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Nuclear Medicine is becoming a significant source of population exposure to ionizing radiation. The phenomenal growth of this medical specialty, probably the most rapidly growing specialty in the United States today, hinges on several interrelated factors. First of all, the realization of the usefulness of radionuclides for medical diagnosis is just becoming apparent to the medical community. Second, technological advances in radiation detection and imaging instrumentation as well as radiopharmaceutical development have tremendously expanded these potential beneficial applications. Procedures in most laboratories doubled in the period between 1958 and 1965, a growth rate of about 15 percent per year. These figures are borne out in the recent National Center for Radiological Health report "Survey of the Use of Radionuclides in Medicine: Preliminary Report" (1). In addition, it has been our experience at the Radioisotope Laboratory at General Hospital, Cincinnati, Ohio, that between 1965 and 1968 there has been an additional doubling of procedures, a growth rate of 33 percent per year. Since approximately 95 percent of the procedures in Nuclear Medicine are diagnostic in nature, it is probably best compared to diagnostic radiology. We are, however, in a unique position with Nuclear Medicine not possible in the early days of radiology; that is, we are in a position prospectively to influence dose reduction procedures and concepts in this field. Furthermore, the growing field has been commendably "dose conscious," and higher dose procedures have been replaced and abandoned as soon as new techniques are available, usually with the premise that minimal doses necessary to obtain valid information be used.

This presentation will review personnel and patient doses as a result of radioisotope procedures, beginning with some typical personnel exposures in our laboratory. These data are based on commercially supplied film badges worn at the waist level by three full-time technicians (in a radioisotope laboratory that averages 250 procedures per month, two-thirds of which involve scanning procedures). The average exposure for the 1965-1966 period was 36 mR for each three-month period, with a range of 11 to 63 mR. The average exposure for the 1967-1968 period was 110 mR per three-month period, with a range of 33 to 215 mR. These data indicate a three-fold increase in exposure, because of the increased number of procedures in the 1967-1968 period, as well as the initiation of the use of generators in January 1967. However, even the 1967-1968 figures do not approach the maximum permissible occupational exposure of 100 mR per week (or 1200 mR for 3 months) recommended in the National Commission on Radiation Protection Report No. 33.

particularly with the initiation of the use of generators, is dose to body portions other than what is considered to be whole body, namely to extremities. An example of such doses is presented by one of our technicians involved in eluting ^{99m}Technetium from a ^{99}Molybdenum generator. The technician wore six film badges, which indicated the following doses in one week: Neck-13 mR; waist-27 mR; right wrist-33 mR; left wrist-31 mR; finger of right hand-112 mR; finger of left hand-101 mR. These data are an average of two separate one-week work periods involving clinical procedures with patients and involving six elution procedures in which a total activity of 900 millicuries of Technetium -99m was milked per one-week work period. Recommended permissible exposure levels to extremities are given as about 15 times maximum permissible exposure levels to whole body, or about 1500 mR per week. In order to minimize personnel exposure, technicians are rotated so that each technician is involved in elution procedures only approximately 1/3 of his work time. Readings of film badges worn by personnel are maintained in a permanent file.

There appears to be general agreement that both professional and technical personnel are receiving an increasing but not excessive exposure and that this is probably due to the increased number of clinical procedures as well as the increasing number of high activity generators in most laboratories. Perhaps results are related to the fact that through the years two systems of radiation safety procedures have been developed, one for the therapeutic use of radioisotopes and the other for diagnostic procedures. In the past, diagnostic procedures have always been at low activity levels, i.e., a few microcuries. Now, suddenly, diagnostic activity levels are millicurie amounts, and handling procedures have perhaps not been adjusted accordingly. Further decrease in personnel exposure can perhaps be achieved by re-education concerning radiation safety procedures.

With the increased use of radionuclides and the advent of radionuclide generator systems, new problems in nuclear medicine personnel protection have been created. Reports of both facility contamination and internal contamination of personnel are increasing. Consequently, the use of film badges alone for personnel monitoring is not adequate; additional detection systems for recognizing exposures are desirable. Periodic in vivo or bioassay monitoring of personnel is recommended to assess possible internal contamination levels. Use of a whole body counter is desirable for this purpose. In our laboratory, personnel are counted periodically (at least once every six months) in a whole body counter. The whole body counting procedures have resulted in the detection of picocurie levels of I-131 in one professional employee and picocurie levels of Technetium-99m and Iodine-131 in one technician. These data are recorded on a regular radioisotope laboratory patient chart for each worker. We will refer to this chart in more detail in a few minutes. Each worker then has a radioisotope laboratory patient number and the results of his repeated whole body counting procedures are entered as a permanent record on his chart.

