

THE RADIOLOGICAL HEALTH SIGNIFICANCE OF
CARDIOVASCULAR SPECIAL PROCEDURES

By

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Published information has indicated that radiation exposure to patients and personnel involved with cardiac catheterization procedures is high. A study of the radiation exposure to both groups has been carried out. Variations in exposure levels related to factors such as patient classification, equipment configuration and operational procedures have been investigated. Based on the findings in this study, a comprehensive set of radiological health recommendations are given. Equipment modifications that would allow acquisition of the necessary diagnostic information with less exposure are also proposed.

An analysis of the personnel monitoring records from ten medical facilities involved with the conduct of cardiac catheterization special procedures showed exposure levels

significantly higher than those reported for diagnostic x-ray workers in general.

Exposures at various body sites on the physician and technologists involved with catheterization examinations of pediatric and adult patients were also investigated. The unshielded head and neck regions were seen to receive the highest exposures when compared to the established radiation protection guides for various parts of the body. Physician exposures during studies of acquired heart disease in adults were typically at least twice that received during pediatric congenital defect studies. Annual exposure to a technologist in a facility examining both pediatric and adult patients would be expected to be similar to that of an adult cardiologist involved with a typical yearly case load.

The radiation exposure to more than 300 patients undergoing cardiac catheterization for congenital and acquired heart disease have been studied. The incident exposure area product, $R.cm^2$, for each patient has been related to multiple surface TLD measurements obtained on a selected subgroup. Adult and pediatric phantoms were used to determine the relationship of incident surface exposure to the resultant dose delivered to specific internal organ systems or parts of the body. These exposure values have been correlated with the examination techniques and equipment used to determine where modifications could be made to

reduce these levels. Utilization of pulsed video disk fluoroscopy and 105 mm fluorography may result in reductions of 25 to 60%.

CHAPTER I
INTRODUCTION

In the last few years, the United States has experienced a drastic increase in the number of cardiac catheterization laboratories. The exact number of these facilities is not presently known, but based upon unpublished manufacturers sales projections, it may be as high as 600. Wholey (1974) states that it has been estimated that approximately 400,000 coronary examinations are being performed in the world yearly. If each laboratory carried out 300 procedures per annum, which is the minimum number of examinations recommended by the Inter-Society Commission for Heart Disease Resources (1971) required to maintain expertise of the professional team, the number of procedures performed in the U.S. may be as high as 180,000 per year. This is 45% of the world estimate and does not include other acquired valvular, pulmonary, conduction or congenital studies. In a limited number of published studies the radiation exposure to patients and personnel has been shown to be high. Incident exposures in excess of 200 Roentgens (R) have been reported for an individual procedure. The International Commission on Radiological Protection (ICRP) (1973) has identified this area of radiologic concern. This study was initiated to investigate

the radiological health aspects associated with these cardiac special procedures.

Cardiac catheterization is an invasive medical diagnostic procedure combining hemodynamic and angiographic techniques. Patient application is found in the evaluation of congenital and acquired heart disease.

The evaluation of coronary arterial disease constitutes the largest proportion of the acquired heart disease studies. The procedure is typically performed with single plane fluoroscopy (fluoro) and associated cinefluorography (cine). The examination will usually consist of a left ventricular-gram and selective coronary angiography. The patient is placed in a rotation cradle to aid in positioning for right and left oblique geometry. Also used is equipment in which the patient position is fixed and the x-ray source and image receptor are rotated on a C-arm support. The cardiac special procedure room may also be equipped to use rapid film changers or a 70, 100 or 105 mm fluorographic camera. For the study of congenital heart disease, fluoro and serial bi-plane radiography are commonly used. The patient will usually be positioned on a flat, floating-top table.

The technique of intravascular catheterization can be traced back to Fritz Bleichroder (1912). He passed a catheter from his thigh into the inferior venacava without fluoro. Werner Frossman (1929) is generally credited with being the first individual to pass a catheter into the heart

of a living human subject. At the time of his investigation, Frossman was a 25-year-old German medical student. His concern was to develop a technique whereby drugs could be introduced directly into the heart of patients in severe cardiac distress. Following initial trials on cadavers, he attempted his first investigation on a living subject through self-experimentation. During his first trial he passed an oiled urethral catheter from an arm puncture site 35 cm into the vein toward his heart. At this point the experiment was aborted due to his colleagues' fear that any further advancement of the catheter might be risky. A week later Frossman made a second attempt with the aid of a nurse. During this trial he advanced the catheter approximately 65 cm under fluoroscopic observation from a left elbow venasection. He then walked, with the catheter in place, to the hospital radiology department so a radiograph could be taken to verify the placement of the catheter in the right heart chamber.

Frossman described the utilization of this technique in a patient suffering from a perforated appendix (Sourkes, 1966). The patient subsequently died, but he states that the effect of the catheter, which had been left in place for approximately 5-1/2 hours, was not the cause.

Following his initial investigation the technique of heart catheterization was not put to any general use until 1940 when Andre Cournard and Dickerson Richards utilized it in their research studies relating to the physiology of the

heart (Cournard and Ranges, 1941). The impact of this research, using heart catheterization techniques, resulted in their receipt of the 1956 Nobel Prize for medicine and physiology. Frossman was also included as a co-recipient of the award due to his initial work.

The use of heart catheterization techniques for applied clinical investigations dates back less than 20 years. Dexter and colleagues (1947) was one of the first to report on its use in the study of congenital heart defect studies. Until 1950, investigations had been limited to the right heart. Zimmerman and colleagues (1950) described a retrograde technique whereby the catheter was advanced into the left heart via an artery over the aortic arch. The alternate technique of trans-septal puncture in which the catheter is passed through the septal wall of the heart to gain access to the left heart chambers was described by Ross (1959) and Cope (1959).

One of the primary uses of cardiac catheterization techniques today is in the study of acquired heart disease. The work of Sones and colleagues (1959) in the development of cine angiographic procedures opened the door to selective coronary studies in common use today. In the so-called Sones technique, the catheter is introduced into a brachial artery after it has been surgically isolated. Using the percutaneous puncture technique described by Seldinger (1953), Ricketts and Abrams (1962) described an alternative procedure where the catheter is introduced into a femoral artery in the groin.

Judkins (1967) has further developed this percutaneous technique in combination with the use of preshaped catheters for selective coronary artery studies.

Objectives of Study

Recognizing the potential high exposure levels that exist during cardiac catheterizations, an evaluation of the radiological health significance of these procedures was undertaken. The specific objectives of the study were as follows:

1. Identify key factors relating to equipment, clinical personnel and procedures currently found in a cross-section of cardiovascular special procedure facilities.
2. Measure patient and operator exposure and evaluate the magnitude of these levels in terms of the doses delivered to selected organ systems or regions of the body.
3. Develop and evaluate equipment and procedural changes that would result in a reduction of unnecessary radiation exposure.
4. Develop guidelines for the radiological evaluation and operation of a cardiovascular x-ray special procedure facility.

The above objectives were achieved by (1) conducting a field survey to provide insight into the range of current practices

and (2) performing an in-depth study in the cardiovascular laboratory of the Shands Teaching Hospital of the University of Florida (UF cardiovascular laboratory). The radiological health aspects were, for the most part, divided into the two broad areas of patient and operator exposure.

CHAPTER II
CARDIOVASCULAR X-RAY PRACTICES

A general overview of the range of cardiovascular laboratory organization and practices was obtained through a field survey of selected facilities within the State of Florida. In addition, more specific information on a single laboratory was obtained in the initial stages of the in-depth investigations carried out in the UF cardiovascular laboratory.

Nine Florida Facilities

The exposures to patients and personnel during cardiovascular special procedures would be expected to vary from facility to facility. Factors such as equipment setup and operational characteristics, patient classification and procedural techniques might be expected to be of key importance. To investigate the variations that exist among facilities, a field survey of ten cardiac catheterization laboratories in nine Florida hospitals was conducted. The surveys were conducted in cooperation with the Radiological Health Section of the Florida Division of Health and one or more representatives from that agency were present during each field visit.

The results of the field survey have been broken down into the areas of facility operational structure, personnel staffing, x-ray equipment and radiological health procedures. Table 1 gives a breakdown of the organizational and operational characteristics of the nine facilities. Two were part of a department of radiology and a third, although structurally separated from radiology, was operated under the direct supervision of a radiologist. The remaining six facilities were administratively structured within departments of cardiology. Four of the facilities had been operating for five years or more while the remaining five laboratories were about one year old. Although the number of facilities was limited and selection had not been based on statistical considerations, the general trend regarding the expansion of new cardiac catheterization laboratories on a nationwide basis seems to be borne out by the number of new facilities in this sample. In two-thirds of the facilities, only cardiac studies were performed. For the remaining three, additional noncardiac special procedures were carried out in the room. In each case, these additional studies were conducted by an alternate group of physicians on a second priority basis.

Table 2 gives a breakdown of the personnel associated with each laboratory. In the majority of the cardiac catheterization laboratories, a cardiologist alone was responsible for operation of the facility. In the two

TABLE 1

Organization and Operational Characteristics for
Nine Cardiac Catheterization Facilities

| Comment | Facility Identification Number | | | | | | | | |
|---|--------------------------------|------|------|------|------|------|------|------|-----|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
| Organizational Structure: | | | | | | | | | |
| a. under direct control of radiology | x | | | | | | x | | |
| b. radiology and other department | | | | | | | | | x |
| c. completely separate from radiology | | x | x | x | x | x | | x | |
| Length of time facility in operation (years) | 1 | 1.5 | 1 | 1 | 8 | 15 | 5 | 1 | 12 |
| Type of examinations performed and yearly patient load (examinations/year) | | | | | | | | | |
| a. adult (acquired heart disease) | 200 | 600 | 450 | 300 | 800 | 800 | 700 | 650 | 375 |
| b. pediatric (congenital heart disease) | none ^a | none | 375 |
| Is facility used for other than cardiac procedures | yes | no | no | no | no | no | yes | yes | no |

^apediatric cardiologist has just been hired at time of survey.

TABLE 2
Operating Personnel Structure for Nine Cardiac Catheterization Facilities

| Comment | Facility Identification Number | | | | | | | | |
|---|--------------------------------|------|------|------|------------------|------------------|------------------|------|------------------|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
| Number and classification of physicians: | | | | | | | | | |
| a. cardiologists | 3 | 1 | 1 | 1 | 2+1 ^a | 4+3 ^a | 6 | 2 | 5+5 ^a |
| b. radiologists | 2 | none | none | none | none | none | none | none | 2+2 ^a |
| Number and classification of technologists: | | | | | | | | | |
| a. cardiovascular | 1 | none | 1 | 3 | 1 | 6+4 ^b | none | 4 | 5+4 ^b |
| b. pulmonary function | none | none | none | none | none | none | 2 | none | none |
| c. x-ray | 3 | 3 | none | none | none | none | 2+1 ^b | 1 | none |
| d. registered nurse | 1 | 1 | 1 | none | 2 | none | none | none | 2 |
| e. other | none | 1 | 1 | none | 1 | none | none | none | 1 |
| Makeup of typical examination team: | | | | | | | | | |
| a. physician | lor2 | 1 | 1 | 1 | 1+1 ^a | 1+1 ^a | lor2 | 1 | 1+1 ^a |
| b. technician | 2or3 | 4 | 4 | 2 | 2or3 | 3+1 ^b | 4+1 ^b | 3or4 | 4+1 ^b |

^a Training fellow

^b Student technologist

TABLE 2 Continued

| Comment | Facility Identification Number | | | | | | | | |
|--|--------------------------------|----|----|----|----|------------------------|----|----|------------------------|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
| Is a radiation or health physicist involved in operation of laboratory (full or part time, in house or consultant) | no | no | no | no | no | yes part time in house | no | no | yes full time in house |

laboratories where radiologists were involved, they acted as technical directors, and cardiologists were still primarily responsible during patient examination. In addition, they were available for consultation with and often assisted the cardiologist during the angiographic portions of a study. The technical support staff were predominantly cardiovascular technologists. This is a relatively new medical technology specialty, but due to an active junior college training program at one location in Florida, a number of graduates have been made available to the laboratories visited in this survey. Better than one-half of the facilities were found to have no x-ray technologist and four had neither a radiologist nor an x-ray technologist. The input of a radiation or health physicist was also seen to be minor. Of the two facilities that are listed as having the input of such an individual, the first was the hospital safety officer who admitted his only involvement was in followup studies when high film badge readings were obtained. The participation at the second laboratory related to the author's activity at the University of Florida as a graduate student.

Table 3 gives a brief outline of the x-ray equipment setup in the nine facilities (note that facility number six was equipped with two separate special procedure rooms). The x-ray generators represented three manufacturers. Nine of the procedure rooms were equipped to perform single plane fluoro/cine (facility number four had two image intensifiers,

TABLE 3

X-ray Equipment Configuration in Nine Cardiac Catheterization Facilities

| Comment | Facility Identification Number | | | | | | | | | |
|-------------------------------|--------------------------------|-----|-----|------------|-----|------|-------------|-----|-------|-----|
| | #1 | #2 | #3 | #4 | #5 | #6 | | #7 | #8 | #9 |
| | | | | | | Rm A | Rm B | | | |
| X-ray Generators: | | | | | | | | | | |
| a. number | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 2 |
| b. single or 3 phase | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| c. rated power (kW) | 100 | 125 | 125 | 100 | 100 | 125 | 100 | 125 | 125 | 100 |
| d. manufacturer ^a | Ph | GE | P | Ph | Ph | P | Ph | GE | GE | Ph |
| Fluoro Image Receptor: | | | | | | | | | | |
| a. number | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 |
| b. single(s) or bipiane(b) | s | s | s | s | s | s | b | s | s | s |
| c. nominal size (inches) | 6 | 6/9 | 6/9 | 6, 6/9 | 6 | 6 | 6/9, 6/9 | 6/9 | 4/6/9 | 6 |
| c. type of phosphor | CsI | CsI | CsI | CsI CsI | CsI | CsI | CsI | CsI | CsI | CsI |
| Cine: | | | | | | | | | | |
| a. single(s) or bipiane(b) | s | s | s | s | s | s | b | s | s | s |
| b. size format (mm) | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |

^aManufacturers code as follows: General Electric (GE), Franklin (F), Elema Schonander (ES), Spectrum (S), Picker (P), Philips (Ph) and Cordis (C).

TABLE 3 Continued

| Comment | Facility Identification Number | | | | | | | | | |
|-------------------------------|--------------------------------|------|-----|------|------|------|------|------|------|------|
| | #1 | #2 | #3 | #4 | #5 | Rm A | Rm B | #7 | #8 | #9 |
| Serial Radiographic Changer: | | | | | | | | | | |
| a. single(s) or biplane(b) | s | b | b | s | b | b | b | s | b | b |
| b. manufacturer ^a | F | ES | ES | ES | ES | P | ES | F | ES | ES |
| Fluorographic Camera: | | | | | | | | | | |
| a. single(s) or biplane(b) | s | none | s | none |
| b. size format (mm) | 70 | | 105 | | | | | | | |
| Examination Table: | | | | | | | | | | |
| a. add-on (over table) | x | x | x | x | x | x | x | x | x | x |
| b. in table | S | S | P | Ph | C | P | Ph | C | S | Ph |
| c. manufacturer ^a | | | | | | | | | | |

^aManufacturers code as follows: General Electric (GE), Franklin (F), Elema Schonander (ES), Spectrum (S), Picker (P), Philips (Ph) and Cordis (C).

but a single fluoro/cine x-ray source). For the one facility that had the capability to perform biplane cine, they stated that it was infrequently used at the current time. All facilities were equipped with serial film changers; 70% were capable of simultaneous biplane exposures. Only two of the rooms were equipped with fluorographic cameras and neither was used during cardiac procedures. All facilities were equipped with some type of patient rotation cradle. In one-half of the cases this device was an add-on cradle that elevated the patient above a lower flat table surface.

Table 4 lists a number of items directly relating to radiation safety. Seven of the laboratories had been previously inspected by the State and/or an in-house or outside consultant. Two facilities had not been previously inspected, but both had been in operation for only approximately one year. No determination of the content or adequacy of the prior inspections was attempted.

The number of protective aprons available at each facility was consistent with the number of individuals involved with a procedure. Apron design and lead equivalence varied. A number of situations were noted where a technician indicated that he positioned a non-wrap-around apron on his back since the greatest anticipated exposure would result when he was standing with his back to the patient. In most cases the aprons were stored in the procedure room. At one facility an individual entering the room after a procedure

TABLE 4

Radiological Health Characteristics Associated
With Cardiac Catheterization Facilities

| Comment | Facility Identification | | | | | | | | |
|---|-------------------------|-----|-----|-----|-----|-----------------|-----|-----|-----|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
| Had a previous radiation survey been performed? | yes | yes | no | no | yes | yes | yes | yes | yes |
| If yes, by: | | | | | | | | | |
| a. State Health Department | x | x | | | x | x | x | x | x |
| b. in house physicist | | | | | | x | | | x |
| c. private consultant | x | | | | x | | | | |
| Protective Lead Apron | | | | | | | | | |
| a. number and design: | | | | | | | | | |
| (f) frontal | 8 | 10 | 4 | 4 | 6 | 7 | 7 | 7 | 8 |
| (w) wraparound | | | 1 | 1 | | 5 | | | |
| b. lead thickness: | | | | | | | | | |
| 0.25 mm equivalent | 7 | 10 | 5 | 5 | 6 | 12 | 4 | 7 | 7 |
| 0.5 mm equivalent | 1 | | | | | | 3 | 7 | 1 |
| c. apron stored in room: | x | | | | x | | | x | |
| d. apron stored out of room: | | x | | x | | x | x | | x |
| Shielded control booth provided? | yes | yes | yes | yes | yes | yes/ | yes | yes | yes |
| | | | | | | no ^a | | | |

^aNo shielded control booth in second room (physiological monitor controls located next to procedure table in both rooms).

TABLE 4 Continued

| Comment | Facility Identification | | | | | | | | |
|--|-------------------------|-----|---------|----|----|------|-------|------|---------|
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
| Location of physiological monitor controls: | | | | | | | | | |
| a. in procedure room | | | x | x | x | x | x | | |
| b. in shielded booth | x | x | | | | | | x | x |
| Is access by personnel limited in room during: | | | | | | | | | |
| a. cine exposures | no | no | no | no | no | no | no | no | some |
| b. serial radiography ^b | NUR | NUR | all out | LP | LP | | LP 2T | NUR | all out |
| Position of film badge: | | | | | | | | | |
| a. under apron | vary | x | x | x | | x | x | x | |
| b. outside | | | | | x | | x | | x |
| c. additional hand site | | | | | | | x | x | |
| Is any personnel rotation carried out? | some | no | no | no | no | some | no | some | yes |
| Is any index of patient exposure recorded? | no | no | no | no | no | no | no | no | yes |
| Have gonad shields ever been used? | no | no | no | no | no | no | no | no | no |

^bWhere serial radiography was not used regularly (NUR), access of personnel was not noted. Where serial radiography was used, the number of physicians (P) and technologists (T) in the room are indicated.

had started would have to walk past the procedure table to select an apron.

A shielded control booth was present in all but one room, but the physiological monitor controls were located in the room in close proximity to the procedure table in six out of ten cases.

The personnel radiation monitoring procedures varied from facility to facility. A discussion of the type and position of the monitoring device and records of the exposures received are discussed in Chapter IV. Briefly, it can be stated that badge sites outside and under the protective lead apron were used. In a number of situations no firm policy regarding the badge site existed with the decision as to site being left up to the individual. In only two of the nine facilities were more than one monitor per person used.

In one facility an organized rotation of technical support personnel existed. Although the primary purpose was to give experience in all aspects of the procedure to the staff, a distribution of exposure was also achieved. Three other facilities indicated some rotation occurred, but in 50% of the cases each person had a non-varying job assignment.

In general, no policy was followed to position non-essential individuals at sites away from the patient during cine exposures. Of the five facilities that utilized serial

radiographic techniques on a regular basis, the physician remained next to the patient during serial radiography and was often assisted by one or more technicians.

University of Florida Cardiovascular Laboratory

The following discussion reports conditions in the UF cardiovascular laboratory at the time of the study.

Equipment

This room was used to study both adult and pediatric patients. The room was equipped with two Philips^a "Maximus-100" x-ray generators. An under table x-ray source with over table image intensifier used for fluoro and cine exposures. The cine camera was a 35 mm unit which operated at frame rates up to 64 frames per second. Two ceiling mounted radiographic tubes were used in conjunction with biplane Elema Schonander^b cut film serial changers.

The x-ray generators were three-phase units. The maximum tube potential for radiographic exposures was 150 kVp. During radiographic operation, the generators utilized the falling load principle. This falling load, or isowatt principle, which has been described by Van de Wetering (1971), achieves the maximum tube loading for any specified setting

^aPhilips Medical Systems, Inc., Shelton, Connecticut.

^bElema Schonander, Inc., Elk Grove Village, Illinois.

of tube potential and exposure time. During the exposure, tube current is initiated at a high value so that the maximum rated anode temperature is quickly achieved. Tube current is subsequently reduced by means of a motor-operated variable resistor in the primary filament circuit. The advantage of this system is that the desired exposure in the minimum exposure period is automatically achieved without the need to reference the tube rating charts. During fluoro the x-ray system is operated in a single phase mode with a maximum tube potential of 110 kVp.

The procedure table had a flat floating top that allowed longitudinal and lateral movement. For pediatric congenital heart studies, the patient was strapped to a restraint board constructed from 0.64 cm (0.25 inch) fiber board covered with a foam pad. Adult patients were usually examined in an add-on rotation cradle. Figures 1 through 3 show the geometric arrangements for the under table fluoro cine tube and the two biplane radiographic sources. The measured half value layer (HVL) values for the x-ray tubes and examination conditions are listed in Table 5.

During this study, two image intensifiers were alternately installed in the system. Both intensifiers had a cesium iodine (CsI) input phosphor. One tube was a single mode intensifier and the second a dual mode; they were described by the manufacturer as a six inch and nine inch, respectively. The visible area measured at the input

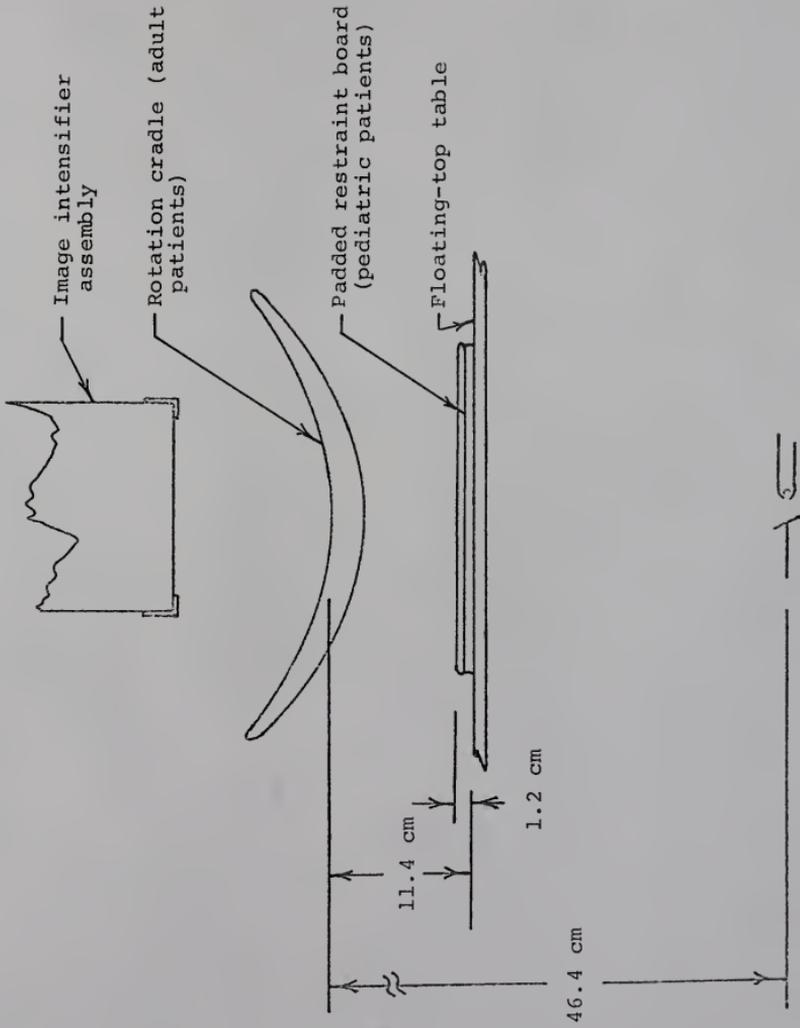


Figure 1. Dimensional Configuration for Under Table X-ray Source.

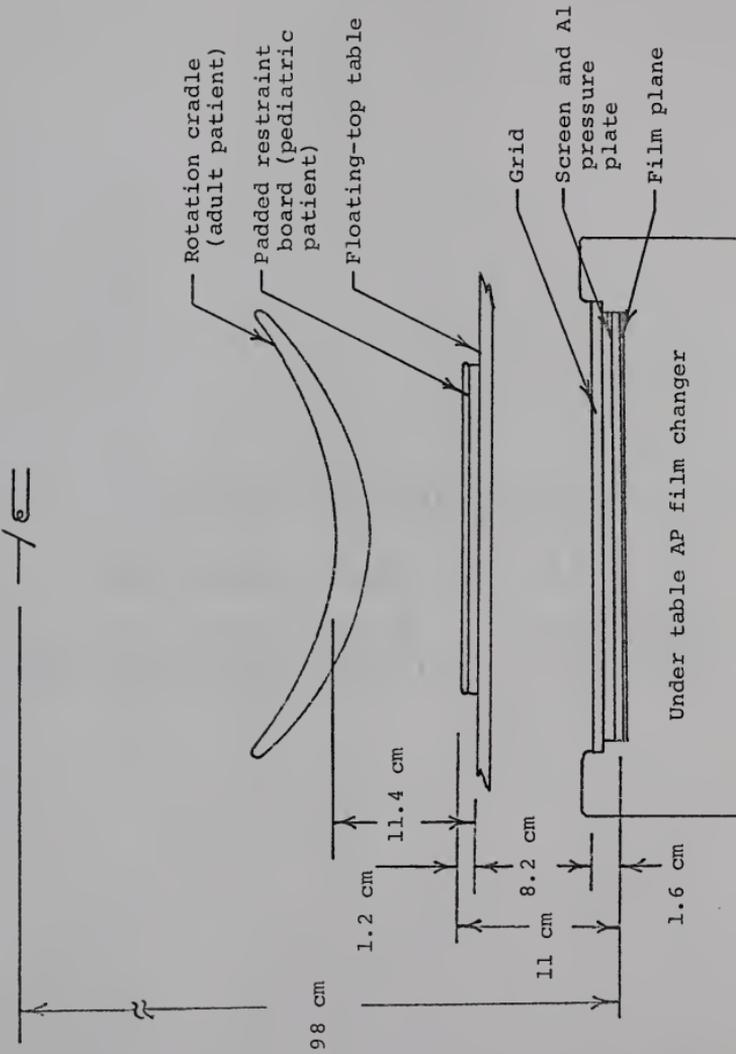


Figure 2. Dimensional Configuration for AP Biplane Film Changer.

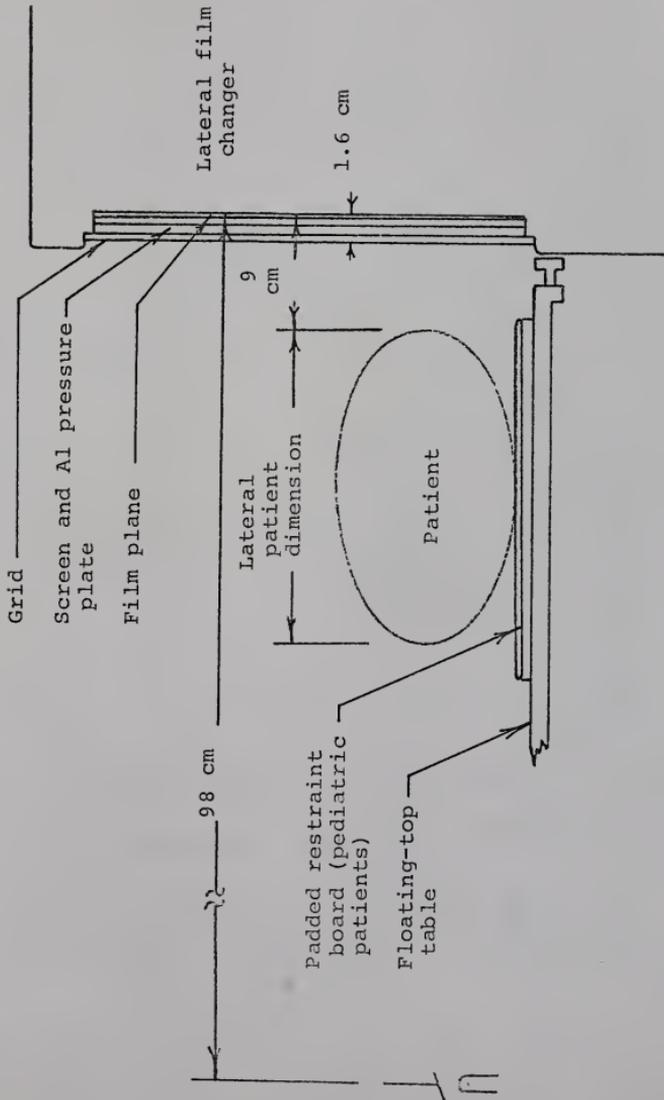


Figure 3. Dimensional Configuration for Lateral Biplane Film Changer.

TABLE 5
 Measured First Half Value Layer for Various
 X-ray Source and Patient Geometries

| <u>X-ray Tube and Geometry Identification</u> | <u>Measured HVL^a at 80 kVp (mm Al)</u> |
|---|---|
| Vertical, PA, radiographic source (Machlett "Dynamax" 69B) | 3.3 |
| plus flat table surface | 4.2 |
| plus flat table surface and pediatric restraint board | 4.4 |
| plus flat table surface and cradle | 4.5 |
| Horizontal, LAT, radiographic source (Machlett "Dynamax" 64B) | 3.1 |
| Under table fluoro/cine source (Philips grid controlled) | |
| plus flat table surface | 4.4 |
| plus flat table surface and pediatric board | 4.7 |
| plus flat table surface and cradle | 4.9 |

^aAll values measured with PTW exposure area product chamber attached to diagnostic source assembly.

phosphor of the single mode tube was 156 cm^2 (diameter of 14.1 cm) and for the dual mode tube 143 cm^2 (diameter 13.5 cm) and 296 cm^2 (diameter 19.4 cm). A 60 line 6:1 grid was used with both intensifiers. A 35 mm cine camera, normally operated at 64 frames per second, was used in conjunction with both intensifiers.

The biplane film changers utilized 14 x 14 inch cut film and had a maximum rating of six films per second. The changer magazine would accept 30 films so the maximum number of films exposed in a biplane angiographic run was limited to 60 films. The lateral changer was equipped with an 80 line criss-cross grid and the under table anterior-posterior (AP) changer with an 80 line 12:1 focused grid. The position of the film with respect to the input grid surface for each film changer is shown in Figures 1 and 2.

The fluoro/cine system was equipped with an automatic brightness control system. The brightness of the output phosphor of the image intensifier was monitored by a photo-tube. The signal from this photo-tube detector was then compared with a pre-set reference value. The output of the x-ray tube was then automatically varied until the monitored and reference signals matched. The brightness control system used with the single-mode tube was a current modulation system. For the dual-mode intensifier tube, potential was varied to maintain the desired brightness level.

Appendix A gives characteristic data for operation of the isowatt falling load system. Measured exposure output data for radiographic and fluoro operations are also given.

Patient and Examination Trends

The cardiac catheterization records at the Shands Teaching Hospital of the University of Florida were reviewed to extract information regarding patient age, frequency of repeat examinations and fluoro time. A tabular listing of the patient age and fluoro time is given in Appendix B.

Figure 4 shows a plot of the age distribution for catheterization patients less than 18-years old. This group consists primarily of patients evaluated for suspected congenital heart defects. The histogram shows a bimodal distribution with a large peak in the birth to 6-month period and a second at 5 to 6-years. Fifty percent of the catheterizations on patients less than 18-years old were conducted on individuals less than 4-years old. Data for the adult patient studies are shown in Figure 5. Fifty-one percent of these studies were carried out on patients in the 40 to 60 age period.

Table 6 lists the frequency rate of cardiac catheterization on a per patient basis. Approximately 1/4th of the pediatric patients received multiple catheterizations. The maximum number of these repeat procedures was six. For the adult patient, only 15% were examined more than once. The maximum number of multiple examinations was found to be five

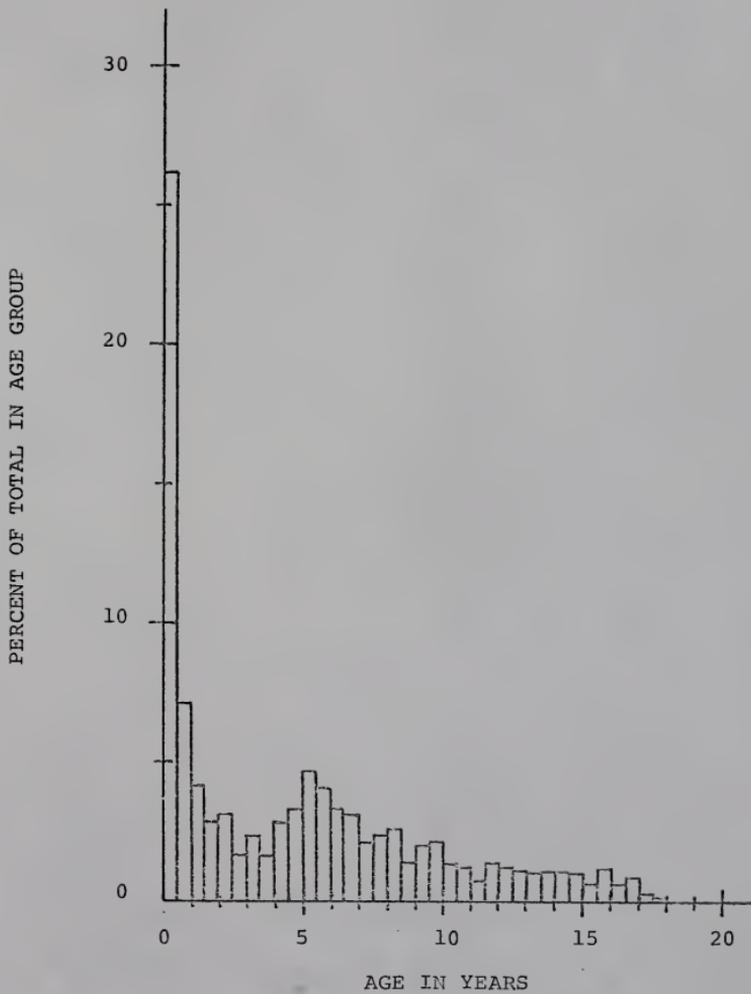


Figure 4. Distribution of Cardiac Catheterization Patients in the Age Range 0 to 18 Years.

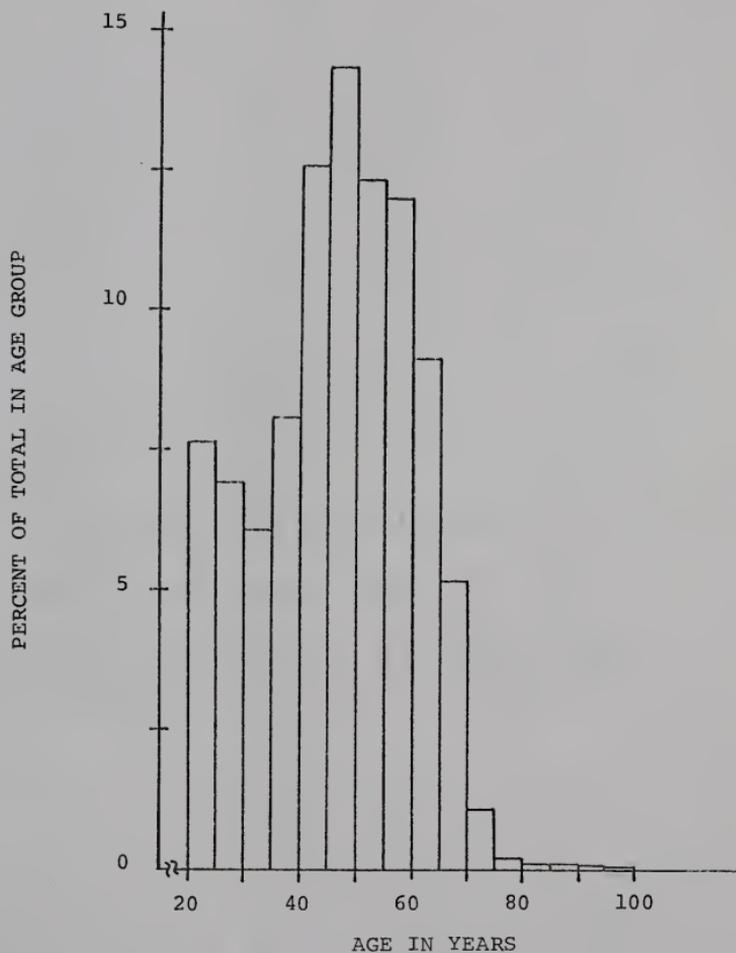


Figure 5. Distribution of Cardiac Catheterization Patients in the Age Range 20 to 100 Years.

TABLE 6

Frequency of Cardiac Catheterization Examinations in the
University of Florida Cardiovascular Laboratory

| Patient Classification | Number of Cardiac Catheterizations per Patient | Number of Patients | Number of Cardiac Catheterizations | Percentage of Patients Having Indicated Number of Examinations |
|---------------------------------|--|--------------------|------------------------------------|--|
| Pediatric (<18 years old) | 1 | 1614 | 1614 | 76.2 |
| | 2 | 397 | 794 | 18.7 |
| | 3 | 87 | 261 | 4.1 |
| | 4 | 14 | 56 | 0.7 |
| | 5 | 3 | 15 | 0.1 |
| | 6 | 4 | 24 | 0.2 |
| | 1-6 | 2119 | 2764 | 100.0 |
| Adult (>18 years old) | 1 | 1526 | 1526 | 85.0 |
| | 2 | 223 | 446 | 12.4 |
| | 3 | 40 | 120 | 2.2 |
| | 4 | 6 | 24 | 0.3 |
| | 5 | 1 | 5 | 0.1 |
| | 1-5 | 1796 | 2121 | 100.0 |

Data taken from records of an approximate 12-year period through March 1974.

for one individual. Patients seen in a large teaching hospital typically consist of second party referrals. The referral is often made on the basis of a complex or out-of-the-ordinary diagnosis. This factor might be expected to have some bearing on the examination frequency. In the case of the referral patient, the probability that a prior catheterization had been performed would be expected to be significant. No attempt was made to establish the contribution from heart catheterization examinations at other institutions.

Figures 6 and 7 show average fluoro times for pediatric and adult patients studied over a 12-year period. The data points represent the one-month mean for the third and ninth months of the respective years. For 1973 and 1974, data for each month are shown. Although the conduct of a congenital heart study in children differs from the acquired heart disease evaluation in an adult, the mean fluoro times are seen to be quite similar. Mean values of approximately 15 minutes per procedure were observed during 1963 and had increased to the low twenties by 1973. The increase may be associated with the added complexity and amount of information obtained from the catheterization procedure over this time period.

Starting in late 1973 a consistent decrease in fluoro times for pediatric patient studies can be observed. During this period no significant changes in staff or examination

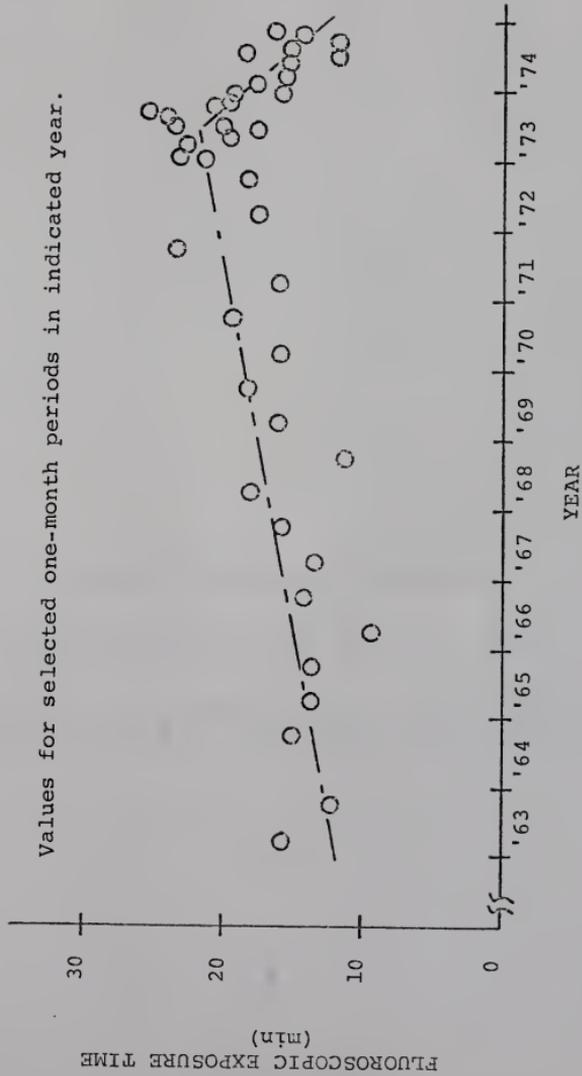


Figure 6. Mean Fluoroscopic Exposure Time During Cardiac Catheterization Procedures on Patients <18 Years Old.

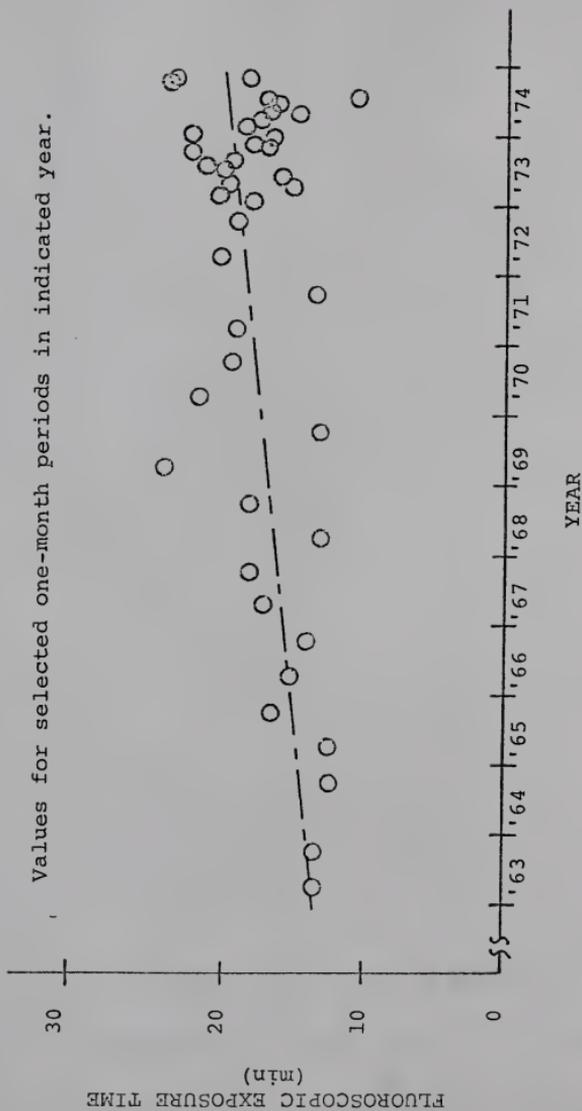


Figure 7. Mean Fluoroscopic Exposure Time During Cardiac Catheterization Procedures on Patients ≥ 18 Years Old.

techniques were made. The decrease may be associated with an increased awareness of potential radiation hazards on the part of the physician since the decrease directly parallels the initiation of this study. No similar change in the mean fluoro times for the adult examinations was observed.

CHAPTER III
RADIATION MEASUREMENT EQUIPMENT AND TECHNIQUES

The same radiation measurement equipment was used for studies of both personnel and patient exposure. A thermoluminescent dosimeter (TLD) system was used for personnel, patient and phantom monitoring. The various x-ray sources were equipped with transmission ionization chamber systems which measured beam area integrated output as an index of the total incident energy delivered to the patient. In addition, a free air calibrated ionization chamber system was used as a reference instrument for calibration of the other systems and for selected beam intensity measurements.

Thermoluminescent Dosimetry

Thermoluminescent dosimetry technique has been used extensively in this study. For the assessment of doses associated with diagnostic x-ray procedures TLD offers a number of advantages when compared to alternate techniques, such as film or ionization methods. The dynamic range for TLD's is large, extending over a range from low mR values to thousands of R. The size of the crystal dosimeters is small compared to ionization chambers or film, thus introducing minimum problems when placed on patients or personnel. One

of the major disadvantages of using film dosimetry is the large energy dependence of the emulsion in the diagnostic energy region. In comparison, a TL phosphor, such as lithium fluoride (LiF), shows very little change in sensitivity in this energy region.

The utilization of TLD as a radiation dosimetry technique involves the quantification of light emitted from a heated crystal that was previously exposed to ionizing radiation. Becker (1973) points out that of approximately 3,000 natural minerals, over three-quarters exhibit this effect. The basic physical principle is associated with the elevation of electrons from the valence band to the conduction band when exposed to radiation. The freed electron and associated hole move through the crystal and may recombine or be trapped at a lattice defect or impurity site. When the crystal is subsequently heated, the electron or hole can be released from the metastable trap and return to its ground state. During this readjustment in energy states, a light photon will be emitted. The quantitative relationship between the thermally stimulated luminescence and the previous exposure facilitates its use as a radiation dosimeter.

Harshaw^a LiF TLD-100 was the particular phosphor used. The material was in the form of 0.32 x 0.32 x 0.09 cm (1/8 x 1/8 x 0.035 inch) chips. This particular phosphor is

^aHarshaw Chemical Company, Solon, Ohio.

presently the most widely utilized TLD material and the one for which the greatest amount of published information exists. It is well suited for x-ray dosimetry in the diagnostic x-ray range. The energy response of TLD-100 is relatively independent of photon energy. However, it does have an increase in sensitivity for photon energies of less than 100 keV effective and is approximately 30% more sensitive at an effective energy of 25 keV than at ^{60}Co energies (Cameron et al., 1968). Harshaw states the effective atomic number of LiF TLD-100 for photoelectric absorption is 8.2. This value is close to that of tissue (7.42) and air (7.64). From a dosimetry standpoint this means that the phosphor's response could be considered approximately air or tissue equivalent. Due to the small difference in the effective atomic numbers of LiF and tissue, the chips cannot be seen in a diagnostic x-ray image when positioned on the body of a patient. Thus, the possibility of confusion or misdiagnosis introduced by a dosimeter(s) being interpreted as clinical anatomy in the image is eliminated.

Harshaw TLD-100 contains a mixture of ^6Li and ^7Li in their natural isotopic ratio of 7.5 to 92.5% respectively. The crystal matrix also contains some impurities. Becker (1973) states that although the identity and amount of these impurities have not been officially disclosed by the manufacturer, those of dosimetric importance are thought to be magnesium (Mg) and titanium (Ti). Edelman (1967) has shown

that the addition of 0.0013 mole percent of Mg to pure LiF produces a maximum increase in sensitivity for this activator impurity. Becker and colleagues (1970) have carried out spectral chemical analysis of TLD-100. Based upon this work, Becker states that the probable concentration of Ti is 0.001 mole percent. It is also possible that aluminum (Al) and/or cadmium (Cd), which were also shown to be present in the TLD-100, may play a role as activator or co-activator.

