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Medical Imaging for Health Professionals: Technologies and Clinical Applications, First Edition.
Edited by Raymond M. Reilly.

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Introduction to Medical Imaging

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1.1 Medical Imaging Procedures

Medical imaging is widely used in patient care to diagnose disease, to plan treatment, and to monitor response to treatment. Medical imaging includes radiological technologies such as X-ray, computed tomography (CT), mammography, ultrasound (US), and magnetic resonance imaging (MRI) as well as nuclear medicine imaging, which includes single photon computed tomography (SPECT) and positron emission tomography (PET). In the United States (U.S.), there were almost 400 million radiological imaging procedures performed in 2006 (most recent data) including 18 million nuclear medicine studies, a 10-fold increase since 1950 [1]. Worldwide, there were more than 3.6 billion medical imaging procedures performed annually from 1997 to 2007 and 36 million nuclear medicine tests [1]. More recent data from Canada in 2015 show that nine million imaging tests are performed each year, including 1.5 million SPECT/CT studies and almost 80 000 PET procedures (Table 1.1). Statistics in the U.S. are likely more than 10-fold higher, due to the population size differences between Canada and the U.S. PET has been more widely adopted in the U.S. and it is estimated that there are more than 1.5 million PET scans performed in that country each year [2]. Medical imaging procedures are used to diagnose a wide range of disease conditions including infections, cancer, myocardial perfusion and function, abdominal masses, thyroid disorders, renal dysfunction, liver and biliary tract diseases, Alzheimer's and Parkinson's disease, muscle and bone abnormalities, and many others. Chapters 2–6 in this book present the basic principles of medical imaging technologies while Chapters 7–15 discuss the clinical applications of medical imaging. In this chapter, the general considerations of different medical imaging technologies will be discussed.

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Table 1.1 Number of medical imaging procedures in Canada each year.

Technology	Number of imaging systems	Number of procedures each year (million)
CT	538	5.28
MRI	340	1.95
SPECT and SPECT/CT	478	1.48
PET	47	0.077

Source: Data from https://www.cadth.ca/canadian-medical-imaging-inventory-2015.

1.1.1 Procedures Involving Ionizing vs. Nonionizing Radiation

Some medical imaging procedures (X-ray, CT, mammography, SPECT, and PET) employ radiation that has sufficient energy to ionize biological molecules, while other procedures (MRI and US) do not cause such ionizations. Since the body is composed mostly of water molecules, most ionizations result in formation of hydroxyl free radicals (HO•) and hydronium ions (H_3O^+). These species have the potential to cause DNA strand breaks that could increase the long-term risk for cancer (see Section 1.2). The minimum energy required to ionize molecules is >5–100 electron volts (eV). An electron volt is defined as the energy acquired by an electron when accelerated across a potential difference of 1 V. The energy of different forms of electromagnetic radiation in electron volts is shown in Table 1.2. X-ray, CT, and mammography, which utilize X-rays for imaging, and SPECT and PET, which employ γ-rays emitted by radiopharmaceuticals, cause ionizations in biological molecules. In contrast, MRI employs radiofrequency (RF) energy, which has insufficient energy to cause ionizations. US imaging employs high-frequency sound waves that have extremely low energy in eV ($8–40 \times 10^{-9}$ eV), which is not able to cause ionizations. Thus, sometimes a technology that is nonionizing (e.g. MRI or US) may be preferred over one that is ionizing (e.g. CT, SPECT, or PET) to minimize the risk for long-term effects such as cancer, especially if these technologies are available and provide equivalent diagnostic information. When imaging technologies that use ionizing radiation are required, the radiation dose to the

Table 1.2 Energy of different forms of radiation in electron volts (eV).

Type of radiation	Imaging procedure	Energy (eV)
Ultrasound waves	US	<0.000 000 04
Radiofrequency	MRI	<0.001
X-rays	X-ray and CT	1000–10 000
γ-Rays	SPECT and PET	100 000–500 000

patient is kept as low as possible to minimize long-term risks (As Low as Reasonably Achievable [ALARA] principle). Nonetheless, these risks from medical imaging procedures are very low (see Section 1.2).