Next we will discuss patient dose as a result of radioisotope procedures. When each patient is sent to the Radioisotope Laboratory for a clinical procedure, a form of the type shown in figure 1 is filled out. This form is coded for computer processing. It consists of five sections: patient information; clinical report; results; interpretation; and miscellaneous data. Of particular importance in this presentation are the information blocks at the bottom of the patient information section (see figure 2). These include: number of previous isotopic procedures; isotopic material; dose (which should really be the administered activity); route of administration; date the isotope was administered; and clinical procedure. The back of the form contains certain codes which can be used for supplying information to the isotope material block and to the procedures block. As I indicated previously, a chart of this type is also maintained for each worker in the laboratory for monitoring purposes. There are five color-coded copies of this form, distributed as follows: referring physician; biometrics; radioisotope laboratory patient chart; accountant; and an extra copy.

The increasing use of radionuclides in medical diagnosis and research requires that we have greater knowledge of radiation exposure to patients than these forms provide. Since 1964, concentrated efforts have been made by several groups throughout the United States to obtain the information required to better estimate patient doses. In October of 1964, the Society of Nuclear Medicine initiated a Medical Internal Radiation Dose (MIRD) Ad Hoc Committee to serve the needs of nuclear medicine in the determination of radiation dose to patients who are administered radiopharmaceuticals. Tissue distribution data relating to biologically-distributed radionuclides had been gathered primarily for the purpose of establishing Health Safety Standards for workers exposed to elemental forms of radionuclides rather than specific chemical forms (radiopharmaceuticals). Thus, it was generally agreed that the data and information available to the profession at that time were not adequate to determine to the desired accuracy the dose resulting from the use of radioactive materials in diagnostic studies. The needed data were scattered and not easily available. Also, there was doubt that the data were the best that could be generated, in view of new developments in nuclear spectrometry, computerized dose computation techniques and improved measuring techniques for determining the tissue distribution and life-times of radiopharmaceuticals in patients. Finally, the increase in the use of radionuclides that emit low-energy photons presented some serious challenges to the accepted methods of calculating dose.

The data which we will present today include the efforts of the following: the MIRD Committee (2); the Radioisotope Laboratory (headed by Dr. Eugene L. Saenger) of the University of Cincinnati College of Medicine; the Cincinnati Nuclear Medicine Laboratory (headed by Dr. Henry Wellman) of the Bureau of Radiological Health; and Dr. Edward Smith, Jackson Memorial Hospital, Miami, Florida. The average dose from an internally administered radionuclide varies with the radionuclide, its chemical form and its route of administration.