The TLD chips were read on an Eberline^a model TLR-5 system with nitrogen flow. This system employs a low temperature dump during which the chip to be read is heated to a pre-selected temperature sufficient to release the low temperature peaks. During this dump portion of the readout the counter is not gated on. The chip is then elevated to the readout temperature and the reader registers the counts under the major photopeak. For use with the TLD-100 chips the unit was adjusted for the dump and read cycles as follows: 140°C for six seconds followed by 250°C for 12 seconds.

For dosimetry measurements, the TLD chips were arranged in sensitivity-selected pairs following the procedure suggested by Gooden and Bricker (1972). Three hundred virgin chips were obtained for use in this project. These chips

^aEberline Instrument Company, Santa Fe, New Mexico.

were first arbitrarily divided into three groups of 100 chips each. Each group was then simultaneously exposed to a known exposure level and read out. This procedure was repeated three times so that an average sensitivity for each chip could be obtained. Each group of chips was annealed prior to the first exposure and between each subsequent exposure following the procedure to be described below. During the exposure each chip was placed in a numbered gelatin capsule so that its identity could be maintained. The average reading for the three exposures was then calculated for each chip. Within each group of 100, the chips were then ranked according to sensitivity. The sensitivity grouping procedure consisted of first pairing the least and most sensitive chips and sequentially working toward the center chips in the ranking scheme.

Once the sensitivity selecting procedure was completed, each group of 50 dosimeter pairs was utilized individually. A calibration factor for each group was determined whenever that group was utilized. When any chip pair within a particular group required annealing, all pairs in the group were included. This procedure was followed so that any changes in sensitivity resulting from the annealing procedure would be equalized in all chips in a particular group.

The annealing procedure utilized was that suggested by Harshaw. It consisted of one hour at 400°C followed by two hours at 100°C. The chips were positioned on a

pre-numbered brass plate. Two ovens were used so that close temperature control could be maintained.

The six-second low temperature dump in the TLR-5 read-out cycle is intended to remove the low temperature peaks. However, where dosimeter pair exposures within a specific group of chips may range from low mR to R values, the possibility that the low temperature peaks may not be equally removed during the six-second reader dump would be a major source of error. To minimize the possibility of this source of error a post-exposure pre-reading annealing at 100°C for ten minutes was also carried out as recommended by Harshaw. The 100°C for ten minutes' annealing was carried out by placing the chip pairs in a 6 x 50 mm Pyrex culture tube. Multiple tubes were then placed in a pre-numbered lucite support grid and suspended in boiling water for the specified time period.

With continued use, the sensitivity of a group of TLD chips might be expected to change. Due to an effect seemingly similar to that causing supra-linearity, an increase in sensitivity in TLD-100 following previous exposures has been reported by Cameron and colleagues (1968). The increase in sensitivity was noted to be as great as a factor of six for an annealing cycle utilizing a high temperature of 280°C for one-half hour. The effect was minimal for a 400°C, one-hour annealing cycle. For periods of greater than one hour at 400°C, a decrease in sensitivity, by as much as 20% from its

original value was noted. A change in sensitivity might also be expected due to cracks or chips in the crystal dosimeters. The accumulation of dirt on the chips would be expected to reduce the sensitivity since a smaller portion of the light would be able to escape and be counted by the photomultiplier tube. Another factor of major importance in this study has been the day-to-day variation of the TLD reader. To account for these factors that can affect sensitivity, a calibration was performed each time a group of chip pairs was used.

Calibration exposures were carried out utilizing a Siemens 250 kVp x-ray therapy unit. The unit was operated at an indicated 80 kVp with a source-to-dosimeter distance of 150 cm. The measured HVL of the beam was 4.1 mm of Al with all added filtration removed. This is in reasonable agreement with the HVL reported for the various tubes used on the diagnostic x-ray system. The beam was adjusted to a 10 x 10 cm field at the 150 cm source-to-chip distance. The chips were supported on a thin sheet of paper 30 cm from the floor. At this distance the effect of backscatter is negligible. A Victoreen 555-LMA probe was positioned simultaneously in the beam with the chips to determine the delivered exposure.

From a 50 chip pairs group, ten chip pairs typically would be set aside for calibration. Two chip pairs would be unexposed and used as background controls. Two pairs each

would then be exposed to exposure levels in the range from 150 mR to 5.5 R. The calibration factor could then be obtained from the numerical average or the slope of the straight line drawn through a plot of TL units versus exposure.

Linearity of Calibration Factor with Exposure Level

The Eberline TLR-5 reader has a high and low sensitivity setting (low and high range respectively). For the chips used in this study and read on the Eberline system operating in the high sensitivity range, a calibration factor of 4.5 TL units per mR would be typical. The reader has a five-digit decimal display with a resultant maximum counting capacity of 10^5-1 . This means that for a chip exposed to greater than 22.2 R, the reader would be expected to exceed its maximum counting capacity and recycle through zero.

The operator has two options when reading a chip exposed to a suspected exposure level greater than this limit. He can switch to the low sensitivity range or manually observe the number of times the counter cycles through zero. When the system is switched from high to low sensitivity, the voltage on the photomultiplier is lowered. Trial readings made after switching ranges demonstrated that a period of 12 to 24 hours was required for the system to stabilize following such a change. Due to this unreasonable stabilization period and the fact that additional calibration chips would be required when using both sensitivity

ranges, the system was operated in the high sensitivity (low range) position only.

To evaluate the response of the dosimetry system, calibration exposures were made over a range up to 100 R. Two chip pairs were exposed at each calibration point. An average calibration factor for each point was determined. A second order polynomial least square fit of these data was calculated. A plot of these data as percent decrease in intensity from the values measured at 5 R or less versus exposure is given in Figure 8. The curve shows the decrease in sensitivity for exposure values greater than 6 R. This effect is felt to be due to the reader since the response of TLD-100 has been shown to be linear with exposure for values to approximately 10^3 R (Eggermont et al., 1971). At this level a supralinear effect is observed which increases the dosimeter response.

Calibration exposures were made over the range of 150 mR to 5.5 R. In calculating the calibration factor, it was assumed that the calibration factor had a flat response over the range used. To check this assumption, the experimental data for nine calibration runs were statistically analyzed. An analysis of variance was carried out by separating the data into nine blocks with four exposure level treatments for each block. The nominal treatments were 150, 550, 2000 and 5500 mR respectively. The experimental data and analysis of variance tables are shown in Appendix C. The calculated F

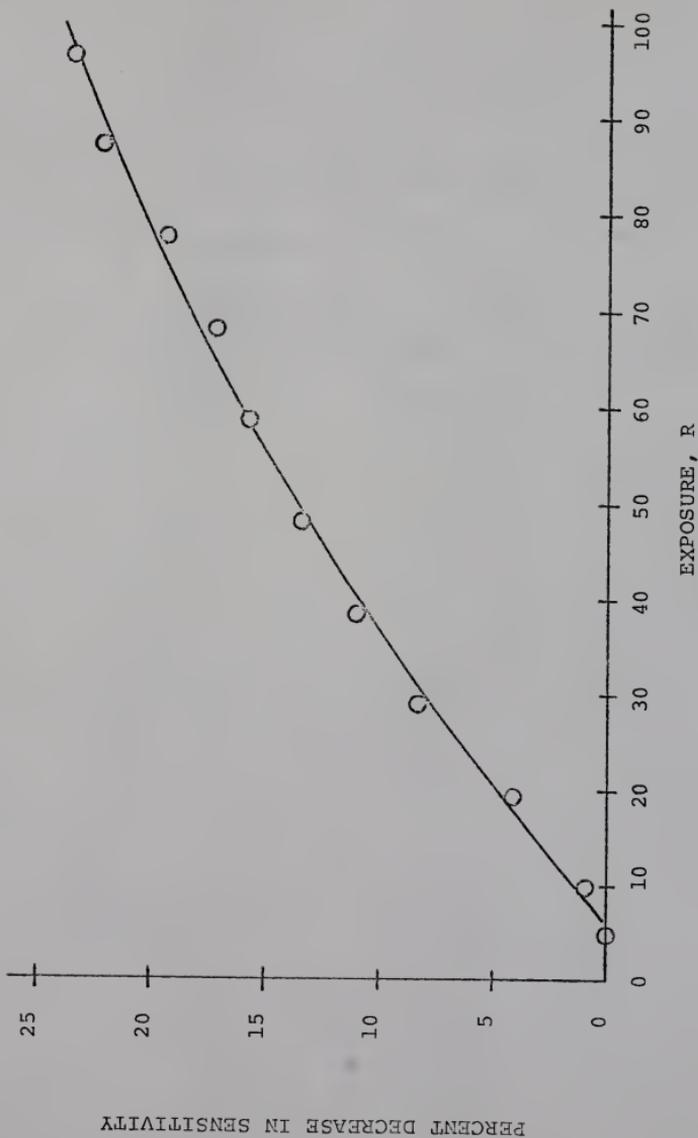


Figure 8. Percent Decrease in Sensitivity of Harshaw TLD-100 Chips Read on Eberline Model TLR-5 System as a Function of Incident Exposure.

statistic for the treatments (different exposure levels) was not significant to indicate there was departure from linearity over this exposure range. By comparison, the variation between calibration runs is seen to be significant. This is consistent with the expected variation of factors previously discussed and establishes the requirement to run a calibration point for each use of a particular paired group of chips.

Dosimeter Package

The TLD chips used in the measurement of patient and operator exposure were sealed in polyethylene packages. The chips were first sandwiched between a fold of black art construction paper. This protected the chips from light (ultraviolet) exposures that can affect chip readings. The enclosed chips were then positioned between the polyethylene and the edges fused with a heat-sealing device. The sealed package was air and water tight and could be sterilized by emersion in a liquid solution, if required. The dimensions of the completed dosimeter packages were approximately 1.5 x 1.5 cm. Figure 9 shows an exploded view of the packaging.

The International Commission on Radiation Units and Measurements (ICRU) (1962) presents graphical data relating to the required thickness of unit density material required to establish electron equilibrium as a function of photon energy. For the minimum energy of 100 keV given by the ICRU, the density thickness of build up material required is approximately 0.015 g/cm^2 . The density thickness of the

polyethylene and paper surrounding the TLD chips was found to be 0.0216 g/cm^2 . This is in reasonable agreement with the ICRU value for x-ray photons in the diagnostic energy region.

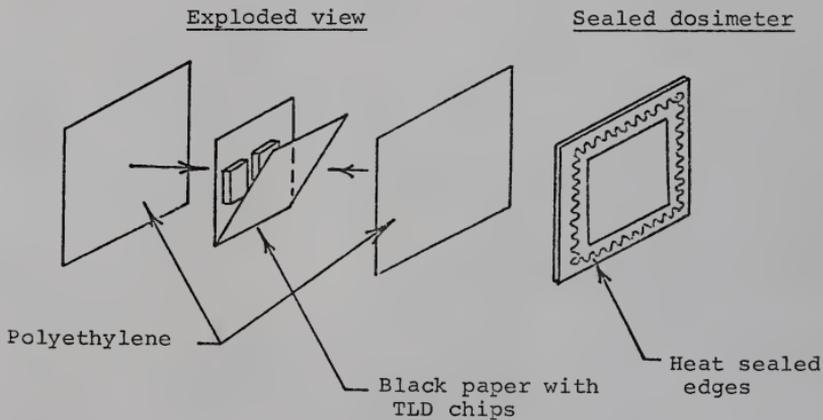


Figure 9. TLD Dosimeter Package.

Victoreen 555 System

A Victoreen^a model 555 Radocon II integrating ratemeter was used as the primary dosimetry reference instrument for radiation measurements performed in this study. Victoreen states that the precision of the model 555, operating in the integrate mode, is $\pm 1\%$ for all scale ranges except the 30 mR range. For this most sensitive scale, the precision is $\pm 2\%$. For long term operation (over a period of 90 days or greater) these values must be increased by $\pm 0.2\%$. In the rate mode the precision is $\pm 2\%$ for all except the most sensitive scale for which the value is $\pm 4\%$. The long term precision for the rate mode of operation must be increased by $\pm 1\%$ for periods greater than 90 days.

The chamber calibration inaccuracy for the 555-0.1MA, 555-1MA and 555-10MA probes is given as $\pm 5\%$ over the energy range of 30 to 400 keV effective. These three chambers (serial numbers 170, 225 and 262 respectively) were calibrated at the Bureau of Radiological Health, U.S. Department of Health, Education and Welfare using a Victoreen model 481 free air ionization chamber. This free air system has a stated accuracy of $\pm 0.5\%$ over its operational range. The calibration data are given in Table 7 and the calibration

^aVictoreen Instrument Division, Cleveland, Ohio

TABLE 7
Free Air Chamber Calibration of Victoreen 555

| Chamber ^a Ident. | Tube Potential (kVcp) | Total Filtration (mm Al) | HVL (mm Al) | Integrate Mode | | Rate Mode | |
|--------------------------------|-----------------------------|--------------------------------|----------------|------------------|----------------|------------------|----------------|
| | | | | Range Setting | Cal. Factor | Range Setting | Cal. Factor |
| 0.1MA (SN 170) | 30 | 0.64 | 0.50 | 300 mR | 1.22 | 1 R/min. | 1.19 |
| | 50 | 0.84 | 0.97 | 300 mR | 1.13 | 1 R/min. | 1.12 |
| | 75 | 1.34 | 1.69 | 300 mR | 1.06 | 1 R/min. | 1.07 |
| | 100 | 1.91 | 2.52 | 300 mR | 1.07 | 1 R/min. | 1.06 |
| 1MA (SN 225) | 100 | 4.00 | 4.01 | 300 mR | 1.02 | 1 R/min. | 1.01 |
| | 30 | 0.64 | 0.40 | 1 R | 1.26 | 3 R/min. | 1.25 |
| | 50 | 0.84 | 0.98 | 1 R | 1.16 | 3 R/min. | 1.13 |
| | 75 | 1.34 | 1.65 | 1 R | 1.10 | 3 R/min. | 1.09 |
| 10MA (SN 262) | 100 | 1.91 | 2.54 | 1 R | 1.08 | 3 R/min. | 1.06 |
| | 100 | 4.00 | 4.10 | 1 R | 1.02 | 3 R/min. | 1.03 |
| | 30 | 0.64 | 0.40 | 100 mR | 1.33 | 300 R/min. | 1.32 |
| | 50 | 0.84 | 0.98 | 100 mR | 1.21 | 300 R/min. | 1.20 |
| | 75 | 1.34 | 1.65 | 100 mR | 1.15 | 300 R/min. | 1.14 |
| | 100 | 1.91 | 2.54 | 100 mR | 1.10 | 300 R/min. | 1.11 |
| | 100 | 4.00 | 4.10 | 100 mR | 1.03 | 300 R/min. | 1.04 |

^aAll chambers calibrated with Victoreen 555 electrometer system (SN 627).

correction factors are plotted as a function of the HVL in Figure 10.

Since the first HVL is not a unique description of the quality of a continuous x-ray spectra, the validity of plotting the correction factor as a function of this index was checked by calibrating a 555-10MA chamber with the HVL held constant (Morgan and Fewell, 1973). The results of this evaluation are shown in Figure 11. For the calibration points from 70 to 100 kVcp, the experimental calibration factors are seen to vary by 2.6% of the mean. This variation is generally consistent with the stated precision of the 555 system when operated in the integrate mode. The random nature of the calibration points in this energy range may indicate that a straight line can be drawn through the mean value. If this mean value is extended as a smooth curve through the lower energy calibration points, the chamber seems to have a flat response (to 2.6%) for a constant HVL of 1.25 mm Al over the kVcp range of 50 to 100. No calibration values for operation at kVcp value greater than 100 are given due to operational limits on the free air ionization chamber. If the calibration had been carried out for a higher HVL, such as 3 to 4 mm of Al consistent with the values for the diagnostic tubes used in this study, the calibration factor would be expected to vary even less due to the reduction of the lower energy components of the x-ray spectrum.

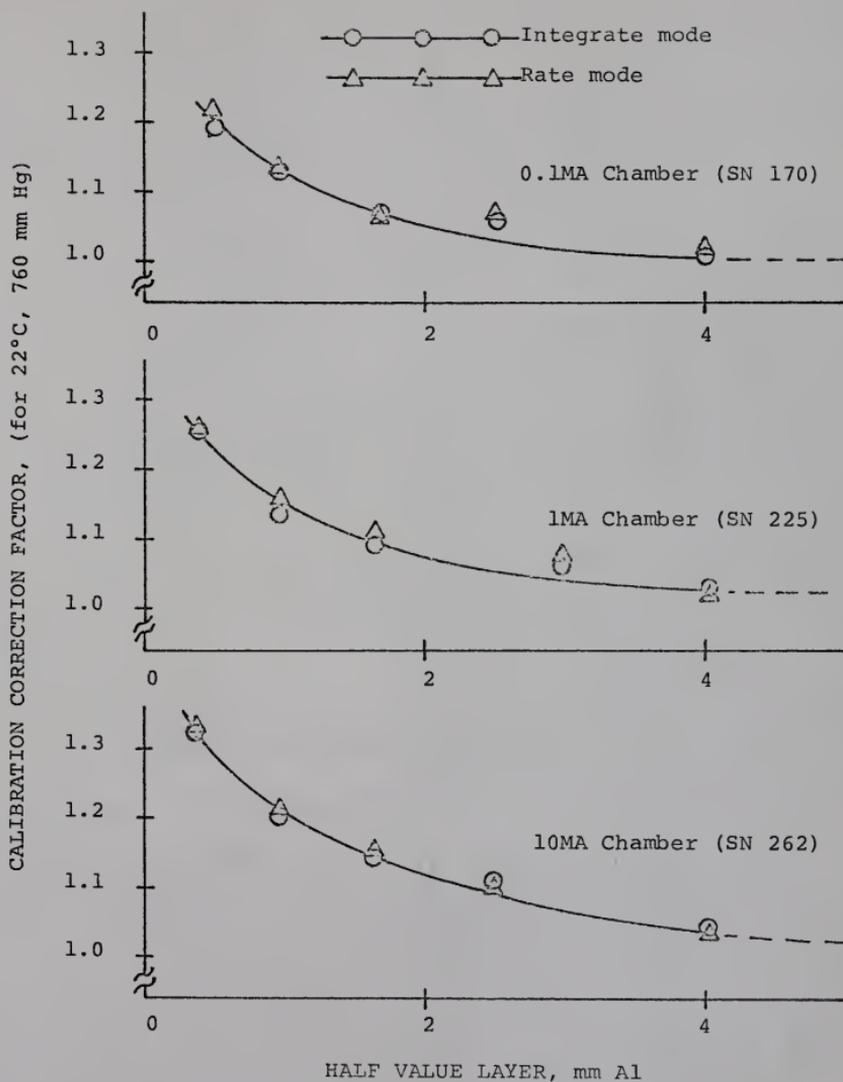


Figure 10. Victoreen 555 Calibration Correction Factors as a Function of Half Value Layer.

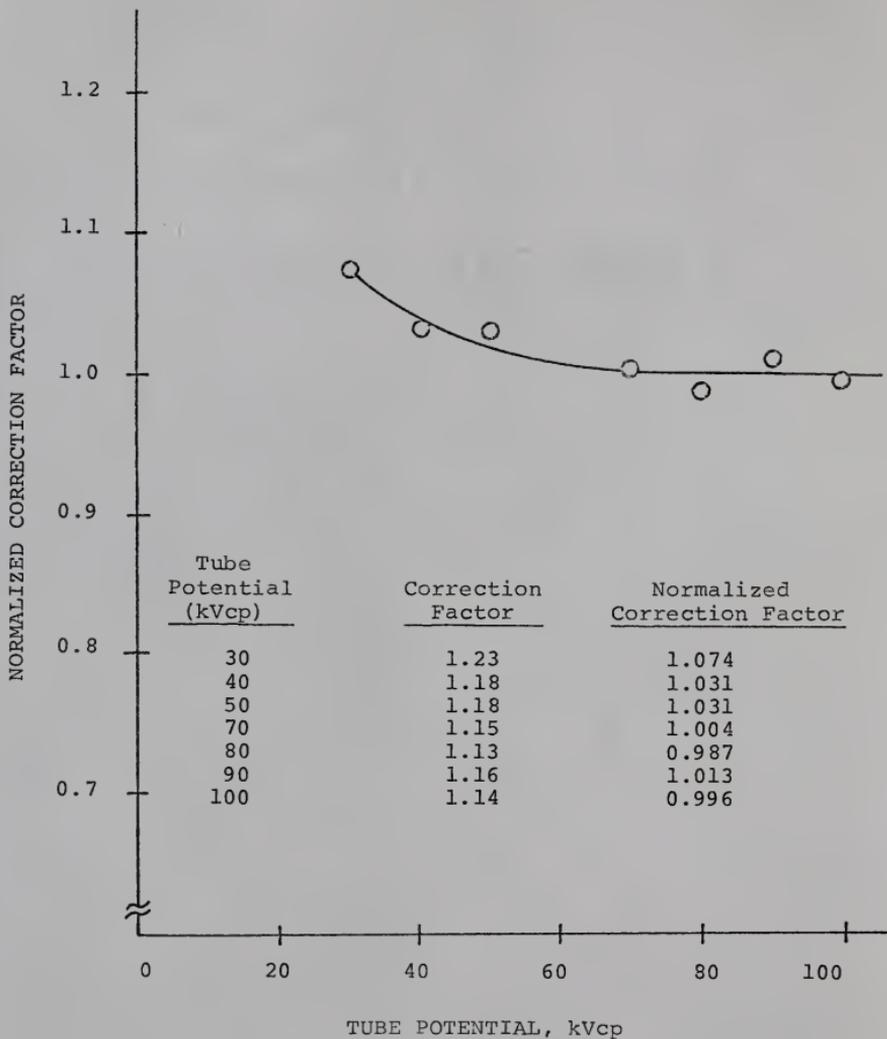


Figure 11. Calibration Correction Factors for Victoreen 555 as a Function of X-ray Tube Potential (HVL held constant at 1.25 mm Al Victoreen 555-10MA chamber used).

Exposure Area Product Measurement

In many situations it is desirable to know the exposure, dose or some other index, such as integral dose, received by a patient undergoing a diagnostic x-ray examination. The exposure at any specified point, such as the incident skin surface, is a complex function of a multitude of factors including tube potential and wave form, tube current and time of exposure, filtration, source-to-patient distance and field size. If the dose delivered to a specific body site or organ system is desired, additional factors must be considered.

Calibration data for a particular x-ray unit can be obtained for its various operating conditions to allow determination of the resultant patient exposure if all the variables for a particular examination are recorded. This requirement to obtain and record all of the variables associated with each individual exposure can be time consuming. In the case of special procedure work where multiple modes of viewing and recording such as fluoro, cine and/or radiography may be employed, the recording task becomes nearly impossible to perform.

A number of authors have described the use of x-ray monitors attached to the x-ray unit to directly measure incident energy. Feddema and Oosterkamp (1953) measured the product of beam area and irradiation time during fluoro. They attached a watt-hour meter to the x-ray unit and modulated its reading by a connection to the adjustable diaphragm

of the x-ray unit via potentiometers and cog wheels. Morgan (1961) described an incident-energy monitor which used a two-compartment ethane-filled ionization chamber. The monitor was designed to give a chamber response relatively independent of radiation quality for a HVL range extending from 0.5 mm Al to 10 mm of Al. Reinsma (1962) utilized an ionization chamber designed so that its spectral response was reasonably independent of the quality of radiation over the usual diagnostic range. This unit, marketed as the Philips Diagnostic Monitor, was attached directly over the exit port of the collimator. The measurement chamber was not transparent to light and thus had to be physically moved when it was necessary to use the collimator light localization system.

An alternate approach has been the development of instruments that measure the exposure or exposure area product (EAP). Airth (1959) was one of the first to report such a system. His unit consisted of an ionization chamber built into a fixed rectangular beam-defining cone. The unit was calibrated to read in units of R exposure at the patient skin surface. Arnal and Pychlau (1962) and Carlsson (1965) have described "pancake" type ionization chambers that are positioned on the distal port of the beam limitation system. The chamber is larger than the maximum dimensions of the beam and, therefore, will measure the EAP. The Arnal and Pychlau system, with a transparent 0.5 mm Al equivalent ionization chamber, is currently manufactured by Physikalisch-Technische

Werkstätten (PTW) of Freiburg, West Germany and known as the "Diamentor".

Ardran and Crooks (1963, 1965) have evaluated the Philips Diagnostic Monitor and two models of the PTW Diamentor. The Diamentors tested were those utilizing the opaque 2.0 mm Al equivalent ionization chamber and the transparent 0.5 mm Al equivalent unit (Arnal and Pychlau, 1962). They state that the Philips unit, which reads in terms of incident energy, is difficult to calibrate since no applicable direct measurement method exists. It is their opinion that since it is currently impossible to judge the biological effect of a delivered diagnostic dose level to a large area of the body, as opposed to the same dose over a single or small number of areas of the body, the refinement necessary to develop an instrument that will read directly in energy units is unnecessary. The incident energy is also not equivalent to integral absorbed dose. Correction for backscatter, lateral scatter and transmitted energy must be made and can account for variations up to a factor of two (Carlsson, 1963).

Instrumentation of X-ray Unit

For the purpose of this study, the under table x-ray source (for fluoro/cine) and the two ceiling-mounted tubes (for biplane radiography) in the UF cardiovascular laboratory were equipped with EAP meters. These measurement systems,

manufactured by PTW,^a use a 0.5 mm Al equivalent light-transparent ionization chamber and remote digital readout. Individual measurement systems were installed on the two radiographic sources and the under table fluoro/cine tube. The readout for the fluoro/cine chamber had a dual register so that the fluoro and cine signals could be registered separately.

Figure 12 shows a block diagram of the PTW system. The light-transparent ionization chamber is attached across the exit port of the x-ray beam-limiting device. The chamber is connected to the preamplifier and control unit by a 18 meter triaxial cable. The preamplifier and control modules were located in the shielded control booth of the special procedure room.

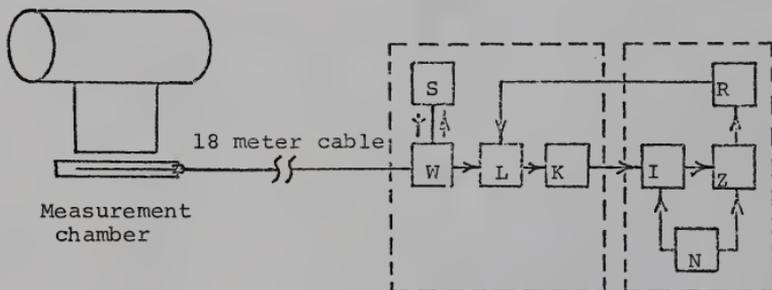
During radiographic and cine exposures, the signal from the ionization chamber can exceed the input rate of the control readout module. When this occurs, the input signal is shunted to a storage capacitor in the preamplifier section. This signal is subsequently gated through a constant-current resistor into the control module. In practice, this phenomenon can be observed in a continued count registration by the readout system following termination of the exposure. This creates no problem with the biplane radiography since

^aDistributed in U.S. by Nuclear Associates, Westbury, New York.

Diagnostic
source assembly

Preamplifier and
gate

Control



S - storage capacitor
 W - Electronic switch
 L - Constant current resistor
 K - Flip-flop (ADC)

R - Feedback
 N - Power supply
 Z - Register
 I - Pulse shaper

Figure 12. Block Diagram of PTW - Diametror Exposure Area Product Measurement System.

each radiographic tube was instrumented with individual ionization chamber and readout system. For the under table fluoro/cine tube, where one chamber was used with a dual register readout, a 220 volt signal from the primary cine contactor in the x-ray control was used to activate a relay gate in the dual register EAP control. This allowed automatic separation of the exposure signals resulting from fluoro and cine. Since the cine signal would often exceed the input count rate of the measurement system, a time delay relay was added. This modification, shown in Figure 13, allowed the counter to remain in the cine mode for a predetermined time following termination of the exposure. The variable time delay relay allowed a delay period of 0 to 10 sec. A setting of 5 sec was found to be adequate to register the maximum exposures that might occur for the large adult patient.

Exposure Area Product Meter Calibration

The EAP meters were calibrated following installation and at periodic intervals. The calibration procedure involves first measuring the beam size at a predetermined position. X-ray film or Kodak Linograph direct print paper can be used for this field size measurement. A calibrated ionization chamber is then positioned at the same position for which the field size was determined. This measurement position is not critical, but should be at a sufficient distance from the

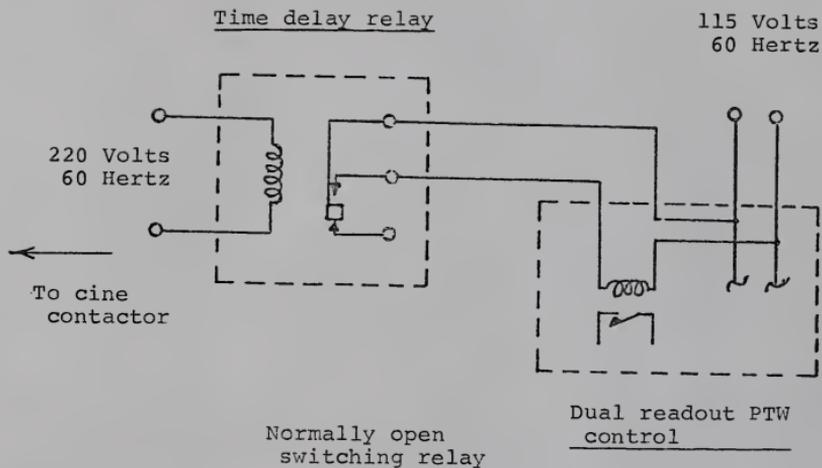


Figure 13. Setup of Time Delay Relay for Cine Input Signal on Dual Register PTW Exposure Area Product Measurement System.

table top or other support surface to minimize the effect of backscatter. An x-ray exposure is then made and the calibration factor determined as follows:

$$\text{EAP Calibration Factor} = \frac{(\text{Measured R}) (\text{beam size, cm}^2)}{\text{EAP meter reading}}$$

Due to the nature of the analog-to-digital converter (ADC) used in the PTW meter, a maximum uncertainty of up to one count can exist. This results when a signal almost sufficient to trigger the ADC flip-flop circuit has been collected. To minimize this possible error, at least 75 counts should be registered on the EAP meter. This will reduce this source of error to no greater than 1.3%.

All calibrations were carried out at an indicated tube potential of 80 kVp. This value represents a typical operating potential. The beam size was adjusted to approximately a 10 x 10 cm field. Sources of error for the EAP system when operating at other technique factors, beam size and setup geometry will be outlined below.

With the patient in the cradle, the beam at the patient entrance surface will be attenuated and a correction factor must be applied to the fluoro/cine EAP calibration factor. Experimental data at 80 kVp indicate that the EAP meter calibration for this setup must be multiplied by 0.66.

Effect of backscatter

Ardran and Crooks (1963,1965) measured the effect of backscatter on two PTW measurement chambers, a light opaque 2 mm Al equivalent chamber and a 0.5 mm Al equivalent transparent unit similar to the ones used in this study. In their investigation, the chambers were positioned 30 cm from the x-ray focal spot. The beam size was fixed so that a 40 x 40 cm field at a source-to-field distance of 100 cm was obtained. A 12 x 12 x 8 inch Mix-D phantom was then exposed at various phantom-chamber separation distances. The effect of backscatter expressed as the ratio of phantom to free air value at various phantom-chamber distances is shown in Figure 14.

In the present study, an intercomparison check was made at 20.5 and 40 cm, two distances that are representative of the chamber to incident patient surface distances for fluoro and radiographic exposures. A 32 x 28 x 12 cm water phantom was used. The beam size was 107 cm² and 204 cm² at the surface of the phantom for the respective phantom-chamber distances and the x-ray unit was operated at 80 kVp.

Measurements were made with a Victoreen 555 and 555-0.1MA chamber positioned at the same irradiation distance as the target-to-phantom surface distance. This chamber location allowed determination of the incident x-ray exposure without backscatter. Four free air exposures and four exposures with the water phantom in the beam were alternately made at each distance. The multiple exposures were carried out to help

average out any variations in the output of the x-ray unit or reading of the model 555 dosimeter. The R output for the phantom exposures were assumed to be equal to the average exposure for the four free air measurements.

The effect of backscatter at 20.5 cm was found to increase the Diamentor reading by 3.3%. At a 40 cm phantom-chamber distance, no increase was noted. These values are also plotted in Figure 14, and are seen to be in agreement with the published data of Ardran and Crooks.

Energy dependence

Triplicate calibration checks were obtained at indicated tube potentials of 60, 80, 100 and 120 kVp. Using the measured HVL of 3.3 mm Al at 80 kVp for the Machlett Dynamax 69B tube housing assembly with collimator and PTW ionization chamber, representative HVL values for the other tube potentials were determined from the values of Reinsma (1960). Using these HVL values, appropriate correction factors for the Victoreen 555-0.1MA chamber measurements were applied to the measured PTW calibration factors. The results are shown in Table 8. These data indicate a maximum variation of 3% for the PTW system over a tube potential range of 60 to 120 kVp.

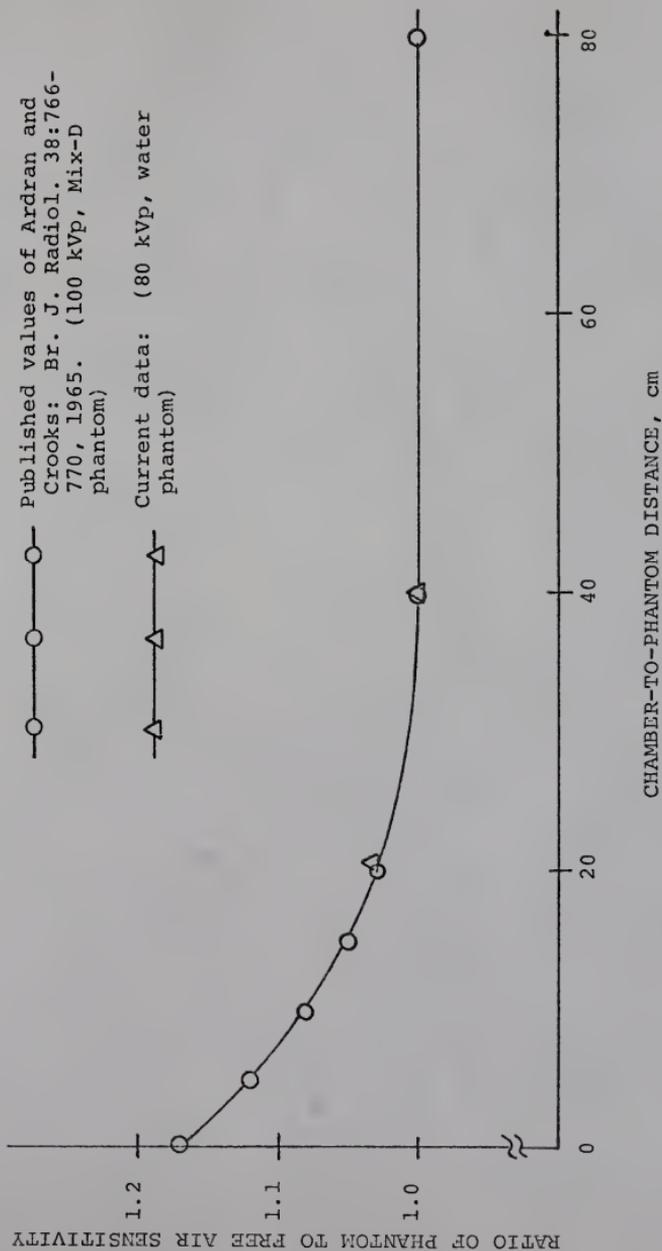


Figure 14. Effect of Backscatter on PTW Exposure Area Product Chamber at Various Phantom-to-Chamber Distances.

TABLE 8

Energy Dependence of PTW Exposure Area Product Measurement Chamber

| Indicated Tube Potential (kVp) | HVL of Beam (mm Al) | Uncorrected | | Victoreen 555 Correction Factor | Corrected | |
|---|---------------------------|---|---|---------------------------------------|---|----------------------------------|
| | | PTW Cal. Factor (R.cm ² /unit) | PTW Cal. Factor (R.cm ² /unit) | | PTW Cal. Factor (R.cm ² /unit) | Normalized to 80 kVp Value |
| 60 | 2.5 | 3.87 | 1.08 | 4.18 | 1.03 | |
| 80 | 3.3 | 3.98 | 1.02 | 4.06 | 1.00 | |
| 100 | 4.1 | 4.10 | 1.01 | 4.14 | 1.02 | |
| 120 | 5.1 | 4.15 | 1.01 | 4.19 | 1.03 | |

CHAPTER IV

RADIATION EXPOSURE TO CLINICAL PERSONNEL

A number of authors have reported on radiation exposure received by clinical personnel during cardiac catheterization procedures. These published data show a large variation in results. This might be expected since each study generally was carried out in a single institution and the variation between studies reflects differences in factors such as equipment configuration, room layout, patient classification and procedural techniques. Although differences in personnel exposure exist, the general levels reported demonstrate the potential for high operator exposure during this classification of diagnostic special procedure.

The ICRP (1973) has noted the large increase in the number of coronary artery examinations that has taken place during the last few years. Wholey (1974) states that it has been estimated that 80% of the coronary artery cardiac examinations are currently being performed by cardiologists. In the nine hospitals visited in the field survey described in Chapter II, only two were under the control of a department of radiology. In the majority of cases a cardiologist had sole responsibility for the layout of the room, purchase of the equipment and day-to-day operation of the

catheterization laboratory. Often the cardiologist had received no specific training in radiology or radiation protection.

The technical support staff is also typically composed of individuals with little or no x-ray background. Although an x-ray technologist may be associated with the cardiovascular examination team, the support staff is usually drawn from other areas. Currently there are three associate degree programs in the U.S. to train cardiovascular technologists. The number of individuals with this formal background are presently insufficient in number to meet the needs of the large number of cardiac special procedure laboratories in operation. Thus, individuals with backgrounds in nursing, pulmonary function, bioengineering, etc., are often recruited to work as part of the catheterization team. Their training is primarily on-the-job and would be expected to be minimal in areas relating to radiation protection.

Cardiac catheterization is a manipulative surgical technique. The aseptic conditions that must be maintained restrict the use of scatter shields such as the lead rubber flaps that are normally attached to a fluoroscope since they cannot be conveniently sterilized. The physician cannot wear protective lead gloves since their use would inhibit his ability to manipulate the catheter.

Because of the potential for high personnel exposures in cardiac catheterization, a detailed evaluation of typical exposure levels and their relationship to classification of personnel, equipment configuration and procedural methods was performed.

Literature Review

Hills and Stanford (1950) reported on radiation exposures to surgeons, anesthesiologists and radiologists involved with catheterization and angiographic studies of the heart. The techniques and equipment used at the time of their work differed significantly from those utilized today; therefore the results of their study are of historical interest only. Fluoro was performed with a conventional direct-view fluoro screen. A home-made photofluorographic camera with a 5 x 5 inch Eastman Kodak aerial camera was utilized for single-plane rapid-sequence filming (Hills, 1948). An operational limit of 20 minutes of fluoro was placed on any single examination. This time limit was established to limit the exposure to a typical patient examined on their equipment to one-fourth an erythema dose.

More recently, Wold and colleagues (1971) placed TLD's at 13 body sites on physicians performing cardiac catheterization studies. The x-ray setup utilized an under table x-ray source and over table image intensifier. Although their report states that operational values for fluoro time,

fluoro and cine current and feet of cine film were recorded, this information is not presented in their published results. The average exposure to the dosimeter positioned on the forehead (eye indicator) was 26 mR per procedure. This site received the highest fraction of the appropriate maximum permissible dose equivalent values recommended by the NCRP (1971).

Malsky and colleagues (1971) reported on exposures to physician and auxiliary personnel while performing coronary arteriography using the Judkins technique. The procedures were carried out on a single-phase x-ray unit equipped with a 22 cm diameter (nominal nine inch) image intensifier. The reported fluoro times ranged from 4 to 20 min with 4 min of associated cine (no frame rate or footage of cine film was given). The beam size at patient entrance surface was stated to be in the range of 180-330 cm².

Ardran and Fursden (1973) reviewed the film badge records of 17 individuals in one institution involved with the conduct of cardiac catheterization examinations. The badges were worn under the protective lead apron; and Ardran calculated the average exposure to the protected trunk of the body to be approximately 2 mR per procedure. In addition, he measured the exposure at four sites on the body of 20 cardiologists involved in 18 procedures. The catheterization examinations averaged 18.6 min of fluoro and 35 sec of cine. The three-phase x-ray unit used in these procedures was equipped

with a 22.8 cm diameter (nominal nine inch) image intensifier, but no recording of actual beam size used in the procedure was given.

A tabulation of the exposures reported by Wold, Malsky and Ardran are shown in Table 9. A comparison of the exposure values for these studies shows the Wold and Malsky levels to be significantly higher than those of Ardran. The only real difference between the Malsky and Ardran procedures seems to be the average cine time, 4 min reported by Malsky, versus 35 sec by Ardran. The Wold data cannot be evaluated since no operational factors are given. Ardran states that if the values for his exposure measurements were extrapolated to account for an average of 4 min of cine the personnel exposure would still be considerably less than those of Malsky and colleagues.

These differences can only be accounted for by presently undefined conditions unique to each institution. It is improper to say that the lower values reported by Ardran must be achieved by every catheterization laboratory since factors such as classification of patient, equipment configuration, procedure format, etc., must also be considered. The value of these studies is the illustration they provide regarding the existing institution-to-institution variation in operator exposure.

TABLE 9

Reported Physician Exposure Per Procedure at Indicated Site

| Location of Dosimeter | Exposure in mR Reported by Indicated Author ^a | | |
|--------------------------|---|-------------------------|------------------|
| | Wold et al. (1971) | Malsky et al. (1971) | Ardran (1973) |
| Eye | 26 | < 10 | |
| Collar (thyroid) | 28 | 20 | 3.5 |
| Chest (outside Pb apron) | | 245 | 4.4 |
| Chest (under Pb apron) | | 24 | 1.5 |
| Wrist | 41 | 33 | 4.6 |
| Back | | < 10 | |
| Gonad | < 1 | < 10 | |

^aWold and Malsky data obtained from TLD and Ardran data from film badge readings.

Stacey, Davis and Kerr (1974) and Wholey (1974) have reported on the increased exposure to personnel for units with the x-ray source above the patient and the image intensifier assembly under the table. The exposure levels around a unit of this type are higher than for the conventional under table x-ray source due to an increased contribution from leakage from the tube housing assembly and collimator, as well as backscatter from the patient. Wholey states that field size reduction with extension cones, retinal eye

shields and protective side panels for both tube and table are all essential features that must be included for this configuration of equipment.

The "Year 2000" report of the special study group for the Federal Radiation Council on Estimates of Ionizing Radiation Doses in the United States, 1960-2000 (Klement et al., 1972) gives a breakdown of occupational radiation exposure. The reported values were based primarily on occupational exposure records for the period 1969-1970 obtained from the military services and other Federal agencies involved with radiation, as well as data from state and nongovernmental sources. The report lists an estimated mean annual dose of 210 mrem/worker for an occupationally exposed population of approximately 772,000 individuals. The subcategory of medical x-ray workers constitute 26.4% of these individuals.

Table 10 gives a summary of these exposure values for the various employer classifications with a breakdown in the medical related area.

The report of the United Nations Scientific Committee on the Effects of Atomic Radiation (1972) also reports values for occupational exposure to personnel in various countries.

In the category of medical employment associated exposure, the values range from 70 to 380 mrad/year with the U.S. listed as 340 mrads/year.

TABLE 10
Occupational Exposure by
Employer Classification with
Breakout of Values for Medical Related Areas

| Primary Employer Classification | No. of Individuals Occupationally Exposed | Estimated Mean Annual Dose per Individual (mrem) | Percent of Workers in Medical Related Area | Estimated Mean Annual Dose to Personnel in Medical Related Area (mrem/year) |
|---------------------------------|---|--|--|---|
| Army | 7,445 | 100 | 49.6 | 95 |
| Air Force | 17,591 | 88 | 46.0 | 90 |
| Navy | 55,051 | 198 | 10.0 | 83 |
| AEC | 102,918 | | | |
| Other Federal | 2,508 | 129 | | |
| All Other | 689,219 | 223 | | |
| a. Medical x-ray | | | 28.2 | 320 |
| b. Dental x-ray | | | 24.8 | 125 |
| c. Medical radium | | | 5.5 | 540 |

Values summarized from Estimates of Ionizing Radiation Doses to the United States, 1960-2000 (Klement et al., 1972).

In reviewing these occupational exposure levels, one must keep in mind the fact that the primary sources of these data are personnel exposure records. Personnel monitoring programs are established to provide an index of exposure, as contrasted to exact dosimetry data. Factors such as the variation in the site of dosimeter placement on the body, lack of standards for accuracy of dosimeter reading, and the variation of units of reported exposures (i.e., R, rad, rem) by different personnel dosimetry services must be considered. An inability to accurately account for these factors as well as a limited data base for the non-governmental medical related exposures were identified in the "Year 2000" report as resulting in the greatest uncertainty for the values reported in this category.

Recorded Personnel Exposures
in Ten Catheterization Laboratories

The personnel monitoring records for individuals working in cardiac catheterization laboratories in ten hospitals in Florida were obtained. These data represent the results for 83 individuals, 38 physicians and 45 technicians. Two of the hospitals were large teaching institutions and accounted for 58% of the physicians and 42% of the technicians in the survey population. It might be expected that the average yearly exposure per patient catheterized in these facilities would be less than in a small hospital since the large staff allows for personnel rotation.

The position of badge placement varied from facility to facility with a greater percentage of personnel selecting a site under the protective lead apron. Four physicians in one institution utilized monitors both outside and under the apron. Finger badges were utilized by six physicians at two facilities.

Values for cumulative exposure were obtained as far back in time as consistent data could be found. In general, the information represents exposure histories up through at least August of 1974. A summary of these data are shown in Table 11. In calculating the average yearly exposure, no data for individuals monitored for less than a quarter of a year are included. Of the 38 physicians for which exposure records were obtained, five had minimal non-detectable levels recorded. In at least two of these cases the values are known to be inaccurate. One individual was the sole physician working in the catheterization laboratory. In the second case the individual had been performing catheterization examinations for over six years. During this entire six-year period the total cumulative exposure had been 20 mrem reported during one monitoring interval. In both cases it seems obvious that the monitoring badge was not worn. Since it was impossible to establish the frequency at which badges may have not been worn, the data in Table 11 are reported as found in the records without adjustment. Errors of this type would result in the tabular values being an underestimate of the actual exposure.

TABLE 11
 Personnel Monitoring Records for Individuals
 Involved with the Conduct of Cardiac Catheterization Procedures

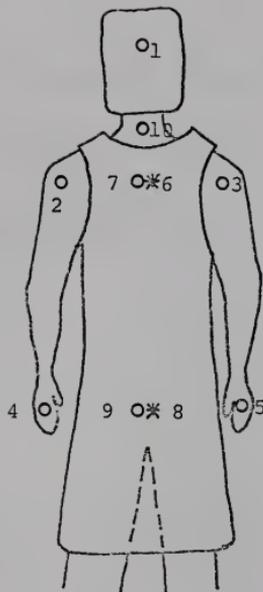
| Classification of Individual | Number | Badge Site | Average Period for Which Exposure Data Were Obtained (year) | Estimated Yearly Exposure at Site Indicated (mrem) |
|---------------------------------|--------|---------------|---|---|
| Physician | 23 | Under Apron | 3.49 | 184 |
| Physician | 19 | Outside Apron | 1.10 | 1376 |
| Physician | 6 | Hand | 0.92 | 4440 |
| Technician | 25 | Under Apron | 2.70 | 251 |
| Technician | 20 | Outside Apron | 1.78 | 625 |

The values for the exposure to the hands varied drastically between the two hospitals at which hand badges were worn. At one institution, where two cardiologists carried out all procedures, the average yearly dose to the hands was 12.4 rem. At the second facility at which four cardiologists wore hand badges, the average dose was 0.46 rem/year and the hand dose to no single individual was greater than 0.56 rem/year. The yearly patient load in each facility was equivalent; it was not determined if the difference was associated with physician technique, frequency at which the badge was worn, or some other factor.

