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NUCLEAR MEDICINE PRACTICES IN THE 1950s THROUGH THE mid-1970s AND OCCUPATIONAL RADIATION DOSES TO TECHNOLOGISTS FROM DIAGNOSTIC RADIOISOTOPE PROCEDURES

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Abstract

Data on occupational radiation exposure from nuclear medicine procedures for the time period of the 1950s through the 1970s is important for retrospective health risk studies of medical personnel who conducted those activities. However, limited information is available on occupational exposure received by physicians and technologists who performed nuclear medicine procedures during those years. To better understand and characterize historical radiation exposures to technologists, we collected information on nuclear medicine practices in the 1950s, 1960s, and 1970s. To collect historical data needed to reconstruct doses to technologists, a focus group interview was held with experts who began using radioisotopes in medicine in the 1950s and the 1960s. Typical protocols and descriptions of clinical practices of diagnostic radioisotope procedures were defined by the focus group and were used to estimate occupational doses received by personnel, per nuclear medicine procedure, conducted in the 1950s-1960s using radiopharmaceuticals available at that time. The radionuclide activities in the organs of the reference patient were calculated using the biokinetic models described in ICRP Publication 53. Air kerma rates as a function of distance from a reference patient were calculated by Monte Carlo radiation transport calculations using a hybrid computational phantom. Estimates of occupational doses to nuclear medicine technologists per procedure were found to vary from less than 0.01 μSv (thyroid scan with 1.85 MBq of administered ^{131}I -iodide) to 0.4 μSv (brain scan with 26 MBq of ^{203}Hg -chlormerodine). Occupational doses for the same diagnostic procedures starting in the mid-1960s but using $^{99\text{m}}\text{Tc}$ were also estimated. The doses estimated in this study show that the introduction of $^{99\text{m}}\text{Tc}$ resulted in an increase in occupational doses per procedure.

Keywords

Nuclear medicine; historical; occupational; radiation; dose

INTRODUCTION

The use of radioisotopes and radiopharmaceuticals in diagnostic medicine began in the 1950s with the increased availability of radioiodine and evidence of medical utility rapidly gained in popularity with the development of various imaging devices, in particular, the rectilinear scanner and later, gamma camera imaging systems. Over time, additional radioisotopes became available. Development methods of attaching them to specific chemicals led to the concept of radiopharmaceuticals and opened the door to what subsequently became the field of nuclear medicine.

To provide useful diagnostic information, isotopes used in nuclear medicine procedures needed to emit x- or gamma-rays, resulting in potential ionizing radiation exposure of medical personnel involved in performing diagnostic nuclear medicine studies. Occupational exposure can, of course, result from any aspect of procedures that would bring practitioners into proximity with the radioactivity either in the container shipped during its preparation for an administration to, or when it is present within the patient before, during, or after imaging. Despite the possibility for occupational exposure, during the early years of the developing field of nuclear medicine, scientific and medical publications primarily focused on interpretation of the data and images obtained from the procedures, instrumentation and

other clinical matters, with little attention given to monitoring occupational radiation exposure. Moreover, because the field evolved by the efforts of a few individual specialists, early imaging protocols did not exist for diagnostic procedures but evolved over many years. For these reasons, there was little standardization in the early years of factors critical to dose estimation, e.g., activities administered, distances maintained between the patient and the attending staff, and protection taken to minimize radiation exposure. The absence of standardization in the early years led to wide variations in how procedures were conducted and presumably in the magnitude of occupational exposures received.

In the earliest years of nuclear medicine development, technologists trained in conventional radiographic procedures assisted the physicians and physicists involved. By the mid-1960s, however, the American Registry of Radiation Technologists (ARRT™) developed training requirements and certification in “nuclear medicine technology” and by the end of the 1960s, there were 700 certified technologists amongst the more than 56,000 technologists certified in more general practice of radiology (ARRT 2012). With increasing levels of training, both physicians and technologists became more aware of occupational radiation exposure and its health hazards.

Monitoring of personnel for radiation exposure received while conducting procedures with radiopharmaceuticals has relied over the decades on the same technologies used for monitoring other types of medical radiation exposures, i.e., film-badges, thermoluminescent dosimeters, and similar devices. One significant difference in how exposures are received compared to more conventional radiographic imaging relates to the geometry of nuclear medicine sources which are typically closer to point or line sources when in their shipping containers but a more diffuse sources while they are administered to the patient. A second substantial difference is that energies of many isotopes are significantly greater than energies of *bremsstrahlung* radiations used in conventional radiography. These differences in the sources of radiation, in addition to the the fact that many early technologists practiced both conventional radiography and nuclear medicine, have complicated estimating radiation exposures from each activity. Even, for example, when historical records of occupational doses for radiologic technologists are available, film badge doses represent total combined exposure resulting from all occupational radiation-related activities.