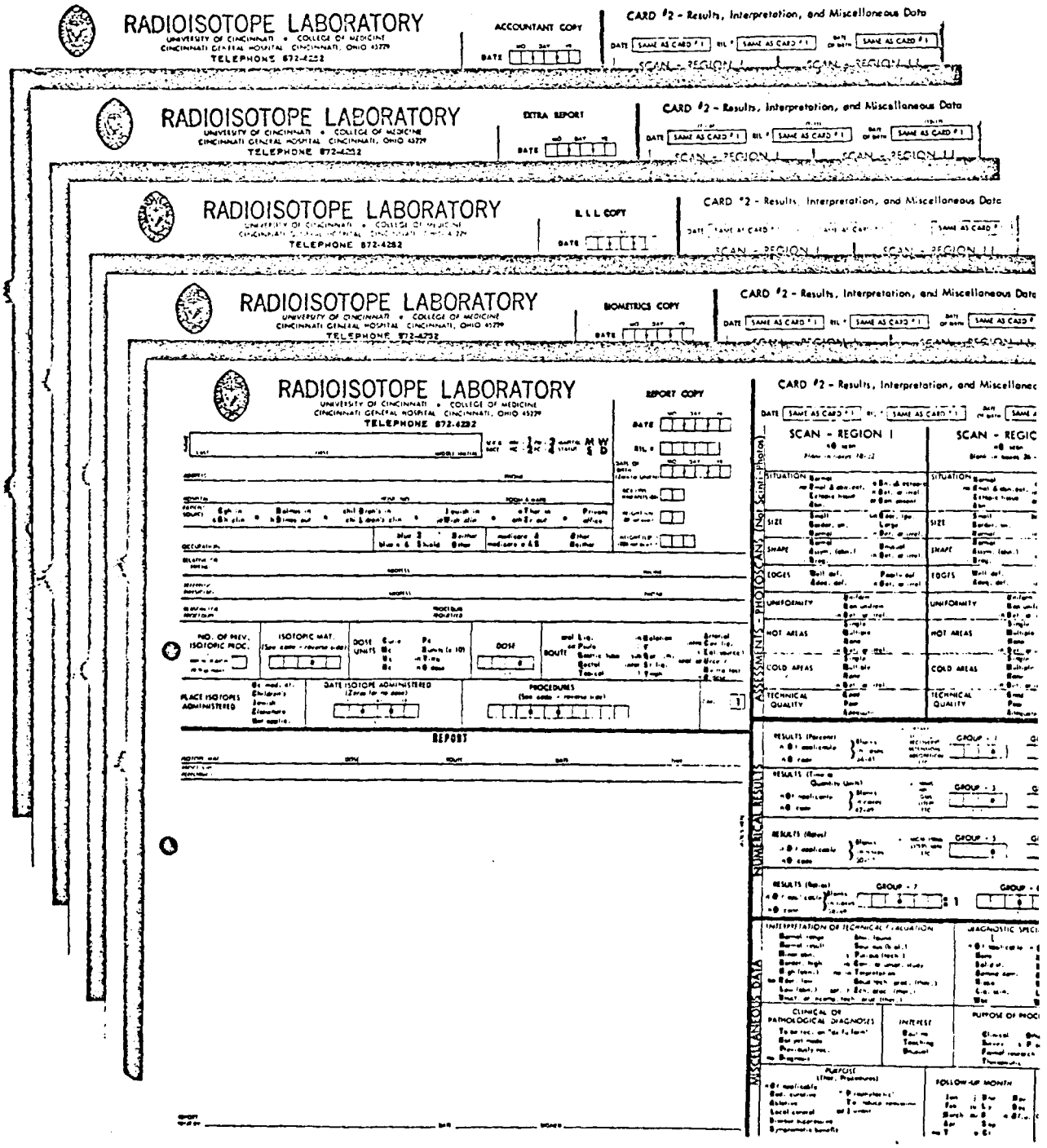
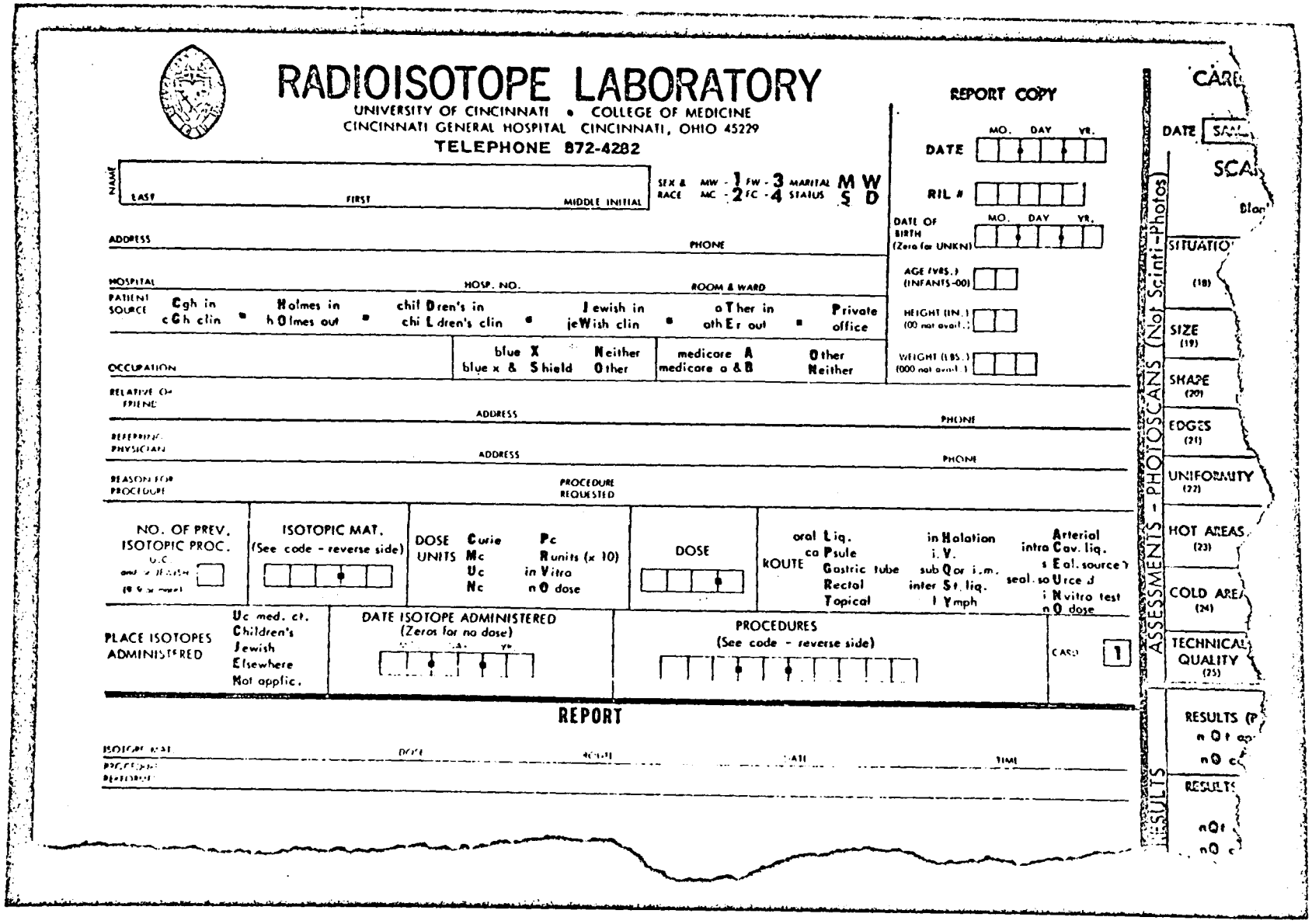