1.2 Radiation Doses from Medical Imaging Procedures

The energy deposited per unit mass of tissue by radiation is known as the *radiation dose*. The SI unit of radiation dose is the Gray, which is defined as 1 Joule per kg ($\mathrm{J\,kg^{-1}}$). An older unit still in use in the United States is the rad, which is defined as 100 $\mathrm{ergs\,g^{-1}}$ of tissue (0.01 $\mathrm{J\,kg^{-1}}$). Since different types of radiations exhibit different abilities to cause biological damage, this is further incorporated into the term *equivalent dose*, which has units of Sievert (Sv) or rem. The Sv or rem is the Gy or rad multiplied by a radiation weighting factor (w_R). The w_R for X-rays and γ-rays is 1, thus in medical imaging, 1 Sv = 1 Gy and 1 rem = 1 rad. Once radiation doses are estimated, a further refinement takes into account the relative radiation sensitivity of tissues by multiplying the dose estimates by a tissue sensitivity factor (w_T) to provide the *effective dose*. The units of effective dose remain the Sv or rem. Estimates of radiation doses from medical imaging procedures inform on possible acute effects as well as long-term risks such as the development of cancer. The radiation doses from most medical imaging procedures range from 1 to 14 mSv (Table 1.3) [3].

Table 1.3 Radiation doses from common medical imaging procedures.[a]

Imaging procedure	Modality	Radiation dose (mSv)
Chest	X-ray	0.02–0.04
Lumbar spine	X-ray	0.7
Mammogram	X-ray	0.7
Abdomen	CT	10.0
Coronary angiogram	CT	4.6–15.8
Bone scan (^{99m}Tc-MDP)	SPECT	4.2
V/Q lung scan (^{99m}Tc-MAA/^{99m}Tc aerosol)	SPECT	2.0
Renal scan (^{99m}Tc-MAG$_3$)	SPECT	3.6–5.2
Myocardial perfusion scan (^{99m}Tc-sestamibi/^{99m}Tc-tetrofosmin)	SPECT	11.2
Whole body scan (^{18}FDG)	PET	14.0

[a] Whole-body dose.

Source: Data from https://hps.org/documents/meddiagimaging.pdf.

A mSv is 1/1000th of a Sv. To put these doses in perspective, a whole-body PET scan is associated with a radiation dose of 14 mSv (Table 1.3), which is more than 130-times lower than the minimum dose of radiation required to cause significant toxicity to the bone marrow (2 Sv), one of the most radiation sensitive tissues in the body. A single chest X-ray deposits 1 000 000 times less radiation dose than that required to cause bone marrow toxicity. Harmful radiation doses to the liver or kidneys are 15–20 Sv and 20–30 Sv, respectively [4]. A whole-body PET scan deposits doses of radiation that are 1000–2000 times less than the radiation doses required to cause toxicity to the liver or kidneys. These dose-related acute effects of radiation are termed *non-stochastic effects*. These effects are not considered clinically significant at the radiation doses associated with medical imaging procedures. *Stochastic effects* of radiation are not necessarily related to radiation dose and include the long-term risk for development of cancer. However, back-extrapolation of data from the atomic bomb blasts in Japan suggests that the risk of cancer from radiation is not significantly increased above that in the general population at doses <100 mSv [5]. As mentioned, radiation exposure from medical imaging procedures is <10–15 mSv (Table 1.3).

1.2.1 Estimating Radiation Doses from Medical Imaging

Radiation doses from radiological imaging procedures (X-ray, CT) are estimated using “phantoms,” which are models of the body or regions of the body (e.g. chest or abdomen) filled with water which approximates the density of tissues, into which are placed dose-measuring devices called dosimeters (Figure 1.1). These phantoms are imaged and the dose deposited in simulated organs in the phantom is measured by the dosimeter. Radiation doses from nuclear medicine procedures that employ radiopharmaceuticals (see Chapters 3 and 4) are more complex to estimate, since they depend on the properties of the radionuclide, pharmacokinetics of the radiopharmaceutical, and the geometry of organs in a phantom model of the body (Figure 1.2). The method of estimating radiation doses from radiopharmaceuticals is called the Medical Internal Radiation Dose (MIRD) formalism [7]. The MIRD formalism incorporates a source organ (S) into which radioactivity accumulates and a target organ (T) that receives radiation dose from radioactivity in the source organs. In some cases, the source and target organs may be the same, e.g. radioactivity in the liver irradiating and depositing dose in the liver. In other cases, the source and target organs are different, e.g. radioactivity in the liver irradiating and depositing dose in the lungs.