The motivation to better understand occupational radiation doses from conducting nuclear medicine procedures is, in part, to better characterize post occupational risks to medical practitioners. In a broader sense, however, because medical practitioners who use radiation potentially receive exposure over the many decades of their career, studies of health effects in those persons can lead to a better understanding of risk from chronic radiation exposure. One long-running study on radiologic technologists by the U.S. National Cancer Institute focuses on exposures and related health risks, particularly, the risk of the development of cancer (Boice et al., 1992, Sigurdson et al. 2003, Simon et al. 2006). Studies of health risk associated with medical radiation exposure can potentially increase our overall understanding of radiation risks, though all such studies require quantitative estimates of occupational doses for all cohort members.

As noted, detailed information on historical practices in administering radioisotopes for diagnostic imaging procedures and the related occupational doses from performing those procedures is scarce for the years before the mid-1970s. Not only is there a paucity of details concerning administered activities and other important parameters related to protocol details, but there are few reported measurements of occupational doses or data that would be crucial to the calculation of radiation exposures from conducting nuclear medicine procedures in the 1950s through the mid-1970s. The absence of published exposure data emerged from an extensive literature review we conducted to evaluate occupational doses to radiologic technologists involved in nuclear medicine since the 1950s. In particular, we found that there is limited information on occupational exposure from nuclear medicine procedures conducted in the 1950s until the mid-1970s. Therefore, to obtain historical data needed to reconstruct occupational doses to personnel involved in nuclear medicine practices, we assembled a focus group and interviewed practitioners who had worked in nuclear medicine during that time interval. The data sought from the focus group included description of the radiopharmaceuticals used, activities administered, and clinical practices related to time, distance, and protection.

The primary purposes of our paper are to present the data collected from the focus group meeting and to provide estimates of occupational radiation doses on a per-procedure basis received by technologists involved in clinical nuclear medicine activities from the 1950s to the 1970s.

MATERIALS AND METHODS

Literature review

A search for full-text articles published between the 1950 and 2012 was performed using PubMed, Science Direct and journals' web-sites if full text papers were not available from PubMed or Science Direct (e.g., Health Physics) and/or were not completely indexed by PubMed (e.g., Radiat Prot Dosim (indexed from the 1980s)); Med Phys; Eur J Nucl Med; J Nuc Med Tech (indexed from the 1990s); Pharmaceutical J). The keywords used in searching included "occupational", "exposure", "radiation", "technologist", "diagnostic isotope", "nuclear medicine". In addition, references listed in each article were used to trace publications that were not captured by electronic search. We found that limited information is available on occupational exposure from the conduct of nuclear medicine procedures from the 1950s until the mid-1970s. The lack of published or archived radiation measurement data for occupational exposures led to discussions with experts as an alternative source of information.

Focus group interview

To collect historical data needed to reconstruct occupational doses to personnel involved in performing diagnostic radioisotope procedures, a focus group interview strategy was used. The focus group interview is a technique for obtaining information from memory recall of experts who discuss the subject freely in a group setting. Focus groups have the advantage of being able to stimulate recall from discussions about the time period in general, with an emphasis on specific questions of interest. Participant interaction is a unique and compelling

feature of focus groups where participants share their experiences to describe the range of experiences in a group (Kitzinger 1995). This data collection technique has been used, for example, to gather data about historical dietary patterns (McLafferty 2004) and other lifestyle information useful for radiation dose reconstruction (Schwerin et al 2010).

The nuclear medicine focus group met at the National Cancer Institute (NCI) in Bethesda, MD in November, 2010 to discuss historical nuclear medicine practices. The participants in the focus group were persons who started to work in the 1950s and the 1960s in the field of diagnostic imaging now known as nuclear medicine. The types of medical institutions of the participants were large hospitals and medical centers and included: Cornell New York Hospital, Johns Hopkins University Medical Center, Massachusetts General Hospital, Mt. Sinai Medical Center, National Institutes of Health (NIH) Clinical Center, National Naval Medical Center, University of Maryland Medical Center, University of Michigan Medical Center, University of New Mexico Medical Center, Vanderbilt University Medical Center, Veteran Affairs (VA) Hospitals (Los Angeles, New York, Buffalo), and the Washington Hospital Center.

The primary purpose of the focus group discussion was to describe in comprehensive manner how diagnostic radioisotope procedures were conducted in past with particular emphasis on the decades when nuclear medicine was an emergent medical discipline (1950s through mid-1970s). To identify the most frequently conducted diagnostic radioisotope procedures in the time period of interest, prior to the focus group meeting we sent a list of specific procedures to the expert practitioners and asked them to list the typical numbers of patients per month at their institution who underwent these procedures in the 1950s through mid-1970s. Due to the rapid increase in usage of ^{99m}Tc beginning in the mid-1960s, our discussions separately focused on two periods: before and after ^{99m}Tc introduction into the clinic: 1950-1965 and 1965-1975, respectively.