Fig. 1. Radioisotope laboratory patient form



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REPORT COPY

NAME LAST FIRST MIDDLE INITIAL
SEX & RACE MW - 1 FW - 3 MC - 2 FC - 4
MARITAL STATUS M W S D
DATE MO. DAY YR.
RIL #
DATE OF BIRTH (Zero for UNKN) MO. DAY YR.
AGE (YRS.) (INFANTS-00)
HEIGHT (IN.) (00 not avail.)
WEIGHT (LBS.) (000 not avail.)
ADDRESS PHONE
HOSPITAL HOSP. NO. ROOM & WARD
PATIENT SOURCE Cgh in cGh clin • Holmes in hOlmes out • chil Dren's in chi Ldren's clin • Jewish in jeWish clin • oTher in othEr out • Private office
OCCUPATION blue X blue x & Shield Neither Other medicare A medicare a & B Other Neither
RELATIVE OR FRIEND ADDRESS PHONE
REFERRING PHYSICIAN ADDRESS PHONE
REASON FOR PROCEDURE PROCEDURE REQUESTED
NO. OF PREV. ISOTOPIC PROC. U.C. and or JEWISH (9 or more)
ISOTOPIC MAT. (See code - reverse side)
DOSE UNITS Curie Mc Uc Nc Pc Runits (x 10) in Vitro nO dose
DOSE
ROUTE oral Liq. ca Psule Gastric tube Rectal Topical in Halation i.V. sub Q or i.m. inter St. liq. l Ymph Arterial intra Cav. liq. s Eal. source seal. so Urce d i Nvitro test nO dose
PLACE ISOTOPES ADMINISTERED Uc med. ct. Children's Jewish Elsewhere Not applic.
DATE ISOTOPE ADMINISTERED (Zeros for no dose) MO. DAY YR.
PROCEDURES (See code - reverse side)
CARD 1
REPORT
ISOTOPE MAT. DOSE ROUTE DATE TIME
PROCEDURE REPORT
ASSESSMENTS - PHOTOSCANS (Not Scinti-Photos)
CARD
DATE
SCA
SITUATION (18)
SIZE (19)
SHAPE (20)
EDGES (21)
UNIFORMITY (22)
HOT AREAS (23)
COLD AREA (24)
TECHNICAL QUALITY (25)
RESULTS
RESULTS (P
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RESULTS
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Fig. 2. Patient information portion of radioisotope laboratory patient form