Personnel Exposure Measurements in
University of Florida Cardiovascular Laboratory

To determine more accurately the values for the expected radiation exposure received by the physician and technicians during cardiac special procedures, a series of body site measurements were made during individual clinical procedures. Sensitivity paired TL dosimeters were positioned at selected sites on the bodies of the personnel. The characteristics of the patient, examination techniques and the position of the personnel during the examination were recorded so that these factors could be related to the measured exposure levels.

The dosimeter sites were selected so that an estimate of the dose to the eyes, thyroid, hands, gonads and whole body could be obtained. Figure 15 shows the selection of monitoring sites on the body. During the initial phase of



| <u>Site No</u> | <u>Identification</u> |
|----------------|----------------------------------|
| 1 | Forehead |
| 2 | Right shoulder |
| 3 | Left shoulder |
| 4 | Back of right hand |
| 5 | Back of left hand |
| 6 | Collar, under lead apron |
| 7 | Collar, outside lead apron |
| 8 | Gonad region, under lead apron |
| 9 | Gonad region, outside lead apron |
| 10 | Thyroid |

Figure 15. Identification of TL Dosimeter Sites for Exposure Measurements on Physicians and Technicians.

this study the exposures received during the examination of seven pediatric and six adult patients were evaluated. The preliminary results of this work were reported by Gignac (1974). Physician exposures during an additional seven adult patient study were subsequently carried out. For these measurements an additional dosimeter was positioned on the neck at the level of the thyroid (site number 10) to determine the difference between this position and the outside apron collar site (site number 7).

During the first series of 13 procedures, the x-ray system was equipped with a single-mode nominal six inch image intensifier. In the additional measurements for which the added thyroid site was monitored, the image intensifier had been changed to a dual-mode six inch to nine inch unit.

During a catheterization procedure the clinical staff consists of at least one physician and normally three or four technicians. Since the University of Florida is a teaching facility, additional physicians, technicians or observers are often present. It is not uncommon to find eight to ten individuals present during a procedure.

Figure 16 shows a floor plan of the procedure room. The floor was marked off with tape into eight numbered zones. These zones are delineated in the figure with dashed lines. The patient lies on the table with his head toward zone three. The physician conducting the procedure occupies zone one and is positioned next to the extended arm or groin of the

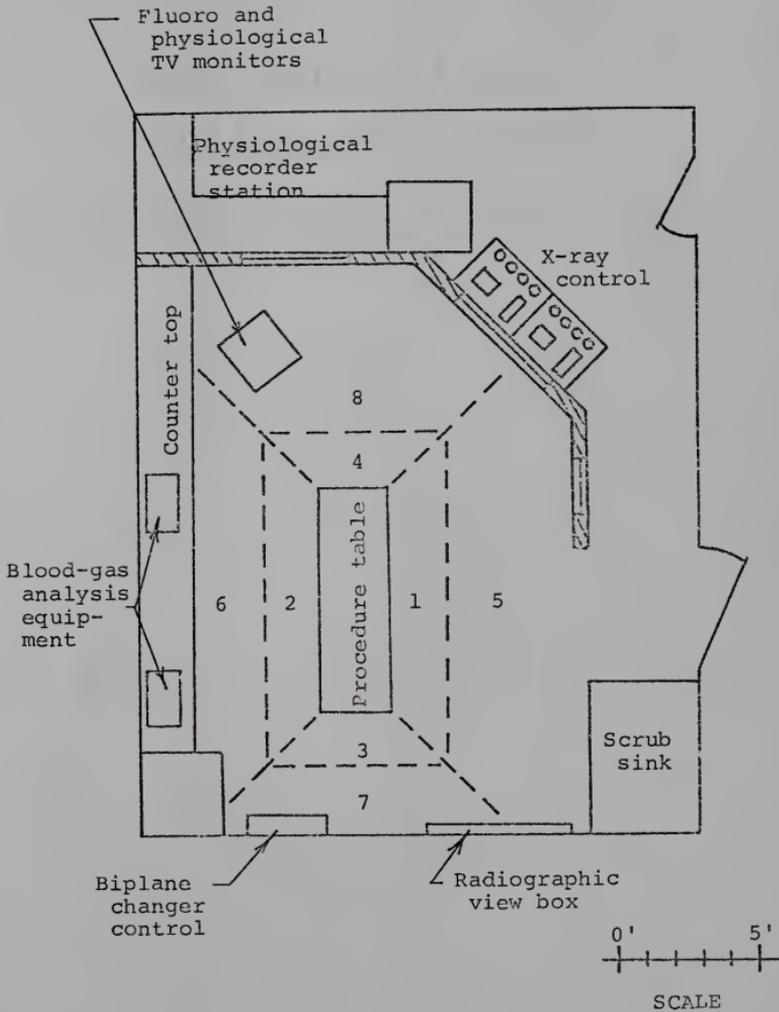


Figure 16. Room Layout of the UF Cardiovascular Laboratory Showing Work Zones.

patient into which the catheter is inserted. One technician remains in zone two. This person will raise and lower the image intensifier, assist the physician from this cross-table position and give physiological aid to the patient. A second technician occupies the area in zone three at the head of the table. The controls for beam limitation and table movement are the primary responsibility of this individual. A third technician, who might be thought of as a floater, will usually be present in the room. This individual will move through zones four, five and six assisting the physician and operating the blood-gas analysis equipment located on the counter top area in zone six. A technician is also positioned behind a glass panel and has the responsibility for operating the physiological recording equipment.

At the start of the procedure the TLD's were placed on the physician and three of the technicians; those intending to occupy zone two, three and four-five-six respectively. The dosimeter pairs positioned on the hands of the physician at sites four and five were positioned on the back of the hands under the surgical gloves. The sealed dosimeter package attached to the hands was sterilized in a liquid solution for approximately 30 minutes prior to the start of the procedure. A log of patient and procedure information was maintained. The exposure and associated examination factors are given in Appendix D. Tables 12, 13 and 14 list mean and range values for the exposure measurements at the various sites.

TABLE 12

Summary of Measured Exposures to
Physicians During Cardiac Catheterization Examinations

| Monitoring Site | Exposure at Site Indicated (mR/examination) | | |
|--------------------------|---|------|----------------------------|
| | 7 Pediatric Patients Range | Mean | 13 Adult Patients Range |
| 1. Forehead | <1- 6 | 4 | <1- 15 |
| 2. Right shoulder | <1-12 | 6 | <1- 18 |
| 3. Left shoulder | <1-33 | 16 | 3- 75 |
| 4. Right hand | <1-53 | 11 | <1- 18 |
| 5. Left hand | <7-64 | 36 | 4-109 |
| 6. Collar, under apron | <1- 3 | 1 | <1- 3 |
| 7. Collar, over apron | 3-25 | 17 | <1- 27 |
| 8. Gonad, under apron | <1- 2 | < 1 | <1- 6 |
| 9. Gonad, over apron | <3-24 | 11 | 4- 88 |
| 10. Thyroid ^a | | | 4- 38 |
| | | | Mean |
| | | | 7 |
| | | | 6 |
| | | | 34 |
| | | | 5 |
| | | | 28 |
| | | | 2 |
| | | | 15 |
| | | | 1 |
| | | | 37 |
| | | | 16 |

^aThyroid utilized during seven adult catheterization procedures.

TABLE 13

Summary of Measured Exposures to Technicians During
Cardiac Catheterization Examinations
on Adult Patients

| Monitoring Site | Exposure at Site Indicated (mR/examination) | | | Zone 4,5,6 | | |
|------------------------|---|------|-----------------|------------|-------|------|
| | Zone 2 Range | Mean | Zone 3 Range | Mean | Range | Mean |
| 1. Forehead | 8-25 | 15 | 9-14 | 11 | 1-19 | 9 |
| 2. Right shoulder | 5-42 | 24 | <1-12 | 5 | <1-16 | 7 |
| 3. Left shoulder | 1-15 | 7 | 4-15 | 8 | 3-15 | 7 |
| 4. Right hand | 12-34 | 25 | <1-33 | 7 | 2- 7 | 5 |
| 5. Left hand | 4-28 | 13 | 3-57 | 18 | 1- 6 | 4 |
| 6. Collar, under apron | < 1- 4 | 2 | <1- 3 | 1 | <1- 3 | 1 |
| 7. Collar, over apron | 8-30 | 16 | 3-25 | 8 | <1-24 | 9 |
| 8. Gonad, under apron | < 1- 4 | 2 | <1- 2 | 1 | <1- 6 | 2 |
| 9. Gonad, over apron | 17-35 | 25 | <1-26 | 6 | <1-44 | 13 |

TABLE 14

Summary of Measured Exposures to Technicians During
Cardiac Catheterization Examinations
on Pediatric Patients

| Monitoring Site | Exposure at Site Indicated (mR/examination) | | | | | |
|------------------------|---|------|--------|------|------------|------|
| | Zone 2 | | Zone 3 | | Zone 4,5,6 | |
| | Range | Mean | Range | Mean | Range | Mean |
| 1. Forehead | 2-9 | 5 | 1-6 | 4 | 1-6 | 3 |
| 2. Right shoulder | 3-14 | 9 | 1-11 | 5 | <1-7 | 3 |
| 3. Left shoulder | 1-7 | 3 | <1-5 | 3 | 1-3 | 2 |
| 4. Right hand | 4-22 | 11 | <1-7 | 3 | 1-7 | 3 |
| 5. Left hand | 2-18 | 6 | <1-4 | 2 | <1-6 | 2 |
| 6. Collar, under apron | <1-3 | 1 | <1-2 | 1 | <1-3 | 1 |
| 7. Collar, over apron | 4-12 | 8 | 1-7 | 4 | 1-5 | 3 |
| 8. Gonad, under apron | <1-3 | 1 | <1-2 | 1 | <1-2 | 1 |
| 9. Gonad, over apron | 4-9 | 6 | <1-4 | 2 | <1-4 | 2 |

The average fluoro time was 14.7 minutes for the adult catheterization procedures and 22 minutes for the pediatric. Cine was utilized in all adult studies and in 43% of the pediatric cases. The average number of cine frames exposed was 2,483 and 775 respectively. At 64 frames per second this is equivalent to 39 and 12 seconds of cine. No data were recorded regarding the biplane procedures carried out on the pediatric patients since all personnel leave the room during these rapid sequence filmings and the exposure to operating personnel is negligible.

During the initial 13 procedures in which a comparison between adult and pediatric examination technique could be obtained, it was seen that adult catheterizations resulted in a greater exposure to personnel than pediatric examinations. In addition to the greater patient thicknesses, which require higher incident exposure, the predominant use of cineradiography during adult examinations is the cause for these higher exposures. It was found that considerable nonuseful exposure occurs during the examination; this was due mainly to the "cine test" procedure, which accounts for 19% of the total exposure during the examination. This test procedure was required to be carried out prior to the actual cine run. The x-ray system utilized a current modulation automatic brightness system. The dynamic range of this system was limited and the cine test was carried out to set the current level at a nominal mid-range operational point. The procedure

consisted of making a test exposure during which the x-ray tube was activated, but the cine film was not advanced. During this exposure the tube potential was manually adjusted to a value that would allow the required brightness level to be achieved at a mid-range tube current setting. The test setup was required at the start of the first cine run and prior to subsequent runs where the patient's geometry was substantially changed, such as occurred when the patient was rotated into the oblique positions. From a diagnostic standpoint the exposures received during these test procedures were of no benefit. An additional source of nonuseful exposure occurred as a result of the procedure used for identification of the cine film. Lead identification letters were used to spell out the patients name, hospital number, date and institution name. Prior to the first cine run the paddle on which this identification information was arranged was placed in the beam between the patient and the input surface of the intensifier. A short strip of film was then exposed and when developed would serve as an identification leader. This technique resulted in an average 2% increase in incident exposure to the patient.

When the single-mode, nominal six inch, image intensifier and current-modulated automatic brightness control system were replaced by the dual-mode, six inch to nine inch unit and kV modulated automatic brightness system, the test exposure was no longer required and the unnecessary

exposure associated with the test procedure was eliminated. It also became standard operating procedure to mark the cine film prior to arrival of the patient.

From Table 12 it can be seen that the highest exposure to an unshielded body site received by the cardiologists involved with adult patients was measured on the left shoulder (site number 3). With the exception of the exposure to the hands, the values recorded during the adult patient studies were about double those received during the pediatric studies. This is logical since one would expect a higher scatter level to be associated with the larger adult patients. Cine techniques were utilized in all of the adult patients studied, but in the pediatric catheterizations they were employed less than 50% of the time. The number of cine frames per procedure for the adult studies was more than three times that used in the pediatric studies. As previously noted, during the biplane rapid film radiographic techniques employed for the evaluation of congenital heart defects in children, all personnel leave the procedure room and thus receive negligible exposure. The higher exposure to the hands of the physician performing catheterization procedures on children results from their closer proximity to the primary beam.

The technician working in zone two during an adult catheterization study receives exposures similar to those incident on the physician. Where the left shoulder had been

observed to be the high unshielded site for physicians, the right shoulder of the technician is seen to be highest. This can be correlated with the normal position of these two individuals. The fluoro and physiological TV monitors are positioned near the foot end of the procedure table. As a result of this placement the left and right sides of the physician and technician are positioned closest to the patient or source of scatter radiation. The measured exposures received by the technicians in zones three and four-five-six are seen to drop off sequentially from those recorded for zone two. The values are generally higher for the adult studies.

As previously noted, during the first series of measurements the thyroid was assumed to receive the same exposure as recorded by the dosimeter positioned on the outside of the protective lead apron at the collar (site number 7). A comparison of the values in Table 12 for the actual measurements made over the thyroid with those at the collar of the apron (sites 7 and 10) establishes the validity of this assumption.

Although no correlation between surface exposure and absorbed organ dose is made, sites 1, 4 and 5, 8 and 10 are indicators of exposure to the lens of the eye, hands, gonad and thyroid respectively. For whole body exposure a single site estimate cannot be used since body surface exposure at different sites varies considerably. If blood-forming organs were considered the critical tissue (NCRP report 39, 1971,

page 196) for whole body exposure, a weighting system based on its distribution in the body can be developed.

Jones (1964) carried out a series of phantom dosimetry measurements to determine the dose absorbed in various organ systems as a function of the incident external exposure. The exposure at sites within and on the surface of the phantom were measured with TLD for beams incident on the AP surfaces, as well as for a rotational setup. In addition, exposures at the same points in space were measured in the absence of the phantom. For an effective energy of 38 keV, which is similar to the energy of scattered x-rays received by personnel during diagnostic procedures, the bone marrow dose to free air exposure for the three exposure geometries was found to be approximately 0.25 rads/R. The relationship between the exposure measured at a typical personnel monitoring site on the anterior chest surface, at the level of the seventh thoracic vertebra, was also found to be related to the bone marrow dose by a factor of 0.25 for the incident anterior and rotational geometries.

Figure 17 shows the outline of the human body with a lead apron typical of that worn by operating personnel in a cardiac catheterization laboratory. The body has been divided into four major zones which include: the head and neck down to the seventh cervical vertebra, the arm and exposed shoulder outside of the lead apron and the trunk of the body predominantly covered by the apron. The bone marrow

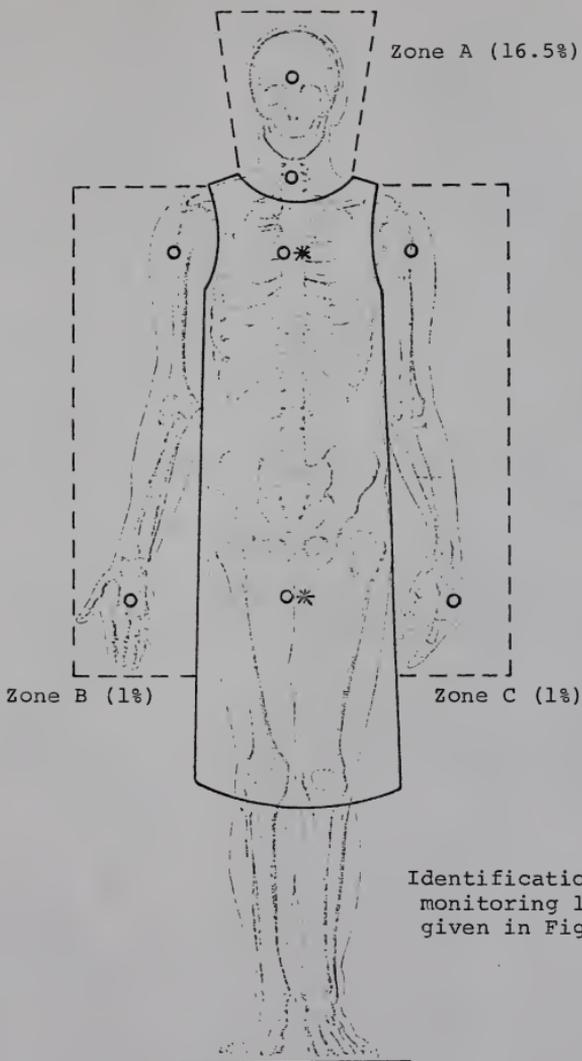


Figure 17. Subdivision of Body of X-ray Operational Personnel Wearing Lead Apron with Identification of Active Bone Marrow Fractions.

distribution for these respective areas, based on the data of Ellis (1961), is shown in Table 15. Using these bone marrow distribution values and the relationship between incident exposure and bone marrow dose of Jones, a whole body "bone marrow dose index" can be derived as follows:

$$\text{Whole Body Bone Index} = \frac{(\text{Sites } 1 + 7 + 10)(0.165)(0.25)}{3} + \frac{(\text{Sites } 2 + 3)(0.02)(0.25)}{2} + \frac{(\text{Sites } 6 + 8)(0.815)(0.25)}{2}$$

TABLE 15

Red Bone Marrow Distribution
in Body Zones Identified in Figure 17

| Body Zone | Anatomical Location | Mass of Marrow ^a (g) | Percent of Total Bone Marrow |
|-----------|-------------------------|---------------------------------|------------------------------|
| A | Cranium | 124.3 | 16.5 |
| | Mandible | 12.3 | |
| | Cervical vertebra | <u>35.8</u> | |
| | | 172.4 | |
| B and C | Humerus (head and neck) | 20.0 | 2.0 |
| D | All other | <u>853.3</u> | <u>81.5</u> |
| | | 1,045.7 | 100.0 |

^a

Red bone marrow values from Ellis (1961).

The measured exposure values received by operating personnel were interpreted in terms of the established radiation protection guides for various tissues. The following yearly workload assumptions were used to develop estimated annual dose values:

1. A staff adult cardiologist performs 250 procedures per year.
2. A staff pediatric cardiologist performs 125 procedures per year.
3. A technician may assist in the procedure room during 300 examinations per year. The patient classification will be evenly split between adult and pediatric. An equal rotation of duties will result in one-third of the time being spent in zone two, three and four-five-six respectively.

The results of this evaluation are presented in Table 16.

Scatter Levels Around Examination Tables

The requirement for a sterile field during cardiac catheterization has previously been noted. This requirement, which usually results in the absence of a scatter shield attached to the equipment, results in exposure levels higher than for other fluoro procedure rooms such as a typical gastrointestinal suite. Since scatter radiation cannot be adequately controlled through the use of a drape shield, the design of the table becomes a matter of primary concern.

TABLE 16
 Estimated Yearly Occupational Exposures Received by
 Physicians and Technicians in UF Cardiovascular Laboratory

| Critical Organ or Region of the Body | MPD ^a (rem/year) | Cardiologist Adult | | Cardiologist Pediatric | | Technician | |
|--|--------------------------------|---|-------------------|---|-------------------|---|-------------------|
| | | Yearly Dose Equivalent ^c (rem) | Percent of MPD | Yearly Dose Equivalent ^c (rem) | Percent of MPD | Yearly Dose Equivalent ^c (rem) | Percent of MPD |
| Eye | 5 | 1.8 | 36 | 0.5 | 10 | 2.4 | 50 |
| Thyroid | 15 | 4.0 | 27 | 2.1 | 14 | 2.4 | 16 |
| Hand ^b | 75 | 8.5 | 11 | 4.5 | 6 | 2.5 | 3 |
| Whole body "bone marrow dose index" | 5 | 0.2 | 4 | 0.1 | 2 | 0.2 | 4 |
| Gonad | 5 | 0.3 | 6 | 0.1 | 2 | 0.4 | 8 |

^aMaximum permissible dose equivalent limits recommended by the NCRP (1971).

^bCalculation of hand exposure to physician based on high left hand values. For technicians, an average of the left and right measurements were used.

^cConversion of dose (rad) to dose equivalent (rem) using a quality factor of one.

Exposure Measurements for Under Table X-ray Source

A number of different source-patient-image receptor configurations are used. The most common setup consists of an under table x-ray source and over table image intensifier assembly. The geometry of the source-image receptor combination is fixed, except for allowing variation of source-to-receptor distance. The patient examined on this type of equipment is positioned on a floating-top table and positioned in the beam by controlling table motion. The table typically allows use of a flat or rotation cradle surface. If serial radiography is to be carried out, it is usually desirable to position the patient as close to the film changer as possible to reduce the magnification effect. To accomplish this, the flat table surface is employed. For studies such as coronary angiography, cine is the predominant recording mode and it is necessary to rotate the patient for various oblique projections. To accomplish this the patient is strapped in the rotation cradle. Tables of this type in current use have either interchangeable tops or have an add-on cradle that is positioned above a permanent flat table surface. The table currently in use at the UF cardiovascular laboratory is of the add-on cradle type.

Using an adult Rando phantom, radiation scatter levels in various planes were measured with the phantom on the table and in the cradle. String was used to establish a grid which identified measurement sites on 30 cm centers. The x-ray system was then operated in the fluoro mode and measurements

were made with a Nuclear Chicago,^a Model 2588, cutie pie type survey meter. The x-ray technique factors were adjusted in accordance with standard operational procedures. Tube potentials of 80 and 92 kVp at a tube current of 2 mA were used for the flat table and cradle configurations respectively. These settings resulted in an optional fluoro brightness level reading of 100 units representative of normal operating conditions. The input surface of the image intensifier assembly was positioned 5 cm from the anterior mid-chest surface of the phantom. The intensifier was operated in the nominal six inch mode with the edges of the rectangular x-ray field tangent to the circular visible image (exact collimation).

Figures 18 through 20 show the isoexposure rate contours determined with the phantom on the flat table surface. Figure 18 represents a plane perpendicular to the longitudinal dimension of the table and intercepting the central axis of the x-ray beam. This position is approximately that occupied by the physician during a catheterization procedure. The vertical plane at the head of the table is shown in Figure 19. At this position, occupied by the technician in charge of table movement, the exposure rates are seen to be less than at the side of the table. At this head-of-table position, the distance to the central axis of the x-ray beam is greater

^aSearle Analytic Inc. (formerly Nuclear Chicago), Des Plaines, Illinois.

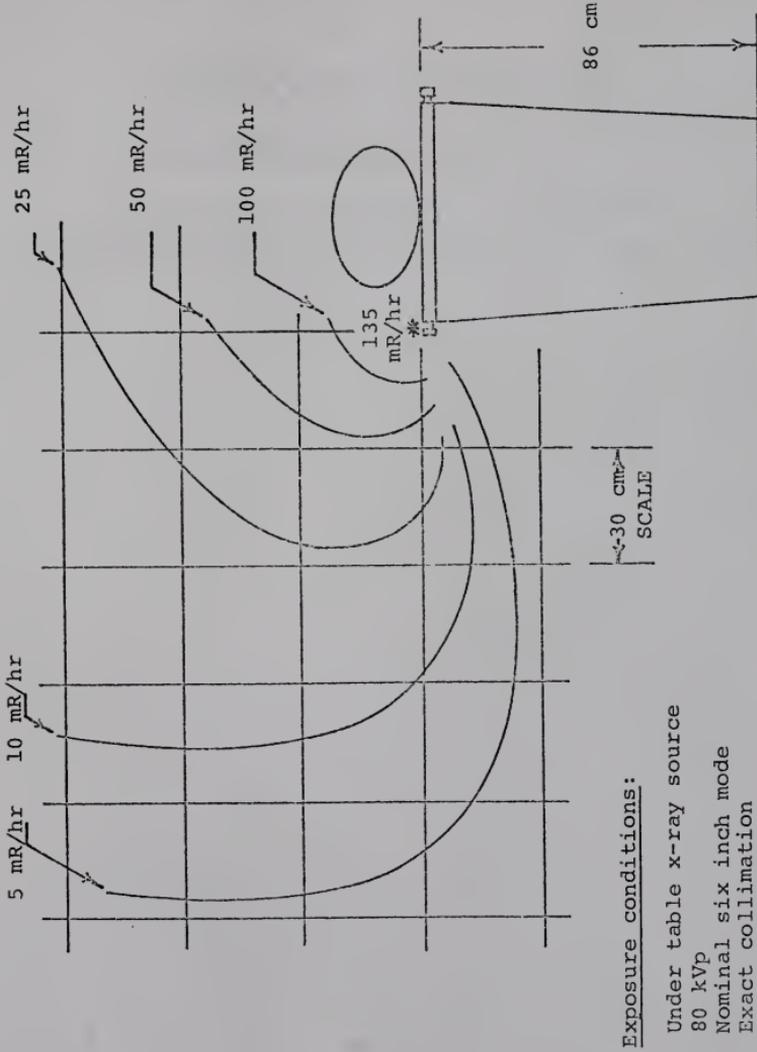


Figure 18. Isoexposure Contour in Vertical Plane at Side of Table Intercepting Central Axis of X-ray Beam. Adult Phantom on Flat Table Surface.

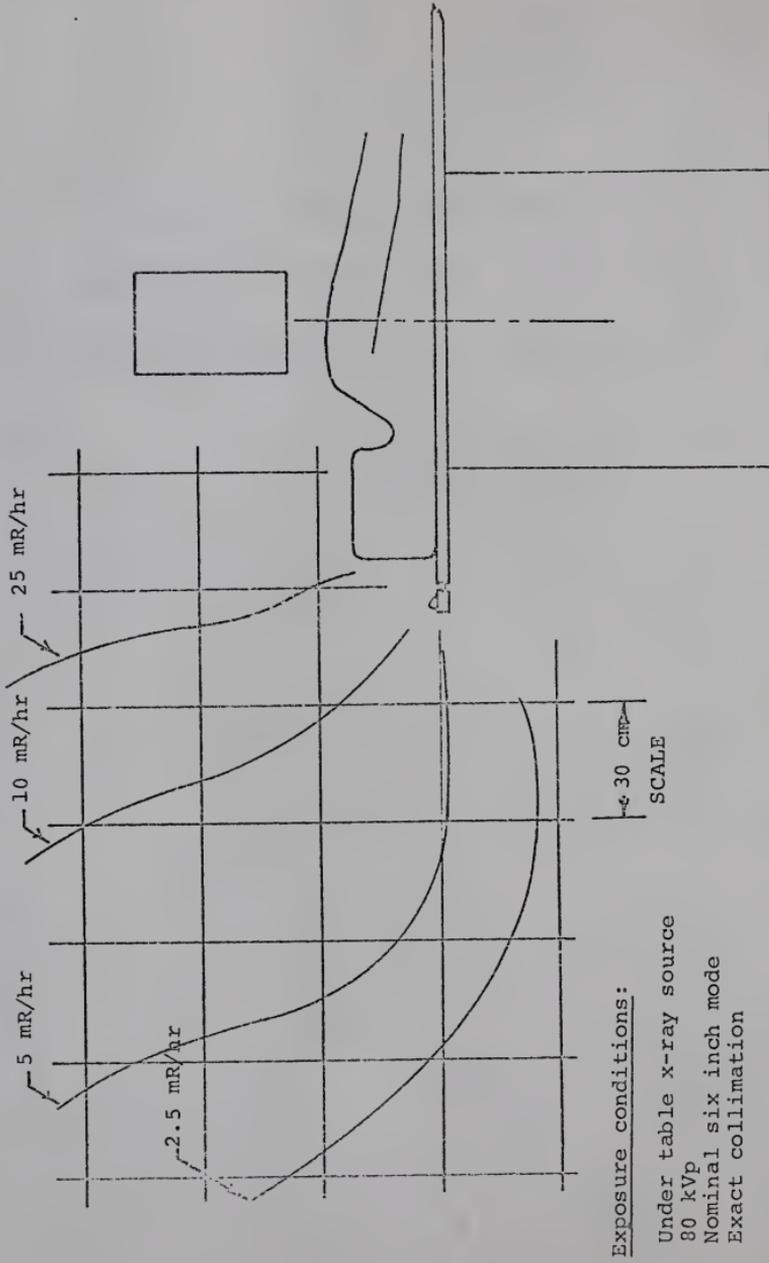


Figure 19. Isoexposure Contour in Vertical Plane at Head of Table Intercepting Central Axis of X-ray Beam. Adult Phantom on Flat Table Surface.

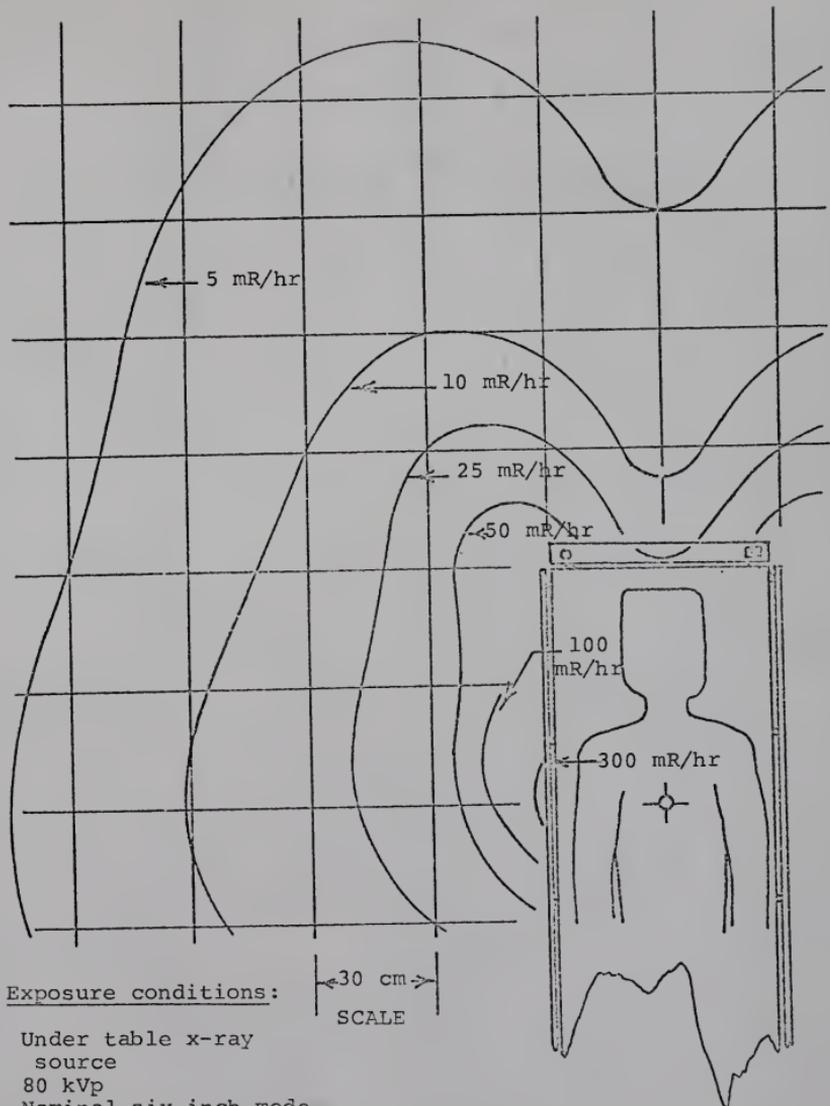


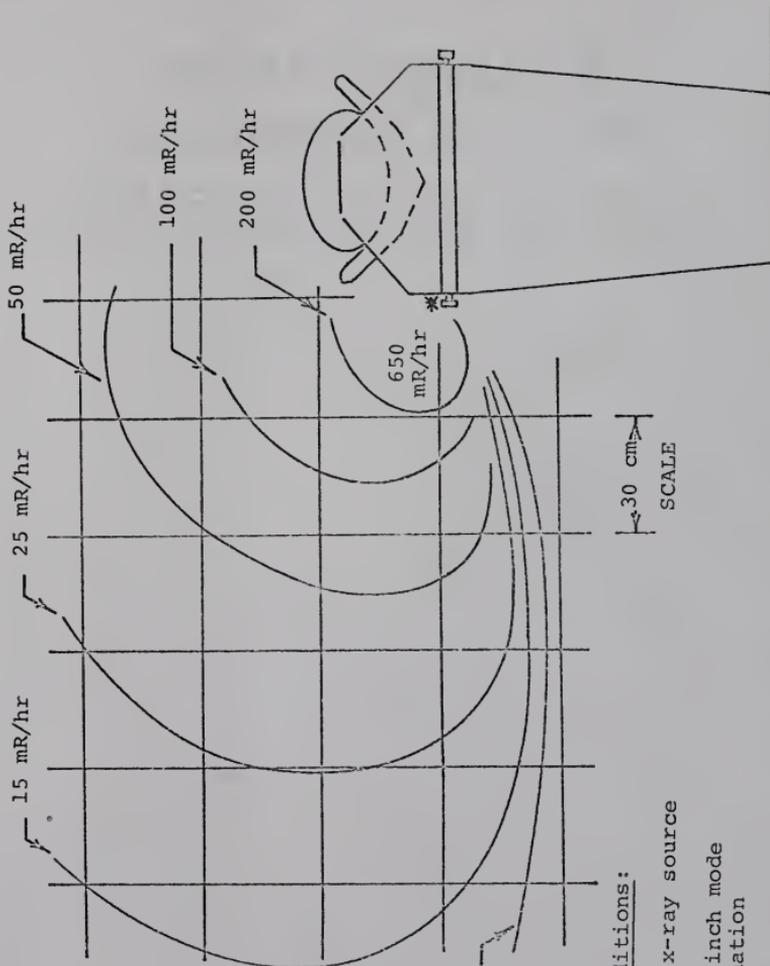
Figure 20. Isoexposure Contour in Horizontal Plane at Table Top Surface Height. Adult Phantom on Flat Table Surface.

than at the side of the table. The amount of patient tissue between the incident beam and the exit patient surface is also greater for this position thus providing a greater attenuation of scattered radiation.

Figures 21 through 23 show the scatter levels in the vertical and horizontal planes with the patient in the cradle. As noted by the increased tube potential required for operation in this configuration, a higher x-ray tube output is required. This is due to the added attenuation of the cradle and the greater source-to-image receptor distance. The elevated position of the patient when positioned in the cradle results in a significant amount of backscatter. These effects are seen to increase the exposure rate at the side edge of the table by a factor of approximately five times over that measured for the flat table geometry.

The exposure levels at the head end of the table are not seen to be significantly different for the flat table or cradle position. The head end cradle support houses the motor drive assembly for this apparatus and also provides additional shielding.

The back and side scatter could be considerably reduced by addition of some type of scatter shield. To evaluate such a modification, a 0.5 mm strip of flexible lead vinyl was attached to the edge of the cradle. The length was such that when the cradle was in the extreme right anterior oblique



Exposure conditions:

Under table x-ray source
 80 kVp
 Nominal six inch mode
 Exact collimation

Figure 21. Isoexposure Contour in Vertical Plane at Side of Table Intercepting Central Axis of X-ray Beam. Adult Phantom in Rotation Cradle.

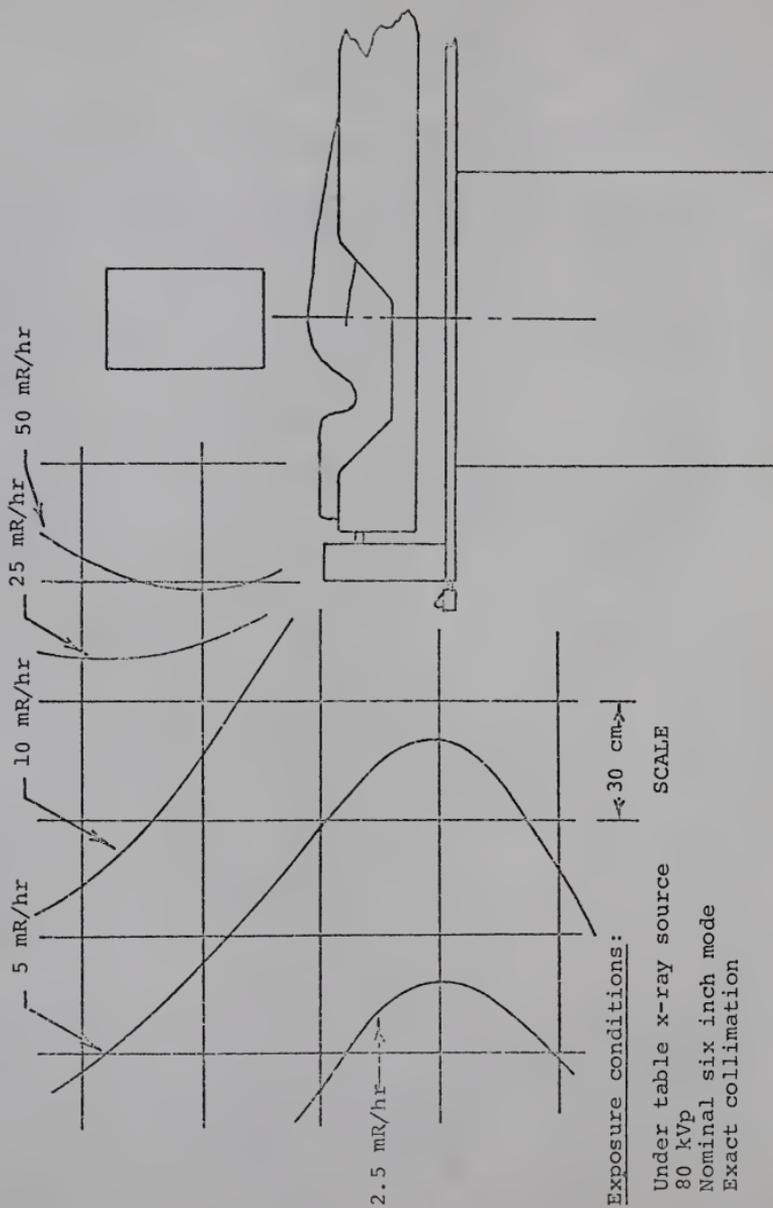


Figure 22. Isoexposure Contour in Vertical Plane at Head of Table Intersecting Central Axis of X-ray Beam. Adult Phantom in Rotation Cradle.

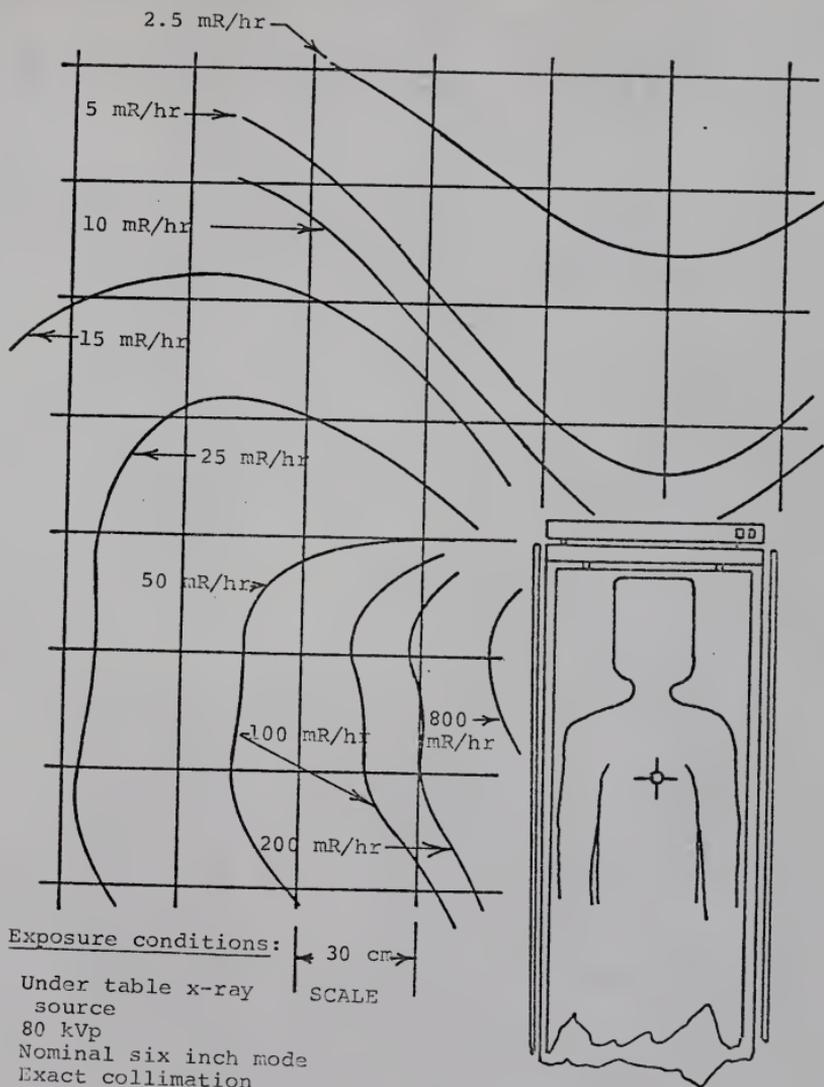


Figure 23. Isoexposure Contour in Horizontal Plane at Flat Table Surface Height. Adult Phantom in Rotation Cradle with Scatter Shield Added.

position the drape still extended over the edge of the table. The isoexposure rates for the horizontal and two vertical planes are shown in Figures 24 through 26.

Figure 26 represents a plane 30 cm above the flat table surface. The isoexposure contours, although differing in shape, somewhat correspond to those previously measured in the horizontal table top plane with the phantom on the flat table surface (Figure 20). This is as expected and indicates that these values would be consistent with the expected exposure rates for a removable cradle that fits flush with the edges of the table structure.

Expected Exposures for Other Configurations

In addition to the conventional under table x-ray source configuration, over table and C-arm units are in use. The potential for high personnel exposures from an over table fluoro x-ray source have been noted by Jacobson (1971). These result primarily from backscatter from the primary incident beam and the increased probability of getting the hand in the primary beam.

Stacey and colleagues (1974) reported on a comparison of personnel exposures from units with under table and over table x-ray tubes used for cardiac catheterization. From a design standpoint, the over table source has two advantages. First it is not necessary to provide an additional x-ray tube for use with an under table serial film changer. The

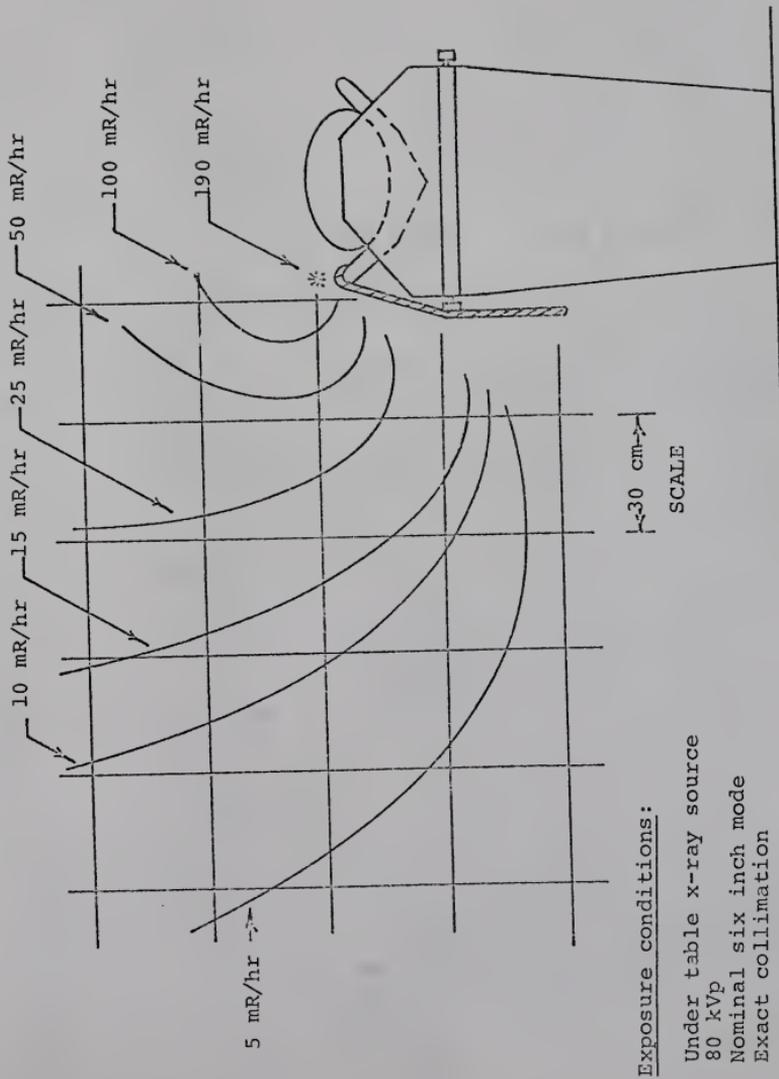


Figure 24. Isoexposure Contour in Vertical Plane at Side of Table Intercepting Central Axis of X-ray Beam. Adult Phantom in Rotation Cradle with Scatter Shield Added.

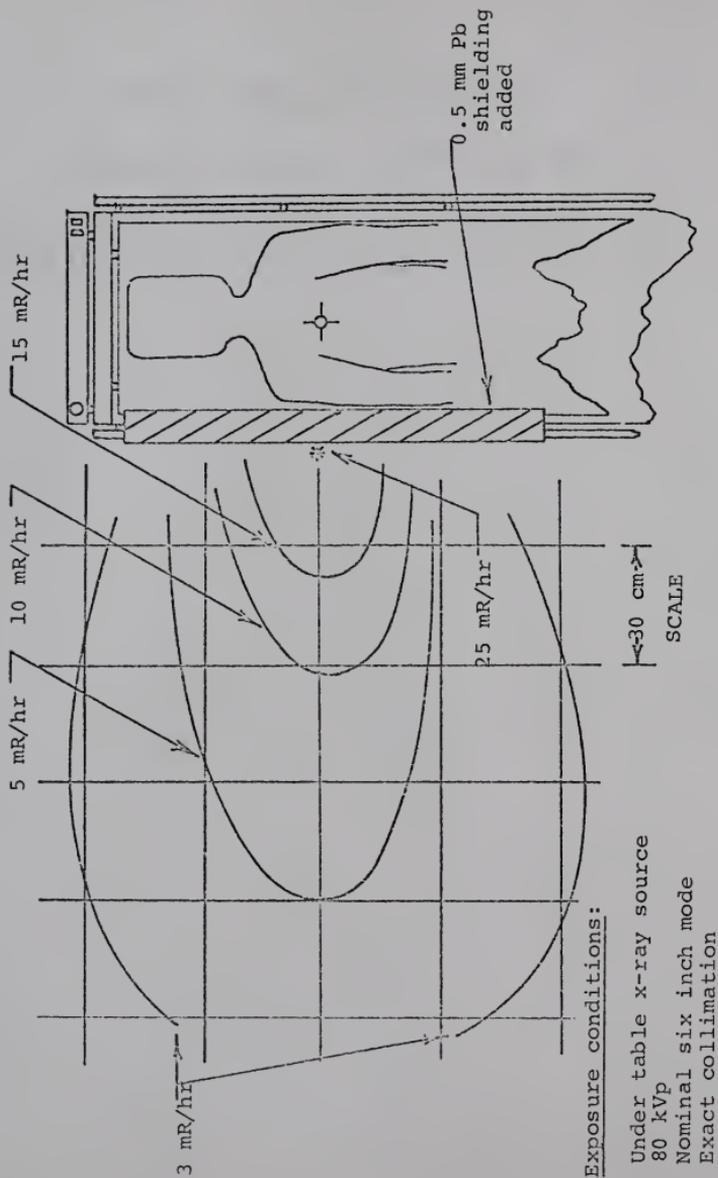


Figure 25. Isoexposure Contour in Horizontal Plane at Flat Table Surface Height. Adult Phantom in Rotation Cradle with Scatter Shield Added.