During the focus group discussion, typical protocols and clinical practices were described for the most frequently used diagnostic radioisotope procedures conducted during the period 1950-1975. The information discussed included administered activities, mode of administration, waiting time before conducting the study, and how much time technologists spent either in contact or close to patients during positioning and imaging. Factors that would have influenced occupational doses, e.g., how the radiopharmaceuticals were administered, were also discussed. Participants in the focus group noted that there was a broad range of occupational doses received by technologists. The focus group identified some reasons that may have contributed to great variation in occupational doses among technologists who performed diagnostic radioisotope procedures in the 1950s through the mid-1970s.

The typical protocols of diagnostic radioisotope procedures defined during the focus group discussion were used to calculate occupational radiation doses received by personnel as described in the following section.

Estimation of occupational radiation dose

Radiation doses received by technologists conducting diagnostic radioisotope procedures were calculated in this study as personal dose equivalent, $H_p(10)$, as defined by the International Commission on Radiation Units and Measurements (ICRU 1993). The air kerma to which the technologist was exposed is determined by the administered activity of the radiopharmaceutical used, the distance between technologist and patient, and by the time spent by the technologist at specific distances. Dose to a technologist acquired during a diagnostic procedure from the radiopharmaceutical distributed in a patient's body was calculated as:

$$H_p(10) = \sum_l \dot{K}_{a,l} \times (H_p(10) / K_a) \times t_l, \quad (1)$$

where $H_p(10)$ is personal dose equivalent (μSv); $\dot{K}_{a,l}$ is the air kerma rate free-in-air (usually referred to as “air kerma rate”) at distance l from the patient, $\mu\text{Gy h}^{-1}$; is conversion coefficient from air kerma free-in-air to personal dose equivalent, $H_p(10)$, Sv Gy^{-1} ; and t_l is the length of time the technologist is exposed at distance l . Values of conversion coefficients were taken from the International Commission on Radiological Protection (ICRP) Publication 74 (ICRP 1996) and (Simon 2011) to be equal to 1.32 Sv Gy^{-1} for ^{131}I (photon energy of 0.364 MeV); 1.29 Sv Gy^{-1} for ^{198}Au (photon energy of 0.412 MeV); 1.9 Sv Gy^{-1} for ^{197}Hg (weighted mean energy of K X-rays of 0.07 MeV); 1.39 Sv Gy^{-1} for ^{203}Hg (photon energy of 0.279 MeV); and 1.64 Sv Gy^{-1} for $^{99\text{m}}\text{Tc}$ (photon energy of 0.140 MeV).

As can be seen from eqn (1), to calculate the dose per procedure to technologists it is necessary to know (i) the air kerma rate at specific distances from the patient due to the radiopharmaceutical distribution in the patient's body; and (ii) typical protocols and work practices for each procedure that specify distance between technologist and patient and the length of time the technologist might be exposed at one or more distances.

Air kerma rate at distance l from the patient was calculated as:

$$\dot{K}_{a,l} = 3.6 \cdot 10^{15} \times K_l \times A, \quad (2)$$

where 3.6×10^{15} is the conversion coefficient, $\text{s h}^{-1} \mu\text{Gy Gy}^{-1} \text{ Bq MBq}^{-1}$; K_l is air kerma free-in-air per photon at distance l from patient, Gy photon^{-1} ; A is the activity of radionuclide in source organ in MBq.

Air kerma rates per photon (free-in-air) at specified distances from a patient were calculated in this study for selected radionuclides and source organs by using Monte Carlo radiation transport computations. Several distances were considered: close contact (0.05 m), 0.5 m, 1 m and 2 m. Figure 1 shows the frontal view of an adult male hybrid phantom with the locations of the four calculation points such that the radionuclides are distributed within the liver, kidneys, spleen, and rest of body. For all diagnostic radioisotope procedures (except thyroid scans) the points of calculation of air kerma were defined to be located on the left side of the supine patient at the level of the abdomen on the plane located at mid-thickness

of the patient. For thyroid scans, the four points of calculation (close contact, 0.5 m, 1 m, and 2 m distant) were defined to be located on the plane against the anterior surface of the neck just below the cricoid cartilage.

To have a realistic model of the source geometry in terms of location and photon attenuation in the body of the patient, an adult male hybrid phantom (Lee et al. 2010; Hurtado et al. 2012) with organ masses, anthropometric parameters, and elemental compositions matched to the standard data reported by the ICRP and the United States Centers for Disease Control and Prevention (CDC) was used in the calculations. Only photon particles emitted by radionuclides are considered since the electrons have too little energy to contribute to the exposure of the technologist (ICRP 2008).

The activity of radionuclide in the different source organs in the patient's body was calculated using biokinetic models of the radiopharmaceuticals in the human body given in ICRP Publication 53 (1987). Purpose of this study was to estimate occupational radiation doses from historical diagnostic radioisotope procedures. To check the validity of our calculations, occupational doses from the same procedures using ^{99m}Tc as the radionuclide were also calculated and compared with more-recently measured doses reported in the literature (for example, Barrall and Smith 1976; Boutcher and Haas 1985).