Average doses were calculated using the beta-gamma formulas given in Figure 3. We will concentrate here on the beta dose and on the absorbed fraction concept for the gamma dose determination. The application of these formulas requires careful consideration of certain of the parameters, namely 1) absorbed fraction, A.F., values as a function of photon energy for various cylinder sizes, values which have only become available during the past few years; 2) the concentration, C_o (in μCi/g), which indicates knowledge of the amount of radioactivity in the organ per gram of the organ (here gross assumptions concerning organ size are made in many cases); and 3) T_e, the effective half-life (in days), which involves both the physical and biological half-life. The biological half-life is largely a function of the rate of metabolism of the radiopharmaceutical by the individual and thus varies considerably among individuals. Figure 4 shows the absorbed fraction as a function of photon energy for various cylinder sizes. As far as the concentration is concerned, for some clinical procedures, e.g., thyroid uptake, the amount of activity in the organ or gland can be estimated to a good degree of accuracy. Estimates of organ size are at best crude and account for a considerable portion of the error in dose estimation. Estimates of the effective half-life can only be made from measurements on various individuals administered radionuclides. This information cannot be obtained by the administration of radionuclides to normal individuals; therefore, this information is obtained by periodic counting of an individual administered radionuclides for a clinical procedure.

Fig. 3. Dose formulae for internal dosimetry

BETA : $D = 73.8\ \bar{E}_\beta C_o T_e$

GAMMA: $D = 73.8\ (n\bar{E}_\gamma) C_o T_e$ (A.F.)

A.F. = Absorbed fraction-that fraction of emitted gamma-ray energy absorbed by a phantom of specified mass and geometry

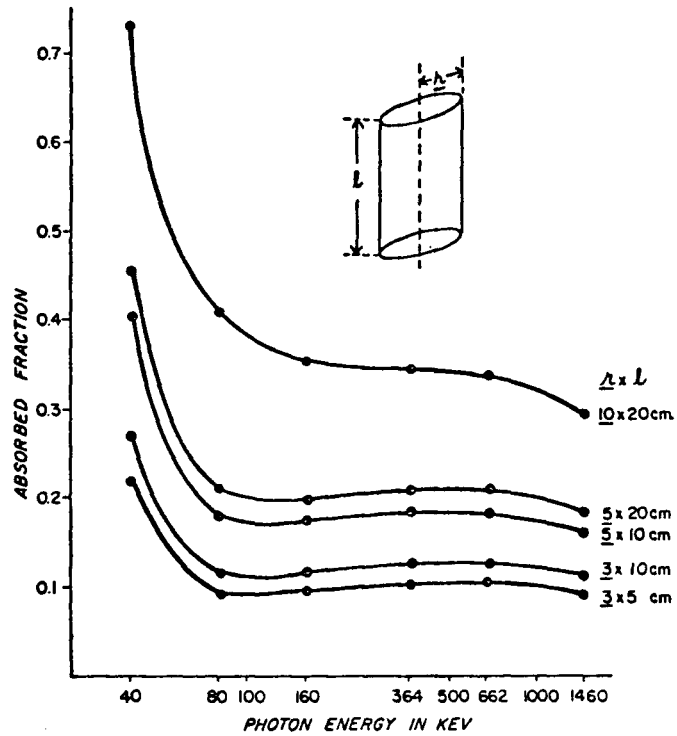


Fig. 4. Absorbed fraction as a function of photon energy for various cylinder sizes (extension of data of Ellett, et. al.) (3,4).

