative to perform long-term, follow-up studies of patients who have had cardiac catheterizations in childhood.

Clinical Implications

The regression equation based on our data correlates well with the observed chest dosage in our laboratory. However, it is unlikely that the same formula would yield reliable predictions in other laboratories, owing to differences in radiographic systems, geometry, table composition and filtration. We believe that the same factors (fluoroscopy time and body surface area) are likely to be the relevant variables. To have a useful regression equation, each laboratory must generate its own exposure data and analysis.

Radiation exposure can be decreased during standard catheterization procedure in many ways. (1) Field size during catheter manipulation should be very small. (2) Real-time echocardiographic visualization of size and location of cardiac structures provides important precatheterization information especially in complex malformations, which may shorten catheter manipulation time and thus indirectly decrease radiation exposure. (3) Angiography is usually performed after completion of all hemodynamic studies due to the large osmotic load and toxic effects of contrast agents. However, in extremely complex anomalies, even with preparatory echocardiographic studies, uncertainty regarding anatomy or blood flow patterns may lengthen the procedure and increase the risk. In such cases, consideration may be given to an initial angiogram before extensive catheter probing/mobilation. (4) Though radiation exposure of the abdomen and gonads during cardiac catheterization is low, a large-plate abdominal/gonadal shield may further decrease exposure. (5) In small children, frequently it is not possible to narrow the field to exclude the thyroid area and still visualize the aortic arch structures. A small, malleable lead shield should be placed between the primary beam and the neck to protect selectively the lower nuchal region. (6) Though biplane filming provides more information than single-plane mode, there are occasions in which only one plane is of interest, e.g., the four-chamber view of the atrial septum. In such situations, single-plane filming may be used to decrease radiation. (7) The customary filming speed of 60 frames/sec generally provides excellent line resolution and detail. However, in some situations, e.g., spot cines for catheter course, left superior vena cava injection for visualization of the brachiocephalic anastomosis, slower rates (15 or 30 frames/sec) allow reduction in radiation without loss of crucial data.

Alternatives to current practice might also be considered to reduce radiation exposure. Low-pulse-rate fluoroscopy26, 27 should be operationally and dose-tested in children; if an appreciable decrease in exposure is achieved, the system should be recommended for all pediatric catheterization laboratories. Selective chamber/great artery contrast echocardiography can provide considerable information formerly available only by angiography. This is especially true when using two-dimensional echocardiographic equipment. Increasing utilization of this technique should decrease the number of angiograms and volume of dye administered.

Long-term follow-up studies decades after cardiac catheterization in childhood will provide a more realistic appraisal of the possible dangers of catheterization-related x-ray exposure.

Potentially hazardous tests are often performed (i.e., cardiac catheterization) when the disease process poses a greater danger to the patient than the test. The need for cardiac catheterization usually indicates the possibility of surgical intervention. Thus, the child with heart disease is at risk from the heart defect as well as the surgery that may be required. Erroneous or incomplete diagnosis poses a much greater danger to the patient than any potential hazard from catheterization-related irradiation. Thus, while radiation exposure should be minimized, this must not be done at the expense of diagnostic accuracy.

Acknowledgment

Our gratitude is expressed to Drs. George Kaplan, Sidney C. Smith, Jr., Kenneth Miller and to George Cowman and Charles Koch for support and encouragement in this project.

Addendum

After acceptance of this paper, a low-pulse rate fluoroscopy system using a video-disc memory (VAS) was installed and interfaced with the Philips radiographic system. Flicker rate was maintained at 10 pulses/second. The effect on absorbed thoracic radiation during fluoroscopy was assessed in 12 consecutive children during cardiac catheterization and the results in these children were compared with those in the original study group. The original (continuous fluoroscopy) and the new (pulsed fluoroscopy) study groups are comparable in age, body surface area and fluoroscopy time (table A1). An 88% reduction in absorbed thoracic radiation was achieved with use of pulsed fluoroscopy.
### Table A1. Effect of Pulsed Fluoroscopy on Absorbed Chest Dose

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<th></th>
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<th>Mean BSA (m²)</th>
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<th>Mean absorbed chest dose (mR)</th>
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</tbody>
</table>

Abbreviations: BSA = body surface area; y = years; m = months.

### References

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