RESULTS

Information collected by focus group interview

Diagnostic radioisotope procedure most frequently used in the 1950s-1970ss

—The list of nuclear medicine procedures was prepared in advance of the focus group meeting based on literature data (USDHEW 1968) and subsequently discussed by the expert practitioners attending the focus group meeting. Based on the recall of the focus group participants, Table 1 and Table 2 provide a ranking of the procedures in the two time periods (1950-1965 and 1965-1975), respectively, based on the typical number of patients per month per institution. It should be noted that the typical number of patients per month cannot necessarily be generalized to smaller institutions since the data are representative only of the relatively large size of institutions represented by the participants. Typical administered activities presented in Table 1 and Table 2 were derived from the literature (Beierwaltes et al. 1957; Fields and Seed 1957; Blahd et al. 1958; King and Mitchell 1961; Reba et al 1962; Wagner 1968; Belcher and Vetter 1971; Maynard 1971; Sodde and Early 1972; Mettler et al. 1986; Wagner 1995) and discussed by the focus group participants.

The data obtained from the focus group interview were compared with literature data. In a similar fashion to Tables 1 and 2, Table 3 ranks the diagnostic radioisotope procedures in 1966 by the number of patient administrations reported in a nationwide survey of the U.S. Department of Health, Education, and Welfare (USDHEW 1968). *In vivo* measurements, such as determination of blood volume using ^{131}I -HSA, or of red cell volume using ^{51}Cr or of the Schilling test conducted with ^{57}Co or ^{60}Co , are included as Other (no rank) in Table 3. Although the literature data in Table 3 are for 1966, near to the time when ^{99m}Tc was introduced, in general we found moderately good agreement between the frequency of

diagnostic radioisotope procedures reported by the focus group experts and the published literature reports.

Participants of the focus group concluded that the most frequently conducted diagnostic radioisotope procedures in the 1950s- mid-1970s were the following:

- Thyroid scan and thyroid uptake;
- Brain scan;
- Liver scan; and
- Renal scan.

Typical protocol and clinical practices for the most frequently used

procedures—Typical protocols defined by the focus group and clinical practices typically associated with the most frequently conducted diagnostic radioisotope procedures in the 1950s – mid-1970s are shown in Table 4. The table reflects a consensus of the focus group participants on the following characteristics of the procedure's protocol: administered activity of the radiopharmaceutical, mode of administration, waiting time before beginning of the procedure, duration of positioning and scanning, as well as time spent by the technologist at a range of distances from the patient. The distance between the technologist and the patient is one of the most important parameters assumed in our calculations since the occupational dose varies significantly with changes in distance. As can be seen from Table 4, technologists typically stayed more than 1 meter from the patient for a majority of the time during each procedure. Patients in poor health, however, may have required more care and assistance, thus requiring the technologist to be close to the patient for longer times.

Occupational doses from historical diagnostic radioisotope procedures

The following radionuclides and source organs in patient were considered in this study:

- ^{131}I and $^{99\text{m}}\text{Tc}$ in thyroid gland;
- ^{198}Au and $^{99\text{m}}\text{Tc}$ in liver;
- ^{198}Au and $^{99\text{m}}\text{Tc}$ in spleen;
- ^{197}Hg , ^{203}Hg and $^{99\text{m}}\text{Tc}$ in kidneys;
- ^{131}I , ^{198}Au , ^{197}Hg , ^{203}Hg and $^{99\text{m}}\text{Tc}$ in the rest of the body which is referred to in this study as “rest of body”.

Activities of radionuclides in source organs were calculated at the time of the beginning of the procedure (Table 5) using published radiopharmaceutical biokinetic models in the human body (ICRP 1987). Since the effective half-lives of typically-used radionuclides in the 1950s and 1960s were much longer than the duration of the scans, our dose calculations assumed no change in activity of the radioisotope in the source organ during the procedure.

Table 6 presents findings on the calculated air kerma per emitted photon, K_I , of radionuclide in the patient's organs and rest of body at a range of distances from the patient. Using eqn (2) and activities of the radionuclide in different source organs for the most frequently

conducted procedures (Table 5), air kerma values were calculated at different distances from the patient. Fig. 2 shows the air kerma rate at different distance from the patient at the beginning of scanning calculated for typical administered activities given in Table 4.