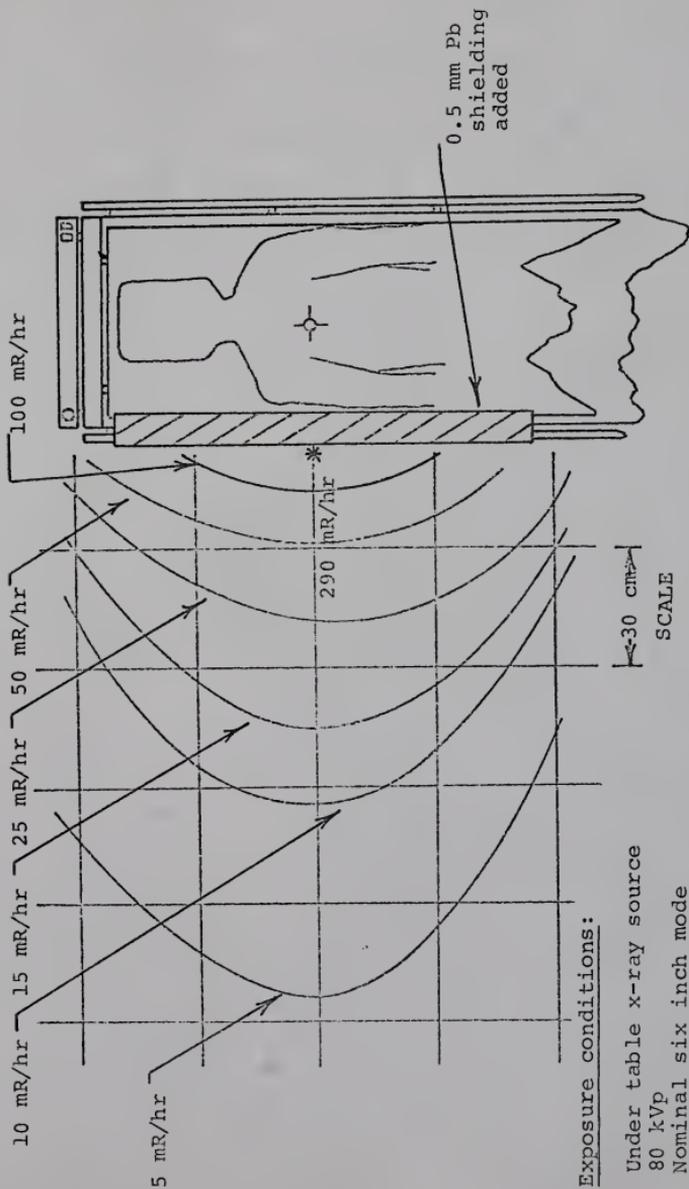


Figure 26. Isoexposure Contour in Horizontal Plane 30 cm Above Flat Table Surface. Adult Phantom in Rotation Cradle with Scatter Shield Added.

second advantage results from the fact that serial radiography can follow fluoro without moving the patient. These advantages are counter balanced by much higher scatter levels. Stacey measured the exposures to the same group of cardiologists working with the under table and over table systems. Although the exposure to the forehead was found to be slightly less for the over table configuration, the levels at the chest, waist and shins were increased by factors of three, 40 and 60 respectively. An estimated increase in physician bone marrow dose by a factor of 1.7 was given for the over table unit. Wholey (1974) has also reported on the potential higher exposure levels that would be expected with an over table x-ray source.

The C-arm configuration, which is specifically designed for acquired heart disease studies, is currently available with various modifications from at least four manufacturers. In these units the patient is placed on a flat cantilevered table. The source and image receptors are mounted on opposite ends of a C-or U-arm. This assembly is rotated instead of the patient to achieve the oblique projections. Although no measurements were made on a unit of this type, one might anticipate the operator exposure to be equal or greater than that expected with an over table source. Shielding to reduce backscatter is not used and the rotational freedom would be expected to increase the possibility of the physicians or technicians getting their hands in the beam.

One of the manufacturers' advertised features of the C-arm configuration is the increased patient load that can be handled. In at least one of the available models, the removable table top fits on a patient transport stretcher. The increased efficiency is achieved by use of a pre- and post-catheterization preparation area. The initial patient preparation, including cutdown and vessel isolation or percutaneous puncture is carried out in the preoperative area. The patient is then moved to the x-ray suite. Following completion of the examination, the patient is again moved to a postoperative area. By proper scheduling an increased patient load can be accommodated since the x-ray equipment is tied up during the examination phase only.

This increased efficiency only compounds the potential radiological hazards. These units should be viewed with extreme caution and may be acceptable only when sufficient staff is available to allow liberal rotation.

Protective Lead Aprons

The use of protective lead aprons by personnel involved with diagnostic x-ray procedures is a well-accepted principle. However, the selection of the correct design and weight for the apron to be used in a particular room is often overlooked. A knowledge of the duties and work habits of the wearer must be considered in relation to radiation scatter levels. In terms of the accepted health physics goal of reducing

unnecessary exposure to a minimum, an apron providing the maximum x-ray attenuation should be worn. In practice this must be balanced against the physical strength of the individual and period of time over which the apron must be worn. At the UF cardiovascular laboratory both 0.25 and 0.50 mm lead-equivalent aprons are available. With the exception of a few male physicians who use the 0.50 mm variety, all other personnel routinely select the lighter one. The weight of the 0.50 mm aprons currently used is too great for the average female to wear for the two to three hours that may be required to complete a procedure.

In a cardiac catheterization special procedure room, it is a common practice to see one or more of the technicians with their backs to the patient. These individuals, who may be running physiological monitors, blood analysis equipment, etc., have often been observed to wear their apron on their back or use an additional lap apron strapped across the lower back. Although these solutions are adequate if correctly employed, it is difficult to assume that the person who finds it necessary to position the apron on his back will not turn and face the patient and source of x-ray scatter from time to time. If a second device, such as the lap apron, is required for adequate protection, it would be expected that it would be forgotten from time to time.

Over a period of one month the external exposure on the surface of two protective lead aprons was measured.

Thermoluminescent dosimeters were attached at 14 sites on each apron, as shown in Figure 27. The aprons were randomly worn by physicians and technicians. No attempt was made to record this frequency. The chips were removed and read after the first, second and fourth weeks.

The results of these measurements are shown in Table 17. The maximum exposure is seen to be at the mid-chest position (site number 5). This is consistent with the maximum scatter levels measured at this position. The exposure at the two sites on the back of the apron (sites numbered 13 and 14) are seen to be less than 10% of the mid-chest values.

Using these exposure measurements in conjunction with an understanding of the human flow patterns in a typical special procedure room as a guide, a set of criteria was developed for the optimum protective lead apron for use in a cardiac catheterization special procedure room. The criteria are as follows:

1. The maximum thickness of attenuation material must be in the mid-chest and gonad regions.
2. Some shielding should be provided for the neck and thyroid region.
3. The apron should provide wrap-around 360° protection for the lower pelvic area.

Figure 28 shows a sketch of the proposed design. The length is intended to extend to the mid-thigh level of the wearer. This apron length is shorter than that provided by

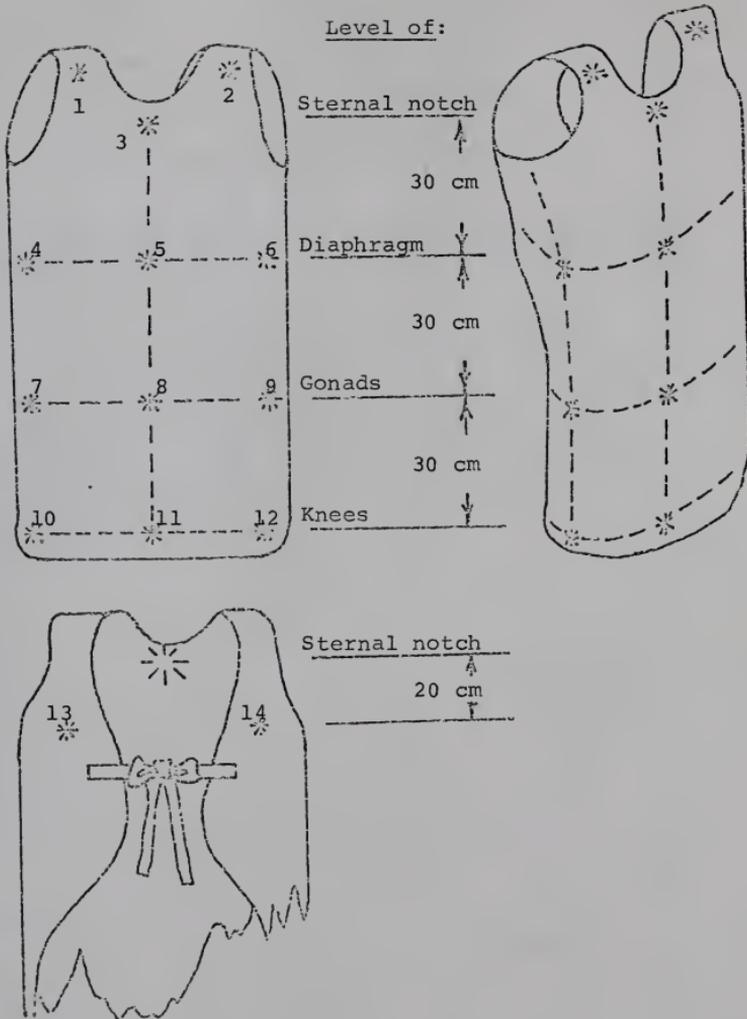


Figure 27. Position of TLD Monitors on External Surface of Protective Lead Apron.

TABLE 17
 Measured Exposure in mR at External Sites
 of Lead Aprons Worn by Personnel in a Cardiac Catheterization Laboratory

| Site no. | Apron A | | | | | Apron B | | | | | Average for A&B Normalized to Site 5 | |
|----------|---------|--------|-----|-----|--------------------------|---------|--------|-----|-----|--------------------------|--------------------------------------|--|
| | Week 1 | Week 2 | 3&4 | Sum | Normalized to Site no. 5 | Week 1 | Week 2 | 3&4 | Sum | Normalized to Site no. 5 | | |
| Front | | | | | | | | | | | | |
| 1 | 7 | 38 | 76 | 112 | 0.34 | 5 | 10 | 85 | 100 | 0.25 | 0.31 | |
| 2 | 7 | 50 | 143 | 200 | 0.56 | 6 | 32 | 147 | 185 | 0.46 | 0.51 | |
| 3 | 11 | 65 | 176 | 252 | 0.71 | 9 | 40 | 225 | 274 | 0.69 | 0.70 | |
| 4 | 6 | 73 | 38 | 117 | 0.33 | 4 | 4 | 182 | 190 | 0.48 | 0.41 | |
| 5 | 9 | 120 | 226 | 355 | 1.00 | 10 | 48 | 341 | 399 | 1.00 | 1.00 | |
| 6 | 3 | 7 | 60 | 70 | 0.20 | 2 | 76 | 27 | 105 | 0.26 | 0.23 | |
| 7 | 4 | 63 | 49 | 116 | 0.33 | 2 | 4 | 151 | 157 | 0.39 | 0.36 | |
| 8 | 3 | 81 | 154 | 238 | 0.67 | 6 | 80 | 256 | 342 | 0.86 | 0.77 | |
| 9 | 1 | 12 | 100 | 113 | 0.32 | 2 | 123 | 45 | 170 | 0.43 | 0.38 | |
| 10 | 4 | 75 | 48 | 127 | 0.36 | 3 | 5 | 137 | 145 | 0.36 | 0.36 | |
| 11 | 3 | 50 | 80 | 133 | 0.37 | 2 | 16 | 194 | 212 | 0.53 | 0.48 | |
| 12 | 1 | 25 | 42 | 68 | 0.19 | 1 | 12 | 48 | 61 | 0.15 | 0.17 | |
| Back | | | | | | | | | | | | |
| 13 | 1 | 11 | 11 | 23 | 0.06 | 1 | 4 | 13 | 18 | 0.05 | 0.06 | |
| 14 | 2 | 23 | 12 | 37 | 0.10 | 1 | 3 | 18 | 22 | 0.06 | 0.08 | |

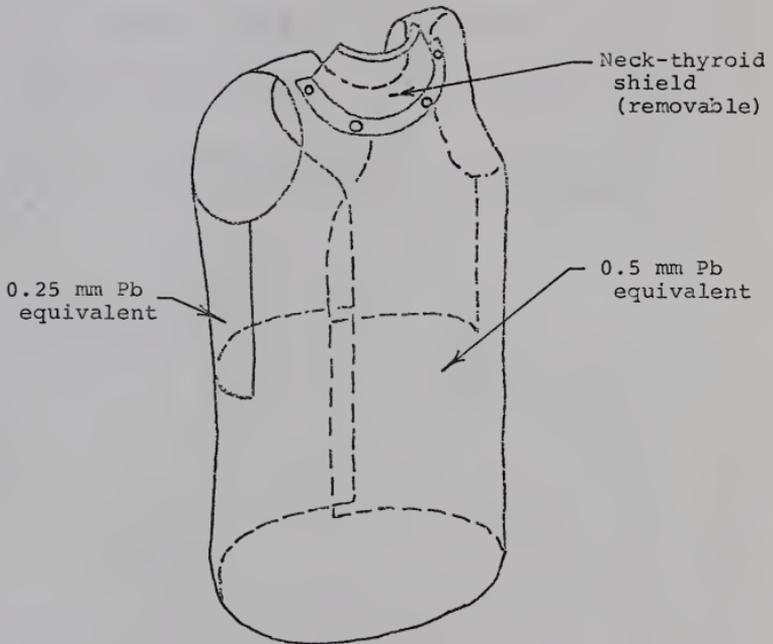


Figure 28. Wrap-around Lead Protective Apron with Removable Thyroid Shield.

the aprons in current use which extend to the mid-calf of a six foot adult male. This shorter length will allow redistribution of attenuation material to areas of higher anticipated scatter and/or biological radiosensitivity. A detachable thyroid shield has also been added. This attachment is removable since it is only felt to be a mandatory prerequisite for individuals working directly next to the patient. Although the detachable shield could be inadvertently forgotten or put aside, this compromise is considered necessary so that one apron design can be used for all individuals in a special procedure room. The apron incorporates a wrap-around design with 0.50 mm lead equivalence over the gonadal area. To achieve a weight that is acceptable to the small female wearer and still provide adequate protection for the large male, aprons in proportioned sizes should be provided.

CHAPTER V

PATIENT EXPOSURE STUDY GENERAL CONSIDERATIONS

An evaluation of the radiological health significance of cardiac catheterization procedures, as they relate to the patient, involves a number of considerations. In addition to quantification of the anticipated radiation dose, factors such as patient age and life expectancy are of key importance. If the examination involves a small population group where alternate diagnostic techniques do not exist and the absence of medical intervention will result in deterioration or life-threatening consequences, the concern regarding radiation exposure of the patient may be insignificant. Although the radiation hazards may assume a role of reduced importance in a benefit/risk analysis in some situations, every step should be taken to carry out those procedures that are felt to be necessary with the minimum exposure.

Advances in cardiac surgical techniques create a changing environment in which the radiation hazards must be considered. These advances in operative techniques are continuously increasing the life expectancy of the patient. This, in turn, alters the anticipated somatic and genetic effects that may potentially be manifest in the individual.

The majority of cardiac catheterization examinations are performed on patients suspected of having acquired heart problems with coronary arterial disease being the major contributor. The large expansion in the number of cardiac catheterization laboratories that has recently occurred in the U.S. are primarily involved with these adult patient studies. In many situations the patient is beyond the reproductive age and the somatic consequences need only be considered. As the availability of facilities equipped to perform these procedures expands, their use on an ever increasing population group can be expected. When a medical facility invests one-half million dollars or more in a special procedure room, the patient load must be maintained to cover the investment. The utilization of cardiac catheterization as a screening technique on healthy subjects in certain occupational groups, such as airline pilots, is already being used. In these situations the efficacy of the examination must be considered.

Prospective Cardiac Catheterization Patients

Accurate statistical data on the number of cardiac catheterizations currently performed, or age distribution of patients, do not exist. In the congenital area, a review of the incidence of cardiac defects will help identify the maximum patient population. Children evaluated for rheumatic heart disease must also be considered in this patient age category. The majority of adult acquired heart disease

studies involve coronary angiography. In this case, statistical data regarding the individual with angina pectoris, who is a prime candidate for this examination, can be evaluated.

A number of studies of the incidence of congenital cardiac defects has been reported. MacMahon and colleagues (1953) studied all children born in Birmingham, England between 1940 and 1949. The total number of births during this period was 199,418. The incidence of cardiac defects diagnosed in this population was 0.32%. The incidence of discovered defects increased in direct proportion to the length of time over which the subjects were followed. MacMahon states that the reported incidence frequency was suspected to be an underestimate due to this factor. Using methods similar to those employed by MacMahon, Richards and colleagues (1955) found an 0.8% incidence of cardiac malformations for infants born in New York City between 1946 and 1953. The study was based on a group of 6,053 children.

Two studies originating from the Massachusetts General Hospital illustrate the influence of the time period during which a study is performed. McGinn and White (1936) reported that 0.9% of the patients seen by autopsy between 1895 and 1935 were diagnosed to have had congenital heart defects. A later study for the period 1936 to 1951 by White (1955) showed the identification of congenital cardiac defects had increased in number by greater than a factor of two. This change was

not thought to be related to an increased frequency of this problem, but to a better understanding and subsequent recognition of the specified defects. In reviewing the various published studies regarding the incidence of congenital cardiac defects, Fontana and Edwards (1962) also point out this problem. They state that pathologic studies carried out by them through 1962 indicate the incidence may be as high as one percent.

The impact of surgical techniques, such as the insertion of prosthetic heart valves and coronary vein bypass grafts, have been one of the major factors associated with the increase in the number of adult patient studies. The ICRP (1973) noted the increased number of coronary angiographic procedures that are being carried out and their direct relation to patient exposure.

In the last few years the U.S. has experienced a drastic increase in the number of cardiac catheterization laboratories. The large majority of these facilities are concerned with the study of adult patients with acquired heart disease. The exact number of these facilities is not presently known, but based upon unpublished manufacturers sales projections, it may be as high as 600. Since a majority of adult catheterization studies are for the evaluation of coronary arterial disease, the life expectancy of the patient with angina pectoris is of interest.

White, Bland and Miskall (1943) reported that 90% of 500 patients seen in their practice and diagnosed as having angina died within eight years. In a followup report in which 456 of these patients were traced over a 25-year period, Richards, Bland and White (1956) found only 12 individuals alive at the end of the period. The initial 5-year survival in this study group of 456 was 64% for men and 74% for women and after ten years the survivals were 41% and 44% respectively.

Block et al. (1952) reported on a much larger group of nearly 7,000 angina patients. They found an average annual mortality, after the first year, of about 9%. The 5-year survival rate was 58.4%. Kannel and Feinleik (1972) reported on the fate of angina patients in the Framingham study. In this study an initial group of 5,127 patients were selected based on their absence of any clinical manifestation of coronary heart disease. In a 14-year followup, 492 individuals in the original group developed angina pectoris. The annual death rate for men in the angina group was about 4%. By the end of an 8-year period following the initial diagnosis of angina, 40% of those over the age of 50 were dead.

The death rate for patients in the Richards and Block studies is seen to be greater than that for the Framingham group. This might be expected since the population study groups in the Richards and Block evaluation were composed of

patients who had sought medical help for their angina symptoms. In the Framingham study, the angina subgroup had evolved from an original asymptomatic population. It might, therefore, be expected that the Framingham group would include individuals with less advanced coronary complications.

From the above studies it can be seen that the individual with angina pectoris, who is a prime candidate for a coronary arterial examination, has a limited prospect of longevity. When considering the typical latent period of 10 to 20 years that may exist between the time of radiation exposure and the development of a carcinoma, leukemia, etc., concern for these somatic effects for this group of individuals is minimal. Genetic effects are also of little concern for a large segment of these adults due to the age of the typical patient studied for coronary artery disease.

Review of Published Dosimetry Studies

Recognition of the potential high radiation exposure that can be received by patients during cardiac examinations was reported on as early as 1950 by Hills and Stanford. They state the risk to the patient undergoing this type of examination is that he may receive a skin dose sufficient to produce some degree of "x-ray burning."

During angiocardiology they used an over table x-ray tube and under table photofluorographic system. This specially designed unit, described by Hills (1948), would

result in an incident exposure to the chest of an adult patient of approximately 1.3 R/frame of information. Fluoro was carried out with an under table x-ray tube and a conventional direct-view fluoroscopic screen. They state that a typical table top exposure rate for their system might be 5.5 R/min. Based on this exposure rate, they limited fluoro time during catheterization to no greater than 20 minutes.

These investigators reported typical patient entrance exposure levels of 136 R for a complete examination which included a chest film, a barium swallow with 3-1/2 min of screening, 20 min of fluoro during the catheterization portion of the examination and a 10 film angiographic series. Approximately 80% of the exposure was delivered during the catheterization phase of the cardiac examination.

Larsson (1956) measured incident skin exposure during 32 cardiac catheterization examinations performed in seven hospitals. Sixty-three percent of the procedures involved exposures of less than 50 R, but one value of 206 R was reported.

The advent of modern image intensifiers and fast film screen image receptor systems have resulted in a large increase in the amount of diagnostic information obtained per unit of incident exposure. Concurrent increases in the amount of diagnostic information desired during heart catheterizations have also occurred. As recently as 1968, Gaugh, David and Stacey (1968) reported incident skin exposures similar to those of Hills and Stanford.

Gaugh and colleagues reported the estimated skin, gonad and bone marrow doses received by 91 patients having cardiac catheterization examinations in Brampton Hospital in London. The values for incident skin exposure were estimated from output calibration data for the x-ray unit used in conjunction with the recorded technique factors employed during a particular procedure. The gonad and bone marrow doses were in turn calculated using the incident exposure estimate with beam size and patient geometry assumptions.

Probably the greatest error in the Gaugh study was the fact that he had no way of measuring fluoro beam size and assumed a maximum of 20 x 20 cm (400 cm²) for the entire examination. This value may be as much as four times larger than is required or usually employed, according to measurements made by Ardran and colleagues (1970). Beam size is a key factor in Gaugh's determination of bone marrow dose since the calculation is based on a known fraction of the ribs, sternum and number of thoracic vertebrae in the primary beam. For 85 patients, which included both pediatric and adult subjects, a mean marrow dose of 1.4 rads was reported. The maximum individual marrow dose was 3.81 rads.

Estimates of bone marrow dose received during cardiac catheterization have also been reported by Seidlitz and Margalis (1974). Phantom measurements were made to relate body surface exposure to absorbed dose in the vertebral column. Surface exposures were then measured during ten

clinical procedures. The mean integral vertebral marrow dose was 1,700 g-rads with individual values ranging from 760 to 2,900 g-rads.

As part of a study of exposure to patients during angiographic procedures, Kaude and Svahn (1974) reported on the male gonad and integral dose received during cardiac procedures. The examination facility in which the measurements were carried out was equipped with biplane image intensifiers, each with 35 mm cine and 70 mm fluorographic cameras. Biplane serial film changers were also used as an alternate mode of examination. During five adult procedures, the mean male gonad dose was found to be 10 mrad and was reduced to 4 mrad by use of gonad shielding. For 12 examinations of children 15 years old or less, the mean gonad dose was reported as 13 and 280 mrad determined with and without testicular shielding. During 10 adult procedures, the mean integral dose was 58 kg-rad and for 12 pediatric studies it was 16 kg-rad. The range for the individual values in the respective groups were 17 to 101 and 1 to 42 kg-rads respectively. Although some measurements were made during discrete phases of the procedures to estimate the contribution of different modes of viewing, the values for an entire examination as referenced above gave no breakdown as to the extent each mode of examination was utilized.

The exposures resulting from cardiac special procedure work can be expected to vary from facility to facility. These variations will reflect the differences in technique, patient classification and equipment configuration. Rowley (1974) compared the use of a 16 mm cine camera operated at 200 frames per second to serial angiography. In pediatric cardiac studies, the patient doses were similar. For adult coronary studies, the exposure resulting from use of this high cine frame rate was felt to be prohibitive. When operated in the range of 50 to 100 frames per second, the combined fluoro and cine exposure in 37 patient studies had a mean incident exposure value of 41 R with individual values ranging from 11.5 to 100 R.

New technical advances in x-ray equipment design may lead to reduced exposures in the future. Dorph and colleagues (1970) and Grollman and colleagues (1972,1974) have described the use of pulsed fluoro carried out with a video disk recorder. Grollman states that adult coronary studies carried out using this technique have resulted in patient dose reduction of up to a factor of three. The employment of pulsed fluoro and the wider use of 70, 100 or 105 mm fluorography have been noted by the ICRP (1973) as areas where equipment developments may aid in lowering dose.

Need for Patient Dosimetry Study

Although a limited number of reports of patient exposure during cardiac catheterization procedures have been made, it is difficult to draw conclusions with regard to the radiologic significance of these exposures. The data were often obtained from mixed patient groups including both pediatric and adult subjects. An adequate description of the equipment performance and examination technique was usually lacking. The exposure or dose index reported by the various authors also varied widely.

Due to these shortcomings of the existing data, a study of patient exposure was carried out. This study included both phantom and live patient investigations. The patient simulations and clinical patient studies will be discussed separately in Chapters VI and VII.

CHAPTER VI

PATIENT EXPOSURE STUDY PHANTOM MEASUREMENTS

Data necessary to estimate dose to selected internal patient body sites during cardiac catheterization were developed by monitoring human-equivalent dosimetry phantoms with TL dosimeters under typical examination conditions. A commercial adult phantom was used to simulate conditions of an acquired heart disease study, while two specially fabricated pediatric phantoms were employed to simulate congenital heart studies.

The phantom measurements were reported by Katta (1975). A description of the procedures and summary of the results will be reviewed. The internal organ dose values have been converted to units of absorbed dose instead of the R exposure units given by Katta. The values for the bone marrow dose have been recalculated to more accurately account for the amount of red bone marrow in the primary beam for the PA fluoro/cine projections. Adjustments have also been made in the bone marrow values for the AP and LAT radiographic exposure conditions to correct for geometric restrictions associated with the infant and child phantoms.

Description of Phantoms

Human-equivalent phantoms are commonly used to investigate the doses resulting from the medical uses of ionizing radiation. Dosimetry at internal body sites, which is often impossible to carry out in live patients, is facilitated by the use of these devices. The ICRP and ICRU (1961) have outlined a number of factors that must be considered in the makeup of a human representative phantom. The effects introduced by the differences in composition of soft tissue, bone and air cavities must be considered. The photoelectric effect predominates in the energy range used in diagnostic radiology, therefore the differences in density and attenuation coefficient for these components that make up the body are important.

To simulate the adult patient, an Alderson^a "Rando" phantom was used. The Rando phantom consists of a human skeleton surrounded by a thermosetting synthetic plastic. Alderson Research Laboratories (1969) states this material has an effective atomic number of 7.30 and a mass density of 0.985 (both held to a tolerance of 1-1/4%) and represents a composite of muscle, normal body fat and fluids. The lungs

^a Alderson Research Laboratories, Stamford, Connecticut.

are constructed of a microcellular plastic foam of density 0.32 ± 0.01 having the same effective atomic number as that of the soft tissue material. Air spaces are provided to simulate the oronasal pharynxes, the larynx, the trachea and the stem bronchi. Alderson and colleagues (1962) state that the anthropomorphic specifications for the Rando are based on a U.S. Air Force survey of male personnel slightly modified to conform with results of a second civilian survey. The adult male model is proportioned to a representative individual 1.73 m high who weighs 73.5 kg (Lanzl, 1973). The phantom is divided into 2.5 cm thick transverse sections. Each section is subsequently drilled on 3 cm centers to facilitate internal dosimeter placement. The holes are plugged with removable Mix-D inserts (Jones and Raine, 1949).

No commercial phantom is available to simulate the pediatric patient. From the review of the catheterization patient records (Chapter II), the age at the time of the catheterization was seen to have a bimodal distribution with peaks in the 0 to 6-month and 5 to 6-year ranges. Representative phantoms in these two age groups were subsequently custom fabricated.^a The height and weight records

^aConstruction by private fabricator under sponsorship of the Bureau of Radiological Health, Food and Drug Administration, Department of Health, Education and Welfare.

of the UF cardiovascular laboratory were analyzed to determine representative values for patients in the two age groups. Radiographs were subsequently obtained from patients matching the representative values to aid in the anatomical modeling of the phantoms.

To simulate soft tissue, a 50% mixture of Microvan-1600^a and beeswax was used. This mixture has a density of 0.94; it is solid and durable at room temperature but can be easily molded at elevated temperatures. The lungs were constructed of polystyrene foam having a density of 0.3. Inserted into the plastic foam were the heart and pulmonary vessels made of the soft tissue wax mixture. The bones were fabricated from equal weights of calcium phosphate and calcium carbonate mixed with melted paraffin. The ratio of calcium to wax was varied until a simulated bone producing the same radiographic density as an equivalent-sized sample of bone was obtained. The mineral content of this simulated bone material typically accounted for 65 to 75%, by volume, of the bone phantom material.

The skeletal structure was first molded from the bone-simulation material. The lungs were inserted and soft tissue was then added to build up to the normal external dimensions of the representative subject. The head was removable and

^a Microcrystalline wax manufactured by the Exxon Corporation.

the chest was sectioned so that mid-plane dosimeter sites could be used. The dimensions of all three phantoms are given in Table 18.

Figure 29 shows a photograph of the sectioned adult Rando phantom. Photographs and whole-body x-rays of the representative 6-month and 6-year old phantoms, which will subsequently be referred to as the "infant" and "child" phantoms are shown in Figures 30 through 33.

Phantom Dosimetry Sites

Radiation measurements were made at multiple external and internal sites on the phantoms with TL dosimeters. The sites were chosen so that the doses delivered to the bone marrow, thyroid, gonads, skin (entrance exposure) and lens of the eye could be determined. Liver and spleen were also monitored for the pediatric exposures. Physiologically the liver and spleen play a role in erythropoiesis and lymphopoiesis during the early stages of life, while the bone marrow is the chief hematopoietic organ. Although the exact radiobiological consequence of exposure to the spleen and liver during this early stage of life is not known, some indication of the dose delivered was felt to be important.

Ten external body sites were monitored with TL dosimeters. Table 19 and Figure 34 identify these sites. For the measurements made with the adult Rando phantom, 28 internal body sites were chosen. Twenty-four were

TABLE 18
Weight, Height and Dimensional Characteristics of Phantoms Used in Study

| Identification | Adult Rando Phantom | | Section Number | Representative Child Phantom | Representative Infant Phantom |
|---------------------|---------------------|-------|----------------|---------------------------------|----------------------------------|
| | Characteristic | Value | | | |
| Weight ^a | 73500 g | | | 18000 g | 6500 g |
| Height ^a | 173 cm | | | 110 cm | 64 cm |
| Mid-chest | | | 17 | | |
| AP | 23.5 cm | | | 13.5 cm | 10 cm |
| LAT | 31.5 cm | | | 19.5 cm | 11.5 cm |
| Waist | | | 26 | | |
| AP | 21 cm | | | 11 cm | 10.5 cm |
| LAT | 27 cm | | | 19 cm | 11.5 cm |
| Hips | | | 33 | | |
| AP | 22 cm | | | 12.5 cm | 10 cm |
| LAT | 32.5 cm | | | 20.5 cm | 11 cm |
| Vertex of skull to: | | | | | |
| lens of eye | 10 cm | | 3 | 9 cm | 7.5 cm |
| thyroid | 24 cm | | 9 | 18.5 cm | 15 cm |
| mid-chest | 44 cm | | 17 | 27 cm | 21 cm |
| assumed ovary | | | | | |
| location | 78 cm | | 30 | 52 cm | 32 cm |
| crotch | 90 cm | | 35 | 62 cm | 37.5 cm |

^aWeight and height for representative complete body.



Figure 29. Alderson Rando Phantom.



Figure 30. Representative Six Month Old Infant Phantom.



Figure 31. Whole Body X-ray of Infant Phantom.

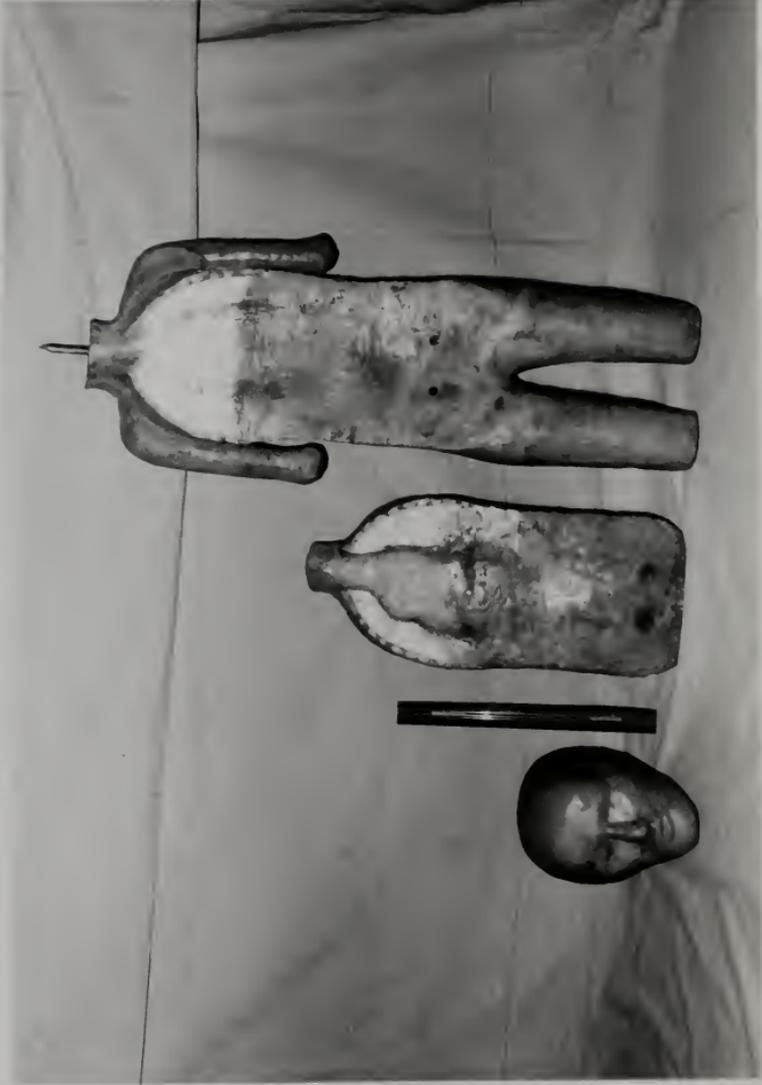


Figure 32. Representative Six Year Old Child Phantom.



Figure 33. Whole Body X-ray of Child Phantom.

TABLE 19
Location of External Dosimetry Sites on
Phantoms and Patients

| Site Number | Location ^a |
|-------------|--------------------------------------|
| 1 | Forehead at glabella |
| 2 | Right lobe of thyroid |
| 3 | Left lobe of thyroid |
| 4 | Anterior mid-chest (mid-sternum) |
| 5 | Left lateral mid-chest |
| 6 | Posterior mid-chest |
| 7 | Right lateral mid-chest |
| 8 | Anterior lower abdomen |
| 9 | Posterior lower abdomen |
| 10 | Left inner thigh adjacent to scrotum |

^a See Figure 34.

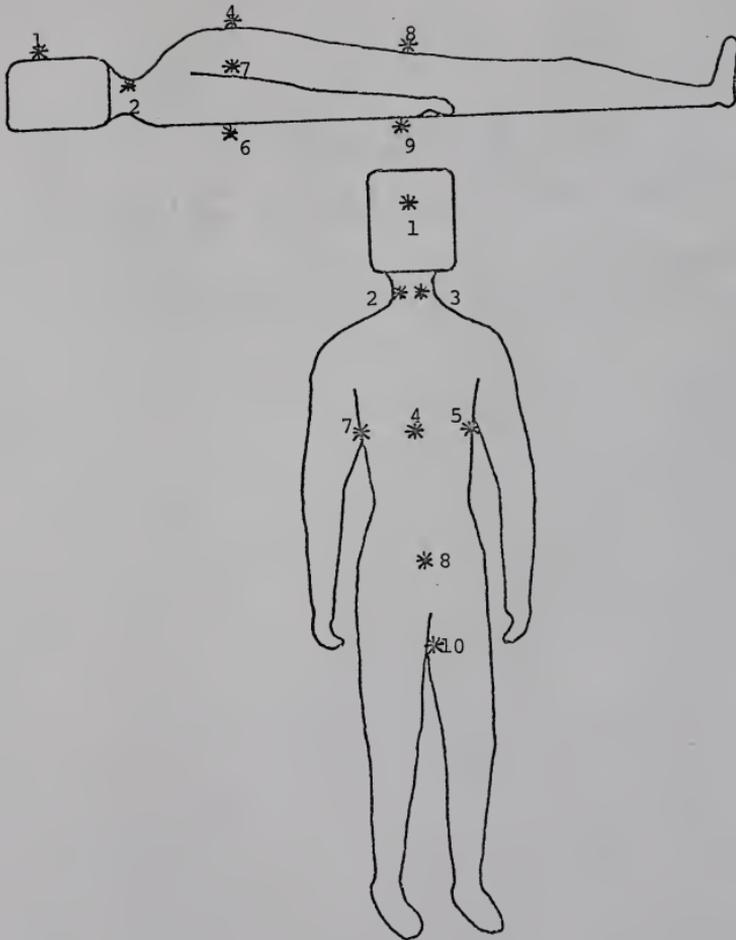


Figure 34. Location of External Dosimetry Sites on Phantoms and Patients.

associated with determination of the bone marrow dose and two each with thyroid and ovarian estimates. In the two pediatric phantoms, 18 internal sites were used, 13 at selected bone marrow sites, two at the thyroid and one each at the assumed location of the ovaries, spleen and liver.

Adult Bone Marrow Sites

Any method of estimating exposure to the total bone marrow must take into account the distribution of active marrow in the skeleton. Relatively little research has been conducted to determine the bone marrow distribution in adults and children. Ellis (1961) described an estimation of the active bone marrow distribution in the 40-year old adult. Qualitative distributions of marrow in humans had been studied by Piney (1922), Higgins and Blockson (1963) and Custer (1949); and a study of the quantitative distribution of the marrow space was conducted by Mechanik (1926). Ellis applied a correction factor, based on Custer's work on cellularity, to Mechanik's data to generate the percentage of active red bone marrow in each bone of the 40-year old adult. These results, tabulated in Appendix E, were utilized in the adult bone marrow dose calculation.

To estimate the bone marrow dose, a method similar to that employed by Liuzzi et al. (1964) was utilized. The adult human skeleton was subdivided into a total of 15 subfields, as shown in Figure 35. In the establishment of the subfields, the fractionation of individual bones was avoided

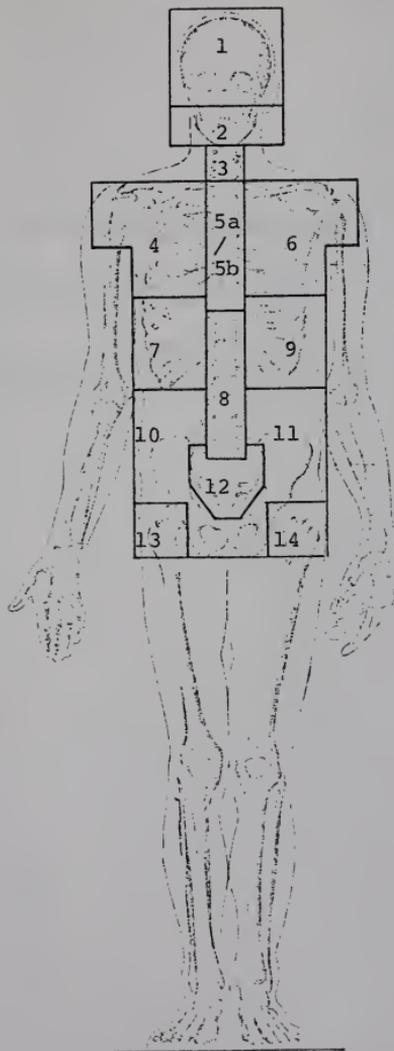


Figure 35. Location of Subfields for the Adult Phantom Model.

as much as possible to facilitate the determination of the marrow fraction in each subfield. The mass of red marrow in each subfield was determined by identifying each bone, or part of bone, in each subfield and assigning that bone with a mass of the red marrow from Ellis' distribution. Appendix E gives a detailed breakdown of the bone structure and red marrow mass within each of the 15 subfields. Dosimetry sites were then selected so that exposure values representative of the entire subfield could be obtained. The adult phantom subfield sites are listed in Table 20.

Pediatric Bone Marrow Sites

Since anatomical differences in bone marrow distribution of children and adults are present, it was necessary to develop a different model for pediatric total average bone marrow exposure determination. While the bone marrow distribution in adults is fairly constant after age 25, there is a continual change of the distribution in children. No determination of pediatric bone marrow distribution was made until Hashimoto and Yamaka's study in 1964. They determined the bone marrow distribution for 3 to 7-year old Japanese children. Although not expressly stated, the marrow distribution can be considered the red marrow distribution as nearly all marrow in the young child is active red marrow. The Hashimoto values were also used for the infant phantom since no better infant bone marrow distribution data exist.

TABLE 20

Identification of Bone Marrow Dosimetry Sites and Red Bone Marrow Fraction in 15 Subfields of Adult Phantom

| Subfield | Internal Dosimetry Site | Fraction of Total Red Marrow in Subfield |
|----------|----------------------------------|--|
| 1 | Frontal bone Occipital bone | 0.1236 |
| 2 | Mandible Vertebra (C4) | 0.0258 |
| 3 | Vertebra (C6) | 0.0252 |
| 4 | Right scapula Right rib 3 | 0.0594 |
| 5a | Sternum | 0.0224 |
| 5b | Vertebra (T6) | 0.1001 |
| 6 | Left scapula Left rib 3 | 0.0594 |
| 7 | Right rib 7 Right rib 10 | 0.0206 |
| 8 | Vertebra (T12) Vertebra (L 3) | 0.1427 |
| 9 | Left rib 7 Left rib 10 | 0.0206 |
| 10 | Right ilium Right ischium | 0.1114 |
| 11 | Left ilium Left ischium | 0.1114 |
| 12 | Sacrum | 0.1392 |
| 13 | Right femoral head | 0.0191 |
| 14 | Left femoral head | <u>0.0191</u> |
| | Total | 1.0000 |

The same subfield model was used for the infant and child phantoms. The layout consisting of 12 subfields is shown in Figure 36. A detailed identification of the principal bone structures in each subfield is given in Appendix E. Table 21 lists the dosimetry sites and red marrow fraction for each subfield.

Method of Interpreting Dosimetry Data

The phantom TL dosimetry values reported by Katta were expressed in R exposure units normalized to an incident EAP of 10^3R.cm^2 . These data have been re-analyzed with regard to the method of calculation. The exposure values have also been converted to units of absorbed dose. For soft tissue such as the skin, thyroid and reproductive organs, an f-factor^a of 0.88 (Johns and Cunningham, 1974) was utilized. Further consideration regarding the lens of the eye, reproductive organs and bone marrow doses are described in the following.

Dose to the Lens of the Eye

The production of a lenticular opacification is the biological effect of concern for radiation exposure to the eye. In an evaluation of patient exposure during carotid angiography, Bergstrom and colleagues (1972) measured the

^af-factor is the value used to convert values of exposure to dose (R to rad).

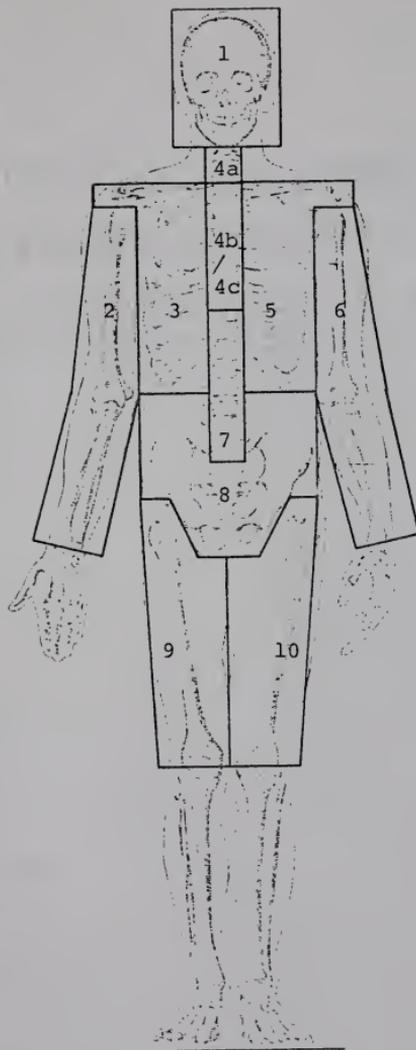


Figure 36. Location of Subfields for the Pediatric Phantom Model.

TABLE 21

Identification of Bone Marrow Dosimetry Sites and Red Bone Marrow Fraction in 12 Subfields of Pediatric Phantom

| Subfield | Internal Dosimetry Site | Fraction of Total Red Marrow in Subfield |
|----------|--------------------------------|--|
| 1 | Occipital bone Frontal bone | 0.0694 |
| 2 | Right humerus | 0.0516 |
| 3 | Right rib 6 (lateral) | 0.0772 |
| 4a | Sternum | 0.0250 |
| 4b | Vertebra (C4) | 0.0271 |
| 4c | Vertebra (T2) | 0.0922 |
| 5 | Left rib 6 (lateral) | 0.0772 |
| 6 | Left humerus | 0.0516 |
| 7 | Vertebra (T10) | 0.1352 |
| 8 | Sacrum | 0.2875 |
| 9 | Right femur | 0.0530 |
| 10 | Left femur | <u>0.0530</u> |
| Total | | 1.0000 |

lens tissue dose. Measurements in a 1 cm thick stack of TL dosimeters placed at the eye position on a representative human phantom were related to known lid and lens distances for a standard model of the eye. Negligible difference between the dose measured over the eye lid and that to the center of the lens was found.

The forehead site chosen for patient measurements during cardiac catheterization is only a few centimeters from either eye and would be expected to receive approximately the same exposure as a site on the eye lid. As shown by Bergstrom, the exposure measured at eye lid would be expected to be representative of that at the lens. The forehead measurements were thus directly converted to the lens of the eye dose by using the usual factors for exposure to dose conversion in soft tissue.

Dose to Reproductive Organs

To estimate the dose to the male gonads, a measurement site on the left inner thigh next to the testes was used. A more difficult problem is posed in selecting a dosimetry site for the female ovaries. The actual location of the ovaries is known to vary from individual to individual and will shift depending upon whether the woman is standing or in a prone position. In measurements of ovarian dose made by Morgan and Gehret (1971), the ovaries were assumed to be in the center of the abdomen at a distance midway between

a transverse plane passing through the superior iliac crest and the symphysis pubis. The selection of internal ovary sites was based upon this assumption.

Bone Marrow Dose

The dose to irradiated bone marrow is increased over that expected in a large soft tissue mass due to photoelectron emissions from the surrounding mineral bone. This variation in absorbed dose is a function of the dimensions of the trabecular bone marrow space and the energy of the x-ray photons. The ICRU (1959) points out that this change can be thought of in two ways: (1) the macroscopic distribution is altered by a reduction in intensity for soft tissue beyond the bone; (2) on a microscopic scale, the tissue adjacent to bone will receive a higher dose due to the increased number of photoelectrons from the mineral bone.