We would like to point out here that, during the past few years, a considerable number of these clinical procedures have been performed on children. Our group has stressed the need for dividing the infant and child population into specific groups to allow better estimates of dose (5). These groups are shown in table 1, along with information on average body weights and organ weights (6). Dose estimates for children were in many cases based on information reported for adults. Because of the possible difference between the physiological response of adults and that of children, continuing studies are being carried out by our group to obtain information on the metabolic fate of several radiopharmaceuticals in infants and children who were referred for various illnesses or because of diagnostic problems. If the radionuclide is distributed uniformly throughout the body, information on T_e can be obtained by counting the patient periodically in a whole body counter (standard chair counting position as shown in figure 5). The use of collimated crystals can provide information as to the effective half-life of radionuclides which tend to concentrate in various organs. Data such as those in figure 6, which shows serial counts of thyroid and thigh tissue over a period of time, provide information on T_e which can be inserted into the formula for dose estimate purposes. As shown in table 2, the uptake in a newborn was measured as 67 percent, whereas the thyroid uptake for other children studied ranged from 9 percent to 22 percent. Thyroid uptake values for children vary greatly. The I-131 uptake is elevated at birth; after 1 week, it returns to values in the lower portion of the normal range for older children. Doses to the thyroid in rad per microcurie of I-131 administered are also given in table 2. Since others have also reported high uptakes during the first week following birth, with an apparent reduction in the iodine uptake in the thyroid after the first week or so of life, it is recommended that radioisotope tests be deferred for this period unless the diagnostic procedure is a life-saving one. Similar studies for other radionuclides are shown in the next two tables. Table 3 shows whole body doses for Chromium-51 (sodium chromate) and Iron-59 (ferrous citrate) for children of various ages, based on observed effective half-life values. Table 4 shows radiation doses from radiopharmaceuticals such as Mercury-197 (chlormerodrin), Calcium-47 (calcium chloride) and Strontium-85 (strontium nitrate) with both whole body doses and organ doses given for children in various age groups. These doses are given in millirad per microcurie administered.

TABLE 1

Body Weights and Organ Weights for Various Ages (6)

Organ	Organ weight (grams)					
	Newborn	1 year	5 years	10 years	15 years	Standard man
Whole body	3,540	12,100	20,300	33,500	55,000	70,000
Thyroid	1.9	2.5	6.1	8.7	15.8	20.0
Kidney	23	72	112	187	247	300
Liver	136	333	591	918	1,289	1,700
Spleen	9.4	31	54	101	138	150

TABLE 2

Thyroid doses from ^{131}I (sodium iodide) in children (7)

Age	Uptake (%)	Effective Half-life (days)	Thyroid Dose	
			Observed Rad/μCi Administered*	Calculated Rad/μCi Administered**
2 days	67	4.7	23.8	32
1 month	10	7.0	5.0	10-32
3 months	9	4.2	2.7	10-32
2 years	10	5.2	2.5	4.3-10
4 years	21	6.3	3.9	4.3-10
6 years	22	4.8	2.4	3.1-4.3
15 years	16	5.9	0.9	1.7

*Based on values measured in this study

**Based on previously reported standard child groups (8)

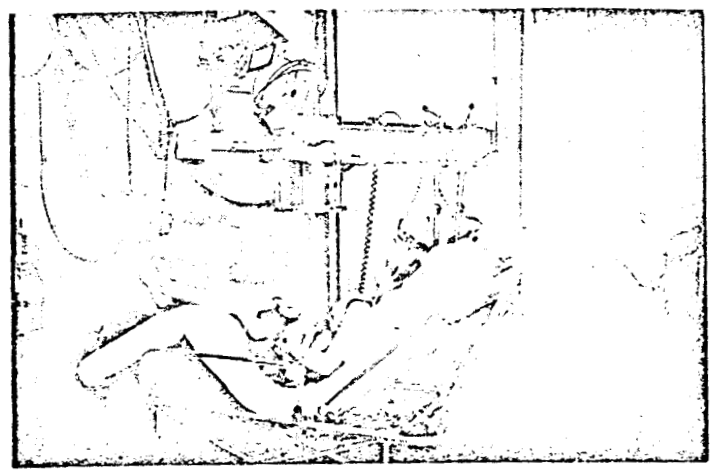


Figure 5. Whole body counting (standard chair position)