Values of air kerma at specific distances from patients and typical time-distance relationships described by the participants of the focus group were used to estimate occupational doses to technologists. Table 7 presents calculations of personal dose equivalent, $H_p(10)$, to nuclear medicine technologists from historical diagnostic radioisotope procedures and from those performed more recently using ^{99m}Tc , the latter using data on $[H_p(10)/K_a]$ from ICRP Publication 74 (ICRP 1996) as discussed by Simon (2011). As can be seen in Table 7, occupational doses per procedure were found to vary from less than 0.01 μSv (thyroid scan with 1.85 MBq of administered ^{131}I iodide) to 0.4 μSv (brain scan with 26 MBq of administered ^{203}Hg -chlormerodrin). Introduction of ^{99m}Tc resulted in increased occupational doses to technologists. As can be seen from Table 7, the estimated doses per procedure to the technologist who conducted scans using ^{99m}Tc compared to historical radioisotope procedures increased notably. For those conducting thyroid scans using ^{131}I the dose increased on average from less than 0.01 to 0.8 μSv ; for those who conducted renal scans with Hg isotopes from 0.01-0.02 to 1.8 μSv ; for those who conducted liver scans with ^{198}Au from 0.2 to 1.7 μSv ; and for those who conducted brain scans with Hg isotopes from 0.2-0.4 to 2.5 μSv .

DISCUSSION

Occupational doses to nuclear medicine technologists from procedures conducted in the 1950s through 1960s, as well as from the same procedures using ^{99m}Tc conducted in mid-1960s to the mid-1970s, were estimated from data derived from the group discussion. The data useful for these calculations included: (i) administered activity, and (ii) time spent in close proximity to the patient. The exposure to the technologists from radiopharmaceuticals distributed in a patient's body was calculated by Monte Carlo-based radiation transport calculations using a hybrid computational phantom to represent a typical patient. This strategy of calculation has allowed us to use a realistic model of the geometry of radiation source and photon attenuation in the body while avoiding a conservative estimation of doses from the patient when a point or line source of radioactivity represents the patient (de Carvalho et al. 2011).

To validate the approach used and the results obtained we compared the calculated occupational doses in this study for more recently-conducted procedures utilizing ^{99m}Tc , with measured occupational doses as reported in the literature. Personal dose equivalent (ICRU 1993) calculated in this study was assumed to be the same quantity reported in the literature from individual personnel monitoring devices, e.g., film badges. For comparison purposes, doses calculated in this study and published occupational doses were normalized to 1 GBq administered activity. As can be seen from Table 8, there is good agreement between doses calculated in this study and those measured. The estimated dose to the technologists while conducting a thyroid scan using ^{99m}Tc -pertechnetate was 4.6 μSv per GBq of activity administered to patients compared to measured dose of 3.3 μSv per GBq that is average of doses measured by Barrall and Smith (1976) and Chiesa et al. (1997). The

estimated dose to the technologists conducting brain scans with ^{99m}Tc -pertechnetate was calculated as 4.5 μSv per GBq compared to average measured dose of 4.6 μSv per GBq (Barrall and Smith 1976; Boucher and Haas 1985; Sloboda et al 1987). For renal scans utilizing ^{99m}Tc -DTPA, the occupational dose was calculated to be 4.8 μSv per GBq compared to 3.2 μSv per GBq measured by Harding et al (1987) and Clark et al. (1992). Less consistent agreement was found between calculated and measured doses to technologists who performed liver scans utilizing ^{99m}Tc -sulfur colloid: 5.9-9.1 μSv per GBq compared to 4.0 μSv per GBq that is average of measured doses presented in publications (Barrall and Smith 1976; Boucher and Haas 1985; Harding et al 1987; Sloboda et al. 1987; Clarke et al 1992).

We estimated effective doses to patients from historical procedures and from more recent procedures conducted using ^{99m}Tc (Table 9). To calculate the effective dose to patients, known administered activity of radiopharmaceutical and effective dose per unit administered activity were used, given data in ICRP Publication 53 (1987) and updated for ^{99m}Tc -pertechnetate and ^{99m}Tc -DTPA in ICRP Publication 80 (1998). As can be seen from Table 9, introduction of ^{99m}Tc in nuclear medicine procedures in the mid-1960s resulted in the lowering of doses to patients, except for those receiving renal scans performed with ^{99m}Tc -DTPA. Effective doses to patients receiving brain scans decreased from 44 mSv to 2.3 mSv when ^{203}Hg -chlormerodrin was replaced with ^{99m}Tc -pertechnetate. When ^{99m}Tc was introduced and replaced ^{131}I -iodide there was a ten fold decrease in effective dose to patients: from 20 mSv with ^{131}I -iodide to 2.4 mSv. In contrast, introduction of ^{99m}Tc resulted in an increase of occupational doses to technologists.

Although a single estimate of occupational dose was derived for each historical diagnostic radioisotope procedure, there are, obviously, uncertainties associated with the estimated doses that arise from a variety of sources, including:

1. Variations in the time spent close to patients by different technologists. The length of time spent near the patient was often related to the degree of experience of a technologist, each patient's health conditions, and amount of space in the imaging room. Reports describe up to 3-fold variation in occupational exposure among technologists due to these factors (Sloboda et al. 1987, Chiesa et al. 1997, McElroy 1998).
2. Variations in the amount of administered activity of radiopharmaceuticals among different facilities due to differences in patient weight. Based on the results of nationwide surveys it was determined that for the majority of diagnostic radioisotope procedures the administered activity varied two-fold between facilities (USDHEW 1970, USDHEW 1976).