Spiers (1969) states that for photoelectrons produced from an incident energy x-ray beam of 200 keV or less, the particulate range in bone is of the same order as the thickness of trabeculae. Under these conditions, each cavity can be considered as surrounded by an equilibrium thickness of bone. For this case the calculation of bone marrow dose can be based on an assumed geometry configuration of a single cavity.

The size and geometry of trabecular bone spaces are of key importance in any analysis of the relationship between

exposure and absorbed dose in bone marrow. Shleien (1973) has reviewed the work of various authors regarding the dimensions of bone marrow cavities. With few exceptions, these studies have been isolated to adult subjects. The values are shown to vary over a range of 50 to 2,000 microns. The ICRU (1959) states that representative mean dimensions might be 100 microns for bone lamellae and 400 microns for the marrow interspaces.

Using this representative geometry, the ICRU gives calculated values for mean dose (\bar{D}) per unit exposure (X) for a cubical (plane slab) marrow space geometry. Spiers has examined both spherical and cylindrical cavities. He states that the values for the spherical model lie a little above those for the cylindrical. The spherical geometry is probably the best approximation of the actual trabecular structure.

Figure 37 shows the values for \bar{D}/X at various photon energies for the spherical, cylindrical and plane slab geometry.

The dimensions of the TL dosimeters used in this study are large compared to the range of the photoelectrons in bone resulting from exposure to x-rays in the diagnostic region. Consequently the effect of the increased photoelectron emission from the mineral bone will be minimal and the chip readings can be interpreted directly in terms of the R through its calibration value. The exposure to dose

conversion values can then be based upon calculated values as shown in Figure 37. For a typical effective photon energy of 30 keV, the \bar{D}/X conversion factor is observed to vary from 0.985 to 1.045. Since the exact shapes of the trabecular spaces are not known, the exposure and dose values were assumed to be equal.

Katta determined the bone marrow dose for each phantom and x-ray projection by multiplying the average measured exposure in each subfield by its representative bone marrow fraction and then summing these values over all subfields. Where this method seems valid for regions out of the incident primary beam, which receive only scatter or attenuated primary beam radiation, some error will result for those subfields partially in the incident primary beam. An over or under estimate of the subfield contribution would be obtained depending on whether the measurement site is in or out of the primary beam. This error would be expected to be greatest for the PA fluoro/cine setups due to the large contribution of bone marrow in the vertebral column which is in the primary beam.

Figure 38 shows a plot of the normalized exposure measurements at the vertebral marrow sites for the child phantom. Due to the lack of measurement sites, it was assumed that the intensity did not vary over the dimensions of the primary beam. Similar curves were obtained for the adult and infant phantoms. By physical inspection of the phantoms and x-rays

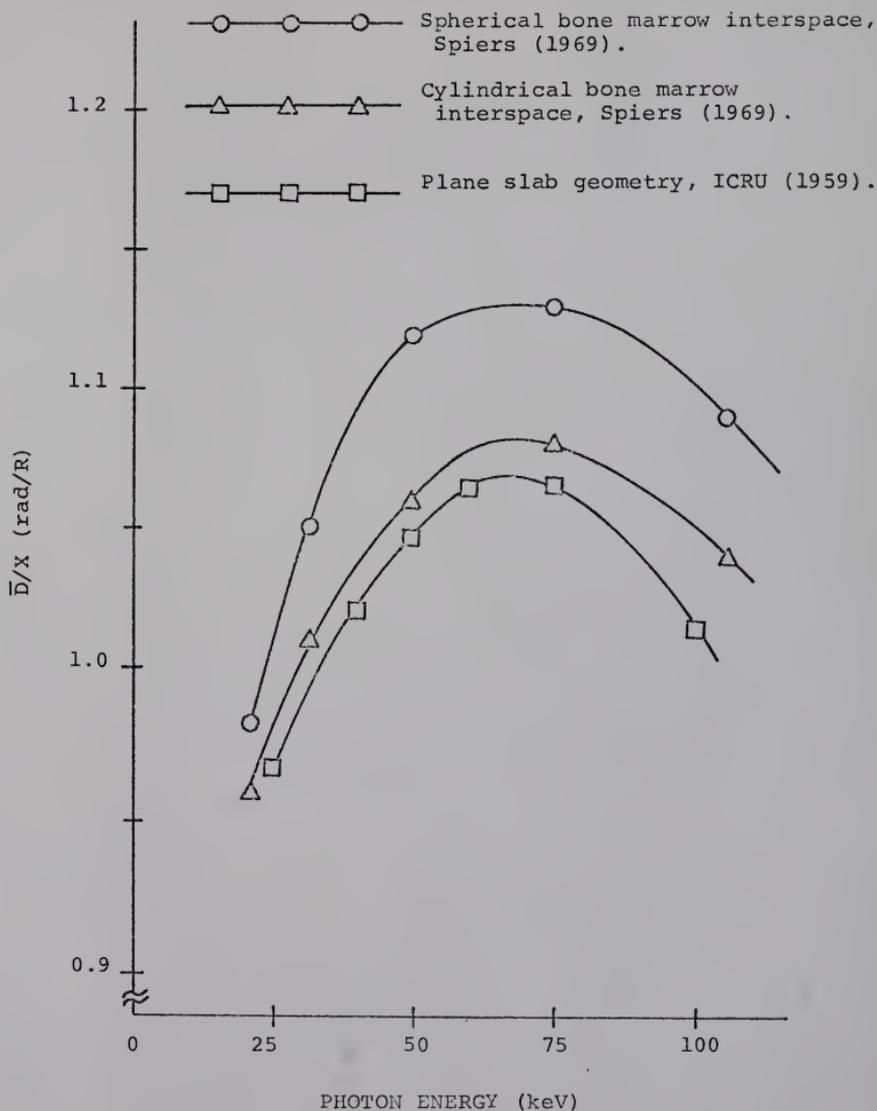


Figure 37. Average Bone Marrow Dose per Unit Exposure at Marrow Site.

of their vertebral structure, the vertebrae in and out of the primary beam were identified. The individual vertebra were separated into three subclasses; those in the primary beam, a transitional segment at the edge of the primary beam and those receiving only scatter radiation. Table 22 lists the breakdown of the vertebrae for the various exposure conditions.

The bone marrow dose contribution for these vertebral sites was then calculated. For each case a dosimeter site was located in the primary beam and its reading was used as representative of all vertebrae in the primary beam. A factor of 0.5 and 0.05, of this primary beam value, was used to estimate the dose received by vertebrae in the transitional and scatter zones.

A second correction to the Katta results was made for the AP and LAT radiographic projections of the child and infant phantoms. During live patient serial biplane radiography, the arms are lifted over the head or positioned out to the side so that they will not be observed in the lateral chest image. The position of the phantom arms could not be changed from their normal position at the side of the body. The dosimeter site for subfields 2 and 6 containing the humerus, radius and ulna was located in the primary beam of the LAT beam and at the edge of the beam for the AP beam. Use of these nonrepresentative values would result in an overestimate of the bone marrow dose. The measurement site in

TABLE 22

Identification of Vertebrae in the Primary, Transition and Scatter Zones
for PA Phantom Exposures

| Phantom and Exposure Conditions | Identification of Vertebrae in Respective Zone | | | | | |
|---------------------------------|--|--------------------|--------------------|--------------------|---------------|--|
| | Upper Scatter | Upper Transition | Primary | Lower Transition | Lower Scatter | |
| Adult (nominal 6 inch) | T2 (3/4)T3 | (1/4)T3 (3/4)T4 | (1/4)T4 (1/4)T8 | (3/4)T8 (1/4)T9 | (3/4)T9 L5 | |
| Adult (nominal 9 inch) | T2 | T3 | T4 T8 | T9 | T10 L5 | |
| Child (nominal 6 inch) | T1 T3 | T4 | T5 T10 | T11 | T12 L5 | |
| Child (nominal 9 inch) | T1 | T2 | T3 T12 | L1 | L2 L5 | |
| Infant (nominal 6 inch) | | T1 | T2 T11 | T12 | L1 L5 | |

the cervical vertebra was felt to be the best approximation of the dose received by the marrow in the right and left arms for the more realistic position. The values for these two subfields were re-calculated using this assumption.

Phantom Dosimetry Results

The results of the adult and pediatric phantom exposures are given in Tables 23, 24 and 25. The dose in mrad to the selected tissue or organ system has been normalized to an incident EAP of 10^3R.cm^2 . The data were obtained from multiple phantom exposures for each patient geometry simulation. For the nine inch PA and six inch RAO adult simulations triplicate exposures were made, but in all others two were carried out. One of the duplicate infant AP radiographic experimental runs was carried out with an atypical large beam dimension. The data from this run were considered to be nonrepresentative and the normalized dose indices were calculated from a single phantom exposure run. The recorded x-ray operational character, incident EAP, tube current and potential, and measured beam size for each experimental run are shown in Appendix E.

TABLE 23
 Normalized Dose Index Values for Adult Phantom

| Site Identification | Normalized Dose (mrad/10 ³ R.cm ²) Fluoro/Cine | | | |
|-----------------------------------|---|---------------------------|--------------------------------|--------------------------------|
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | 6 inch Mode 45° RAO Projection | 9 inch Mode 45° RAO Projection |
| A. Bone marrow subfield | | | | |
| 1 | 1.0 | 0.3 | 0.7 | 0.4 |
| 2 | 1.0 | 0.5 | 0.6 | 0.4 |
| 3 | 1.8 | 1.9 | 1.1 | 0.7 |
| 4 | 21.8 | 16.4 | 4.2 | 2.9 |
| 5a | 7.5 | 4.6 | 5.9 | 5.3 |
| 5b | a | a | 62.2 | 41.5 |
| 6 | 31.1 | 18.0 | 47.4 | 67.2 |
| 7 | 6.6 | 4.3 | 2.1 | 1.1 |
| 8 | a | a | 19.2 | 9.3 |
| 9 | 6.0 | 3.9 | 60.5 | 31.6 |
| 10 | 0.4 | 0.2 | 0.3 | 0.2 |
| 11 | 0.5 | 0.2 | 1.2 | 0.9 |
| 12 | 2.4 | 1.3 | 1.2 | 0.6 |
| 13 | 0.0 | 0.1 | 0.0 | 0.0 |
| 14 | 0.0 | 0.1 | 0.1 | 0.0 |
| Alternate 5b and 8 subfield value | 615.1 | 282.3 | | |
| Weighted bone marrow dose | 695.3 | 340.1 | 206.6 | 162.1 |

a For PA projections, subfields 5b and 8 are combined in special vertebral calculation.

TABLE 23 Continued

| Site Identification | Normalized Dose (mrad/10 ³ R.cm ²) Fluoro/Cine | | | |
|---------------------------|---|------------------------------|-----------------------------------|-----------------------------------|
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | 6 inch Mode 45° RAO Projection | 9 inch Mode 45° RAO Projection |
| B. Internal Organs | | | | |
| Thyroid | 47.2 | 36.6 | 34.4 | 22.2 |
| Ovaries | 3.8 | 5.9 | 4.0 | 1.5 |
| C. External Sites | | | | |
| 1 Lens of eye | 2.2 | 2.0 | 1.5 | 1.3 |
| 2 Right thyroid | 36.6 | 27.5 | 19.4 | 15.9 |
| 3 Left thyroid | 39.5 | 31.7 | 24.4 | 22.4 |
| 4 Mid-sternum | 233.7 | 103.4 | 408.0 | 176.0 |
| 5 Left lateral | 216.0 | 63.9 | 1067.2 | 5538.2 |
| 6 Posterior thorax | 15145.0 | 7769.8 | 312.8 | 260.0 |
| 7 Right lateral | 117.4 | 74.7 | 31.0 | 19.3 |
| 8 Anterior abdomen | 1.0 | 0.8 | 14.5 | 0.9 |
| 9 Posterior abdomen | 24.3 | 13.9 | 9.5 | 5.1 |
| 10 Scrotum | 5.5 | 0.4 | 1.0 | 0.4 |

TABLE 24

Normalized Dose Index Value for Child Phantom

| Site Identification | Normalized Dose (mrad/10 ⁻³ R.cm ²) | | | |
|-----------------------------------|--|------------------------------|---------------------|----------------|
| | Fluoro/Cine | | Biplane Radiography | |
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | AP Projection | LAT Projection |
| A. Bone marrow subfield | | | | |
| 1 | 2.0 | 1.7 | 3.7 | 2.5 |
| 2 | 28.6 | 21.4 | 12.2 | 1.0 |
| 3 | 80.8 | 59.8 | 42.8 | 466.5 |
| 4a | 32.5 | 15.4 | 118.8 | 105.9 |
| 4b | 3.4 | 2.8 | 6.4 | 5.5 |
| 4c | a | a | 122.9 | 87.0 |
| 5 | 130.5 | 57.7 | 216.8 | 73.3 |
| 6 | 31.0 | 21.1 | 12.2 | 1.0 |
| 7 | a | a | 126.5 | 172.6 |
| 8 | 5.6 | 12.6 | 5.0 | 6.8 |
| 9 | 0.1 | 0.2 | 0.4 | 0.3 |
| 10 | 0.6 | 0.2 | 0.4 | 0.0 |
| Alternate 4c and 7 subfield value | 823.8 | 806.1 | | |
| Weighted bone marrow dose | 1138.8 | 998.9 | 668.0 | 922.5 |

a For PA projections, subfields 4c and 7 are combined in special vertebral calculation.

TABLE 24 Continued

| Site Identification | Normalized Dose (mrad/10 ³ R.cm ²) | | | | | |
|---------------------------|---|------------------------------|------------------------------|---------------------|----------------|----------------|
| | Fluoro/Cine | | | Biplane Radiography | | |
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | 9 inch Mode AP Projection | AP Projection | LAT Projection | LAT Projection |
| B. Internal Organs | | | | | | |
| Thyroid | 152.1 | 113.7 | 464.9 | 380.6 | | |
| Ovaries | 21.0 | 78.3 | 56.3 | 76.3 | | |
| Spleen | 916.5 | 2342.0 | 2422.4 | 669.7 | | |
| Liver | 3049.6 | 2895.0 | 1601.0 | 4492.0 | | |
| C. External Sites | | | | | | |
| 1 Lens of eye | 15.5 | 12.3 | 47.9 | 34.0 | | |
| 2 Right thyroid | 151.9 | 116.6 | 543.8 | 532.6 | | |
| 3 Left thyroid | 140.7 | 117.2 | 687.3 | 487.6 | | |
| 4 Mid-sternum | 894.4 | 507.4 | 5334.1 | 1677.9 | | |
| 5 Left lateral | 414.0 | 364.5 | 1170.2 | 652.4 | | |
| 6 Posterior thorax | 12463.8 | 5237.4 | 1119.9 | 954.7 | | |
| 7 Right lateral | 466.0 | 400.4 | 318.0 | 6343.0 | | |
| 8 Anterior abdomen | 149.1 | 38.3 | 35.8 | 42.3 | | |
| 9 Posterior abdomen | 39.2 | 88.3 | 41.1 | 33.3 | | |
| 10 Scrotum | 2.7 | 5.0 | 11.3 | 5.1 | | |

TABLE 25
Normalized Dose Index Value for Infant Phantom

| Site Identification | Normalized Dose (mrad/10 ³ R.cm ²) | | | |
|-----------------------------------|---|---------------------|----------------|----------------|
| | Fluoro/Cine | Biplane Radiography | | IAT Projection |
| | 6 inch Mode PA Projection | AP Projection | IAT Projection | IAT Projection |
| A. Bone marrow subfield | | | | |
| 1 | 3.8 | 5.0 | | 3.2 |
| 2 | 201.7 | 42.0 | | 23.1 |
| 3 | 314.3 | 919.3 | | 439.7 |
| 4a | 65.0 | 358.9 | | 113.5 |
| 4b | 17.8 | 22.1 | | 12.2 |
| 4c | a | 406.3 | | 519.6 |
| 5 | 349.0 | 538.2 | | 137.8 |
| 6 | 64.2 | 42.0 | | 23.1 |
| 7 | a | 377.5 | | 813.8 |
| 8 | 71.5 | 43.7 | | 88.5 |
| 9 | 1.7 | 2.0 | | 3.0 |
| 10 | 1.9 | 2.2 | | 2.4 |
| Alternate 4c and 7 subfield value | 1408.3 | | | |
| Weighted bone marrow dose | 2499.2 | 2759.1 | | 2173.9 |

a For PA projections, subfields 4c and 7 are combined in special vertebral calculation.

TABLE 25 Continued

| Site Identification | Normalized Dose (mrads/10 ³ R.cm ²) | | | |
|---------------------------|--|---------------------|----------------|----------------|
| | Fluoro/Cine | Biplane Radiography | | |
| | 6 inch Mode PA Projection | AP Projection | LAT Projection | LAT Projection |
| B. Internal Organs | | | | |
| Thyroid | 947.9 | 1626.2 | | 1008.7 |
| Ovaries | 218.2 | 242.7 | | 371.2 |
| Spleen | 3115.4 | 10490.9 | | 2189.6 |
| Liver | 5296.0 | 1859.7 | | 6793.7 |
| C. External Sites | | | | |
| 1 Lens of eye | 29.4 | 69.9 | | 34.9 |
| 2 Right thyroid | 609.9 | 1363.1 | | 714.0 |
| 3 Left thyroid | 672.8 | 1416.5 | | 627.7 |
| 4 Mid-sternum | 1291.5 | 12978.0 | | 3366.9 |
| 5 Left lateral | 1182.8 | 3420.3 | | 1126.5 |
| 6 Posterior thorax | 11032.1 | 2264.5 | | 6400.0 |
| 7 Right lateral | 2194.4 | 750.6 | | 6756.0 |
| 8 Anterior abdomen | 92.1 | 201.0 | | 429.4 |
| 9 Posterior abdomen | 301.7 | 249.6 | | 1218.7 |
| 10 Scrotum | 34.8 | 50.7 | | 70.6 |

CHAPTER VII

PATIENT EXPOSURE STUDY CLINICAL PATIENT MEASUREMENTS

Over a period of approximately one year the radiation exposures to 304 patients undergoing cardiac catheterization at the UF cardiovascular laboratory were measured and analyzed. The intent of this phase of the study was to: (1) determine x-ray examination characteristics as related to patient age and type of procedure and (2) to estimate the doses delivered to various organ systems or regions of the body.

Methodology

The primary radiation measurement devices employed during the clinical patient study consisted of the EAP ionization chambers attached to the fluoro/cine and radiographic x-ray tubes. In addition to recording the cumulative $R.cm^2$ values in the various x-ray modes (fluoro, cine and AP and LAT radiography) during each procedure, additional patient and examination characteristics were logged. For the patient these characteristics included age, weight, height, sex and mid-chest dimensions. Total fluoro time and, where possible, the x-ray tube potential were also recorded.

The Philips "Maximus-100" x-ray generators do not have a tube potential (kVp) meter on the control. During radiographic exposures and for fluoro/cine operation with the tube current modulation automatic brightness system, the operator is required to select the tube potential. For these cases, the indicated dial setting was recorded. During the period in which the x-ray unit functioned with the tube potential modulation brightness system there was no means to establish the operating value.

In a subsample of the clinical patients, the exposures at various body sites were measured with TLD. No statistical selection process was used for designating this subsample, but it consisted primarily of the first patient examined each day during the monitoring period. The sites monitored were those previously used during the phantom exposures. These additional measurements were performed during 62 clinical procedures which represent approximately 20% of the total patient population observed.

Patients were separated into two general groups on the basis of the suspected heart disease being of a congenital or acquired nature. Individuals with suspected congenital heart problems were classified as Group I. During the catheterization procedure for this class of patients, the individual is positioned on the flat floating-top table. Fluoro and serial biplane radiography are the primary x-ray techniques employed with cine sometimes used to augment or

replace the serial radiographic filming. The pediatric phantom studies were set up to simulate this type of examination.

Patients evaluated for suspected acquired heart disease were identified as Group II. The majority of the patients in this group had coronary angiography and/or intracardiac angiographic procedures performed to evaluate the ventricular or valvular function. These patients were positioned in a rotation cradle during the procedures and fluoro/cine was utilized. The adult Rando phantom studies approximated the exposure conditions associated with this type of procedure. The remaining Group II patients were separated due to the difference in x-ray examination techniques used. One subgroup involved pulmonary or aortic angiography. These patients were positioned on the flat table surface to facilitate use of the serial radiographic film changers. A second subgroup involved pacemaker insertion and His bundle conduction studies. During these conduction studies, the patient was on the flat table surface and fluorography alone was used.

Results of Patient Monitoring

Table 26 summarizes the x-ray examination factors recorded for the 304 observed patients. Group I constituted approximately 65% of the patients evaluated during the study. Patient age showed a bimodal distribution similar to the

TABLE 26
Summary of X-ray Examination Factors Utilized in 304 Cardiac Catheterizations

| Patient Classification Group ^a | Age Range (year) | Number | Fluoro Time (min) | | Procedures Using Cine (percent) | Procedures Using Radiography (percent) |
|---|------------------------|--------|-------------------------|-------------|--|---|
| | | | Mean | (range) | | |
| I | < 1 | 63 | 12.8 | (2.0-35.0) | 32 | 98 |
| | 1 | 18 | 17.9 | (8.0-32.0) | 50 | 100 |
| | 2 | 8 | 17.1 | (8.0-41.0) | 63 | 100 |
| | 3 | 5 | 20.2 | (15.7-26.0) | 40 | 100 |
| | 4 | 12 | 18.2 | (9.0-35.5) | 75 | 100 |
| | 5 | 14 | 16.7 | (8.0-30.0) | 57 | 93 |
| | 6 | 14 | 14.9 | (6.9-33.0) | 71 | 86 |
| | 7 | 7 | 12.5 | (3.0-21.0) | 86 | 86 |
| | 8 | 9 | 18.2 | (5.0-40.0) | 67 | 100 |
| | 9 | 9 | 16.1 | (9.0-30.0) | 67 | 89 |
| | 10 | 7 | 15.0 | (9.0-27.0) | 86 | 100 |
| | 11 | 2 | 22.7 | (13.4-32.0) | 100 | 100 |
| >12 | 29 | 21.6 | (5.0-54.0) | 76 | 100 | |
| Total | 197 | 16.2 | | 56 | 97 | |
| IIa | <30 | 11 | 16.6 | (4.6-29.0) | 100 | |
| | 30-<40 | 5 | 15.6 | (6.7-27.0) | 100 | |
| | 40-<50 | 22 | 18.4 | (7.0-31.0) | 100 | |

^aPatients in Group II consisted of: (IIa) examinations in rotation cradle, (IIb) pulmonary and aortic angiography and (IIc) conduction studies.

TABLE 26 Continued

| Patient Classification Group ^a | Age Range (Year) | Number | Fluoro Time (min) Mean (range) | Procedures Using Cine (percent) | Procedures Using Radiography (percent) |
|---|------------------------|--------|---|--|---|
| | | | | | |
| IIa | 50-<60 | 28 | 19.1 (5.0-52.0) | 100 | |
| | >60 | 24 | 21.2 (5.0-39.0) | 100 | |
| | Total | 90 | 19.0 | | |
| IIb | 55- 75 | 5 | 23.6 (4.0-45.5) | 80 | 100 |
| IIc | 39- 83 | 12 | 9.9 (4.0-16.0) | | |

^a Patients in Group II consisted of: (IIa) examinations in rotation cradle, (IIb) pulmonary and aortic angiography and (IIc) conduction studies.

12 year UF pediatric profile described in Chapter II. One-third of the 197 Group I patients were less than 1 year old. Twenty-four percent of the patients fell in the second high-frequency age group of 4 to 7 years. Ninety of the 107 patients in Group II had coronary angiography and/or intracardiac angiographic procedures. The remaining 17 consisted of five pulmonary or aortic angiographic studies and 12 pacemaker or His bundle conduction studies.

For the Group I patients, radiography is seen to be the predominant method of recording being used in 97% of the procedures as contrasted to the 56% utilization of cine. The significance of the radiographic exposures are better illustrated by looking at the distribution of the EAP values for the two recording modes as presented in Table 27. Radiography accounted for 54% of the total incident EAP, whereas cine was responsible for 8%. The mean fluoro times varied randomly as a function of the patient age. Individual values were seen to range from a minimum of 2 min to a maximum of 54 min. The fact that the minimum 2 min time was found in the less than 1 year age group might be expected since newborns would be included in this subgroup. If life-threatening cardiac complications are found at birth, a catheterization will often be performed during the first or second day of life. The patient's condition is often critical and every effort is made to complete the necessary diagnosis as quickly as possible.

TABLE 27
 Summary of Measured EAP Values in 304 Cardiac Catheterizations

| Patient Classification Group | Age Range (year) | EAP (R. cm ²) | | | |
|------------------------------|----------------------|---------------------------|----------------------|--------------------------|------------------------|
| | | Fluoro Mean (range) | Cine Mean (range) | Radiography Mean (range) | Total Mean (range) |
| I | < 1 | 388 (37-2,467) | 30 (28- 331) | 499 (42-1,968) | 917 (107-2,987) |
| | 1 | 562 (172-1,663) | 86 (48-402) | 682 (54-1,637) | 1,331 (367-2,658) |
| | 2 | 522 (149-1,247) | 78 (33-267) | 992 (485-1,404) | 1,592 (1,008-2,252) |
| | 3 | 809 (403-1,636) | 33 (49-118) | 1,157 (659-1,756) | 1,999 (1,111-2,782) |
| | 4 | 754 (347-1,591) | 179 (53-773) | 930 (20-1,977) | 1,863 (480-2,912) |
| | 5 | 510 (183-1,351) | 124 (22-638) | 1,143 (239-2,687) | 1,776 (865-2,965) |
| | 6 | 699 (230-2,043) | 114 (6-378) | 776 (136-2,006) | 1,588 (651-3,249) |
| | 7 | 375 (139- 541) | 102 (67-186) | 1,119 (98-2,042) | 1,595 (139-2,544) |
| | 8 | 85 (184-2,816) | 129 (44-438) | 1,321 (47-2,465) | 2,301 (433-4,749) |
| | 9 | 545 (116-1,202) | 99 (70-236) | 1,260 (194-3,765) | 1,904 (316-4,606) |
| | 10 | 905 (382-1,891) | 178 (72-422) | 955 (62-3,662) | 2,038 (702-4,290) |
| 11 | 1,035 (744-1,326) | 883 (503-1,262) | 1,960 (598-3,322) | 3,878 (2,604-5,151) | |

TABLE 27 Continued

| Patient Classification Group ^a | Age Range (year) | EAP (R. cm ²) | | | |
|---|------------------|---------------------------|----------------------|--------------------------|-------------------------|
| | | Fluoro Mean (range) | Cine Mean (range) | Radiography Mean (range) | Total Mean (range) |
| I | >12 | 1,924 (310-8,195) | 538 (18-1,809) | 2,657 (20-6,709) | 5,119 (541-12,463) |
| | Total | 752 | 158 | 1,087 | 1,997 |
| IIa | <30 | 1,191 (280-2,125) | 1,269 (386-6,881) | | 2,460 (280-4,208) |
| | 30-<40 | 1,150 (384-2,396) | 1,078 (634-1,678) | | 2,228 (1,019-4,074) |
| | 40-<50 | 1,943 (299-4,323) | 3,052 (683-7,915) | | 4,995 (1,340-10,705) |
| | 50-<60 | 2,080 (225-9,937) | 2,029 (164-4,576) | | 4,109 (1,042-11,079) |
| | >60 | 1,824 (111-5,352) | 2,028 (326-5,676) | | 3,851 (437-8,602) |
| Total | 1,818 | 2,133 | | 3,951 | |
| IIb | 55- 75 | 1,761 (32-4,097) | 1,922 (38-3,788) | 2,963 (1,200-5,135) | 6,646 (1,617-9,537) |
| IIc | 39- 83 | 1,554 (518-2,936) | - | | 1,554 (518-2,936) |

^a Patients in Group II consisted of: (IIa) examinations in rotation cradle, (IIb) pulmonary and aortic angiography and (IIc) conduction studies.

For the Group II patients examined in the rotation cradle where fluoro and cine alone are used, the mean incident EAP values were about equally divided (fluoro [46%, cine 54%]). The total mean incident EAP for patients less than 40 years old was approximately half that for the 40 and greater class. The higher values for the older patients is suspected to be related to the greater number of coronary artery examinations carried out. As a result of the multiple selective angiographic exposures that are involved with these procedures, both fluoro time and amount of cine film exposed is great.

The five Group II procedures carried out using the serial film changers (pulmonary or aortic angiography) were seen to result in an incident EAP approximately twice that for the fluoro/cine cradle exposures. This increase is directly associated with the radiographic techniques. For the 12 conduction studies where fluoro alone was used, the mean exposure values were 40% of the fluoro/cine cradle exposures.

Results of Subsample Monitoring with TLD

The TLD monitored subsample consisted of 41 Group I and 21 Group II patients. In addition to the general descriptive information collected on all patients, an observers' log was kept throughout each of these procedures. The fluoro/cine and radiographic beam sizes were determined so that the

incident EAP values could be converted to exposure units and compared with the surface TLD readings. Body TLD sites 7 and 8 on the anterior and posterior abdomen over the assumed ovarian location and site 9 on the inner left upper thigh, used to estimate the male gonad dose, were simultaneously used on all clinical patients irrespective of sex.

Group I Results

The 41 Group I patients were coded as I-1 through I-41 in order of increasing age. Table 28 presents the patient characteristics for this group. Twenty-nine percent of the individuals were in the less than 1 year of age classification. This is in close agreement with the 1/3rd value found for this age group in the total patient population group. The second peak of the expected bimodal distribution of patient age at about 6 years is not obvious due to the small number of patients monitored with TLD. Table 29 lists the patient configuration and the fluoro time, as well as the number of cine frames and/or radiographic films exposed during each procedure. Tables 30 and 31 give the measured EAP and TLD site measurement values respectively.

Group II Results

Table 32 presents the characteristics for the acquired heart disease patients. The patients have been arranged in order of increasing age and coded as II-1 through II-21.

TABLE 28

Group I Patient Characteristics

| Patient Number | Hospital Number | Age | Sex | Ht (cm) | Wt (kg) | Chest Dimensions | |
|-------------------|--------------------|--------|-----|------------|------------|---------------------|-------------|
| | | | | | | AP (cm) | LAT (cm) |
| I- 1 | 250835 | 3 d | M | 50 | 3.2 | 8.0 | 9.5 |
| I- 2 | 248930 | 1 m | F | 49 | 2.7 | 9.0 | 11.0 |
| I- 3 | 252381 | 1 m | M | 53 | 3.3 | 8.5 | 11.0 |
| I- 4 | 256738 | 1 m | F | 47 | 2.7 | 8.5 | 11.0 |
| I- 5 | 254565 | 1 m | M | 47 | 3.0 | 9.0 | 10.5 |
| I- 6 | 250611 | 2 m | M | 58 | 4.5 | 8.0 | 12.5 |
| I- 7 | 255212 | 3 m | F | 58 | 5.0 | 12.0 | 14.0 |
| I- 8 | 251447 | 5 m | F | 64 | 6.2 | 10.0 | 14.5 |
| I- 9 | 241064 | 5 m | M | 68 | 7.4 | 9.5 | 15.0 |
| I-10 | 253411 | 5 m | M | 65 | 4.5 | 13.5 | 12.0 |
| I-11 | 253605 | 7 m | M | 70 | 7.6 | 9.0 | 16.0 |
| I-12 | 233012 | 11 m | M | 77 | 7.9 | 9.5 | 15.5 |
| I-13 | 230886 | 1 y | F | 77 | 10.2 | 11.5 | 16.0 |
| I-14 | 207915 | 1.8 y | M | 84 | 13.3 | 14.0 | 18.0 |
| I-15 | 207173 | 2 y | M | 76 | 9.5 | 13.0 | 17.5 |
| I-16 | 189397 | 3 y | M | 92 | 11.2 | 15.0 | 15.5 |
| I-17 | 181099 | 3 y | M | 94 | 15.7 | 14.0 | 19.0 |
| I-18 | 185945 | 3.7 y | M | 87 | 9.0 | 11.5 | 16.0 |
| I-19 | 238145 | 4 y | M | 102 | 15.6 | 13.5 | 20.0 |
| I-20 | 135527 | 5 y | F | 105 | 15.2 | 12.5 | 16.5 |
| I-21 | 254393 | 5 y | M | 105 | 19.0 | 4.5 | 20.5 |
| I-22 | 239275 | 5.4 y | M | 117 | 20.8 | 14.0 | 20.0 |
| I-23 | 163447 | 6 y | F | 110 | 16.3 | 12.0 | 18.0 |
| I-24 | 281378 | 7 y | F | 125 | 28.4 | 14.0 | 20.0 |
| I-25 | 182201 | 7.6 y | M | 122 | 26.0 | 16.0 | 22.0 |
| I-26 | 233945 | 8.1 y | F | 138 | 29.3 | 15.0 | 21.5 |
| I-27 | 061552 | 9 y | F | 145 | 35.0 | 14.0 | 22.0 |
| I-28 | 181644 | 9 y | F | 127 | 26.3 | 15.0 | 20.5 |
| I-29 | 180581 | 9.5 y | F | 140 | 29.6 | 14.5 | 21.0 |
| I-30 | 188767 | 10 y | M | 143 | 29.7 | 18.0 | 22.0 |
| I-31 | 250549 | 11.5 y | M | 138 | 30.8 | 15.0 | 23.5 |
| I-32 | 211911 | 12 y | F | 144 | 33.9 | 16.0 | 24.0 |
| I-33 | 246919 | 12.6 y | F | 122 | 23.0 | 17.0 | 22.0 |
| I-34 | 233223 | 12.9 y | M | 148 | 54.0 | 19.0 | 27.0 |
| I-35 | 234832 | 14.9 y | F | 163 | 48.0 | 16.5 | 24.0 |

TABLE 28 Continued

| Patient Number | Hospital Number | Age | Sex | Ht (cm) | Wt (kg) | Chest Dimensions | |
|-------------------|--------------------|--------|-----|------------|------------|---------------------|-------------|
| | | | | | | AP (cm) | LAT (cm) |
| I-36 | 236213 | 15 y | F | 172 | 55.8 | 18.5 | 29.0 |
| I-37 | 236392 | 16 y | M | 178 | 53.5 | 16.5 | 24.5 |
| I-38 | 237640 | 18.2 y | F | 168 | 51.0 | 18.5 | 28.5 |
| I-39 | 122814 | 19 y | M | 180 | 77.0 | 21.0 | 30.0 |
| I-40 | 249654 | 20 y | F | 182 | 58.0 | 17.5 | 25.5 |
| I-41 | 247622 | 24 y | F | 163 | 44.5 | 19.0 | 26.0 |

TABLE 29

Procedure Setup and Quantity of Fluoro, Cine and Radiography
Used for Group I Examinations

| Patient Number | Procedure Setup | | Fluoro Time (min) | Number Cine Frames | Number Radiographic Films |
|-------------------|-----------------|--------------------|-------------------------|--------------------------|---------------------------------|
| | Flat Table | Restraint Board | | | |
| I- 1 | | x | 17.5 | | 87 |
| I- 2 | | x | 14.0 | 679 | 51 |
| I- 3 | | x | 23.0 | | 50 |
| I- 4 | | x | 8.5 | | 85 |
| I- 5 | | x | 5.5 | | 83 |
| I- 6 | | x | 35.0 | | 141 |
| I- 7 | | x | 13.3 | | 93 |
| I- 8 | | x | 9.0 | 597 | 43 |
| I- 9 | | x | 6.0 | | 51 |
| I-10 | | x | 21.5 | | 80 |
| I-11 | | x | 22.1 | 475 | 51 |
| I-12 | | x | 3.5 | | 49 |
| I-13 | | x | 8.0 | | 49 |
| I-14 | | x | 19.0 | | 90 |
| I-15 | | x | 15.0 | | 49 |
| I-16 | | x | 8.0 | | 46 |
| I-17 | | x | 15.7 | 319 | 50 |
| I-18 | | x | 20.5 | | 49 |
| I-19 | | x | 24.4 | | 51 |
| I-20 | | x | 11.0 | | 51 |
| I-21 | | x | 8.2 | | 87 |
| I-22 | | x | 23.5 | 546 | 5 |
| I-23 | | x | 33.0 | 326 | 51 |
| I-24 | | x | 16.8 | 459 | 1 |
| I-25 | | x | 12.4 | 447 | 49 |
| I-26 | | x | 5.2 | | 51 |
| I-27 | | x | 10.4 | | |
| I-28 | | x | 15.0 | 510 | 48 |
| I-29 | | x | 8.5 | 892 | 7 |
| I-30 | | x | 13.5 | 414 | 2 |
| I-31 | x | | 32.0 | 746 | 94 |
| I-32 | x | | 13.4 | 2,017 | 1 |
| I-33 | | | 19.8 | | 49 |
| I-34 | x | | 10.0 | 505 | 6 |
| I-35 | x | | 29.0 | 403 | 49 |

TABLE 29 Continued

| Patient Number | Procedure Setup | | Fluoro Time (min) | Number Cine Frames | Number Radiographic Films |
|-------------------|-----------------|--------------------|-------------------------|--------------------------|---------------------------------|
| | Flat Table | Restraint Board | | | |
| I-36 | x | | 30.0 | 442 | 4 |
| I-37 | x | | 21.0 | 1,518 | 8 |
| I-38 | x | | 15.8 | 552 | 1 |
| I-39 | x | | 47.2 | | 45 |
| I-40 | x | | 19.0 | | 6 |
| I-41 | x | | 20.0 | 1,590 | 51 |

TABLE 30
Group I EAP Values

| Patient Number | EAP (R.cm ²) | | | |
|-------------------|--------------------------|-------|-------|-------|
| | Fluoro | Cine | AP | LAT |
| I- 1 | 311 | | 324 | 306 |
| I- 2 | 197 | 45 | 144 | 165 |
| I- 3 | 305 | | 198 | 188 |
| I- 4 | 116 | | 299 | 239 |
| I- 5 | 78 | | 193 | 298 |
| I- 6 | 954 | | 639 | 770 |
| I- 7 | 273 | | 412 | 376 |
| I- 8 | 193 | 68 | 297 | 243 |
| I- 9 | 132 | | 381 | 403 |
| I-10 | 425 | | 326 | 382 |
| I-11 | 493 | 65 | 227 | 304 |
| I-12 | 105 | | 323 | 371 |
| I-13 | 265 | | 465 | 452 |
| I-14 | 459 | | 765 | 872 |
| I-15 | 403 | | 421 | 417 |
| I-16 | 200 | | 622 | 782 |
| I-17 | 400 | 49 | 886 | 867 |
| I-18 | 446 | | 339 | 320 |
| I-19 | 500 | | 585 | 548 |
| I-20 | 249 | | 440 | 651 |
| I-21 | 278 | | 1,130 | 1,551 |
| I-22 | 660 | 132 | 146 | 93 |
| I-23 | 659 | 6 | 450 | 598 |
| I-24 | 541 | 112 | 107 | |
| I-25 | 359 | 82 | 882 | 936 |
| I-26 | 184 | | 740 | 910 |
| I-27 | 316 | | | |
| I-28 | 494 | 163 | 751 | 1,336 |
| I-29 | 207 | 105 | 217 | 129 |
| I-30 | 511 | 175 | 116 | |
| I-31 | 1,326 | 503 | 2,401 | 921 |
| I-32 | 744 | 1,262 | 598 | |
| I-33 | 670 | | 630 | 755 |
| I-34 | 417 | 273 | 278 | 162 |
| I-35 | 1,700 | 305 | 1,006 | 1,214 |

TABLE 30 Continued

| Patient Number | EAP (R.cm ²) | | | |
|-------------------|--------------------------|-------|-------|-------|
| | Fluoro | Cine | AP | LAT |
| I-36 | 1,448 | 312 | 198 | 163 |
| I-37 | 1,806 | 1,061 | 359 | 206 |
| I-38 | 693 | 180 | 64 | |
| I-39 | 2,139 | | 1,849 | 2,352 |
| I-40 | 909 | | 320 | 363 |
| I-41 | 2,344 | 1,809 | 2,220 | 3,136 |

TABLE 31
Group I Patient TLD Exposure Measurements

| Patient Number | Exposure in mR at Indicated Site | | | | | | | | | | |
|----------------|----------------------------------|-------|-------|--------|-------|--------|--------|-----|-----|----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| I-1 | 48 | 2,219 | 7,519 | 7,327 | 1,693 | 9,315 | 5,544 | 64 | 302 | 24 | |
| I-2 | 31 | 2,948 | 276 | 3,454 | 743 | 8,423 | 2,773 | 87 | 276 | 14 | |
| I-3 | 72 | 883 | 528 | 4,212 | 2,665 | 6,556 | 3,943 | 274 | 269 | 14 | |
| I-4 | 58 | 5,512 | 3,941 | 6,629 | 2,838 | 4,202 | 5,943 | 179 | 252 | 27 | |
| I-5 | 16 | 966 | 3,656 | 4,050 | 605 | 2,613 | 4,077 | 119 | 191 | 16 | |
| I-6 | 76 | 1,760 | 2,704 | 10,719 | 8,210 | 17,653 | 11,364 | 279 | 624 | 29 | |
| I-7 | 62 | 4,894 | 5,646 | 5,847 | 1,583 | 7,412 | 5,238 | 79 | 118 | 14 | |
| I-8 | 36 | 2,130 | 850 | 2,982 | 718 | 3,399 | 3,672 | 160 | 241 | 42 | |
| I-9 | 47 | 2,416 | 1,987 | 3,812 | 659 | 3,024 | 767 | 221 | 330 | 16 | 49 |
| I-10 | 55 | 2,365 | 1,342 | 4,818 | 4,904 | 10,438 | 5,746 | 199 | 188 | 22 | |
| I-11 | 36 | 685 | 634 | 3,644 | 2,840 | 12,492 | 4,698 | 208 | 327 | 41 | 121 |
| I-12 | 33 | 3,763 | 674 | 5,099 | 1,655 | 2,193 | 4,519 | 175 | 251 | 29 | 114 |
| I-13 | 84 | 3,189 | 1,096 | 4,940 | 714 | 3,591 | 4,297 | 213 | 64 | 18 | 58 |
| I-14 | 130 | 529 | 622 | 7,442 | 1,272 | 9,747 | 10,495 | 230 | 250 | 29 | 67 |
| I-15 | 55 | 795 | 678 | 5,274 | 3,049 | 12,357 | 4,621 | 204 | 383 | 15 | 27 |
| I-16 | 39 | 539 | 768 | 4,620 | 5,148 | 3,592 | 6,255 | 46 | 21 | 13 | 11 |
| I-17 | 57 | 720 | 631 | 7,723 | 2,048 | 9,014 | 7,021 | 32 | 62 | 16 | 9 |
| I-18 | 18 | 538 | 597 | 4,338 | 2,778 | 8,877 | 3,624 | 28 | 43 | 7 | 6 |
| I-19 | 45 | 959 | 615 | 5,128 | 2,773 | 6,115 | 4,958 | 80 | 120 | 9 | |
| I-20 | 56 | 643 | 358 | 3,644 | 1,988 | 4,649 | 5,203 | 128 | 606 | 11 | |
| I-21 | 80 | 2,438 | 1,072 | 10,370 | 876 | 4,691 | 12,019 | 146 | 149 | 18 | 30 |
| I-22 | 12 | 193 | 119 | 760 | 765 | 8,438 | 794 | 30 | 282 | 7 | 36 |
| I-23 | 39 | 1,075 | 1,164 | 5,554 | 1,962 | 11,135 | 5,001 | 220 | 335 | 9 | 15 |
| I-24 | 6 | 187 | 168 | 344 | 204 | 7,994 | 300 | 448 | 181 | 8 | 20 |
| I-25 | 31 | 636 | 522 | 4,864 | 489 | 2,797 | 4,803 | 700 | 693 | 13 | |
| I-26 | 41 | 182 | 192 | 1,902 | 3,206 | 6,002 | 5,546 | 215 | 240 | 7 | |
| I-27 | 2 | 16 | 21 | 103 | 65 | 3,431 | 39 | 3 | 42 | 1 | |

TABLE 31 Continued

| Patient Number | Exposure in mR at Indicated Site | | | | | | | | | | |
|----------------|----------------------------------|-------|-------|--------|-------|--------|--------|-----|-------|----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| I-28 | 64 | 703 | 738 | 6,472 | 1,205 | 2,603 | 6,632 | 11 | 31 | 3 | 1 |
| I-29 | 10 | 54 | 64 | 795 | 392 | 1,380 | 809 | 352 | 292 | 1 | |
| I-30 | 5 | 48 | 63 | 146 | 301 | 4,972 | 74 | 63 | 317 | 8 | 117 |
| I-31 | 113 | 587 | 643 | 15,993 | 2,284 | 15,785 | 7,929 | 101 | 1,461 | 25 | |
| I-32 | 21 | 105 | 89 | 379 | 1,416 | 6,680 | 402 | 212 | 615 | 21 | |
| I-33 | 17 | 1,020 | 4,717 | 3,398 | 488 | 9,271 | 986 | 25 | 74 | 46 | |
| I-34 | 20 | 161 | 116 | 1,063 | 140 | 3,290 | 1,724 | 23 | 361 | 4 | |
| I-35 | 29 | 215 | 199 | 6,369 | 867 | 4,758 | 7,974 | 212 | 42 | 8 | |
| I-36 | 4 | 38 | 63 | 858 | 637 | 3,463 | 873 | 55 | 187 | 6 | |
| I-37 | 12 | 157 | 228 | 1,544 | 1,160 | 9,139 | 1,615 | 83 | 1,255 | 5 | |
| I-38 | 7 | 23 | 41 | 350 | 76 | 7,166 | 7,521 | 276 | 565 | 2 | |
| I-39 | 82 | 416 | 956 | 8,763 | 558 | 21,702 | 12,751 | 44 | 166 | 6 | |
| I-40 | 17 | 102 | 98 | 1,515 | 243 | 18,358 | 1,872 | 3 | 31 | 1 | |
| I-41 | 62 | 443 | 432 | 12,128 | 1,856 | 28,432 | 5,132 | 201 | 57 | 6 | |

TABLE 32
Group II Patient Characteristics

| Patient Number | Hospital Number | Age (year) | Sex | Ht (cm) | Wt (kg) | Chest Dimensions | |
|-------------------|--------------------|---------------|-----|------------|------------|---------------------|-------------|
| | | | | | | AP (cm) | LAT (cm) |
| II- 1 | 254897 | 16 | F | 163 | 95.0 | 24.0 | 35.5 |
| II- 2 | 243702 | 18 | M | 163 | 50.5 | 17.0 | 29.0 |
| II- 3 | 181416 | 18 | M | 162 | 52.5 | 17.0 | 26.5 |
| II- 4 | 046822 | 19 | F | 165 | 53.6 | 16.5 | 27.0 |
| II- 5 | 252283 | 27 | M | 175 | 62.0 | 18.5 | 27.5 |
| II- 6 | 249755 | 35 | M | 178 | 78.0 | 23.5 | 36.0 |
| II- 7 | 250252 | 44 | M | 178 | 70.0 | 20.0 | 31.0 |
| II- 8 | 251703 | 45 | M | 184 | 83.0 | 24.5 | 32.5 |
| II- 9 | 253476 | 48 | M | 182 | 87.0 | 22.0 | 34.0 |
| II-10 | 257562 | 49 | M | 173 | 82.7 | 24.0 | 36.0 |
| II-11 | 252167 | 55 | F | 160 | 54.7 | 19.5 | 28.0 |
| II-12 | 251876 | 58 | M | 170 | 75.0 | 24.0 | 29.0 |
| II-13 | 252885 | 59 | F | 155 | 56.1 | 18.0 | 26.0 |
| II-14 | 246192 | 59 | M | 160 | 78.5 | 27.5 | 33.5 |
| II-15 | 233479 | 66 | F | 160 | 49.1 | 18.5 | 25.0 |
| II-16 | 225653 | 67 | M | 176 | 85.0 | 25.0 | 32.5 |
| II-17 | 068288 | 68 | M | 171 | 71.8 | 21.0 | 30.0 |
| II-18 | 247298 | 69 | F | 160 | 57.0 | 18.0 | 24.5 |
| II-19 | 257782 | 71 | M | 179 | 69.0 | 24.0 | 32.0 |
| II-20 | 240381 | 25 | F | 167 | 65.0 | 16.0 | 30.0 |
| II-21 | 137527 | 68 | M | 170 | 70.0 | 23.0 | 29.5 |

Patients II-20 and 21 have been separated from the other patients in this grouping since they were conduction studies where fluoro only was used. Table 33 lists the patient setup and amount of fluoro and cine used, as well as the measured EAP values for these modes of exposure. The individual site TLD measurements are given in Table 34.