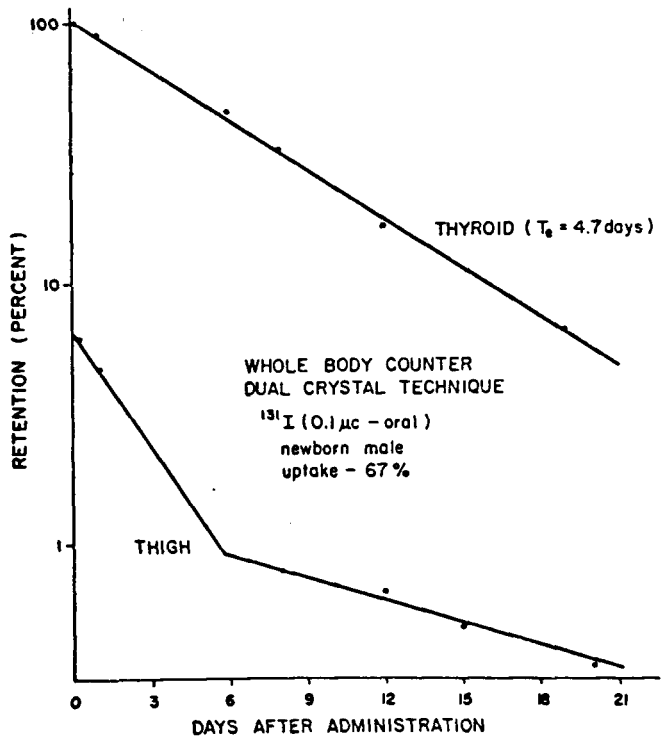


Fig. 6. ^{131}Iodine retention in newborn.

TABLE 3

Radiation Doses from Radiopharmaceuticals in Children (7)

Age	Weight (kg)	Effective Half-life (days)	Whole-Body Doses	
			Observed mrad/μCi Administered*	Calculated mrad/μCi Administered**
		^{51}Cr (Sodium Chromate)		
4 months	8.18	15.0	1.8	4.5
14 months	12.60	20.0	1.7	1.6
5 years	20.00	20.0	1.2	1.0
6 years	13.62	19.4	1.6	0.9
		^{59}Fe (Ferrous Citrate)		
5 years	20.00	38.0	70.3	65
6 years	13.62	31.0	78.0	61
15 years	55.00	39.0	32.0	27

* Based on values measured in this study.
** Based on previously reported standard child groups (9).

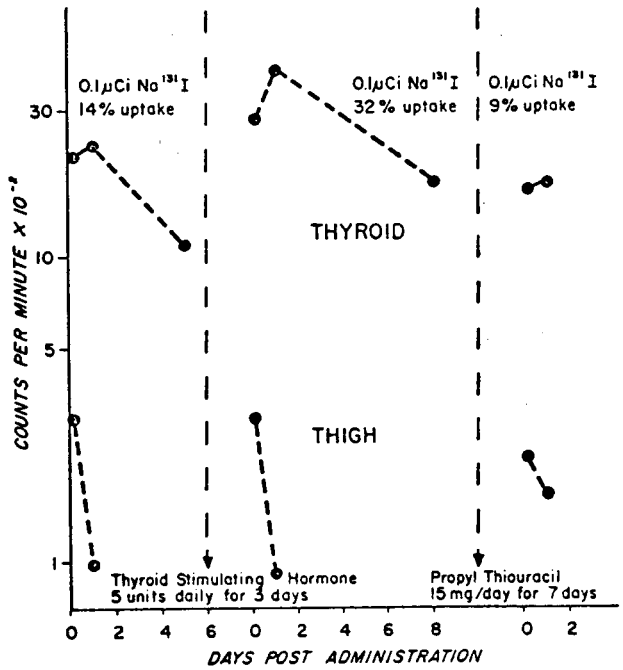
TABLE 4

Radiation Doses from Radiopharmaceuticals in Children (7)

Age	Weight (kg)	Effective Half-life (days)		Doses	
		T_{e_1}	T_{e_2}	Whole body mrad/μCi Administered	Organ mrad/μCi Administered
		^{197}Hg (chlormerodrin)			
3 years	14.55	0.8	2.6	0.16	68.1 (kidney)
12 years	47.28	0.9	2.6	0.07	39.0 (kidney)
		^{47}Ca (calcium chloride)			
7 years	25.00	0.7	4.6	2.8	4.5 (bone)
		^{85}Sr (strontium nitrate)			
4 years	15.47	3.5	58.0	16.3	68.3 (bone)
10 years	32.70	1.3	44.0	6.0	40.8 (bone)
12 years	40.00	1.4	53.0	8.6	32.8 (bone)
12 years	60.00	1.5	30.0	2.5	14.0 (bone)
18 years	48.20	3.6	50.0	4.7	27.0 (bone)