If we assume independence between the two factors above, one might expect that the uncertainty of the occupational dose received per diagnostic procedure conducted to be at least 2-fold in either direction at the one-standard deviation level.

CONCLUDING REMARKS

Historical data needed to reconstruct occupational exposure from diagnostic radioisotope procedures conducted from the 1950s until the mid-1970s were collected by a focus group interview strategy. Typical protocols and clinical practices were described for specific types of nuclear medicine procedures. Those data were used with Monte Carlo radiation transport calculations to estimate air kerma rates as a function of distance from a phantom simulating a typical patient containing a given radiopharmaceutical. The air kerma rates were used to estimate personal dose equivalent received per procedure by the technologists.

Occupational doses to technologists who conducted historical diagnostic isotope procedures were estimated in this study to vary per procedure from less than 0.01 μSv (thyroid scan with 1.85 MBq of administered ^{131}I iodide) to 0.4 μSv (brain scan with 26 MBq of administered ^{203}Hg -chlormerodrin). Introduction of $^{99\text{m}}\text{Tc}$ in nuclear medicine in the mid-1960s resulted in the lowering of doses to patients but to increasing occupational doses to technologists. Indeed, radiation dose estimates per procedure to technologists were found to vary from 0.8 μSv (thyroid scan with 185 MBq of administered $^{99\text{m}}\text{Tc}$ -pertechnetate) to 2.5 μSv (brain scan with 555 MBq of $^{99\text{m}}\text{Tc}$ -pertechnetate).

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Fig. 1.
Frontal view of the adult male hybrid phantom with the locations of the four calculation points.

Fig. 2.
Air kerma rate calculated in this study for a range of distance from the patient.

Table 1

Ranking of diagnostic radioisotope procedures performed in the 1950s to mid-1960s by the typical number of patients treated per month per institution, according to the focus group.

Rank	Procedure	Radiopharmaceutical	Typical number of patients per month per institution	Typical administered activity (MBq)
1.	Thyroid uptake	¹³¹ I-sodium iodide	18-60	0.185
2.	Thyroid scan	¹³¹ I-sodium iodide	15-40	1.85
3.	Brain scan	¹⁹⁷ Hg-, ²⁰³ Hg- chlormerodrin	20	26
4.	Liver scan	¹⁹⁸ Au-colloid	5-20	7.4
5.	Liver scan	¹³¹ I-Rose Bengal	3-20	0.37
6.	Renogram	¹³¹ I-OIH	10-15	0.37
7.	Blood volume	¹³¹ I-HSA	10	0.185
8.	Renal scan	¹⁹⁷ Hg-, ²⁰³ Hg- chlormerodrin	5-10	3.7
9.	Bone scan	⁸⁵ Sr-chloride	2-10	3.7

Table 2

Ranking of diagnostic radioisotope procedures performed in 1965-1975 by the typical number of patients treated per month per institution, according to the focus group.

Rank	Procedure	Radiopharmaceutical	Typical number of patients per month per institution	Typical administered activity (MBq)
1.	Liver scan	^{99m}Tc -SC	25-120	185
2.	Brain scan	^{99m}Tc -pertechnetate	10-80	555
3.	Renal scan	^{99m}Tc -DTPA	20-50	370
4.	Lung scan	^{99m}Tc -MAA	5-60	74
5.	Thyroid scan	^{99m}Tc -pertechnetate	2-30	185
6.	Thyroid uptake	^{131}I -sodium iodide	2-25	0.185
7.	Localization of tumor	^{67}Ga -citrate	10-30	93
8.	Thyroid scan	^{131}I -sodium iodide	2-25	1.85
9.	Renal scan	^{197}Hg - chlormerodrin	5-30	3.7
10.	Bone scan	^{85}Sr -chloride	7	3.7
11.	Bone scan	^{87m}Sr -chloride	7	74

Table 3

Ranking of diagnostic radioisotope procedures in 1966 by number of patient administrations according to the results of a nation-wide survey (USDHEW, 1968).

Rank	Procedure	Radiopharmaceutical	Annual no. of patient administrations	Percent from total number of patient administrations performed
1.	Thyroid uptake	^{131}I -sodium iodide	301,052	32.2
2.	Thyroid scan	^{131}I -sodium iodide	153,089	16.4
3.	Brain scan	$^{99\text{m}}\text{Tc}$ -pertechnetate	63,078	6.7
4.	Liver scan	^{198}Au -colloid	41,855	4.5
5.	Brain scan	^{203}Hg - chlormerodrin	37,746	4.0
6.	Renogram	^{131}I -OIH	33,245	3.6
7.	Lung scan	^{131}I -MAA	22,840	2.4
8.	Liver scan	^{131}I -Rose Bengal	19,721	2.1
9.	Brain scan	^{197}Hg -chlormerodrin	18,489	2.0
10.	Renal scan	^{203}Hg -chlormerodrin	16,223	1.7
	Others (no rank)		228,599	24.4
Total			935,937	