Intercomparison of Dosimetry Techniques

Exposure measurements during clinical studies and for simulated examination conditions using human equivalent phantoms have been performed. The results of these individual measurements, carried out with EAP meters and TLD, were intercompared to identify differences in predicted and measured value.

Incident Exposure

By using the measured EAP values and the TL dosimeter readings, two independent estimates of incident skin exposure can be made. If exposure from a single fixed geometry beam is considered, a surface TL dosimeter at the center of the incidence skin surface should register the same exposure value as that estimated from the EAP measurement. Bushong and colleagues (1973) have shown this to be true for normal chest radiography. However, during cardiac catheterization multiple beam incidences are involved. Under these conditions any individual surface TL dosimeter may be exposed to primary, attenuated primary or scatter radiation.

TABLE 33

Procedure Setup, Quantity of Fluoro, Cine and EAP Values
for Group II Examinations

| Patient Number | Procedure Setup | | Fluoro Time (min) | Number Cine Frames | EAP (R.cm) | |
|-------------------|-----------------|--------|-------------------------|--------------------------|------------|-------|
| | Flat Table | Cradle | | | Fluoro | Cine |
| II-1 | | x | 18.0 | 1,071 | 1,949 | 1,638 |
| II-2 | | x | 13.2 | 1,108 | 562 | 639 |
| II-3 | | x | 23.5 | 1,452 | 1,419 | 841 |
| II-4 | | x | 29.0 | 1,550 | 1,406 | 819 |
| II-5 | | | 12.0 | 876 | 806 | 387 |
| II-6 | x | | 8.0 | 3,350 | 2,396 | 1,678 |
| II-7 | | x | 10.5 | 2,960 | 397 | 943 |
| II-8 | | x | 15.2 | 6,295 | 1,774 | 6,044 |
| II-9 | | x | 10.2 | 4,978 | 869 | 2,364 |
| II-10 | | x | 18.7 | 3,000 | 3,215 | 6,106 |
| II-11 | | x | 10.0 | 2,538 | 364 | 678 |
| II-12 | | x | 8.4 | 2,606 | 473 | 903 |
| II-13 | | x | 21.0 | 430 | 1,085 | 164 |
| II-14 | | x | 9.0 | 3,606 | 555 | 5,302 |
| II-15 | | x | 14.0 | 3,988 | 704 | 2,580 |
| II-16 | | x | 17.0 | 7,007 | 1,397 | 5,804 |
| II-17 | | x | 39.0 | 3,851 | 5,352 | 4,630 |
| II-18 | | x | 17.3 | | 820 | 959 |
| II-19 | | x | 18.7 | 4,844 | 2,768 | 2,794 |
| II-20 | x | | 4.3 | | 208 | |
| II-21 | x | | 7.0 | | 518 | |

TABLE 34
Group II Patient TLD Exposure Measurements

| Patient Number | Exposure in mR at Indicated Site | | | | | | | | | |
|----------------|----------------------------------|-----|-----|-------|--------|--------|-------|----|-------|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| II-1 | 16 | 305 | 395 | 416 | 4,298 | 4,923 | 253 | 3 | 249 | 1 |
| II-2 | 5 | 45 | 43 | 182 | 5,494 | 5,048 | 296 | 2 | 40 | 1 |
| II-3 | 17 | 150 | 138 | 417 | 390 | 11,814 | 965 | 10 | 107 | 2 |
| II-4 | 25 | 93 | 84 | 541 | 1,775 | 15,403 | 478 | 3 | 104 | 1 |
| II-5 | 5 | 46 | 62 | 115 | 131 | 5,601 | 72 | BG | 33 | BG |
| II-6 | 88 | 337 | 386 | 802 | 7,423 | 9,633 | 3,219 | 20 | 191 | 8 |
| II-7 | 11 | 67 | 82 | 698 | 555 | 8,131 | 477 | 8 | 44 | BG |
| II-8 | 30 | 360 | 310 | 1,411 | 3,140 | 4,751 | 2,029 | 10 | 285 | 3 |
| II-9 | 15 | 159 | 193 | 771 | 1,849 | 14,071 | 670 | 5 | 259 | 3 |
| II-10 | 90 | 756 | 784 | 2,430 | 15,550 | 27,200 | 2,604 | 14 | 475 | 7 |
| II-11 | 24 | 101 | 96 | 819 | 4,269 | 3,186 | 763 | 2 | 151 | BG |
| II-12 | 21 | 51 | 51 | 350 | 1,193 | 5,298 | 414 | 29 | 556 | BG |
| II-13 | 10 | 82 | 86 | 512 | 205 | 6,880 | 438 | 3 | 94 | 2 |
| II-14 | 46 | 616 | 634 | 1,346 | 2,149 | 2,129 | 3,383 | 20 | 531 | 6 |
| II-15 | 57 | 290 | 310 | 1,084 | 8,281 | 5,245 | 2,324 | 10 | 228 | 5 |
| II-16 | 96 | 529 | 553 | 1,474 | 2,216 | 11,600 | 2,118 | 34 | 673 | 5 |
| II-17 | 40 | 490 | 378 | 1,594 | 2,919 | 2,999 | 5,584 | 37 | 1,107 | 10 |
| II-18 | 28 | 116 | 138 | 660 | 2,358 | 6,135 | 1,313 | 13 | 330 | 3 |
| II-19 | 7 | 217 | 284 | 1,902 | 4,192 | 6,705 | 7,030 | 17 | 391 | 1 |
| II-20 | 7 | 27 | 22 | 52 | 58 | 1,618 | 18 | 7 | 23 | 6 |
| II-21 | 3 | 9 | 11 | 40 | 52 | 7,336 | 36 | BG | 9 | BG |

Registered exposure equal to counter background (BG).

The beam size at the plane of the image receptor (input phosphor of image intensifier for fluoro/cine and the film plane for radiographic exposures) measured during the procedure was first converted by triangulation to the estimated position of the input skin surface. The geometry assumptions used for the various modes of exposure were discussed in Chapter II. For fluoro and cine, it was assumed that the external input surface of the fluoro image assembly was 5 cm from the surface of the chest. Two cm were then added to account for the distance of the plane of the input phosphor from the intensifier assembly's external surface. The measured EAP value was then divided by the area at the input skin surface and a correction for backscatter, using the data in Appendix A, was made.

To evaluate the difference between the two exposure measurements, the TL dosimeter reading was divided by the estimate obtained from the representative EAP measurement (i.e., TLD site number 6 for fluoro/cine, TLD site number 7 for LAT radiography, site number 4 for AP radiography). The values for the Group I patients are tabulated in Table 35. In general, the posterior chest site (number 5) value was about 80% lower than the $R.cm^2$ fluoro/cine estimate. This would be expected since during a catheterization procedure the fluoro beam is used to aid the physician in advancement and positioning of the catheter. This may involve considerable exposure to areas other than over the heart.

TABLE 35
 Estimated Incident Skin Exposure for Group I
 from EAP Values and Correlation with TLD Site Measurements

| Patient Number | Incident Exposure in mR Estimated from EAP Reading | | | Ratio of Measured Exposure (from TLD) to Estimated Exposure (from EAP) | | |
|----------------|--|-------|--------|--|------|------|
| | Fluoro + Cine | AP | LAT | Fluoro + Cine | AP | LAT |
| I-1 | 7,870 | 4,310 | 4,280 | 1.18 | 1.70 | 1.30 |
| I-2 | 7,250 | 2,440 | 2,600 | 1.16 | 1.41 | 1.07 |
| I-3 | 8,020 | 2,440 | 3,760 | 0.82 | 1.72 | 0.97 |
| I-4 | 4,110 | 4,120 | 4,260 | 1.02 | 1.61 | 1.40 |
| I-5 | 2,350 | 3,650 | 4,440 | 1.11 | 1.11 | 0.92 |
| I-6 | 16,670 | 8,030 | 8,990 | 0.94 | 1.33 | 1.26 |
| I-7 | 8,640 | 5,620 | 5,200 | 0.81 | 1.04 | 1.01 |
| I-8 | 4,420 | 2,930 | 3,550 | 0.77 | 1.02 | 1.03 |
| I-9 | 3,010 | 3,220 | 5,390 | 1.00 | 1.18 | 0.88 |
| I-10 | 7,090 | 3,337 | 5,430 | 1.47 | 1.43 | 1.06 |
| I-11 | 10,410 | 2,220 | 3,690 | 1.20 | 1.64 | 1.25 |
| I-12 | 1,790 | 2,940 | 4,330 | 1.22 | 1.74 | 1.04 |
| I-13 | 4,410 | 3,860 | 4,970 | 0.81 | 1.28 | 0.87 |
| I-14 | 10,020 | 7,240 | 12,310 | 0.97 | 1.03 | 0.85 |
| I-15 | 7,790 | 2,860 | 3,920 | 1.57 | 1.84 | 1.18 |
| I-16 | 5,580 | 3,830 | 4,800 | 0.47 | 1.21 | 1.07 |
| I-17 | 16,680 | 5,000 | 6,570 | 0.54 | 1.54 | 1.07 |
| I-18 | 10,680 | 2,980 | 3,240 | 0.83 | 1.46 | 1.12 |
| I-19 | 10,120 | 4,130 | 7,220 | 0.60 | 1.24 | 0.79 |
| I-20 | 6,750 | 3,780 | 6,460 | 0.69 | 0.96 | 0.81 |
| I-21 | 7,610 | 7,280 | 12,010 | 0.62 | 1.42 | 1.00 |
| I-22 | 19,570 | 750 | 740 | 0.43 | 1.01 | 1.07 |
| I-23 | 15,690 | 3,960 | 4,600 | 0.71 | 1.40 | 1.09 |

TABLE 35 Continued

| Patient Number | Incident Exposure in mR Estimated from EAP Reading | | | Ratio of Measured Exposure (from TLD) to Estimated Exposure (from EAP) | | |
|----------------|--|---------|---------|--|-------------------|-------------------|
| | Fluoro + Cine | AP | LAT | Fluoro + Cine | AP | LAT |
| | Site 6/ | Site 4/ | Site 7/ | Site 6/ | Site 4/ | Site 7/ |
| I-24 | 13,490 | 370 | | 0.59 | 0.93 | |
| I-25 | 11,190 | 5,170 | 5,920 | 0.25 | 0.93 | 0.81 |
| I-26 | 6,480 | 4,390 | 6,570 | 0.93 | 0.93 | 0.84 |
| I-27 | 3,750 | | | 0.92 | | |
| I-28 | 16,990 | 4,540 | 7,500 | 0.15 | 1.43 | 0.88 |
| I-29 | 5,800 | 1,220 | 670 | 0.24 | 0.65 | 1.21 |
| I-30 | 8,500 | 480 | | 0.59 | 0.30 | |
| I-31 | 24,290 | 12,830 | 7,630 | 0.65 | 1.25 | 1.04 |
| I-32 | 47,690 | 1,200 | | 0.14 | 1.18 | |
| I-33 | 15,300 | 4,590 | | 0.61 | 0.74 ^a | |
| I-34 | 12,070 | 960 | 6,680 | 0.27 | 1.10 | 1.74 |
| I-35 | 17,370 | 5,630 | 7,370 | 0.27 | 1.13 | 1.08 |
| I-36 | 21,900 | 810 | 680 | 0.16 | 1.05 | 1.01 |
| I-37 | 29,700 | 1,450 | 1,060 | 0.31 | 1.07 | 1.52 |
| I-38 | 15,400 | 130 | | 0.46 | 2.69 | 1.01 |
| I-39 | 53,300 | 7,100 | 12,400 | 0.39 | 1.22 | 1.08 |
| I-40 | 17,900 | 1,540 | 1,740 | 1.02 | 0.98 | 1.08 ^a |
| I-41 | 47,500 | 11,600 | 19,000 | 0.56 | 1.02 | 0.27 ^a |
| | | | | Mean 0.70 | 1.26 | 1.07 |

^a Value inaccurate due to loss of chip from indicated site during procedure. Value not used in calculation of column mean.

For the AP and LAT radiographic exposures, the ratio of the TL dosimeter to $R.cm^2$ derived exposure estimate would be expected to be one or greater. Except for the intravenous pyelogram (IVP) exposures that may have been taken at the conclusion of the examination, the radiographic beams would be centered over the heart with sites number 4 and number 7 in the respective primary AP and LAT beams. During two procedures (patients I-33 and I-41), the TL dosimeters were inadvertently removed as a result of patient manipulation prior to completion of the procedure. The ratio of the two exposure estimates, as identified by the footnote in Table 35, is seen to be low, as expected. The site number 4 AP values for patients I-29 and I-30 are also seen to be low. For each of these procedures, two IVP films were taken. Patient I-29 had biplane scout films taken, but serial biplane radiography was not performed in either case. The lower value for the site number 4 to AP ratio can thus be explained by the high proportion of the AP exposure during which the site number 4 dosimeter received only scatter radiation.

The precision of the exposure estimates obtained from the EAP values is directly dependent upon the accuracy of the exposure geometry factors. The geometric uncertainties for the PA and AP exposures would be expected to be less than for the LAT projections. The source-to-patient distance for the under table fluoro/cine tube is fixed. For the AP

the only variation that might be involved would be use of an inaccurate measurement of the mid-chest dimension, or technician error in positioning the x-ray tube at the correct source-to-image receptor distance. For the LAT exposure, the patient must be physically slid toward the lateral film changer. The goal is to position the patient as near to the changer as possible. For calculation purposes, a physical separation of 7.4 cm (9 cm from patient surface to plane of film) was assumed, as shown in Figure 3 of Chapter II. If, in fact, the patient is in contact with the changer, the incident exposure estimate calculated from the measured EAP value for a patient with a nominal 20 cm lateral chest thickness would be approximately 20% high. This, in turn, would result in a similar reduction in the site number 7 to LAT ratio and may account for the ratio values less than one.

Table 36 lists the incident exposure estimates calculated from the EAP value and the ratio of the posterior thorax TLD site number 6, to this estimate for the Group II patients. The mean value of the ratio for the 21 patients was found to be 0.21 which is significantly less than the Group I patient values. The primary reason for the lower value is related to the significant amount of exposure that takes place when the patient is in an oblique projection.

TABLE 36
 Estimated Incident Skin Exposure for Group II
 from EAP Values and Correlation with TLD Site Measurements

| Patient Number | Incident Exposure in mR Estimated from EAP Reading | Ratio of Measured Exposure (from TLD) to Estimated Exposure (from EAP) |
|----------------|--|--|
| | Fluoro + Cine | Site Number 6/Fluoro + Cine |
| II- 1 | 40,040 | 0.12 |
| II- 2 | 17,100 | 0.30 |
| II- 3 | 27,900 | 0.41 |
| II- 4 | 25,500 | 0.59 |
| II- 5 | 23,000 | 0.24 |
| II- 6 | 62,800 | 0.15 |
| II- 7 | 28,800 | 0.37 |
| II- 8 | 106,200 | 0.04 |
| II- 9 | 30,600 | 0.46 |
| II-10 | 96,200 | 0.27 |
| II-11 | 23,900 | 0.13 |
| II-12 | 37,500 | 0.14 |
| II-13 | 19,100 | 0.36 |
| II-14 | 62,800 | 0.03 |
| II-15 | 28,400 | 0.18 |
| II-16 | 171,100 | 0.07 |
| II-17 | 163,900 | 0.02 |
| II-18 | 38,800 | 0.16 |
| II-19 | 73,100 | 0.09 |
| II-20 | 5,500 | 0.29 |
| II-21 | 7,200 | 1.01 |
| Mean | 51,878 | 0.21 |

EAP Measurements

To evaluate how representative the exposure conditions, for the subgroup of clinical patients monitored with TLD's were of the similar patients in the total population group, the EAP values were compared. The comparison values are listed in Table 37. For the Group I patients, separate comparisons are made for the 21 year old and the 5 to 7 year olds because the patients in these age groups are comparable in size to the two infant and child pediatric phantoms. The mean EAP values are seen to be similar with the less than 1 year Group I and Group II data varying by 5 and 10% respectively. The Group I 5 to 7 year old TLD patients had a mean EAP 20% greater than the comparable total patient population, but these results were based on data from only four TL monitored patients.

Selected Surface Sites

All of the phantom exposures were carried out with the x-ray beam in line with the transverse sectional plane passing through the heart; however, during clinical procedures this condition is not always met. The scanning of the fluoro beam over the upper or lower portion of the trunk of the body would be expected to alter the dose received by the eyes, thyroid and gonads. To examine the possible magnitude of this effect dose indices derived from TLD measurements at these patient sites were compared with the corresponding phantom-derived dose index values.

TABLE 37

Comparison of EAP Values for TLD Monitored Patients
with Values from Total Patient Population

| Patient Classification | Number of Patients | Total EAP (R.cm ²) Mean (range) |
|-----------------------------------|--------------------|--|
| Adult-Group II (in cradle) | | |
| 1 Monitored with TLD | 19 | 3,552 (1,042- 9,982) |
| 2 All in group | 90 | 3,951 (437-11,079) |
| Child-Group I (5-7 year) | | |
| 1 Monitored with TLD ^a | 4 | 2,069 (1,340- 2,965) |
| 2 All in group | 18 | 1,643 (139- 3,249) |
| Infant-Group I (<1 year) | | |
| 1 Monitored with TLD | 12 | 964 (551- 2,363) |
| 2 All in group | 63 | 917 (107- 2,987) |

^a Includes only patient on which biplane serial radiography was performed.

As in the EAP comparison, patients in the less than 1 year and 5 to 7 year Group I classification and Group II patients examined in the rotation cradle were used for this evaluation. Using the fluoro, cine and AP and LAT radiographic EAP values and allocating between various fluoro and cine modes, a weighted phantom dose index value was obtained for each of the organ systems. For the adult phantom values, the fluoro PA and oblique geometries were weighted equally; whereas for the cine, the oblique projection was assumed to be used 75% of the time. Fluoro was divided equally between the nominal six and nine inch modes, but cine was assumed to be carried out in the six inch mode exclusively. For the child phantom, fluoro and cine was weighted equally between the six and nine inch modes.

The results of this intercomparison are shown in Table 38. In all but two cases the patient and phantom dose indices varied by no more than a factor of approximately two. The measured patient values for the infant thyroid and adult lens of eye are seen to be higher than the phantom-derived values by factors of three and five respectively.

For the infant thyroid site the variation is assumed to be due to its close proximity to the edge of the primary beam. The probability is high that during clinical procedures this site will be in and out of the primary beam. The variation for the adult lens of eye estimate may be due to the difference in geometry for the phantom and patient. The

TABLE 38

Comparison of Patient and Phantom-Derived Dose Indices for
Lens of Eye, Thyroid and Scrotum

| Patient or Phantom Classification | Forehead (eye) | | Thyroid | | Scrotum | |
|---|--|-------|---|-------|---|-------|
| | (Site 1) Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio | (Average Site 2 and 3) Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio | (Site 10) Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio |
| <u>Infant</u> | | | | | | |
| Group I (<1 year (n=12) | 46.8(24.8-77.6) | | 2607.6(532.9-6321.2) | | 22.3(11.3-46.1) | |
| Phantom | 45.0(39.4-49.9) | 1.0 | 903.5(1106.3-1256.8) | 2.9 | 53.0(48.1-58.9) | 0.4 |
| <u>Child</u> | | | | | | |
| Group I (5-7 years (n=6) | 23.2(12.1-36.8) | | 412.6(225.6- 575.1) | | 5.6(4.6- 7.2) | |
| Phantom | 28.9(16.4-35.5) | 0.8 | 365.2(199.7- 514.8) | 1.1 | 6.3(4.9- 7.3) | 0.9 |

^aValues reported as mean and (range of individual values).

TABLE 38 Continued

| Patient or Phantom Classification | Forehead (eye) | | Thyroid | | Scrotum | |
|---|--|-------|---|-------|--|-------|
| | (Site 1) Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio | (Average Site 2 and 3) Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio | (Site 10) ^a Dose Index ^a (mrad/10 ³ R.cm ²) | Ratio |
| Adult | | | | | | |
| Group II (n=19) | 8.8 (1.1-20.3) | | 57.4 (32.2- 93.9) | | 0.7 (0.2- 1.7) | |
| Phantom | 1.7 (1.7- 1.8) | 5.2 | 29.7 (27.8- 31.3) | 1.9 | 2.0 (1.8- 2.1) | 0.4 |

^aValues reported as mean and (range of individual values).

position of the phantom head is fixed. When placed in the cradle, the longitudinal axis of the skull is in line with the horizontal axis of the cradle and does not duplicate the adult patient position. During clinical studies the patient's head is propped up with a pillow. This elevated position places the forehead site, used for the lens of eye measurement, closer to the source of scatter. Attenuation provided by the nose or other skull tissues would also be expected to be less for this patient position. The absolute value of the dose to the eye is small in comparison to the quantities that are significant in cataractogenesis so the variation between the measured patient and phantom-derived predictions is not critical.

The phantom-derived dose indices were judged to be sufficiently comparable to the indices obtained from the clinical patient measurements to justify using them with the EAP values as a practical means of evaluating the magnitude of exposures during cardiac catheterization.

Population Predictions

By reviewing the differences in types of cardiac catheterization procedures in combination with the variation in patient description, it can be seen that the calculation of typical exposure values is difficult. Accurate dose estimates can only be made on a patient-by-patient basis where the individual factors can be appropriately accounted for.

Although these limitations are recognized, the phantom-derived dose index values have been utilized in conjunction with the typical examination conditions observed in the UF cardiovascular laboratory to estimate mean and limit values. These values are given in Table 39.

For the Group I patients the total EAP value was assumed to be equally split between fluoro/cine and AP and LAT radiography. For the 5 to 7 year old patient group the fluoro/cine operation was equally divided between the nominal six and nine inch modes. The image intensifier was operated exclusively in the six inch mode for the less than 1 year old patients.

The contribution from fluoro and cine for the Group II patients examined in the rotation cradle was assumed to be equally divided. The fluoro EAP contribution was equally divided between the PA and oblique geometries for the two intensifier modes of operation. All cine was assumed to be carried out in the nominal six inch mode with the oblique projection used 75% of the time.

The body surface exposure estimates were based on the subsample of patients monitored with TLD since accurate beam size information was available to facilitate conversion of EAP to exposure units. The integral dose values were obtained using the EAP conversion factors developed by Carlsson (1963) as described in Appendix F.

TABLE 39

Summary of Exposures Received by Selected Patient Classes During Cardiac Catheterization with Estimations of Selected Dose Indices

| Patient Exposure Index | Group I Patients <1 Year Old Mean (range) | Group I Patients 5-7 Years Old Mean (range) | Group II Patients (examined in cradle) Mean (range) |
|--|---|---|---|
| Total incident EAP (R.cm ²) | 917(107-2,987) | 1,643(139-3,249) | 3,951(437-11,079) |
| Total incident exposure ^a (R) | 15(9-34) | 23(17-27) | 57(17-171) |
| Integral dose ^b (kg.rads) | | | 47(5-132) |
| Bone marrow dose (mrad) | 2,272(265-7,400) | 1,457(123-2,880) | 1,343(149-3,766) |
| Lens of eye dose (mrad) | 41(5-134) | 52(4-104) | 7(1-19) |
| Thyroid dose (mrad) | 1,095(128-3,567) | 536(45-1,059) | 144(16-403) |
| Ovarian dose (mrad) | 254(30-829) | 100(8-198) | 15(2-43) |
| Testicular dose (mrad) | 48(6-155) | 11(1-22) | 8(1-22) |

^aEstimated for patients monitored with TLD only (value not associated with a single site).

^bR.cm² values converted to integral dose using data of Carlsson (1963) as discussed in Appendix F.

The mean EAP values are seen to increase with patient age with the value for the adult Group II patients being 4.3 times that reported for the Group I patients less than 1 year old. This increase is, in turn, reflected in the mean patient surface exposure which increased from 15 R for the infant to 57 R in the Group II adults. A maximum body surface exposure of 171 R was determined for an individual in the Group II TLD monitored subgroup. This exposure value was determined from the EAP reading, and it must be kept in mind that since the patient is rotated during the examination no individual surface skin site would be expected to receive this total amount of exposure. For the smaller pediatric Group I patients the primary beam(s) intercept a greater portion of the total body surface than for an adult. The maximum skin exposure would thus be expected to more closely approach the estimated surface value.

Although EAP and incident surface exposure values were observed to increase with patient age, all other organ doses decreased. This is directly related to the increase in patient size with age and the resultant decrease in the number of critical tissue sites in or in close proximity to the primary beam.

In all cases the bone marrow received the highest dose and must be considered the critical dose-limiting organ system. Of second importance is the thyroid. The phantom estimated infant thyroid surface dose (anterior neck skin surface) was

shown to be approximately one-third that measured in a limited patient sampling. If this correlation accurately reflects the general situation, the thyroid exposure to the young child may be highly significant. The ovarian dose was found to be greater than the male testicular value.

Comparison with Other Published Data

Table 40 summarizes patient radiation exposure values reported by various authors. Detailed comparative analysis is difficult due to differences in patient populations, equipment dosimetry and procedural techniques. The range associated with all the reported data is seen to vary widely as the values did in the UF patient study. Comparison of the various reported mean values with the UF data shows general agreement within an order of magnitude. In spite of the unquantified differences in patient, equipment and techniques that exist from facility-to-facility, the comparability suggests that the results of this study could be used to make preliminary dose estimates for a wider sampling of cardiac catheterization patients.

TABLE 40
 Summary of Patient Radiation Exposure During Cardiac Catheterization
 Reported by Various Authors

| Dosimetry Parameter and Reference | Patient Population Description | Reported Value Mean (range) |
|--|--|------------------------------------|
| <u>Total Incident Exposure (or dose)</u> | | |
| Larsson (1956) | Adult (n=32) | (<25-209) R |
| Gaugh et al. (1968) | Adult and Pediatric (n=85) | 47(1-131) rad |
| Ardran et al. (1970) | Adults fluoro only (n=54) plus cine (n=23) | 21.4(1.2-91.8) R 2.5(1.8-9.2) R |
| Malsky et al. (1972) | Adult males (n=12) | (24-73) R |
| <u>Integral Dose</u> | | |
| Kaude and Svahn (1974) | Adult (n=10) | 58(17-101) kg.rad |
| <u>Bone Marrow Dose</u> | | |
| Gaugh et al. (1968) | Adult and Pediatric (n=85) | 1.4(0.028-3.81) rad |
| Seidlitz and Margalis (1974) | Adult (n=10) | 1.7(0.76-2.9) kg.rad |

^a Assumed to be adult patients but not specified by authors.

TABLE 40 Continued

| Dosimetry Parameter and Reference | Patient Population Description | Reported Value Mean (range) |
|--------------------------------------|------------------------------------|--------------------------------|
| <u>Gonad</u> | | |
| Gaugh et al. (1968) | Adult and Pediatric male (n=48) | 25 (2-80) |
| Kaude and Svahn (1974) | female (n=37) | 39 (1-100) |
| | Male adult | 42 (6-108) |
| | shielded (n=5) | 4 (<2-7) |
| | unshielded (n=5) | 280 (12-900) |
| | Male pediatric | 13 (3-27) |
| | shielded (n=12) | mrad |
| | unshielded (n=12) | mrad |

CHAPTER VIII
SUMMARY AND CONCLUSIONS

Detailed radiation studies in the UF cardiovascular laboratory and field surveys in other Florida facilities have confirmed the anticipated high potential for significant radiation exposure to patients and personnel involved with x-ray cardiovascular special procedures.

Personnel Exposure

Personnel monitoring records for 38 physicians and 45 technologists associated with 10 Florida cardiac catheterization facilities were reviewed. The locations of the primary monitoring badges were about equally divided between over and under apron positions. Four physicians were found to use duplicate badges so that values for both sites could be determined, but single monitoring sites were used exclusively by the technologists.

The yearly mean dose equivalents at the under apron site were 184 and 251 mrem for the physicians and technologists respectively. At the over apron position the yearly mean values were 1,376 and 625 mrem. The ratio of the shielded to unshielded value is seen to be significantly different with

a value of 7.5 for the physicians and 2.5 for the technologists. This variation may be related to differences in the lead equivalent thickness of the protective aprons worn by the two groups, or variations in workload and procedural duties for the individuals utilizing the respective badge sites. Due to the limited sample population and method of information retrieval, the reason for this difference could not be determined.

In Chapter IV, the published data reporting estimated occupational exposure levels were reviewed. Klement and colleagues (1972) listed mean values for medical x-ray workers in the U.S. ranging from 83 to 320 mrem/year. The United Nations Scientific Committee (1972) reported a similar range for world-wide medical x-ray workers of 70 to 380 mrad/year with the U.S. estimate as 340 mrad/year. These values were based on personnel exposure records, but no information regarding the badge site was given.

If it is assumed that similar under apron and over apron practices exist for medical x-ray workers in general, as was observed in the ten Florida cardiac catheterization facilities, the mean exposure for this subpopulation can be compared to the U.S. mean values.

For the Florida sample, the estimated yearly exposures from the unadjusted personnel monitoring records are 723 mrem for physicians and 417 mrem for the technologists. If the assumptions are correct, these values suggest that

exposures to cardiac catheterization workers may be as much as twice that of medical x-ray workers in general.

Detailed personnel exposure measurements were carried out in the UF cardiovascular laboratory. The exposure received by physicians conducting adult patient studies was at least twice that received by physicians involved with pediatric examinations. The lens of eye and thyroid were found to be the critical dose-limiting sites. The lens of eye was also shown to be the critical tissue for the technologists.

On a per procedure basis, the technologist generally receives less exposure than the physician. When the individual procedure values were converted to anticipated yearly estimates by taking into account typical personnel workload factors, the lens of the eye value for the technologist was slightly greater than for the physicians.

Based on the significant potential for high exposures to personnel during cardiac catheterization, radiation safety is an important consideration in the setup and operation of a laboratory. The input of a medical or health physicist should be included during the initial planning and operational phases.

The layout of the procedure room and configuration of the x-ray source(s) and examination table are of key importance. Appropriately designed protective shielding must be used by all personnel. A wrap-around apron that also

provides shielding to the neck (thyroid) should be used. Since the eyes were shown to be the critical dose-limiting organs for both physicians and technologists, the use of some type of high-density glasses may be appropriate.

For the physician and technologist working in close proximity to the patient, the use of two monitoring badges is recommended. One should be located at the head or neck level at a position external to the lead apron (a site on the collar or shoulder nearest the patient is recommended). The second badge should be positioned on the hand or wrist. The exact location of the badge should be established in relationship to the anticipated scatter radiation contours around the examination table and the position of the personnel during the procedure. The recommended site must be clearly understood by each individual and should be recorded as part of the personnel exposure record.

Patient Exposure

Dosimetry studies using phantoms and clinical patients examined in the UF cardiovascular laboratory were carried out to investigate the dose to various organ systems including the gonads, bone marrow, thyroid and lens of the eye. The bone marrow was found to receive the highest dose in both adult and pediatric patients and may be considered the critical organ system of interest with relation to somatic

effects. For the pediatric patient, the dose received by the thyroid may also be of concern.

The ICRP (1973) has identified the examinations for coronary arterial disease as a protection problem of current concern in which very high exposures are to be expected and maximum effort needs to be continuously exerted to ensure that exposures in these examinations are no higher than necessary. They recommend that the fluoro, cine and radiographic exposures utilized in these procedures be recorded.

The use of EAP measurement systems offers a practical approach to this measurement problem. The $R.cm^2$ value determined with these instruments can be easily converted to surface exposure or integral dose values. Through the use of phantom-derived dose index values, the measured EAP values can be related to selected organ doses.

The majority of cardiac catheterization examinations performed involve adult coronary angiographic procedures. The significance of the radiation exposure in these procedures must be evaluated with respect to the patient's age and life expectancy. The majority of the patients suffering from coronary artery disease are beyond the reproductive age and the genetic consequences of the radiation exposures are usually of minimal concern. The potential for somatic effects must also be viewed in relation to the less-than-normal life expectancy for this class of individual.

At the present time statistical descriptions of the adult cardiac catheterization patient population are not available but would be expected to be heavily weighted in the older age groups with advanced coronary complications. As the number of trained personnel and cardiac catheterization facilities increase it is likely that a younger patient population, whose genetic and life expectancy is significantly different from that presently seen, will be routinely examined. The possible catheterization of asymptomatic subjects in certain occupational areas, such as airline pilots, has also been suggested. The efficacy of these examinations must be questioned.

For the pediatric congenital heart patient the situation may be quite different. Individuals in this group are often catheterized at a very young age and the frequency of recatheterization, as observed in this study, is higher than for the adult acquired heart disease patient. With the advent of new and more successful surgical techniques many of these patients will have normal life expectancies. In this situation the genetic and somatic consequences are of paramount concern.

X-ray Equipment Alternatives

Radiation protection for the patient undergoing a cardiac catheterization examination involves acquisition of the necessary diagnostic information with the minimum

radiation exposure. The two areas where this minimization can be achieved are in the examination techniques used by physicians and the configuration and exposure characteristics of the x-ray equipment. These areas are closely inter-related; the examination procedure may be dictated in a large degree by the characteristics and limitations of the equipment. In the equipment area, every advantage must be taken of new technology. In cardiac catheterization, the use of intermittent pulsed fluoro and fluorography as a substitute for serial radiographic procedures appears promising.

Pulsed Fluoroscopy

During cardiac catheterization, fluoro is used as a visualization technique to assist the physician in placement and manipulation of the indwelling catheter. The diagnostic information is primarily derived from the angiographic, hemodynamic and electrocardiographic procedures. Therefore, during the fluoro visualization phase the information content provided by the normal television setup utilizing a double interlaced 30 Hertz (Hz) frame (two fields) rate may be much more than is required by the physician who is only interested in knowing the position of the catheter. Pulsed fluoro systems utilizing video disk recorders or image storage tubes have been proposed for applications of this type.

Dorph and colleagues (1970) and Grollman and colleagues (1972,1974) have reported on video disk systems. The unit

described by Grollman was utilized for adult cardiac catheterization studies. In the Grollman system, the video disk recorder was operated in a synchronous fashion with a grid-controlled x-ray source. During the 1/60th of a second associated with one field of the double interlaced television display, the x-ray source is gated on and the resultant image stored on the video disk recorder. The disk which is rotated at 60 Hz can be played back each 1/60th of a second so that a continuous display is viewed on the monitor. Since only one field of the usual double interlace display was used, a 945 line television system was substituted for the standard 525 line system to increase vertical resolution in this system.

With the Grollman system the operator could select the desired pulse rate over a range of 15 to 15/16 pulses per second. Operation at 15 and 7-1/2 fields per second have been used during cardiac catheterization. At 15 fields per second, no loss of continuous smooth movement can be seen on the monitor; whereas, at a frequency of 7-1/2 fields per second some loss is apparent. Grollman states that no objection was found at the 15 per second rate and only a few physicians expressed concern over the fact that they thought they might be losing some required information at the 7-1/2 per second rate. During actual clinical studies, Grollman states that the use of this technique did not result in any

increase of the overall fluoro time necessary for an adult catheterization procedure and he found a typical reduction of overall patient exposure of 50%.

A theoretical evaluation of the degree of exposure reduction that can be achieved by use of a pulsed fluoro system has been reviewed by Siedband (1973). He contends that if the fluoroscopists require the same image quality in pulsed mode operation as that obtained during continuous real time fluoro, no dose reduction can be achieved for pulse rates faster than five per second. This prediction is based upon a typical integration time for the eye of 0.2 seconds. For an image of equivalent quality (i.e., equal signal to noise ratio) the same amount of quantum information must be present in a single or series of multiple frame images.

If this conclusion is correct the pulsed images available from the Grollman system, which were obtained at rates faster than the five per second limit, would have been expected to be of reduced image quality. This, in turn, may indicate that during the fluoro portion of a cardiac catheterization examination a pulsed image with some reduction in image quality is acceptable.

The design of a pulsed image system for use in cardiac catheterization might logically employ a lead oxide TV tube used in conjunction with a video disk recorder operating in a field (one-half interlaced frame) storage replay mode. The lead oxide TV tube is superior to a vidicon since it can be

read out after the second observed field (1/30th second) as opposed to a required three or four fields for the vidicon. The half frame, field storage mode of operation would also seem more logical for this application where resolution is not of primary importance. Although vertical resolution would be lost by viewing a single field as compared to full frame viewing, a savings in exposure is realized. The problem of interframe jitter that can exist with full frame replay of a moving object will also not be present in the field mode of operation.

Although it can be expected that some decrease in patient exposure will result from utilizing pulsed fluoro, an accurate prediction cannot be made. The limits to which image quality and pulse rate can be reduced must be established under clinical situations. Grollman's work indicates that operation at 7-1/2 fields per second with an assumed reduction in image quality is acceptable during adult cardiac studies. If these values represent the minimum for adult studies and if these same conditions are applicable to pediatric congenital heart studies is presently unknown. Although a considerable number of unknowns exist, a predicted reduction in the fluoro exposure by at least a factor of two seems within reach. This value is consistent with operation at 7-1/2 fields per second with a times two boost in the exposure rate to partially compensate for the loss in signal-to-noise ratio associated with the pulse mode operation.

Fluorography

A second area where an equipment change may result in a reduction of exposure would be the substitution of fluorographic techniques for the serial film techniques usually employed in congenital studies. Fluorographic techniques typically utilize a 70 or 105 mm camera coupled to the x-ray image intensifier. The exposure per frame of information required for operation in this mode is less than that required for conventional radiographic film. The actual difference in exposure between the two methods depends on a number of factors which include the conversion efficiency of the intensifier and optical chain, as well as the field size, film type and development scheme. Carlsson and Kaude (1968) state that a 70 mm fluorograph required approximately 12% of the exposure of that for a full size radiograph taken with medium-speed screens and high-speed film. For a 105 mm fluorographic camera adjusted for 100 micro R per frame at the intensifier input (external input surface of image intensifier tube), Maddison and Handel (1974) report the fluorographic system required an exposure level 20% of that necessary for radiographic exposures in a serial film changer.

Kaude (1967) has discussed the potential of dose reduction by use of 70 mm fluorography in a number of selected radiographic procedures. He and co-authors have reported on the use of this technique as compared to other modes of

filming during hysterosalpingography, gastrointestinal examinations and voiding urethrocytography (Bang and Kaude (1967), Carlsson and Kaude (1968), Kaude and Reed (1969) and Kaude, Lorenz and Reed (1969)). Although DeVilleneuve (1973) has discussed his use of 70 mm fluorography for congenital heart studies at his institution in the Netherlands, the use of 70 mm techniques for congenital heart studies in the U.S. has not as yet been accepted. Certain restrictions, such as film size and limitation of resolution of the 70 mm format when compared to conventional serial radiographic films may be the reason. The larger 105 mm cameras now available may answer some of the objections associated with the 70 mm.

To carry out an angiographic study with the serial radiographic film changers, the catheter is first positioned at the desired site with the aid of fluoro. The patient must then be moved over the serial changer for the angiographic exposure. Since fluoro can no longer be carried out the physician has no means of knowing if the catheter is still at the desired site or has unknowingly been shifted out of position during the patient repositioning procedure. The adequacy of the examination can only be determined following the development and viewing of the films. If fluorography techniques were used, the patient would not be required to be moved and the status of the catheter could be determined up to and during the actual angiographic injection. By this procedure the possibility of achieving the desired results

during the initial angiographic series is increased. An immediate evaluation of the adequacy of the diagnostic results can instantly be determined. If the catheter was misplaced during the injection phase, the x-ray exposures could be terminated and not allowed to go to completion as is the usual case with a programmed serial changer.

Serial film changers are usually equipped with a programming device which allows the operator selection of the rate and number of films that are to be exposed during an angiographic series. The programmer is provided to overcome the inherent limitations of the changers relating to the maximum number of films that can be loaded at one time. Secondly, limitation of heat loading of the x-ray tube and reduction of exposure to the patient are also achieved by use of the programming device.

During pediatric congenital heart studies carried out in the UF cardiovascular laboratory biplane serial radiography is the primary mode of filming. An acceptable amount of information is presently obtained using Elema Schonander cut film changers. These changers, which hold a maximum of 30 films, can operate at rates up to six films per second. During an angiographic study the programmer is usually set so that the changer is operated at the maximum rate of six frames per second during the initial two or three seconds while the bolus of contrast media is concentrated in the site of interest. Following this initial phase the films are

exposed at some reduced frequency. During actual procedures, it is rarely necessary to utilize the full capacity of the changers. Eighteen to 22 films per changer are usually sufficient.

Presently fluorographic cameras are not equipped with similar programming capabilities. The operator can select various frame rates, but once the camera is in motion this setting cannot be changed. The on-off initiation of the exposure is usually controlled by an operator foot switch. A fluorographic camera such as the General Electric 105 mm unit will hold film sufficient to expose 400 frames and can operate at rates up to 12 per second. The possible dose reduction that might be achieved by substitution of this mode of filming for a serial film changer could not successfully be achieved by operating at a fixed frame rate with manual exposure control. A programming device used in conjunction with a grid controlled x-ray source would have to be developed.

Application of Predictions to Patient Data

The predicted performance characteristics of the pulsed fluoro and 105 mm fluorographic systems have been applied to the patient dosimetry data to estimate the expected overall reduction in patient exposure that might be achieved. The pulsed fluoro system was assumed to result in a reduction of exposure by one-half. For the 105 mm fluorographic camera the factor of five reduction specified by Maddison and Handel

has been used. The results in Table 41 show a reduction of approximately 63% for the Group I congenital studies. For the adult Group II patients a 25% reduction would be expected for studies such as coronary angiography. The 105 mm fluorographic would not be expected to be used for adult pulmonary or aortic angiographic studies. A reduction of 13% would, therefore, possibly be expected to be achieved in this type of examination by using pulsed fluoro. During conduction studies fluoro only is used. The exposure reduction is thus directly related to the performance of the pulsed system.

Radiation Protection Criteria
for Cardiac Catheterization Facilities

The Inter-Society Commission on Heart Disease Resources (ICHHD) has published recommendations regarding the optimal setup and operation of a cardiac catheterization-angiographic laboratory (ICHHD, 1971). The ICHHD is still active and through its radiological study group a revision of these recommendations are currently near completion. The following recommendations, drawn primarily from the observations and findings of this study, were prepared for inclusion in the revised committee report.^a

^aPrepared in cooperation with Dr. Larry P. Elliott, Cardiovascular Radiologist, University of Florida. Dr. Elliott is a working member of the ICHHD radiological study group.

TABLE 41

Estimated Patient Exposure Reduction by Use of Pulsed Fluoroscopy and 105 mm Fluorography

| Patient Classification Group ^a | Age Range (years) | Percent Total EAP | | Predicted Exposure Reduction by use of Specified Technique (percent) | | | |
|---|-------------------|-------------------------|--------|--|---------------------|--------------------------------|----|
| | | Fluoro Cine Radiography | Fluoro | Pulsed Fluoro (7.5 fields/sec with x2 boost) | 105 mm Fluorography | Fluorography and Pulsed Fluoro | |
| I | < 1 | 42 | 3 | 54 | 21 | 43 | 63 |
| | 1 | 42 | 6 | 51 | 21 | 41 | 62 |
| | 2 | 33 | 5 | 62 | 17 | 50 | 67 |
| | 3 | 40 | 2 | 58 | 20 | 46 | 66 |
| | 4 | 40 | 10 | 50 | 20 | 40 | 60 |
| | 5 | 29 | 7 | 64 | 15 | 51 | 66 |
| | 6 | 44 | 7 | 49 | 22 | 39 | 61 |
| | 7 | 24 | 6 | 70 | 12 | 56 | 68 |
| | 8 | 37 | 6 | 57 | 18 | 46 | 64 |
| | 9 | 29 | 5 | 66 | 15 | 53 | 68 |
| | 10 | 44 | 9 | 47 | 22 | 38 | 60 |
| | 11 | 27 | 23 | 50 | 14 | 40 | 54 |
| ≥12 | 38 | 11 | 52 | 19 | 42 | 61 | |
| Mean | | 36 | 8 | 52 | 18 | 45 | 63 |
| IIa | <30 | 48 | 52 | | 24 | | 24 |
| | 30- <40 | 52 | 48 | | 26 | | 26 |

^a Patients in Group II consisted of (IIa) examinations in rotation cradle, (IIb) pulmonary and aortic, angiography and (IIc) conduction studies.

TABLE 41 Continued

| Patient Classification Group ^a | Age Range (years) | Percent Total EAP | | Predicted Exposure Reduction by use of Specified Technique (percent) | | |
|---|-------------------|-------------------------|-----------|--|---------------------|--------------------------------|
| | | Fluoro Cine Radiography | Fluoro | Pulsed Fluoro (7.5 fields/sec with x2 boost) | 105 mm Fluorography | Fluorography and Pulsed Fluoro |
| IIa | 40-<50 | 39 | 61 | 20 | | 20 |
| | 50-<60 | 51 | 49 | 26 | | 26 |
| | >60 | <u>47</u> | <u>53</u> | <u>28</u> | | <u>28</u> |
| | Mean | 47 | 53 | 25 | | 25 |
| IIb | 55- 75 | 26 | 29 | 13 | | 13 |
| IIc | 39- 83 | 100 | | 50 | | 50 |

^a Patients in Group II consisted of: (IIa) examinations in rotation cradle, (IIb) pulmonary and aortic, angiography and (IIc) conduction studies.

Equipment and Facility Design

The x-ray equipment and procedure room should be designed and maintained to meet accepted radiation protection criteria (NCRP, 1968 and 1970; ICRP, 1970). Many of these requirements will be met for x-ray systems manufactured after August 1, 1974 under the Federal performance standards for diagnostic x-ray equipment (42 CFR 1020-30,31,32). Every attempt should be made to upgrade older systems not covered by these requirements.

In addition to the requirements consistent with accepted radiological health criteria for diagnostic x-ray installations, as outlined in the aforementioned references, the following aspects are considered of particular importance for cardiac catheterization laboratories.

Beam limitation for fluoroscopy, cine and spot film fluorography

The x-ray equipment shall be designed to allow x-ray production only when the primary beam is aligned and completely intercepted by the image intensifier for fluoro and cine. The primary physician and assisting personnel should never be positioned so that any portions of their bodies intercept the primary beam. Consequently, the major source of exposure to all personnel within a catheterization laboratory is secondary or scattered radiation. The following are suggestions regarding equipment design for primary beam limitation and protection of personnel from scattered radiation.

Primary beam. Adjustable triple-leaf beam-limitation devices (collimators) with or without additional cones to limit the x-ray field should be utilized. If the fluoroscopist requires visualization of the entire circular image produced by the intensifier, a circular beam-limiting device should be employed. The beam-limitation system should be designed to limit the primary beam to no greater than the dimensions of the visible image. When the x-ray tube image intensifier combination allows independent movement of the image intensifier and/or x-ray tube, the unit should be designed so as to limit the field size at the plane of the intensifier input phosphor to no greater than the dimensions of its visible image. On units equipped with a dual or triple mode intensifier, the beam shall be automatically limited to the dimensions of the particular mode in use.