With the ability to better assess the dose comes the possibility of dose reduction. In the thyroid uptake procedure, for example, a dual crystal technique, as shown in figure 7, can be used instead of the standard procedure in which a crystal is placed at 10 inches from the patient's neck. Two collimated sodium iodide thallium-activated crystals, suspended from a yoke, are brought in contact with the patient's neck. With this technique, it is now possible to carry out studies using 1/10 microcurie, or less, of I-131. Figure 8 shows the results of a series of three studies on one 3-year-old child, each using 1/10 microcurie of sodium iodide-131. The initial procedure indicated a 14 percent uptake, considered low. A repeat study after administration of thyroid-stimulating hormone indicated an increased uptake of 32 percent. The final study following administration of propyl-thiouracil indicated an uptake of 9 percent. The total dose to the thyroid gland for the three uptake procedures on this child was estimated to be 0.87 rad. Hence it is now possible to do repeated studies with low administered activities of I-131. The use of other radioisotopes of iodine, such as iodine-123, could further reduce radiation dose without interfering with diagnostic accuracy. This possibility is being investigated at the Nuclear Medicine Laboratory of the Bureau of Radiological Health by Dr. H. Wellman and Dr. V. Sodd. Iodine-123 is a particularly advantageous radioisotope of iodine because it has a physical half-life of approximately 13 hours, compared to 8.2 days for iodine-131. Since iodine-123 has no beta-particle emission and a low energy gamma ray (159 KeV), shielding requirements are also reduced. It has been estimated that the dose from a thyroid uptake procedure can be reduced by a factor of 10^4 if the standard procedure using iodine-131 is replaced by a dual-crystal technique using iodine-123.

Fig. 7. Dual crystal technique for thyroid gland uptake procedure



Whole Body Counter
Dual Crystal Technique
3 year old male
Secondary hypothyroidism (low uptake, normal response to TSH stimulation, no pituitary reserve with PTU block, PBI 1.8 μg)

Fig. 8. Repeated uptake procedures using low administered activities of ^{131}I (sodium iodide) (7)

The importance of the use of shorter half-life radionuclides in various clinical procedures is shown in the next two tables. In each case, the activity administered is that recommended in order to obtain the proper scan information. Table 5 compares estimated doses in rads from various radiopharmaceuticals used for liver scanning, namely, technetium sulfur colloid, gold colloid, and iodine-131 aggregated albumin. Dose to the liver from 3 mCi of technetium sulfur colloid is 0.72 - 0.99 rads, whereas 150 μCi of gold colloid results in a dose of 3.9 - 6.4 rads to the liver. Table 6 compares estimated doses in rads from various radiopharmaceuticals used for bone marrow scanning. Dose to the red bone marrow from 2.5 mCi of gold-198 colloid is 7 - 18 rads, while 5 mCi of technetium sulfur colloid results in only 0.13 - 0.17 rads to the red bone marrow.

If comparisons are to be made, there has been general agreement that the overall dose per procedure in nuclear medicine is of the same order of magnitude as that in diagnostic radiology. This conclusion was reached at the "Symposium on Reduction of Radiation Exposure in Nuclear Medicine" held at Michigan State University in the fall of 1967 (12). The present philosophy in the field is an awareness of the patient dose for the several procedures and in all instances a desire to use the procedure which will result in minimum dose to the patient compatible with the goal of obtaining optimum information. Perhaps the most fitting expression of this philosophy is Dr. Merrill Bender's statement that "the patient should not be protected out of a diagnosis."

TABLE 5

Comparison of the Dose from Various Radiopharmaceuticals Used for Liver Scanning (11)

Radiopharm	Activity Admin	Dose Estimate (rads)					
		Total Body	Male Gonads	Female Gonads	Liver	Spleen	Red Bone Marrow
^{99m}TcS Colloid	3 mCi	0.05	0.04	0.07	0.72-0.99	0.48-1.3	0.07-0.10
^{198}Au Colloid	150 µCi	0.35	0.06	0.09	3.9 -6.4	3.7-11.0	0.4-1.1
^{131}I Agg. Alb.	150 µCi	0.02	-	-	0.09	-	-

TABLE 6

Comparison of the Dose from Various Radiopharmaceuticals Used for Bone Marrow Scanning (11)

Radiopharm	Activity Admin	Dose Estimate (rads)					
		Total Body	Male Gonads	Female Gonads	Liver	Spleen	Red Bone Marrow
^{99m}TcS Colloid	5.0 mCi	0.08	0.06	0.11	1.1-6.2	0.8-2.2	0.13-0.17
^{198}Au Colloid	2.5 mCi	5.8	0.98	1.5	51-108	62-183	7.0-18
^{199}Au Colloid	2.5 mCi	1.7	0.28	0.49	31-34	32-96	3.5-9.4

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