Table 4

Typical protocols and clinical practices for selected historical and more recent diagnostic radioisotope procedures reported by the participants of the focus group

Scan	Thyroid scan	Liver scan	Brain scan	Renal scan	Thyroid scan	Liver scan	Brain scan	Renal scan
Years when procedures done	1960s-present	1950s-1960s	1950s-1960s	1950s-1970s	mid-1960s-present	mid-1960s-present	mid-1960s-1980s	mid-1960s-1990s
Radiopharmaceutical	^{131}I iodide	^{198}Au -colloid	^{197}Hg / $^{203}\text{Hg}^a$	^{197}Hg / $^{203}\text{Hg}^a$	$^{99\text{m}}\text{Tc}^b$	$^{99\text{m}}\text{Tc}$ -SC	$^{99\text{m}}\text{Tc}^b$	$^{99\text{m}}\text{Tc}$ -DTPA
Radioactive half-life	8.04 d	2.67 d	2.67 d / 46.6 d	2.67 d / 46.6 d	6.01 h	6.01 h	6.01 h	6.01 h
Administered activity (MBq)	1.85	7.4	26	3.7	185	185	555	370
Mode of administration	oral	IV ^c	IV	IV	IV	IV	oral or IV	IV
Waiting time before scan (h)	24	0.5	2	1	0.5	0.5	2	1
Duration of scan (min)	30	75	120	30	30	75	30	30
<i>Time spent (min) by technologist at distance</i>								
close contact with patient ^d	-	1	1	1	-	1	1	1
up to 0.5 m from patient	5	-	-	-	5	-	-	-
0.5 – 1 m from patient	5	-	-	-	5	-	-	-
1 – 2 m from patient	20	75	120	30	20	75	30	30

^aChlormerodrin

^bPertechnetate

^cIntravenous injection

^dPositioning of patient

Table 5

Activity in source organs at the time of the beginning of the scan calculated using biokinetic models of the radiopharmaceuticals in the human body (ICRP 1987).

Scan	Radiopharmaceutical	Administered activity (MBq)	Activity (MBq) at the time of the beginning of the scan in				
			Thyroid	Liver	Spleen	Kidneys	Rest of body
Thyroid (5% uptake)	^{131}I -sodium iodide	1.85	0.093	-	-	-	0.22
Thyroid (55% uptake)	^{131}I -sodium iodide	1.85	0.93	-	-	-	0.11
Liver (normal function)	^{198}Au -colloid	7.4	-	5.2	0.7	-	1.5
Liver (intermediate to advanced liver disease)	^{198}Au -colloid	7.4	-	2.2	2.2	-	3.0
Brain	Hg-chlormerodrin ^a	26	-	3.9	-	12	5.7
Renal ^b	Hg-chlormerodrin ^a	3.7	-	0.2	-	1.6	1.1
Thyroid	$^{99\text{m}}\text{Tc}$ -pertechnetate	185	2.6	-	-	-	164
Liver (normal function)	$^{99\text{m}}\text{Tc}$ -SC	185	-	123	17.6	-	35
Liver (intermediate to advanced liver disease)	$^{99\text{m}}\text{Tc}$ -SC	185	-	53	53	-	70
Brain (blocking agent given)	$^{99\text{m}}\text{Tc}$ -pertechnetate	555	-	-	-	-	440
Renal	$^{99\text{m}}\text{Tc}$ -DTPA	370	-	-	-	24	305

^aFor both ^{197}Hg - and ^{203}Hg -chlormerodrin

^bWith blocking dose of 1 ml of meralluride

Table 6

Calculated values of air kerma at different distance per photon emitted by radionuclides in patient organs.