Scatter. To reduce scattered radiation from the under table tube to as low a level as possible, the following criteria should be followed:

- a. For units with an under table x-ray tube and over table image intensifier, shielding should extend up along the sides of the table to the edge of the table top. In the advent of an add-on cradle which positions the patient above the table surface, shielding should extend up to the cradle edge. In most laboratories with add-on or portable cradles, this form of shielding is not in current use. The elevated position of the add-on cradle

creates an exit port allowing back or side scatter radiation to strike the hands and mid-body region of any person adjacent to the table. The floating-top table surface, which is not used for patient support when a cradle is in use, also increases scatter, which in turn reduces image quality. To maintain the rotational cradle concept, yet abolish the air gap, a table with interchangeable tops should be utilized.

b. Caution should be exercised in the use of equipment of the so-called C- or U-arm configuration. In this unit, the patient remains horizontal while the x-ray tube and intensifier are moved in an arc around the patient. Scatter shielding is difficult to adapt to a unit of this type. As a result, the degree of scattered radiation to operating personnel is high. Limitation of use may be the only acceptable means of maintaining adequate personnel protection.

c. An installation with over table x-ray tube and under table intensifier shall not be used.

d. A detailed determination of isoexposure levels around the x-ray unit shall be made to establish the optimal position for operating personnel. Scattered radiation levels should be obtained with a phantom which approximates the geometry of a typical patient. For personnel required to remain in the room during fluoro or filming, these data will establish areas of

minimum exposure. In addition, design and placement of monitoring equipment, etc., should be made based upon knowledge of these scatter levels.

e. A shielded control room should be included as part of the installation. This should house the main x-ray controls, physiological monitoring equipment, and any other items (i.e., scrub sink) which are nonessential to room use.

Mechanism for primary physician to monitor operational status of x-ray system

The x-ray system should be designed and installed so that the physician conducting the examination can determine the operational status of the fluoro/cine imaging system(s) throughout the entire procedure. Of primary importance is an indication of the brightness level of the image intensifier and the heat loading status of the x-ray tube. The brightness level indication will assure him that the cine films are being exposed to a light intensity consistent with adequate film recording. Knowledge of the moment-to-moment heat loading status of the x-ray tube and housing will allow him to carry out the procedure within the restraints posed by the x-ray equipment.

Of slightly less importance, although highly desirable under ideal conditions, is a system that will provide an indication of the technique factors such as x-ray tube voltage, current or pulse width which is varied automatically by the

x-ray unit or that is required to be adjusted manually to achieve an adequate brightness level. These indications should also be located so that the physician conducting the examination can see them from his usual operating position.

Dose reduction in relation to mode of imaging

Whenever possible a mode of x-ray examination consistent with acquisition of sufficient diagnostic information with the minimal radiation exposure should be utilized. Examples of possible choices include:

1. Video disk pulsed fluoro.
2. Cine film and radiographic film-screen combinations which require minimum radiation exposure.
3. Substitution of 105 mm fluorographic techniques for situations where large film seriographic techniques were ordinarily used.
4. Limitation of cine frame rate to the minimum necessary to obtain the necessary diagnostic information.

Fluoroscopic timer

A cumulative fluoro timing device shall be provided as part of the x-ray control. This device shall indicate the status of fluoro time by an audible signal emitted at time intervals of 5 min or less. The timing unit shall also provide a total cumulative time for an entire procedure. Indication of this total cumulative time should be visible to the physician performing the procedure.

Method of quality control of the radiologic facility

All cardiac catheterization facilities shall be evaluated by a qualified radiological physicist.

1. In the case of a new facility the physicist should be involved during the planning stage. Following installation a complete radiological evaluation shall be performed prior to patient studies.

2. In the established laboratory, periodic evaluation of the radiographic facility at time intervals of six months or less should be made. There are numerous equipment functions that should be periodically evaluated. Those such as the interlocking between the x-ray tube and image intensifier are usually straightforward. On the other hand, slow deterioration of the image intensifier system may go undetected. With the latter, this may involve two major areas: (a) a decrease in quantum conversion efficiency requiring a higher incident x-ray level to achieve the necessary output brightness (more radiation) and (b) a reduction of image resolution capabilities which reduces the quality of diagnostic information available (i.e., radiation adequate, but intrinsic defect in imaging capability of system). Periodic testing of these systems will identify these changes.

3. Following manufacturer service adjustment or replacement of components (x-ray tubes, intensifiers, etc.) a check of system performance should be made.

Examination and Operational Techniques

Apart from the design and installation of the x-ray equipment and facility, reduction of exposure to patients and personnel can only be assured through certain precautions associated with the examination and operational techniques.

Personnel

Radiation monitoring. For occupational exposed personnel, yearly exposure limits are established (Table 42 lists the maximum annual permissible dose equivalent values for occupational exposures to various parts of the body). A maximum exposure of 5 rems/year for whole body exposure is specified. The lens of the eye, gonads and red bone marrow are considered the critical organs for this whole body limit. For an individual wearing a lead apron, the gonads and the major portions of the red bone marrow are shielded, resulting in the eyes being the critical limiting organ. In addition, the next most sensitive portion of the body that is not covered by the lead apron is the thyroid, which has a yearly limit of 15 rem.

A personnel monitoring device, film or TLD badge, should be worn by all personnel. This monitor should be located at the head or neck level at a position external to the protective lead apron.

TABLE 42
Occupational Dose Limitation Recommendations
Suggested by the NCRP

| <u>Portion of Body Exposed</u> | <u>Prospective Annual Limit^a (rem/year)</u> |
|--|--|
| <u>Whole Body</u> | 5 |
| Including lens of eye, gonads and red bone marrow | |
| <u>Skin</u> | 15 |
| Unlimited areas other than hands and forearms | |
| <u>Hands</u> | 75 |
| <u>Forearms</u> | 30 |
| <u>Other Organs, Tissues and Organ Systems</u> | 15 |
| (i.e., thyroid) | |

^aFrom (NCRP 1971)

For the physician and technician working adjacent to the patient, an additional hand or wrist monitor should be worn. The proximity of the hands and arms to the patient and

primary beam can result in high exposure. If exposure levels for these hand positions are shown to be consistently low their day-to-day use may not be necessary. To check on changes in technique and habit patterns, periodic rechecks (for example, every six months) should be carried out to reconfirm the acceptable low levels of exposure at these sites. In addition to maintaining a log of measured personnel exposure levels an indication of the site of measurement should be included as part of the permanent record.

Design of lead apron. The choice of lead apron design should be based on a knowledge of the work habits and tasks required of the wearer. For instance, if an individual is frequently positioned with his back to the patient, a full wrap-around design should be utilized. Although a separate waist apron worn on the back would provide some protection, it is not considered as acceptable as the single wrap-around design. The waist apron covers only the lower portion of the back and cannot be expected to be worn as consistently as the all-in-one wrap-around design. For the physician as well as the personnel working in close proximity to the patient a 0.5 mm equivalent lead apron should be worn. For those circulating in and out of the room, a 0.25 mm lead apron is usually adequate.

Position of personnel during x-ray. During radiographic procedures all personnel shall be behind a protective barrier. During cine fluorography auxiliary personnel not directly assisting the physician, shall step back away from the

procedure table and preferably behind a protective barrier. Neither the physician nor auxiliary personnel shall directly hold the patient for x-ray positioning purposes.

The physician conducting the examination should acquire the habit of verbally alerting the members of the examination team as to his intent to initiate fluoro or cine exposures whenever an individual is in a position where high exposure rates exist. Situations of particular concern exist when an individual with unprotected portions of his body might be present in the room. This could be an individual scrubbing in preparation to assist in the procedure with his back to the patient or any other individual in the room carrying out some task that does not allow him to keep in moment-to-moment contact with the physician's conduct of the examination. To prevent an individual from receiving an inordinate amount of radiation exposure, the various duties dealing with x-ray should be on a rotational basis.

Patient exposure

Patient exposure records. A record of fluoro time, as well as each separate mode of recording should be maintained. This can be done by recording the x-ray technique factors, kVp, mA and pulse width, etc., in addition to total time for fluoro and feet of cine film. If seriographic or fluorographic exposures are made, the x-ray techniques utilized and the number of films exposed should be recorded. Therefore, a

calculation of patient exposure can be made utilizing the aforementioned factors along with a knowledge of the output of the x-ray machine.

Because this type of data retrieval is laborious and time consuming, the use of a Roentgen-area-product ($R \cdot cm^2$) meter can be made. This device utilizes an ionization chamber mounted on the distal end of the x-ray beam-limiting device (collimator) and has a remote readout that will integrate the area exposure product for an entire procedure. A dual register readout can be used to automatically separate the fluoro and cine exposures. The initial installation and format for measurement should be established with the consultation of a radiation physicist.

Dose to reproductive organs. Whenever possible the gonads should be excluded from the primary beam. For patients who are capable of reproduction, the use of gonad shields should be used if the primary beam will intercept the reproduction organs.

- a. For adult patients of reproductive age where the gonads are greater than 5 cm from the edge of the primary beam, gonad shielding may be of limited usefulness (Bureau of Radiological Health, 1974) since scatter originating in the patient will be the major source of gonad exposure. Among females, external body shielding is of little use in reducing ovarian dose. In males only a male gonad shield which isolates the testes will

be effective. As a practical guide, unless other patient information indicates the contrary, persons above age 45 years need not be considered candidates for gonad shielding. Statistics show that over 95% of all babies in the U.S. are born to parents of age 45 or less.

b. The 10 day rule (ICRP, 1969) should be applied to female patients of reproduction age. This rule which calls attention to the embryonic and fetal sensitivity to ionizing radiation, states that all radiological examinations of the lower abdomen and pelvis of women of reproductive capacity that are not of importance in connection with the immediate illness of the patient, be limited to the period when pregnancy is improbable (the 10 day period following the onset of menstruation). Although cardiac catheterizations are not lower pelvic examinations, the high exposures and occasional visualization in the lower abdomen that are often associated with these procedures, makes it appropriate to apply this rule.

c. For pediatric patients, gonadal shielding should be utilized. Even if the gonads are not in the primary beam, the position of the reproductive organs with respect to the primary beam will be much closer than for the adult patient. Every attempt should be made to reduce this unnecessary exposure.

Identification of film. The marking of cine film with patient and institution identification information should be done without the patient in the beam.

Cine quality control

Maintaining quality control in all x-ray systems is the touchstone for obtaining the optimum amount of information with the least amount of radiation. In the area of cine, a routine evaluation of each of the facets of system performance should be made. Because of the complexity of the many varied components forming the cine imaging system (i.e., from generators to ultimate method of viewing), it is not feasible to check each component on a daily basis. The two major areas that are most subject to variation can be evaluated on a day-to-day basis. These are the conglomerate aspects (x-ray source, image intensifier, automatic brightness system, cine cameras and optical chain) of the exposure phase, and the film development phase.

A test of cine operation should be made at the start of each day. Ideally, this includes subjecting two strips of cine film to the following: (1) an x-ray exposure made utilizing a suitable test object, and (2) a film strip exposed with a regulated light sensitometer. The variation in the x-ray exposed strip would indicate problems in either the cine exposure system or development phase. Whereas,

variations in the sensitometer exposed strip can be isolated to processing problems alone.

In addition, it is recommended that a test phantom be included as part of the cine identification frames which are exposed to identify each roll of cine film. This procedure would provide an examination-by-examination index of system operation which may be useful in evaluating the long term operational status of the equipment.

APPENDIX A

X-RAY OPERATIONAL CHARACTERISTICS FOR EQUIPMENT IN
UNIVERSITY OF FLORIDA
CARDIOVASCULAR
LABORATORY

APPENDIX A

During biplane serial radiography the Philips "Maximus-100" x-ray generators were operated in the falling load mode. For pediatric radiography, the exposure time was set at 16 msec and the tube potential varied to achieve the desired exposure value. Figure A1 shows the variation in indicated mAs as a function of the kVp selector setting for operation in the falling load mode. Figure A2 shows the measured free air exposure at a source-to-chamber distance of 73 cm. This distance corresponds to the skin surface of a patient with a 14 x 16 cm AP and LAT chest dimension positioned on a pediatric restraint board (additional geometric factors are diagrammed in Figures 1 to 3 of Chapter II. Inverse square corrections must be applied for other source-to-patient distances.

Figures A3, A4 and A5 give table top exposure values from the under table fluoro/cine tube. Measurements were made on the flat table surface, at the surface of the pediatric restraint board position on the flat table surface and in the cradle. Data were obtained with and without a 15 cm thick water phantom to evaluate the effect of backscatter. All values were measured at a tube current of 1 mA. A linear correction can be applied to determine the output at other tube current values.

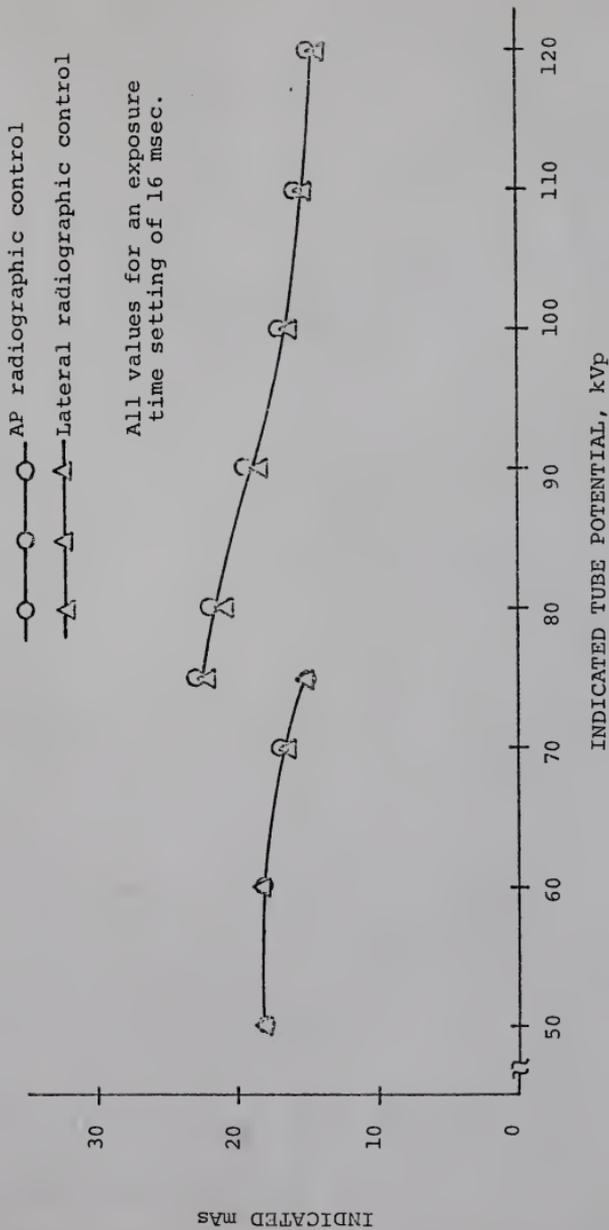


Figure A1. Indicated mAs for X-ray Tube Potential Settings on Philips "Maximus-100" Generators Operating in Iso-watt Falling Load Mode.

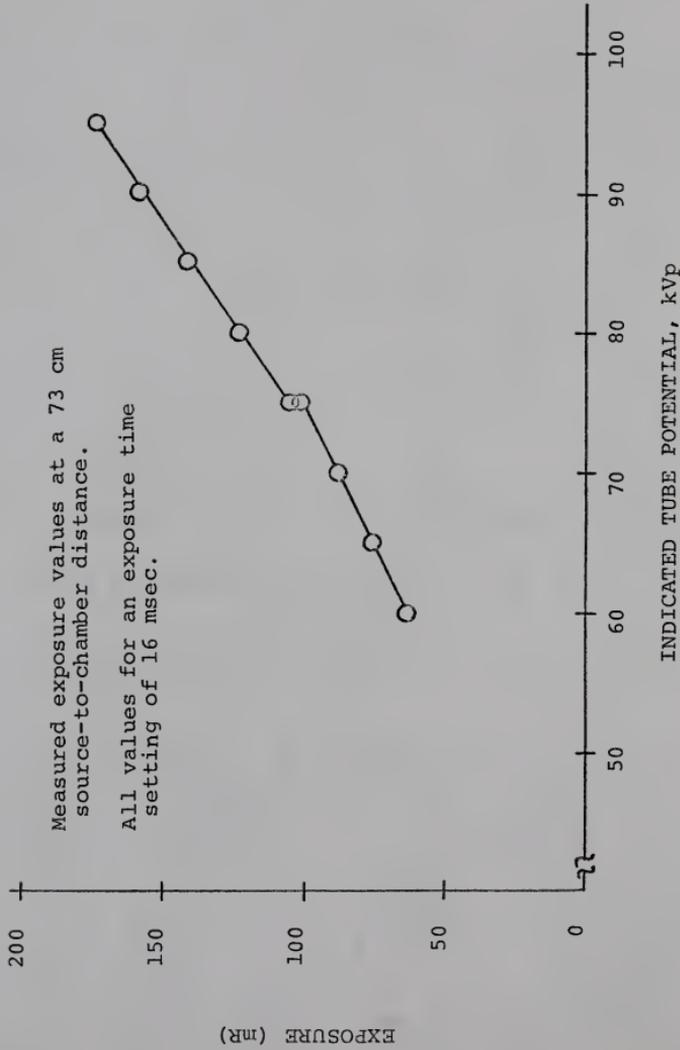


Figure A2. Measured Exposure as a Function of Tube Potential for Philips "Maximus-100" X-ray System Operating in Iso-watt Falling Load Mode.

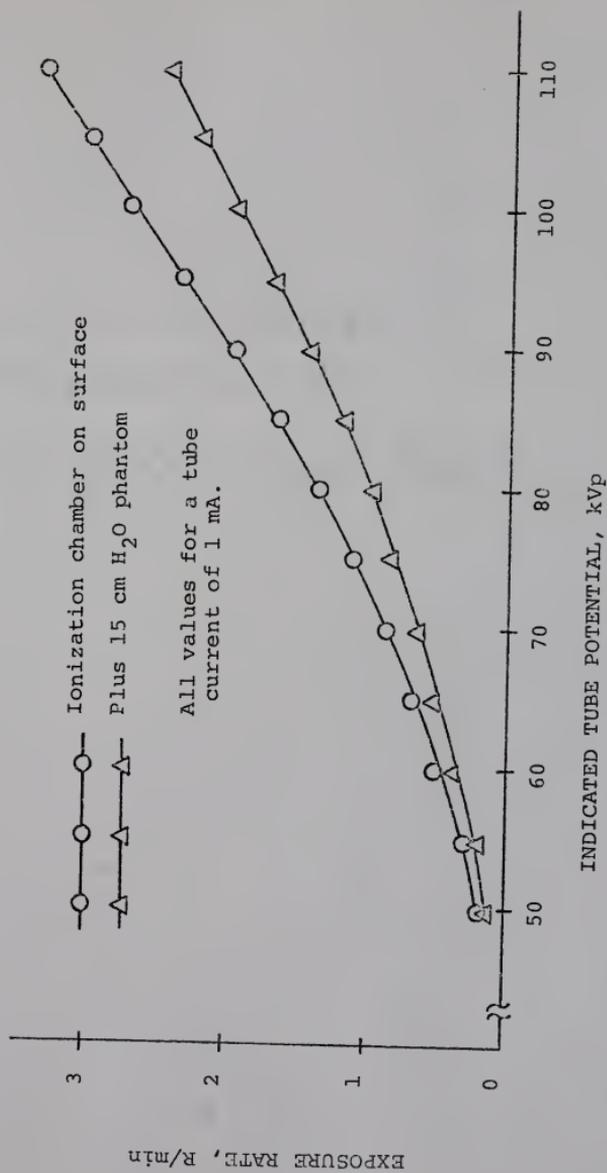


Figure A3. Measured Exposure Rate at Flat Table Surface From Under Table Fluoro/Cine X-ray Tube.

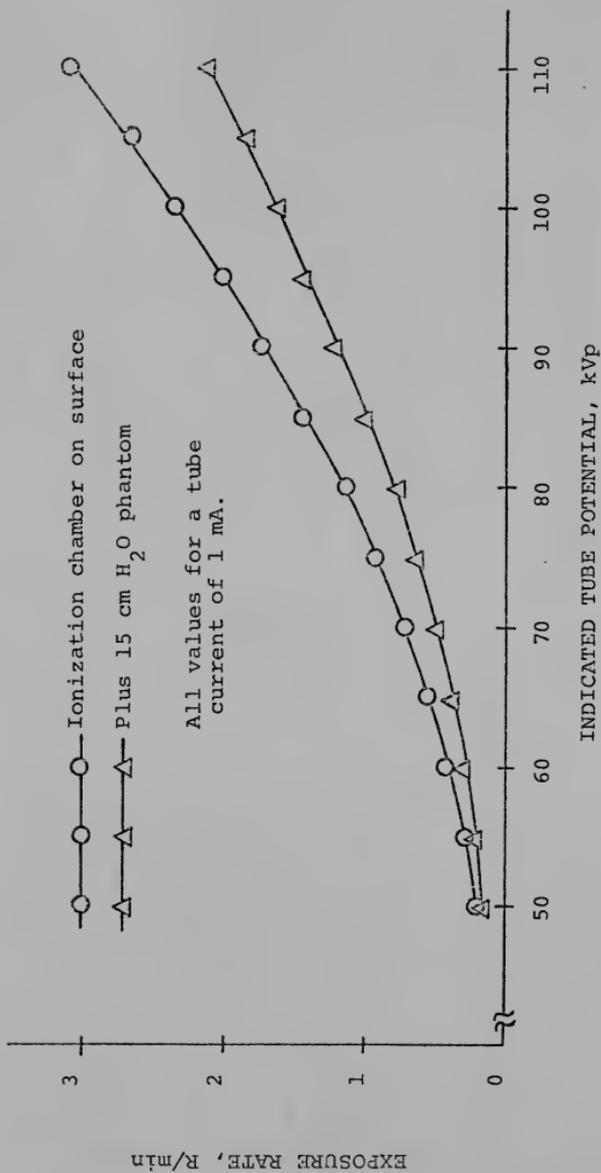


Figure A4. Measured Exposure Rate at Surface of Pediatric Restraint Board Positioned on Flat Table Surface from Under Table Fluoro/cine X-ray Tube.

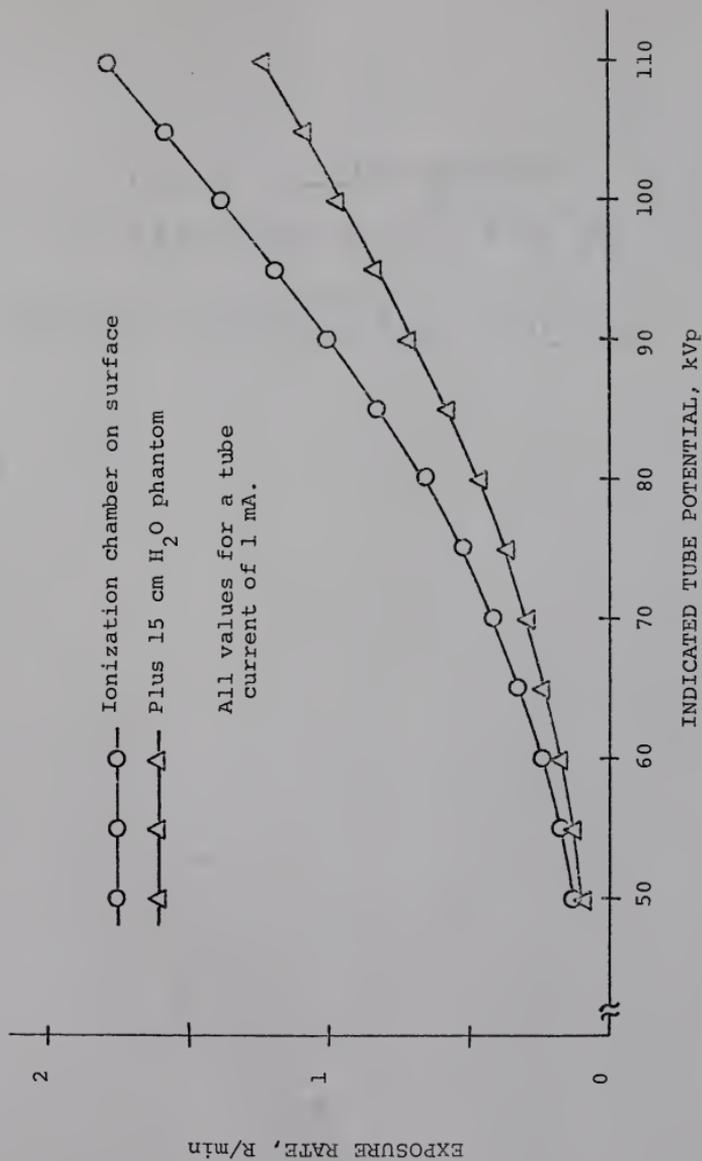


Figure A5. Measured Exposure Rate at Cradle Surface from Under Table Fluoro/Cine X-ray Tube.

The backscatter factor is a function of the beam size and quality of the radiation. During fluoro and cine radiography the beam size is usually restricted to the dimensions of the visible area of the input phosphor of the image intensifier. The variation in beam size during this mode of viewing will thus be much less than experienced during radiography. The variation of backscatter for fluoro and cine operation has thus been determined for a single beam size as a function of x-ray tube potential. The effect of backscatter for the three patient examination positions is shown in Figure A6. The values for the pediatric restraint board and for the cradle are seen to be similar and greater than those determined at the flat table surface. This difference is primarily due to the change in backscatter associated with the increased effective energy of the beam for the cradle or restraint board configuration (see Chapter II, Table 5 for HVL values).

Backscatter values for the serial biplane procedures were obtained from values published in the British Journal of Radiology (BJR) Supplement number 11 (1972). The values given in the BJR report are for circular fields. These data can be used for rectangular beam geometries by first determining the equivalent diameter for the respective rectangular field. Figure A7 shows the values for square fields obtained by this method.

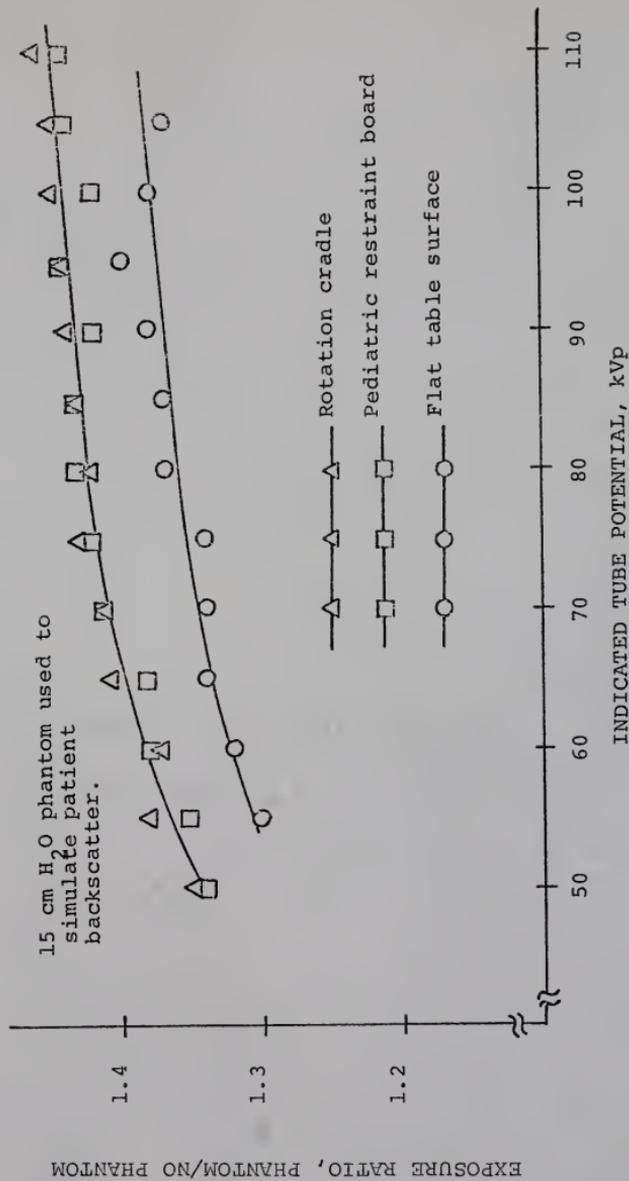


Figure A6. Effect of Backscatter on Surface Exposure Measurements.

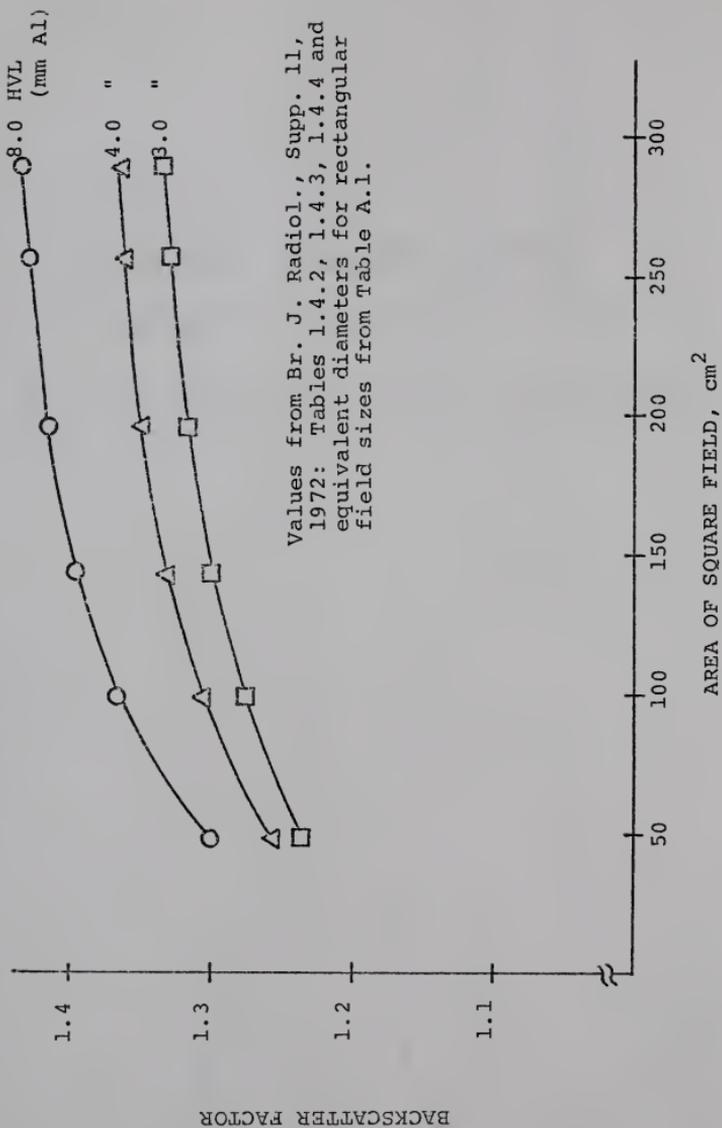


Figure A7. Variation of Backscatter Factor with Square Field Dimensions and Half Value Thickness.

APPENDIX B

PATIENT AGE DISTRIBUTION AND FLUOROSCOPY TIME

TABLE B1

Age Distribution For
Cardiac Catheterization Patients Less Than
18 Years Old Examined in the UF Cardiovascular Laboratory

| Age Classification (year) | Number of Individuals | | | Percent of all Patients <18 Years |
|---------------------------------|-----------------------|--------|-------|---|
| | Male | Female | Total | |
| 0.5 - < 0.5 | 384 | 314 | 698 | 26.8 |
| 0.5 - < 1 | 103 | 87 | 190 | 7.3 |
| 1 - < 1.5 | 61 | 51 | 112 | 4.3 |
| 1.5 - < 2 | 42 | 24 | 66 | 2.5 |
| 2 - < 2.5 | 45 | 30 | 75 | 2.9 |
| 2.5 - < 3 | 25 | 34 | 59 | 2.3 |
| 3 - < 3.5 | 35 | 32 | 67 | 2.6 |
| 3.5 - < 4 | 25 | 24 | 49 | 1.9 |
| 4 - < 4.5 | 42 | 30 | 72 | 2.8 |
| 4.5 - < 5 | 48 | 34 | 82 | 3.2 |
| 5 - < 5.5 | 68 | 50 | 118 | 4.5 |
| 5.5 - < 6 | 59 | 44 | 103 | 4.0 |
| 6 - < 6.5 | 50 | 49 | 99 | 3.8 |
| 6.5 - < 7 | 47 | 53 | 100 | 3.8 |
| 7 - < 7.5 | 31 | 29 | 60 | 2.3 |
| 7.5 - < 8 | 34 | 25 | 59 | 2.3 |
| 8 - < 8.5 | 37 | 22 | 59 | 2.3 |
| 8.5 - < 9 | 21 | 18 | 39 | 1.5 |
| 9 - < 9.5 | 29 | 12 | 30 | 1.2 |
| 9.5 - <10 | 30 | 14 | 44 | 1.7 |
| 10 - <10.5 | 26 | 12 | 38 | 1.5 |
| 10.5 - <11 | 25 | 19 | 44 | 1.7 |
| 11 - <11.5 | 11 | 15 | 26 | 1.0 |
| 11.5 - <12 | 21 | 22 | 43 | 1.7 |
| 12 - <12.5 | 20 | 15 | 35 | 1.3 |
| 12.5 - <13 | 18 | 18 | 36 | 1.3 |
| 13 - <13.5 | 15 | 12 | 27 | 1.0 |
| 13.5 - <14 | 16 | 10 | 26 | 1.0 |
| 14 - <14.5 | 16 | 14 | 30 | 1.2 |
| 14.5 - <15 | 15 | 12 | 27 | 1.0 |
| 15 - <15.5 | 9 | 7 | 16 | 0.6 |
| 15.5 - <16 | 17 | 12 | 29 | 1.1 |
| 16 - <16.5 | 9 | 6 | 15 | 0.6 |
| 16.5 - <17 | 12 | 5 | 17 | 0.7 |
| 17 - <17.5 | 4 | 3 | 7 | 0.3 |
| 17.5 - <18 | 2 | 1 | 3 | 0.1 |

TABLE B2

Age Distribution For Cardiac Catheterization Patients
18 Years Old or Greater Examined in the University of Florida
Cardiovascular Laboratory

| Age Classification (year) | Number | Percent of all Patients <u>></u> 18 Years |
|---------------------------------|--------|--|
| 18 | 39 | 1.8 |
| 19 | 43 | 2.0 |
| 20 | 36 | 1.7 |
| 21 | 26 | 1.2 |
| 22 | 37 | 1.7 |
| 23 | 34 | 1.6 |
| 24 | 33 | 1.5 |
| 25 | 25 | 1.2 |
| 26 | 40 | 1.9 |
| 27 | 28 | 1.3 |
| 28 | 29 | 1.3 |
| 29 | 29 | 1.3 |
| 30 | 26 | 1.2 |
| 31 | 20 | 0.9 |
| 32 | 25 | 1.2 |
| 33 | 21 | 1.0 |
| 34 | 39 | 1.8 |
| 35 | 38 | 1.7 |
| 36 | 34 | 1.6 |
| 37 | 41 | 1.9 |
| 38 | 40 | 1.9 |
| 39 | 23 | 1.1 |
| 40 | 43 | 2.0 |
| 41 | 56 | 2.6 |
| 42 | 63 | 2.9 |
| 43 | 47 | 2.2 |
| 44 | 63 | 3.0 |
| 45 | 69 | 3.2 |
| 46 | 65 | 3.0 |
| 47 | 58 | 2.7 |
| 48 | 52 | 2.4 |
| 49 | 65 | 3.0 |
| 50 | 59 | 2.3 |
| 51 | 54 | 2.5 |
| 52 | 44 | 2.0 |
| 53 | 61 | 2.8 |

TABLE B2 Continued

| Age Classification (year) | Number | Percent of all Patients ≥ 18 Years |
|---------------------------------|--------|---|
| 54 | 58 | 2.7 |
| 55 | 55 | 2.6 |
| 56 | 54 | 2.5 |
| 57 | 54 | 2.5 |
| 58 | 44 | 2.0 |
| 59 | 52 | 2.4 |
| 60 | 45 | 2.1 |
| 61 | 34 | 1.6 |
| 62 | 51 | 2.4 |
| 63 | 43 | 2.0 |
| 64 | 26 | 1.2 |
| 65 | 28 | 1.3 |
| 66 | 31 | 1.4 |
| 67 | 17 | 0.8 |
| 68 | 22 | 1.0 |
| 69 | 14 | 0.7 |
| 70 | 9 | 0.4 |
| 71 | 7 | 0.3 |
| 72 | 4 | 0.2 |
| 73 | 2 | 0.1 |
| 74 | 1 | 0.05 |
| 75 | 2 | 0.1 |
| 78 | 2 | 0.1 |
| 79 | 1 | 0.05 |
| 81 | 1 | 0.05 |
| 82 | 1 | 0.05 |
| 83 | 1 | 0.05 |
| 86 | 2 | 0.1 |
| 88 | 1 | 0.05 |
| 93 | 1 | 0.05 |
| 94 | 1 | 0.05 |
| 99 | 1 | 0.05 |

TABLE B3

Recorded Fluoroscopy Times During Cardiac Catheterization
For Adult (A) and Pediatric (P) Patients in the
University of Florida
Cardiovascular Laboratory

| Time Period | Classification of Patient | Number of Procedures | Fluoroscopy Time (min) | | |
|----------------|---------------------------------|-------------------------|---------------------------|-----|------|
| | | | High | Low | Mean |
| 3/63 | A | 5 | 20 | 8 | 13.7 |
| 3/63 | P | 13 | 30 | 5 | 15.7 |
| 9/63 | A | 10 | 29 | 4 | 13.7 |
| 9/63 | P | 11 | 19 | 2 | 12.1 |
| 9/64 | A | 13 | 43 | 1 | 12.8 |
| 9/64 | P | 18 | 30 | 2 | 15.0 |
| 3/65 | A | 20 | 47 | 5 | 12.9 |
| 3/65 | P | 13 | 23 | 4 | 13.7 |
| 9/65 | A | 10 | 39 | 7 | 16.9 |
| 9/65 | P | 17 | 25 | 5 | 13.6 |
| 3/66 | A | 15 | 38 | 2 | 15.3 |
| 3/66 | P | 19 | 26 | 1 | 9.4 |
| 9/66 | A | 18 | 22 | 2 | 14.3 |
| 9/66 | P | 16 | 31 | 3 | 14.1 |
| 3/67 | A | 15 | 67 | 1 | 17.2 |
| 3/67 | P | 18 | 24 | 4 | 13.5 |
| 9/67 | A | 15 | 62 | 3 | 18.4 |
| 9/67 | P | 11 | 29 | 4 | 15.7 |
| 3/68 | A | 16 | 31 | 2 | 13.1 |
| 3/68 | P | 17 | 57 | 1 | 18.0 |
| 9/68 | A | 12 | 38 | 3 | 18.3 |
| 9/68 | P | 15 | 24 | 5 | 11.3 |
| 3/69 | A | 11 | 70 | 5 | 24.5 |
| 3/69 | P | 20 | 33 | 5 | 16.0 |
| 9/69 | A | 13 | 29 | 1 | 13.2 |
| 9/69 | P | 17 | 34 | 6 | 18.2 |
| 3/70 | A | 13 | 37 | 13 | 22.0 |
| 3/70 | P | 16 | 35 | 7 | 16.0 |
| 9/70 | A | 23 | 50 | 3 | 19.7 |
| 9/70 | P | 18 | 36 | 6 | 19.3 |
| 3/71 | A | 21 | 45 | 3 | 19.2 |
| 3/71 | P | 19 | 48 | 3 | 16.0 |
| 9/71 | A | 11 | 23 | 7 | 13.8 |
| 9/71 | P | 17 | 49 | 9 | 23.3 |

TABLE B3 Continued

| Time Period | Classification of Patient | Number of Procedures | Fluoroscopy Time (min) | | |
|-------------|---------------------------|----------------------|------------------------|-----|------|
| | | | High | Low | Mean |
| 3/72 | A | 10 | 41 | 5 | 25.5 |
| 3/72 | P | 29 | 59 | 5 | 17.5 |
| 9/72 | A | 11 | 34 | 7 | 19.2 |
| 9/72 | P | 14 | 49 | 5 | 18.1 |
| 1/73 | A | 15 | 58 | 9 | 19.8 |
| 1/73 | P | 21 | 37 | 5 | 21.5 |
| 2/73 | A | 14 | 23 | 9 | 20.2 |
| 2/73 | P | 22 | 90 | 3 | 23.3 |
| 3/73 | A | 17 | 37 | 8 | 15.3 |
| 3/73 | P | 24 | 60 | 3 | 22.8 |
| 4/73 | A | 12 | 56 | 8 | 19.9 |
| 4/73 | P | 23 | 47 | 5 | 19.9 |
| 5/73 | A | 17 | 23 | 5 | 15.7 |
| 5/73 | P | 25 | 35 | 5 | 17.5 |
| 6/73 | A | 11 | 60 | 9 | 20.0 |
| 6/73 | P | 18 | 30 | 10 | 20.2 |
| 7/73 | A | 12 | 64 | 8 | 21.4 |
| 7/73 | P | 22 | 72 | 9 | 23.7 |
| 8/73 | A | 15 | 63 | 12 | 19.5 |
| 8/73 | P | 28 | 65 | 7 | 24.0 |
| 9/73 | A | 16 | 51 | 5 | 22.8 |
| 9/73 | P | 17 | 56 | 5 | 25.5 |
| 10/73 | A | 20 | 33 | 2 | 16.7 |
| 10/73 | P | 22 | 60 | 4 | 21.0 |
| 11/73 | A | 11 | 39 | 8 | 17.8 |
| 11/73 | P | 19 | 42 | 8 | 19.9 |
| 12/73 | A | 10 | 51 | 7 | 16.3 |
| 12/73 | P | 10 | 35 | 5 | 19.5 |
| 1/74 | A | 13 | 51 | 6 | 22.4 |
| 1/74 | P | 22 | 31 | 4 | 16.0 |
| 2/74 | A | 6 | 30 | 8 | 18.1 |
| 2/74 | P | 19 | 28 | 10 | 17.8 |
| 3/74 | A | 12 | 23 | 7 | 17.9 |
| 3/74 | P | 21 | 43 | 6 | 15.8 |
| 4/74 | A | 10 | 29 | 4 | 16.9 |
| 4/74 | P | 23 | 33 | 1 | 15.8 |
| 5/74 | A | 12 | 35 | 5 | 14.6 |
| 5/74 | P | 22 | 35 | 8 | 17.9 |
| 6/74 | A | 13 | 47 | 4 | 16.1 |
| 6/74 | P | 25 | 24 | 2 | 12.0 |

40/
1-305.7

TABLE B3 Continued

| Time Period | Classification of Patient | Number of Procedures | Fluoroscopy Time (min) | | |
|----------------|---------------------------------|-------------------------|---------------------------|-----|------|
| | | | High | Low | Mean |
| 7/74 | A | 7 | 35 | 8 | 17.0 |
| 7/74 | P | 20 | 35 | 6 | 18.7 |
| 8/74 | A | 19 | 24 | 4 | 10.1 |
| 8/74 | P | 18 | 30 | 4 | 15.5 |
| 9/74 | A | 11 | 35 | 11 | 24.0 |
| 9/74 | P | 22 | 32 | 6 | 12.0 |
| 10/74 | A | 19 | 39 | 8 | 23.5 |
| 10/74 | P | 20 | 36 | 3 | 14.5 |
| 11/74 | A | 12 | 46 | 3 | 18.1 |
| 11/74 | P | 17 | 30 | 4 | 16.5 |

10/
1475.6

APPENDIX C

STATISTICAL ANALYSIS RESULTS
OF THERMOLUMINESCENT DOSIMETRY CALIBRATION DATA

TABLE C1
 Experimental Calibration Factors for TLD Chips Exposed
 to Levels of 150 mR to 5000 mR

| | Treatment 1 150 mR Exposure | Treatment 2 550 mR Exposure | Treatment 3 2000 mR Exposure | Treatment 4 5500 mR Exposure | Sum of Treatments |
|---------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|----------------------|
| Block 1 | 4.52 | 4.76 | 4.70 | 4.74 | 18.72 |
| Block 2 | 4.20 | 4.44 | 4.51 | 4.30 | 17.45 |
| Block 3 | 5.23 | 5.21 | 5.23 | 5.13 | 20.80 |
| Block 4 | 4.74 | 4.84 | 4.76 | 4.77 | 19.11 |
| Block 5 | 4.25 | 4.26 | 3.95 | 4.40 | 16.96 |
| Block 6 | 4.25 | 4.24 | 4.31 | 4.26 | 17.16 |
| Block 7 | 4.05 | 3.56 | 4.11 | 4.12 | 15.84 |
| Block 8 | 4.21 | 4.19 | 4.31 | 4.07 | 16.78 |
| Block 9 | <u>4.09</u> | <u>4.22</u> | <u>3.37</u> | <u>4.03</u> | <u>16.07</u> |
| Sum | 39.64 | 39.82 | 39.61 | 39.82 | |

TABLE C2
 Analysis of Variance for TLD Calibration Points

| Source | d.f. | SS | MS | F Value |
|--------------------------------|------|-------|--------|--------------------|
| Total | 35 | 5.422 | | |
| Block (calibration run) | 8 | 5.121 | 0.640 | 52.0 |
| Treatment (exposure levels) | 3 | 0.005 | 0.0017 | 0.136 ^a |
| Error | 24 | 0.296 | 0.0123 | |

^a Significant at $F = 4.72$

TABLE C3

Experimentally Determined Reduction in TLD-100 Sensitivity
Read on Eberline TLR-5 and Second Order
Polynomial Regression Fit

| Exposure Level (R) | Reduction in Sensitivity (percent) | Exposure Level (R) | Reduction in Sensitivity (percent) |
|--------------------|------------------------------------|--------------------|------------------------------------|
| Experimental Data | | 25.00 | 6.426 |
| | | 26.00 | 6.739 |
| 4.96 | 0.000 | 27.00 | 7.050 |
| 9.94 | 0.911 | 28.00 | 7.359 |
| 19.46 | 4.100 | 29.00 | 7.665 |
| 28.98 | 8.304 | 30.00 | 7.969 |
| 38.50 | 11.017 | 31.00 | 8.271 |
| 48.02 | 13.398 | 32.00 | 8.571 |
| 58.72 | 15.655 | 33.00 | 8.869 |
| 68.24 | 17.167 | 34.00 | 9.164 |
| 77.84 | 19.383 | 35.00 | 9.457 |
| 87.44 | 22.261 | 36.00 | 9.748 |
| 96.94 | 23.442 | 37.00 | 10.037 |
| | | 38.00 | 10.323 |
| Polynomial Fit | | 39.00 | 10.607 |
| | | 40.00 | 10.889 |
| 6.00 | 0.058 | 41.00 | 11.169 |
| 7.00 | 0.413 | 42.00 | 11.447 |
| 8.00 | 0.766 | 43.00 | 11.722 |
| 9.00 | 1.117 | 44.00 | 11.995 |
| 10.00 | 1.465 | 45.00 | 12.266 |
| 11.00 | 1.812 | 46.00 | 12.535 |
| 12.00 | 2.156 | 47.00 | 12.802 |
| 13.00 | 2.497 | 48.00 | 13.066 |
| 14.00 | 2.837 | 49.00 | 13.328 |
| 15.00 | 3.174 | 50.00 | 13.588 |
| 16.00 | 3.510 | 51.00 | 13.846 |
| 17.00 | 3.842 | 52.00 | 14.101 |
| 18.00 | 4.173 | 53.00 | 14.355 |
| 19.00 | 4.502 | 54.00 | 14.606 |
| 20.00 | 4.828 | 55.00 | 14.854 |
| 21.00 | 5.152 | 56.00 | 15.101 |
| 22.00 | 5.474 | 57.00 | 15.345 |
| 23.00 | 5.794 | 58.00 | 15.588 |
| 24.00 | 6.111 | 59.00 | 15.828 |

TABLE C3 Continued

| Exposure Level (R) | Reduction in Sensitivity (percent) | Exposure Level (R) | Reduction in Sensitivity (percent) |
|--------------------|------------------------------------|--------------------|------------------------------------|
| Polynomial Fit | | | |
| 60.00 | 16.065 | 105.00 | 24.474 |
| 61.00 | 16.301 | 110.00 | 25.131 |
| 62.00 | 16.534 | 115.00 | 25.734 |
| 63.00 | 16.765 | 120.00 | 26.280 |
| 64.00 | 16.994 | 125.00 | 26.772 |
| 65.00 | 17.221 | 130.00 | 27.208 |
| 66.00 | 17.446 | 135.00 | 27.589 |
| 67.00 | 17.668 | 140.00 | 27.914 |
| 68.00 | 17.888 | 145.00 | 28.185 |
| 69.00 | 18.106 | 150.00 | 28.399 |
| 70.00 | 18.321 | | |
| 71.00 | 18.535 | | |
| 72.00 | 18.746 | | |
| 73.00 | 18.955 | | |
| 74.00 | 19.162 | | |
| 75.00 | 19.366 | | |
| 76.00 | 19.569 | | |
| 77.00 | 19.769 | | |
| 78.00 | 19.967 | | |
| 79.00 | 20.162 | | |
| 80.00 | 20.356 | | |
| 81.00 | 20.547 | | |
| 82.00 | 20.736 | | |
| 83.00 | 20.923 | | |
| 84.00 | 21.108 | | |
| 85.00 | 21.290 | | |
| 86.00 | 21.470 | | |
| 87.00 | 21.648 | | |
| 88.00 | 21.824 | | |
| 89.00 | 21.998 | | |
| 90.00 | 22.169 | | |
| 91.00 | 22.338 | | |
| 92.00 | 22.505 | | |
| 93.00 | 22.670 | | |
| 94.00 | 22.832 | | |
| 95.00 | 22.993 | | |
| 96.00 | 23.151 | | |
| 97.00 | 23.307 | | |
| 98.00 | 23.460 | | |
| 99.00 | 23.612 | | |
| 100.00 | 23.761 | | |

APPENDIX D

RADIATION AND EXAMINATION CHARACTERISTICS DETERMINED
DURING PERSONNEL EXPOSURE STUDIES

TABLE D1
Physician Exposure During Adult Cardiac Catheterization Examinations

| Patient Identification | Physician Identification | Exposure at Indicated Site ^a (mR/examination) | | | | | | | | | | | | |
|---------------------------|-----------------------------|--|-----|----|-----|-----|-----|-----|-----|----|----|--|--|----|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | |
| A 1 | Dr. A | 5 | 2 | 75 | 5 | 45 | 3 | 24 | 6 | 77 | | | | |
| A 2 | Dr. A | < 1 | < 1 | 16 | < 1 | 12 | < 1 | < 1 | < 1 | 34 | | | | |
| A 3 | Dr. A | 3 | 2 | 49 | 9 | 5 | 2 | 13 | 3 | 46 | | | | |
| A 4 | Dr. A | 13 | 14 | 22 | 6 | 42 | 3 | 17 | 2 | 18 | | | | |
| A 5 | Dr. A | 15 | 17 | 21 | 18 | 52 | 1 | 27 | < 1 | 20 | | | | |
| A 6 | Dr. B | 4 | 1 | 47 | 4 | 17 | < 1 | 19 | 1 | 73 | | | | |
| A 7 | Dr. C | 14 | 3 | 50 | 4 | 20 | 2 | 26 | 1 | 32 | | | | 25 |
| A 8 | Dr. C | 15 | 11 | 69 | 9 | 29 | 2 | 31 | 2 | 88 | | | | 38 |
| A 9 | Dr. C | 1 | 1 | 10 | 1 | 4 | 1 | 4 | 1 | 4 | | | | 4 |
| A10 | Dr. C | 4 | 18 | 3 | 3 | 9 | 3 | 8 | 1 | 16 | | | | 9 |
| A11 | Dr. C | 9 | 3 | 45 | 6 | 109 | 4 | 17 | 1 | 24 | | | | 24 |
| A12 | Dr. C | 4 | 2 | 18 | 3 | 8 | 1 | 8 | 1 | 39 | | | | 8 |
| A13 | Dr. C | 1 | < 1 | 12 | < 1 | 6 | < 1 | 4 | < 1 | 11 | | | | 4 |
| | Mean | 7 | 6 | 34 | 5 | 28 | 2 | 15 | < 1 | 37 | | | | 16 |

^a See Figure 15 for site identification.