Radionuclide	Distance (m)	Air kerma (Gy/photon) due to radionuclide in				
		Thyroid	Liver	Spleen	Kidneys	Rest of body
I-131	0.05	2.2×10^{-16}	-	-	-	2.3×10^{-17}
	0.5	2.1×10^{-17}	-	-	-	6.0×10^{-18}
	1	6.8×10^{-18}	-	-	-	2.4×10^{-18}
	2	1.9×10^{-18}	-	-	-	8.8×10^{-19}
Au-198	0.05	-	1.2×10^{-17}	3.0×10^{-17}	-	4.4×10^{-17}
	0.5	-	4.3×10^{-18}	1.2×10^{-17}	-	1.2×10^{-17}
	1	-	2.0×10^{-18}	5.0×10^{-18}	-	5.1×10^{-18}
	2	-	8.2×10^{-19}	2.0×10^{-18}	-	1.9×10^{-18}
Tc-99m	0.05	1.5×10^{-16}	2.2×10^{-18}	6.8×10^{-18}	5.7×10^{-18}	1.2×10^{-17}
	0.5	1.5×10^{-17}	1.1×10^{-18}	3.6×10^{-18}	1.8×10^{-18}	3.5×10^{-18}
	1	4.8×10^{-18}	4.8×10^{-19}	1.5×10^{-18}	7.4×10^{-19}	1.5×10^{-18}
	2	1.4×10^{-18}	1.8×10^{-19}	5.5×10^{-19}	3.2×10^{-19}	5.4×10^{-19}
Hg-197	0.05	-	8.4×10^{-19}	-	2.2×10^{-18}	7.3×10^{-18}
	0.5	-	4.4×10^{-19}	-	8.9×10^{-19}	2.2×10^{-18}
	1	-	2.2×10^{-19}	-	4.6×10^{-19}	9.3×10^{-19}
	2	-	8.3×10^{-20}	-	2.0×10^{-19}	3.2×10^{-19}
Hg-203	0.05	-	5.6×10^{-18}	-	1.3×10^{-17}	2.5×10^{-17}
	0.5	-	2.5×10^{-18}	-	3.6×10^{-18}	6.7×10^{-18}
	1	-	1.2×10^{-18}	-	1.6×10^{-18}	2.8×10^{-18}
	2	-	3.8×10^{-19}	-	5.9×10^{-19}	9.6×10^{-19}

Table 7

Personal dose equivalent, $H_p(10)$, to technologists per diagnostic radioisotope procedure: comparison of historical and more recently conducted procedures using ^{99m}Tc .

Scan	Historical diagnostic radioisotope procedure			More recent diagnostic radioisotope procedure		
	Radiopharmaceutical	Administered activity (MBq)	$H_p(10)$ (μSv)	Radio-pharmaceutical	Administered activity (MBq)	$H_p(10)$ (μSv)
Thyroid	^{131}I -sodium iodide	1.85	$0.004^a - 0.03^b$	^{99m}Tc -pertechnetate	185	0.8
Liver	^{198}Au -colloid	7.4	$0.14^c - 0.2^d$	^{99m}Tc -SC	185	$1.1^c - 1.7^d$
Brain	^{197}Hg -chlormerodrin	26	0.2	^{99m}Tc -pertechnetate	555	2.5
	^{203}Hg -chlormerodrin	26	0.4	-	-	-
Renal	^{197}Hg -chlormerodrin	3.7	0.01	^{99m}Tc -DTPA	370	1.8
	^{203}Hg -chlormerodrin	3.7	0.02	-	-	-

^aThyroid uptake of 5%

^bThyroid uptake of 55%

^cNormal liver function

^dintermediate to advance liver disease

Table 8

Comparison of estimates of personal dose equivalent, $H_p(10)$, to technologists per diagnostic radioisotope procedure with ^{99m}Tc as calculated in this study and as reported in literature.

Scan	Radio-pharmaceutical	$H_p(10)$ per procedure per unit administered to patient activity (μSv per GBq)		
		Calculated in this study	Measured	Reference ^e
Thyroid	^{99m}Tc -pertechnetate	4.6	4.7 ^c	Barrall and Smith (1976)
			1.8±0.9	Chiesa et al (1997)
Liver	^{99m}Tc -SC	5.9 ^a – 9.1 ^b	1.8 ^c	Barrall and Smith (1976)
			7.1	Boutcher and Haas (1985)
			1.6	Harding et al (1987)
			5.2±3.3 ^c	Sloboda et al. (1987)
Brain	^{99m}Tc -pertechnetate	4.5	4.3	Clarke et al (1992)
			2.6 ^c	Barrall and Smith (1976)
			8.8	Boutcher and Haas (1985)
Renal	^{99m}Tc -DTPA	4.8	2.5±1.5 ^{c,d}	Sloboda et al. (1987)
			2.3	Harding et al (1987)
			4.0	Clarke et al (1992)

^a Normal liver function

^b Intermediate to advance liver disease

^c Recalculated from dose expressed in units mR using conversion factor of $8.7 \mu\text{Gy mR}^{-1}$

^d ^{99m}Tc -glucoheptonate

^e References are given in chronological order

Table 9

Comparison of effective doses to patients from historical and more recently conducted procedures using ^{99m}Tc .

Scan	Radio-pharmaceutical	Administered activity (MBq)	Effective dose to patients (mSv)
Thyroid ^a	^{131}I -sodium iodide	1.85	20
	^{99m}Tc -pertechnetate	185	2.4
Liver	^{198}Au -colloid	7.4	11
	^{99m}Tc -SC ^b	185	2.6
Brain	^{197}Hg -chlormerodrin	26	4.7
	^{203}Hg -chlormerodrin	26	44
	^{99m}Tc -pertechnetate ^c	555	2.3
Renal	^{197}Hg -chlormerodrin	3.7	0.7
	^{203}Hg -chlormerodrin	3.7	6.3
	^{99m}Tc -DTPA	370	1.8

^aThyroid uptake of 25%

^bNormal function

^cIntravenous injection, blocking agent given