TABLE D2
Physician Exposure During Pediatric Cardiac Catheterization Examinations

| Patient Identification | Physician Identification | Exposure at Indicated Site ^a (mR/examination) | | | | | | | | | |
|------------------------|--------------------------|--|-----|-----|-----|----|-----|----|-----|----|--|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| P1 | Dr. C | 2 | 6 | 17 | 3 | 72 | 1 | 13 | < 1 | 4 | |
| P2 | Dr. C | 4 | 9 | 26 | 8 | 64 | 3 | 14 | 2 | 9 | |
| P3 | Dr. E | 2 | 3 | 3 | 2 | 22 | < 1 | 3 | < 1 | 14 | |
| P4 | Dr. D | <1 | < 1 | < 1 | < 1 | 7 | < 1 | 4 | < 1 | 3 | |
| P5 | Dr. C | 7 | 9 | 23 | 9 | 64 | < 1 | 25 | < 1 | 16 | |
| P6 | Dr. C | 5 | 2 | 33 | 3 | 17 | < 1 | 10 | < 1 | 10 | |
| P7 | Dr. D | 6 | 12 | 10 | 53 | 9 | < 1 | 15 | < 1 | 24 | |
| | Mean | 4 | 6 | 16 | 11 | 36 | 1 | 17 | < 1 | 11 | |

^aSee Figure 15 for site identification.

TABLE D3

Exposure to Technicians in Zone 2 During Pediatric and Adult
Cardiac Catheterization Examinations

| Patient Identification | Technician Identification | Exposure at Indicated Site ^a (mR/examination) | | | | | | | | |
|---------------------------|------------------------------|--|----|----|----|----|-----|----|-----|----|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Adult | | | | | | | | | | |
| A1 | Technician F | 20 | 32 | 7 | 34 | 12 | 4 | 30 | 3 | 33 |
| A2 | Technician G | 9 | 17 | 3 | 12 | 10 | < 1 | 8 | < 1 | 17 |
| A3 | Technician G | 25 | 42 | 15 | 32 | 28 | 3 | 5 | 4 | 34 |
| A4 | Technician H | 17 | 5 | 10 | 22 | 15 | 3 | 18 | 3 | 25 |
| A5 | Technician G | 8 | 18 | 3 | 20 | 4 | 2 | 14 | 1 | 17 |
| A6 | Technician K | 11 | 27 | 1 | 28 | 11 | 2 | 18 | 2 | 22 |
| | Mean | 15 | 24 | 7 | 25 | 13 | 2 | 16 | 2 | 25 |
| Pediatric | | | | | | | | | | |
| P1 | Technician I | 9 | 14 | 2 | 22 | 9 | 1 | 11 | < 1 | 9 |
| P2 | Technician I | 3 | 10 | 2 | 7 | 4 | < 1 | 6 | < 1 | 7 |
| P3 | Technician H | 5 | 13 | 1 | 18 | 4 | 1 | 4 | 1 | 6 |
| P4 | Technician K | 3 | 3 | 7 | 7 | 18 | < 1 | 12 | 1 | 5 |
| P5 | Technician F | 4 | 11 | 1 | 4 | 2 | 1 | 8 | 1 | 4 |
| P6 | Technician H | 6 | 5 | 5 | 9 | 5 | 3 | 11 | 3 | 8 |
| P7 | Technician I | 2 | 8 | 1 | 9 | 3 | 1 | 4 | 1 | 4 |
| | Mean | 5 | 9 | 3 | 11 | 6 | 1 | 8 | 1 | 6 |

^aSee Figure 15 for site identification.

TABLE D4

Exposure to Technicians in Zone 3 During Pediatric and Adult Cardiac Catheterization Examinations

| Patient Identification | Technician Identification | Exposure at Indicated Sites ^a (mR/examination) | | | | | | | | |
|------------------------|---------------------------|---|-----|-----|-----|-----|-----|----|-----|-----|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Adult | | | | | | | | | | |
| A1 | Technician I | 14 | 7 | 9 | 2 | 4 | 1 | 5 | 1 | 4 |
| A2 | Technician J | 7 | < 1 | 4 | < 1 | 31 | < 1 | 4 | < 1 | < 1 |
| A3 | Technician J | 10 | 2 | 8 | 3 | 57 | 1 | 4 | 1 | 3 |
| A4 | Technician I | 11 | 7 | 9 | 3 | 4 | 1 | 3 | 1 | 2 |
| A5 | Technician H | 13 | 12 | 15 | 33 | 10 | 3 | 25 | 2 | 26 |
| A6 | Technician I | 9 | 4 | 5 | 1 | 3 | < 1 | 4 | < 1 | 2 |
| | Mean | 11 | 5 | 8 | 7 | 18 | 1 | 8 | 1 | 6 |
| Pediatric | | | | | | | | | | |
| P1 | Technician G | 6 | 11 | 4 | 4 | 4 | < 1 | 5 | < 1 | 4 |
| P2 | Technician F | 3 | 3 | 2 | 2 | < 1 | < 1 | 2 | < 1 | 1 |
| P3 | Technician G | 4 | 8 | 2 | < 1 | < 1 | < 1 | 5 | < 1 | 3 |
| P4 | Technician F | 1 | 1 | < 1 | 1 | < 1 | < 1 | 1 | < 1 | < 1 |
| P5 | Technician G | 3 | 4 | 2 | 2 | 2 | 1 | 2 | 1 | 2 |
| P6 | Technician I | 4 | 4 | 4 | 5 | 4 | 2 | 3 | 2 | 4 |
| P7 | Technician H | 5 | 3 | 5 | 7 | 4 | 1 | 7 | 1 | 2 |
| | Mean | 4 | 5 | 3 | 3 | 2 | 1 | 4 | 1 | 2 |

^aSee Figure 15 for site identification.

TABLE D5
 Exposure to Technicians in Zones 5, 6 and 7 During Pediatric and Adult
 Cardiac Catheterization Examinations

| Patient Identification | Technician Identification | Exposure at Indicated Sites ^a (mR/examination) | | | | | | | | |
|---------------------------|------------------------------|---|-----|----|---|-----|-----|-----|-----|-----|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Adult | | | | | | | | | | |
| A1 | Technician K | 19 | 16 | 15 | | | 3 | 24 | 6 | 44 |
| A2 | Technician I | 1 | < 1 | 3 | 2 | 1 | < 1 | < 1 | < 1 | < 1 |
| A3 | Technician F | 12 | 6 | 9 | 7 | 6 | 2 | 9 | 2 | 10 |
| A4 | Technician J | 4 | 3 | 4 | 5 | 4 | 1 | 3 | 1 | 7 |
| A5 | | | | | | | | | | |
| A6 | Technician K | 8 | 9 | 5 | 6 | 6 | 1 | 8 | 1 | 6 |
| | Mean | 9 | 7 | 7 | 5 | 4 | 1 | 9 | 2 | 13 |
| Pediatric | | | | | | | | | | |
| P1 | Technician H | 6 | 6 | 3 | 3 | 6 | 2 | 5 | 1 | 4 |
| P2 | Technician G | 3 | 3 | 2 | 2 | < 1 | < 1 | 2 | < 1 | 1 |
| P3 | Technician F | 1 | < 1 | 1 | 1 | 1 | < 1 | 1 | < 1 | < 1 |
| P4 | Technician H | 5 | 1 | 2 | 1 | < 1 | < 1 | 1 | < 1 | < 1 |
| P5 | Technician I | 1 | 2 | 1 | 2 | 1 | < 1 | 1 | < 1 | 2 |
| P6 | Technician H | 5 | 7 | 5 | 7 | 3 | 3 | 6 | 2 | 3 |
| P7 | Technician G | 2 | 2 | 3 | 2 | 2 | 1 | 2 | 1 | 1 |
| | Mean | 3 | 3 | 2 | 3 | 2 | 1 | 3 | 1 | 2 |

^aSee Figure 15 for site identification.

TABLE D6
Patient and Examination Characteristics Recorded During Personnel Exposure Study

| Patient Identification | Patient Characteristics | | | | | Radiological Factors | | | | | |
|------------------------|-------------------------|-------------|-------------|---------------------|----------|--------------------------------|-------------------------|--------|------|-----------------|-----|
| | Age (years) | Height (cm) | Weight (kg) | Mid-chest Dimension | | Total EAP (R.cm ²) | Total Fluoro Time (min) | Fluoro | | Cine (kVp) (mA) | |
| | | | | AP (cm) | IAT (cm) | | | (kVp) | (mA) | | |
| Adult | | | | | | | | | | | |
| A 1 | 65 | 173 | 72.7 | 15.0 | 35.5 | 9350 | 14.0 | 108 | 2 | 100 | 100 |
| A 2 | 36 | 169 | 89.9 | 22.0 | 34.0 | 4582 | 11.4 | 110 | 2 | 95 | 100 |
| A 3 | 63 | 188 | 92.0 | 22.5 | 36.0 | 8558 | 9.4 | 90 | 2 | 95 | 100 |
| A 4 | 54 | 167 | 54.0 | 21.0 | 29.0 | 5170 | 11.9 | 87 | 2 | 90 | 100 |
| A 5 | 63 | 171 | 65.4 | 23.0 | 30.0 | 6457 | 11.3 | 90 | 2 | 105 | 100 |
| A 6 | 60 | 175 | 70.8 | 22.0 | 31.0 | 9482 | 10.8 | 100 | 2 | 110 | 100 |
| A 7 | 66 | 160 | 49.1 | 18.5 | 25.0 | 4793 | 14.0 | 80 | 1.2 | 80 | 100 |
| A 8 | 59 | 160 | 78.5 | 27.5 | 33.5 | 8546 | 9.0 | 88 | 1.4 | 95 | 115 |
| A 9 | 18 | 163 | 50.6 | 17.0 | 29.0 | 1764 | 13.2 | 78 | 1.6 | 94 | 120 |
| A10 | 18 | 162 | 52.5 | 17.0 | 26.5 | 3328 | 23.5 | 72 | 1.7 | 82 | 175 |
| A11 | 45 | 184 | 83.0 | 24.5 | 32.5 | 11513 | 15.1 | 102 | 1.2 | 100 | 150 |
| A12 | 15 | 163 | 95.0 | 24.0 | 35.5 | 5282 | 18.0 | 108 | 1.4 | 105 | 115 |
| A13 | 19 | 165 | 53.6 | 16.5 | 27.0 | 3276 | 29.0 | 73 | 1.7 | 87 | 115 |
| Pediatric | | | | | | | | | | | |
| P 1 | 11 | 155 | 48.9 | 16 | 25 | 3938 | 18.0 | 80 | 2 | 83 | 100 |
| P 2 | 11 | 132 | 30.0 | 18 | 32 | 4098 | 21.0 | 71 | 2 | 83 | 100 |
| P 3 | 4 | 99 | 16.7 | 13 | 19.5 | 2134 | 28.1 | 75 | 2 | 83 | 100 |
| P 4 | 5 | 125 | 17.6 | 13 | 19.5 | 1221 | 13.6 | 60 | 2 | 83 | 100 |
| P 5 | 2 | 69 | 6.8 | 9.5 | 15.5 | 2107 | 23.0 | 65 | 2 | 83 | 100 |
| P 6 | 1 | 69 | 6.1 | 11.5 | 16.5 | 1441 | 20.5 | 65 | 2 | 83 | 100 |
| P 7 | <1 | 18 | 3.1 | 5.0 | 13.0 | 1733 | 30.0 | 55 | 2 | 83 | 100 |

TABLE D7

Summary of Patient and Examination
 Characteristics During Personnel Exposure Study

| Monitored Characteristic | Adult Patients | | Pediatric Patients | |
|---|----------------|------------|--------------------|----------|
| | Mean | Range | Mean | Range |
| Height (cm) | 169 | 160-188 | 95.4 | 18.5-155 |
| Weight (kg) | 69.8 | 49.1-95 | 18.7 | 3.1-48.9 |
| Mid-chest dimension: | | | | |
| AP (cm) | 20.8 | 15-27 5 | 12.3 | 5-18 |
| LAT (cm) | 31.1 | 25-36 | 20 | 13-32 |
| Total R.cm ² | 6323 | 1764-11513 | 2365 | 221-4098 |
| Total fluoro time (min) | 14.7 | 9-29 | 22 | 13.6-30 |
| Fluoro kVp | 91 | 72-110 | 67 | 55-80 |
| Use of cine (percent) | 100 | | 43 | |
| Cine kVp | 95.2 | 2-110 | 81 | 80-83 |
| Cine frames | 2483 | 433-6295 | 775 | 567-896 |
| Cine time (sec) | 38.8 | 6.8-98.4 | 12.2 | 9-14 |
| Number of cine runs per examination | 6.3 | 1-15 | 1.3 | 1-2 |
| Cine as percent of total R.cm ² | 57 | 26-91 | 15-2 | 13-22 |
| Cine test as percent of total cine | 35 | 10-60 | 14 | 0-42 |
| Cine ID frames as Percent of cine | 4 | 2-9 | 4 | 2-6 |

Note: Cine data for pediatric cases was averaged only for the three cases in which cine was employed.

TABLE D8
Recorded Cine Factors During Personnel Exposure Study

| Patient Identification | Total Cine Frames | Cine on-Time (sec) | Number of Cine Runs | EAP (R.cm ²) | | |
|------------------------|-------------------|--------------------|---------------------|--------------------------|------|-----------|
| | | | | Total Examination | Cine | Cine Test |
| Adult | | | | | | |
| A 1 | 3357 | 52.4 | 9 | 9450 | 4400 | 468 |
| A 2 | 433 | 6.8 | 1 | 4582 | 1193 | 721 |
| A 3 | 3208 | 52.1 | 10 | 8558 | 5962 | 1183 |
| A 4 | 1010 | 15.8 | 2 | 5170 | 3157 | 1480 |
| A 5 | 2021 | 31.6 | 5 | 6457 | 3278 | 1579 |
| A 6 | 3166 | 49.5 | 7 | 9482 | 6325 | 1386 |
| A 7 | 3988 | 62.3 | 10 | 4793 | 3765 | NT |
| A 8 | 3606 | 56.3 | 11 | 8546 | 7736 | NT |
| A 9 | 1108 | 17.3 | 2 | 1764 | 939 | NT |
| A10 | 1452 | 22.7 | 5 | 3328 | 1238 | NT |
| A11 | 6295 | 98.4 | 15 | 11513 | 8901 | NT |
| A12 | 1088 | 17.0 | 3 | 5282 | 2412 | NT |
| A13 | 1550 | 24.2 | 3 | 3276 | 1206 | NT |
| Pediatric | | | | | | |
| P2 | 895 | 14.0 | 2 | 4098 | 913 | 385 |
| P6 | 567 | 8.9 | 1 | 1441 | 187 | 0 |
| P7 | 863 | 13.5 | 2 | 1733 | 259 | 0 |

Note: No cine test (NT) made due to modification in automatic brightness control system.

TABLE D9
Analysis of Cine Use During Personnel Exposure Study

| Patient Identification | Cine as Percent of Total (R.cm ²) | Test Cine as Percent of Cine | Number of Identification Frames | Identification as Percent of Cine |
|------------------------|---|------------------------------|---------------------------------|-----------------------------------|
| Adult | | | | |
| A 1 | 47 | 10 | 55 | 2 |
| A 2 | 26 | 60 | 40 | 9 |
| A 3 | 69 | 19 | 59 | 2 |
| A 4 | 61 | 46 | 76 | 7 |
| A 5 | 51 | 48 | 58 | 2 |
| A 6 | 66 | 22 | 107 | 3 |
| A 7 | 79 | | NID | |
| A 8 | 91 | | NID | |
| A 9 | 53 | | NID | |
| A10 | 37 | | NID | |
| A11 | 77 | | NID | |
| A12 | 46 | | NID | |
| A13 | 37 | | NID | |
| Pediatric | | | | |
| P2 | 22 | 42 | 47 | 5 |
| P6 | 13 | 0 | 33 | 6 |
| P7 | 15 | 0 | 23 | 2 |

Note: No identification (NID) frames exposed while patient was on examination table.

APPENDIX E

BONE MARROW DISTRIBUTION
AND EXPOSURE FACTORS USED IN PHANTOM STUDY

TABLE E1

Bone and Red Marrow Assignment for Subfields
of Adult Rando Phantom

| Sub-field | Structure | Red Marrow Mass for Structure (g) | Total Red Marrow Mass in Subfield (g) | Red Marrow Fraction in Subfield |
|-----------|---------------------|-----------------------------------|---------------------------------------|---------------------------------|
| 1 | Cranium | 124.3 | 129.3 | 0.1236 |
| | Vertebra (C1) | 5.0 | | |
| 2 | Mandible | 12.3 | 27.0 | 0.0258 |
| | Vertebra (C2) | 6.3 | | |
| | Vertebra (C3) | 4.1 | | |
| | Vertebra (C4) | 4.3 | | |
| 3 | Vertebra (C5) | 4.4 | 26.3 | 0.0252 |
| | Vertebra (C6) | 5.3 | | |
| | Vertebra (C7) | 6.4 | | |
| | Vertebra (T1) | 8.1 | | |
| | One-half rib pair 1 | 2.1 | | |
| 4 | Right scapula | 25.2 | 62.1 | 0.0594 |
| | Right clavicle | 8.1 | | |
| | Right humerus head | 10.0 | | |
| | Right ribs: | | | |
| | One-half rib 1 | 1.0 | | |
| | Rib 2 | 2.5 | | |
| | Rib 3 | 3.2 | | |
| | Rib 4 | 3.7 | | |
| | Rib 5 | 4.7 | | |
| | One-half rib 6 | 2.4 | | |
| | One-fourth rib 7 | 1.3 | | |
| 5a | Sternum | 23.4 | 23.4 | 0.0224 |
| 5b | Vertebra (T2) | 8.8 | 104.7 | 0.1001 |
| | Vertebra (T3) | 8.5 | | |
| | Vertebra (T4) | 9.1 | | |
| | Vertebra (T5) | 10.1 | | |
| | Vertebra (T6) | 11.5 | | |

a Red bone marrow values from Ellis (1961).

TABLE E1 Continued

| Sub-field | Structure | Red Marrow Mass for Structure (g) | Total Red Marrow Mass in Subfield (g) | Red Marrow Fraction in Subfield |
|-----------|--------------------|-----------------------------------|---------------------------------------|---------------------------------|
| | Vertebra (T7) | 12.1 | | |
| | Vertebra (T8) | 13.9 | | |
| | Vertebra (T9) | 14.8 | | |
| | Vertebra (T10) | 15.9 | | |
| 6 | Left scapula | 25.2 | 62.1 | 0.0594 |
| | Left clavicle | 8.1 | | |
| | Left humerus head | 10.0 | | |
| | Left ribs: | | | |
| | One-half rib 1 | 1.0 | | |
| | Rib 2 | 2.5 | | |
| | Rib 3 | 3.2 | | |
| | Rib 4 | 3.7 | | |
| | Rib 5 | 4.7 | | |
| | One-half rib 6 | 2.4 | | |
| | One-fourth rib 7 | 1.3 | | |
| 7 | Right ribs: | | 21.5 | 0.0206 |
| | One-half rib 6 | 2.4 | | |
| | Three-fourth rib 7 | 3.7 | | |
| | Rib 8 | 4.8 | | |
| | Rib 9 | 4.2 | | |
| | Rib 10 | 3.2 | | |
| | Rib 11 | 2.3 | | |
| | Rib 12 | 0.9 | | |
| 8 | Vertebra (T11) | 16.3 | 149.2 | 0.1427 |
| | Vertebra (T12) | 18.8 | | |
| | Vertebra (L1) | 20.8 | | |
| | Vertebra (L2) | 21.8 | | |
| | Vertebra (L3) | 23.8 | | |
| | Vertebra (L4) | 24.1 | | |
| | Vertebra (L5) | 23.6 | | |
| 9 | Left ribs: | | 21.5 | 0.0206 |
| | One-half rib 6 | 2.4 | | |
| | Three-fourth rib 7 | 3.7 | | |
| | Rib 8 | 4.8 | | |
| | Rib 9 | 4.2 | | |
| | Rib 10 | 3.2 | | |
| | Rib 11 | 2.3 | | |
| | Rib 12 | 0.9 | | |

TABLE E1 Continued

| Sub-field | Structure | Red Marrow Mass for Structure (g) | Total Red Marrow Mass in Subfield (g) | Red Marrow Fraction in Subfield |
|-----------|--|-----------------------------------|---------------------------------------|---------------------------------|
| 10 | Right os coxal (ilium, ischium, pubis) | | 116.5 | 0.1114 |
| 11 | Left os coxal (ilium, ischium, pubis) | | 116.5 | 0.1114 |
| 12 | Sacrum | | 145.6 | 0.1392 |
| 13 | Right femoral head and neck | | 20.0 | 0.0191 |
| 14 | Left femoral head and neck | | <u>20.0</u> | <u>0.0191</u> |
| | | Total | 1,045.7 | 1.0000 |

TABLE E2

Bone and Red Marrow Assignment for Subfields
of Pediatric Phantoms

| Subfield | Structure | Red Bone Marrow Fraction ^a in Subfield |
|----------|--|---|
| 1 | Skull | 0.0694 |
| 2 | Right humerus Right forearm (radius and ulna) | 0.0516 |
| 3 | Right ribs Right scapula Right clavical | 0.0772 |
| 4a | Sternum | 0.0250 |
| 4b | Cervical vertebra | 0.0271 |
| 4b | Thoracic vertebra (T1-T9) | 0.0922 |
| 5 | Left ribs Left scapula Left clavical | 0.0772 |
| 6 | Left humerus Left forearm (radius and ulna) | 0.0516 |
| 7 | Thoracic vertebra (T10-T12) Lumbar vertebra | 0.1352 |
| 8 | Iliac bone Sacrum Ischium | 0.2875 |
| 9 | Right femur | 0.0530 |
| 10 | Left femur | <u>0.0530</u> |
| | Total | 1.0000 |

a Red bone marrow values from Hashimoto and Yamaka (1964).

TABLE E3
Exposure Factors for Adult Phantom Exposures

| Exposure Factors | Exposure Factor Value, Mean (range) | | | |
|---|-------------------------------------|------------------------------|-----------------------------------|-----------------------------------|
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | 6 inch Mode 45° RAO Projection | 9 inch Mode 45° RAO Projection |
| 1 Number of experimental runs | 2 | 3 | 3 | 2 |
| 2 EAP (R.cm ²) | 2168(1984-2352) | 2050(1783-2259) | 1575(1133-1993) | 2729(2702-2755) |
| 3 Indicated tube potential (kvp) | 101(97- 105) | 77(71- 83) | 104(85- 123) | 80(80- 81) |
| 4 Fluoroscopy current (mA) | 1.3(1.2-1.4) | 1.3(0.9-1.6) | 1.0(0.9-1.2) | 1.3(1.2-1.4) |
| 5 Beam size at incident skin surface (cm ²) | 78 ^a | 161 ^a | 85(80- 94) | 175(173- 176) |

a Value estimated from geometry considerations since experimental measurements not made.

TABLE E4
Exposure Factors for Child Phantom Exposures

| Exposure Factors | Exposure Factor Value, Mean (range) | | | |
|---|-------------------------------------|------------------------------|---------------------|-----------------|
| | Fluoroscopy | | Biplane Radiography | |
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | AP Projection | LAT Projection |
| 1 Number of experimental runs | 2 | 2 | 2 | 2 |
| 2 EAP (R.cm ²) | 777(684- 870) | 841(806- 876) | 4502(4116-4887) | 4439(3713-5160) |
| 3 Indicated tube potential (kVp) | 54(53- 55) | 48(47- 49) | 75 | 80 |
| 4 Fluoroscopy current (mA) | 0.7(0.6- 0.8) | 0.6(0.5- 0.6) | | |
| 5 Radiographic mAs setting | | | 120 | 90 |
| 6 Beam area at incident skin surface (cm ²) | 84(80- 87) | 185 ^a | 237(212- 262) | 178(166- 189) |

a Value estimated from geometric considerations since experimental measurements not made.

TABLE E5

Exposure Factors for Infant Phantom Exposures

| Exposure Factors | Exposure Factor Value, Mean (range) | | | |
|---|-------------------------------------|------------------------------|---------------------|-----------------|
| | Fluoroscopy | | Biplane Radiography | |
| | 6 inch Mode PA Projection | 9 inch Mode PA Projection | AP Projection | LAT Projection |
| 1 Number of experimental runs | 2 | | 1 | 2 |
| 2 EAP (R.cm ²) | 486(433- 539) | | 1312 | 1856(1786-1926) |
| 3 Indicated tube potential (kVp) | 46(42- 49) | | 65 | 70 |
| 4 Fluoroscopic current (mA) | 0.7(0.6- 0.9) | | | |
| 5 Radiographic mAs setting | | | 100 | 90 |
| 6 Beam area at incident skin surface (cm ²) | 83(80- 86) | | 108 | 140(132- 147) |

APPENDIX F

INTEGRAL ABSORBED DOSE

APPENDIX F

The integral absorbed dose can be defined by the general formula: $\Sigma = \int_m D dm$. Where Σ is the total integral dose, D the absorbed dose and m the total mass and dm a small element of mass. In general terms the integral dose is equal to the incident energy reduced by the loss from the body due to scatter and transmission. The ICRU (1959) further breaks down the elements of the integral dose as Σ_B , the ingegral absorbed dose within the confines of the beam, and Σ_R , the integral dose absorbed in the body not intercepted by the primary beam. Calculation methods for obtaining Σ_B are quite straight forward. The evaluation of Σ_R is more difficult due to the variation in size and shape of the body in which this quantity is to be determined. The ICRU suggests the methods described by Mayneord (1940) and Meredith and Neary (1944) as providing the most accurate method of estimating values for integral dose as of their 1959 publication date.

Carlsson (1963) re-examined the methods of Mayneord and carried out refinement calculations. In Mayneord's original calculations, the integral dose values were obtained from the central axis depth dose data integrated over the dimensions of the geometric beam and thus do not adequately account for losses due to lateral scatter. This error can be

essentially removed if depth dose data for saturated scatter conditions are used. That is, if the depth dose data used are obtained for field sizes large enough that the central axis values no longer vary with increasing field size. If these central axis values are then integrated over the geometric dimensions of the beam, the loss due to lateral scatter out of this volume is accounted for. If this saturated scatter method is utilized, the assumption must be made that all lateral scatter is absorbed in the body or the method will overestimate the integral absorbed dose. For x-rays in the diagnostic x-ray region Carlsson used the depth dose data of Trout and colleagues (1960).

A second approach used by Carlsson was to calculate the incident energy fluence in air using the measured x-ray spectra of Hettinger and Starfelt (1958) and air attenuation coefficients. He shows that his calculated values are in close agreement with calorimetric determinations made by Laughlin and Genna (1956). Once the energy fluence has been determined, the integral dose can be calculated by accounting for backscattered and transmitted energy. The results of these determinations are presented in Figure F1. Carlsson calculated the integral dose utilizing the depth dose data of Trout and colleagues (1960).

Bomford and Burlin (1963) measured scatter from a 30 x 30 x 22 cm Mix-D phantom. They used circular beam sizes of 100 and 400 cm² and tube potential settings in the

diagnostic range of 100 and 140 kVp. No other statement regarding the geometry or beam quality is given, but it is not unreasonable to assume that they were typical of those utilized in normal diagnostic practice. By integrating their graphical results, the scatter in specified lateral areas was obtained and is shown in Table F1. From these data it can be seen that the greatest scatter is contained in the backscatter region and is accounted for in the depth dose values. The forward scatter which exits the phantom in the 90° to approximately 150° segment is seen to vary from approximately 3 to 11%.

Pychlau and Bunde (1965) attempted to measure the integral dose in an adult wax phantom. Utilizing a NaI scintillation crystal they made multiple scatter measurements around a 1 m diameter cylinder 1.4 m high surrounding the irradiated phantom. The results of these measurements were subtracted from the incident energy flux to determine integral dose. The results of their measurements are also plotted in Figure F1. Their values indicate a smaller value of absorbed energy per incident EAP. The Pychlau and Bunde values differ from the spectral calculated values of Carlsson by up to a factor of two. Since loss to lateral scatter cannot account for this magnitude of difference, some other factor must be involved.

The effect of beam size and quality can be seen from the Pychlau and Bunde data. The integral dose per R.cm² values are observed to increase with a decrease in beam size.

TABLE F1
Lateral X-ray Scatter From a 30 x 30 x 22 cm Mix-D Block

| Tube Potential (kVp) | Beam Size (cm ²) | Geometry Point or Sectional Segment ^a (angles specified with respect to incident x-ray beam) | Exposure ^b as Percent of Primary |
|----------------------|------------------------------|--|---|
| 100 | 100 | Point at 90° | 0.005 |
| 100 | 100 | 30-90° (backscatter) | 11.1 |
| 100 | 100 | 90-150° (forward scatter) | 2.7 |
| 100 | 100 | 30-150° | 13.8 |
| 100 | 400 | Point at 90° | 0.04 |
| 100 | 400 | 30-90° (backscatter) | 11.8 |
| 100 | 400 | 90-150° (forward scatter) | 4.4 |
| 100 | 400 | 30-150° | 16.2 |
| 140 | 100 | Point at 90° | 0.02 |
| 140 | 100 | 30-90° (backscatter) | 19.8 |
| 140 | 100 | 90-150° (forward scatter) | 10.0 |
| 140 | 100 | 30-150° | 29.8 |
| 140 | 400 | Point at 90° | 0.08 |
| 140 | 400 | 30-90° (backscatter) | 19.6 |
| 140 | 400 | 90-150° (forward scatter) | 11.0 |
| 140 | 400 | 30-150° | 30.6 |

^aThe values for sectional segments were obtained by graphical integration of published data.

^bData from Bomford and Burlin (1963).

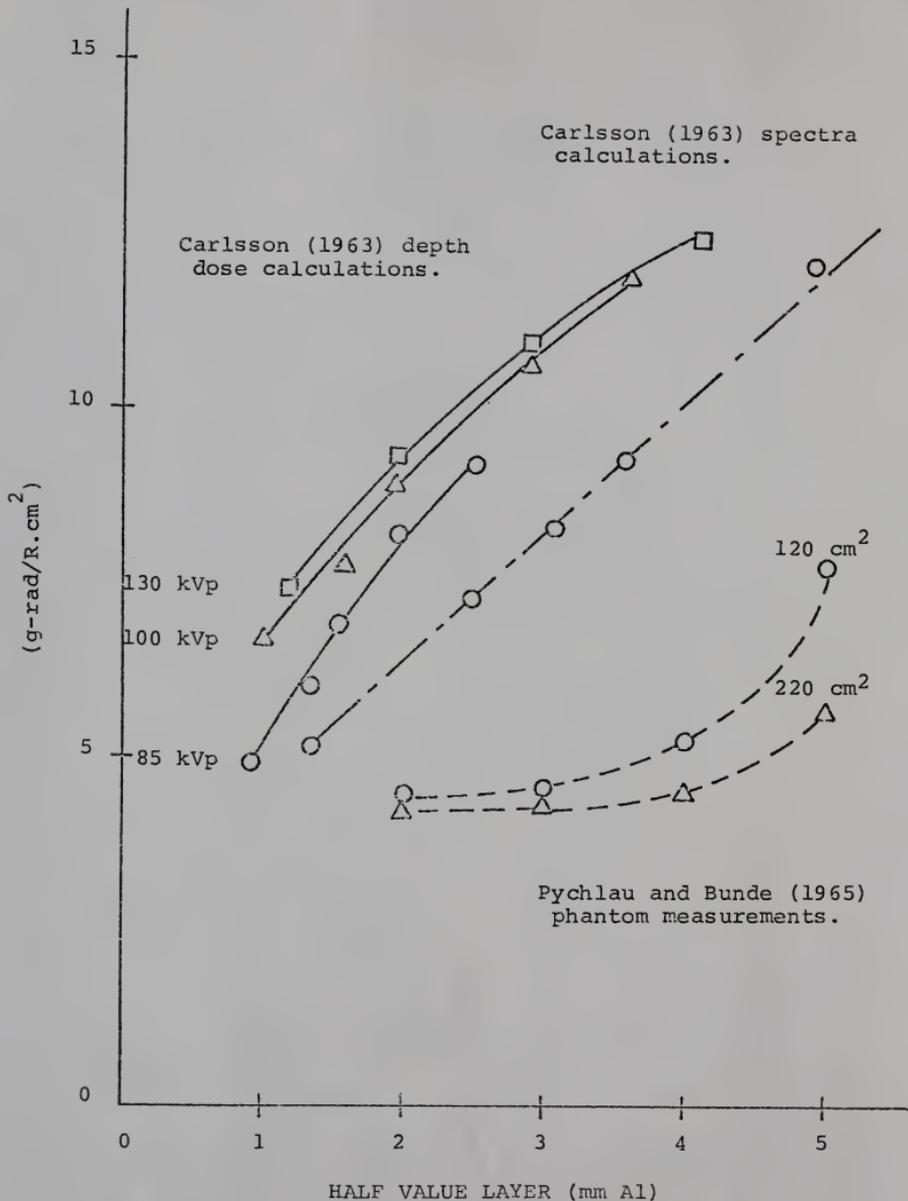


Figure F1. Integral Dose per EAP as a Function of X-ray Beam Quality Reported by Carlsson (1963) and Pychlau and Bunde (1965).

This is due to the greater thickness of tissue surrounding the primary irradiated volume for any decrease in beam size.

Carlsson (1965) states that for a 20 cm thick phantom with infinite lateral dimensions, the integral dose per EAP (g-rad/R.cm²) values calculated from the measured spectra are presumably better than $\pm 20\%$ accurate if the total filtration is equivalent to 4 mm of Al or greater. This determination was made by calculating exposure and energy fluence from the measured spectra. At low energies, in the typical diagnostic region, the resolution of a NaI(Th) detector as used by Hettinger and Starfelt to measure the spectra is reduced to as much as 25% at 25 keV. The large variation of exposure fluence with energy at these low energies is the major source of error.

Additional variations must be considered when these conversion values for R.cm² to g-rad are used on actual patients. Some of these factors include tissue inhomogeneities and positioning of the beam with respect to the body. If the beam does not completely intercept the body these conversion factors will overestimate the absorbed dose. The neglect of lateral scatter in the case of patients of finite dimensions must also be considered. From the work of Bomford and Burlin, it was shown that this loss in a 30 x 30 x 22 cm Mix-D phantom, which might be typical of an adult, ranged from 3 to 11% for tube potentials in the range of 100 to 140 kVp. In the case of a child, an increased loss due to scattered radiation would be anticipated.

Carlsson places the maximum error from neglecting lateral scatter in an adult at less than 8%. He goes on to state that the values he calculated for a 20 cm thick phantom would be 8 to 10% higher for a 15 cm thickness and would underestimate the integral dose from 2 to 9% for a 25 cm thickness.

The determination of absorbed dose from external sources has also been carried out by use of Monte Carlo techniques. Sidwell, Burlin and Wheatley (1969) and Jones and colleagues (1973) have published results for monoenergetic beams. The Sidwell calculations employed a 60 cm high elliptical cylinder whereas Jones's values were obtained utilizing the heterogeneous phantom developed by Snyder and colleagues (1969) for estimation of absorbed fractions from internal emitters. More recently, Poston and Warner (1974) have reported initial results using the Snyder phantom and techniques for continuous x-ray spectra. Using the data on diagnostic x-ray spectra reported by Epp and Weiss (1966) they calculated absorbed dose for a number of selected body sites, as well as values for the whole body. The simulation was established to represent a 36 x 44 cm (14 x 17 inch) beam incident to the posterior mid-trunk of the body. Data are presented for x-ray tube potentials over the range 45 to 105 kVp and added filtration values of 1 and 2 mm of Al.

The Poston and Warner absorbed dose per incident R was converted to integral dose per EAP. The masses for the total body given by Snyder were used. These data are shown in

Table F2 and plotted along with the Carlsson and Pychlau and Bunde values in Figure F2.

In summary it can be seen that values of integral dose per incident EAP have been directly investigated or can be obtained from the published data of a number of authors. Calculations have been performed utilizing depth dose data, x-ray spectra in conjunction with attenuation values and Monte Carlo techniques. Experimental techniques have also been attempted. The results obtained from these methods show variations up to a factor of three for energies in the diagnostic x-ray range. The data reported by Carlsson are in general agreement with values presented by Poston and Warner obtained by utilizing the Monte Carlo calculations. The Carlsson spectrally determined values were applied to the Group II patient data (see summary section of Chapter VII). This set of values was chosen so that a comparison with the patient integral dose values reported by Kaude and Svahn (1975), which also used these conversion values, could be made.

It must be kept in mind that these values are applicable to an x-ray beam incident on the trunk of the body of a normal size adult. For pediatric or large adult patients the values will over and underestimate the g-rad/R.cm^2 respectively. The values for the standard adult cannot be easily scaled to these alternate patients due to the number of variables associated with their determination.

TABLE F2

Integral Dose Per EAP. Data Calculated from Values Obtained by Poston and Warner (1974).

| Tube Potential (kVp) | Added Filtration (mm Al) | HVL ^a (mm Al) | Total Body Dose Per Incident Exposure (rad/R) | Calculated ^b (g-rad/R.cm ²) |
|----------------------|--------------------------|--------------------------|---|--|
| 45 | 1 | 1.0 | 8.15×10^{-2} | 3.6 |
| 55 | 1 | 1.3 | 1.12×10^{-1} | 4.95 |
| 65 | 2 | 1.9 | 1.62×10^{-1} | 7.16 |
| 70 | 2 | 2.2 | 1.87×10^{-1} | 8.27 |
| 80 | 2 | 2.5 | 2.15×10^{-1} | 9.51 |
| 90 | 2 | 2.9 | 2.34×10^{-1} | 10.35 |
| 98 | 2 | 3.2 | 2.52×10^{-1} | 11.14 |
| 105 | 2 | 3.4 | 2.75×10^{-1} | 12.16 |

^a Measured HVL values of Epp and Weiss (1966).

^b Based on phantom total body mass of 70,036 g.

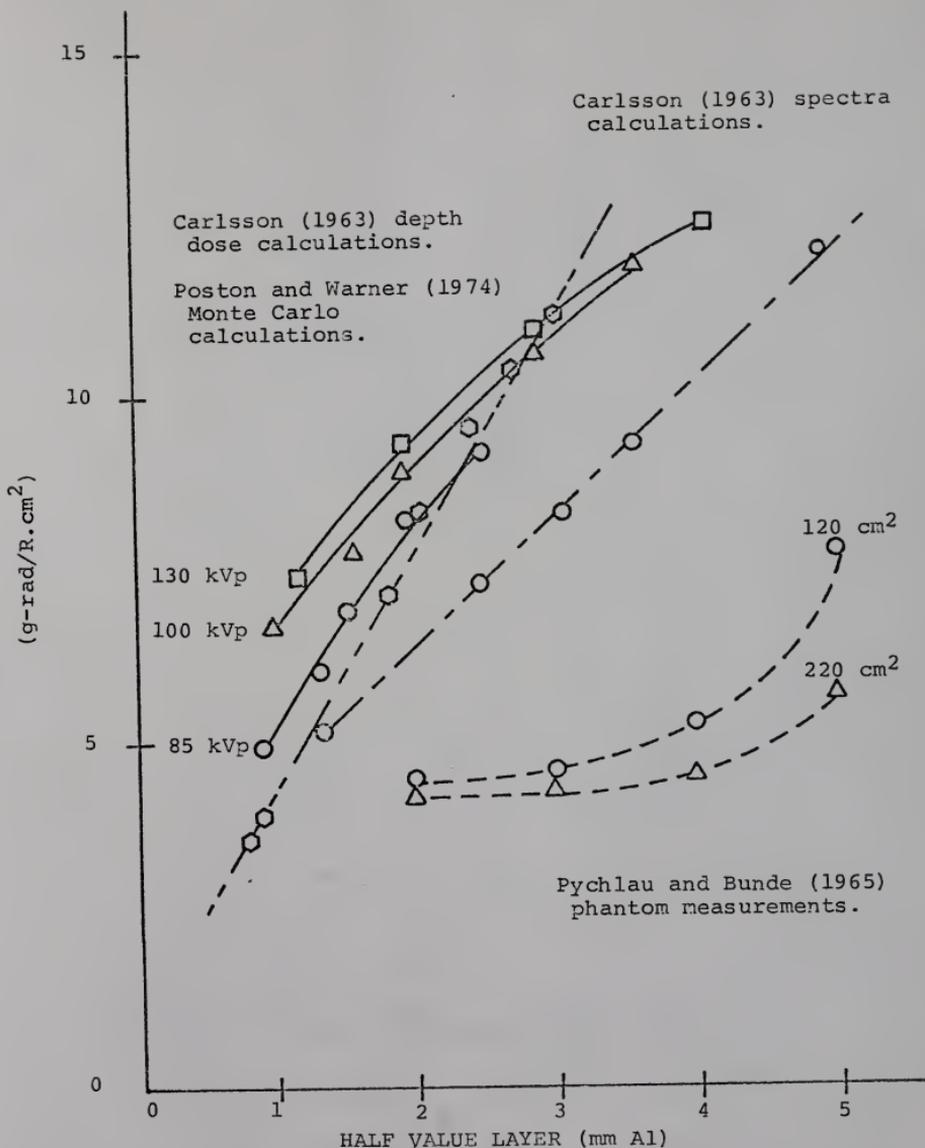


Figure F2. Integral Dose per EAP as a Function of Beam Quality Showing Additional Values Obtained from Monte Carlo Calculations of Poston and Warner (1974).

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BIOGRAPHICAL SKETCH

William Stuart Properzio was born February 21, 1940, in Keene, New Hampshire. He is married to the former Sharon Carlisle and they have one daughter, Angela Marie. He attended the primary and secondary schools of Winchendon, Massachusetts graduating from Murdock High School in 1958. In 1962 he received a bachelor of science degree in electrical engineering from Worcester Polytechnic Institute.

Following graduation he was briefly employed as a computer systems design engineer with the International Business Machines Corporation. In 1962 he accepted an appointment in the Commission Corps of the United States Public Health Service. At the present time he is still on active duty and holds the rank of engineer - senior grade (equivalent to a Naval Commander, 0-5).

Assignments in the Public Health Service have all been in areas related to radiological health. From 1962 to 1965 he was at the Robert A. Taft Engineering Center, Cincinnati, Ohio. He was next assigned to the X-ray Science and Engineering Laboratory program at Oregon State University from 1965 to 1968. While at Oregon State he held the rank of instructor and was involved with both teaching and research. During the academic year 1966/1967 he was a full

time graduate student and received a master of science degree in radiological physics.

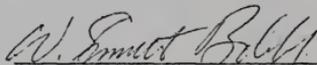
In 1968 he was transferred to the Bureau of Radiological Health's headquarters in Rockville, Maryland, where he worked in the X-ray Exposure Control Laboratory and was in charge of laboratory operation from 1969 to 1972. Graduate study at the University of Florida was initiated in September of 1972.

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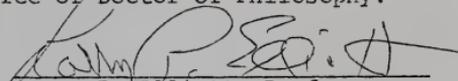
Charles E. Roessler, Chairman
Associate Professor of
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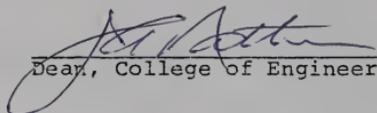
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This thesis was submitted to the Graduate Faculty of the College of Engineering and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

June, 1975



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