The equation for radiation dose deposited into a target organ is:

$$D_{\mathrm{T}\leftarrow\mathrm{S}} = \tilde{A}_{\mathrm{S}} \times S$$

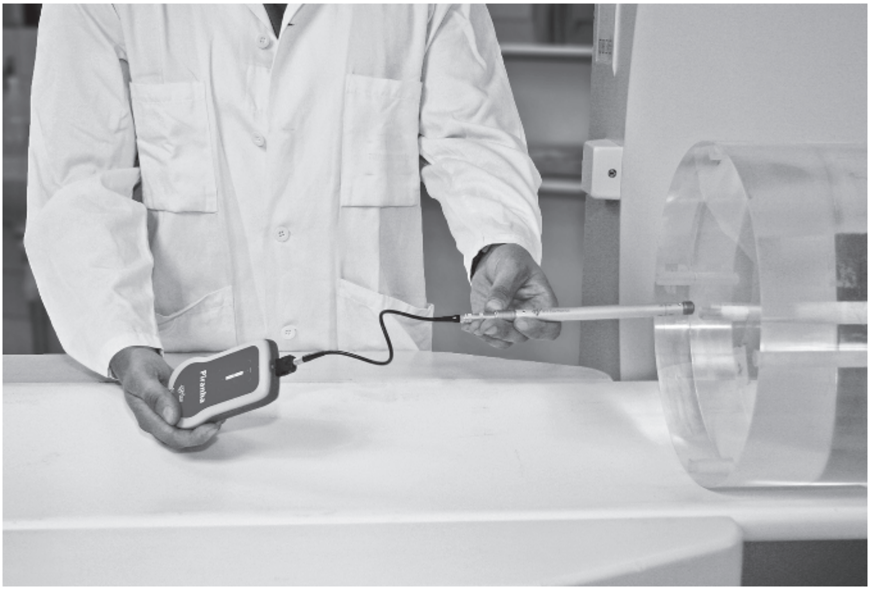

Figure 1.1 Estimating radiation doses from radiological procedures (e.g. CT) by imaging a phantom model of a region of the body with a dosimeter to measure radiation exposure. *Source:* From info@rtigroup.com.

where $D_{T \leftarrow S}$ is the dose ($\text{Gy Bq}^{-1} \times$ seconds) deposited in a target organ (T) per unit cumulative radioactivity in a source organ (S), $\tilde{A}_S$ is the cumulative radioactivity in the source organ (Bq × seconds), and S is the Snyder factor.

The cumulative radioactivity in the source organ ($\tilde{A}_S$) is determined by quantitative imaging in patients administered the radiopharmaceutical in a clinical trial by integrating the radioactivity vs. time curve for the organ (Figure 1.3). The Snyder factor (S) takes into account the properties of the radionuclide (physical half-life [$t_{1/2p}$] and the type, energy, and abundance of all emissions) as well as the geometry of organs (size and distance between organs) in the phantom (Figure 1.2). The total radiation dose to a target organ is the sum of the individual doses deposited from radioactivity in all source organs. An interesting aspect of radiation doses from radiopharmaceuticals is that the total body dose is *not* the sum of all of the doses to individual organs. Rather, the total body is considered as a separate target organ in the MIRD formalism. Moreover, since radiation dose is the amount of energy deposited per kg of tissue and the body is a large target organ (50–70 kg in an adult), the radiation dose to the whole body can often be lower than the dose to any individual organ in the body (Table 1.4). Computer software (OLINDA/EXM) has been introduced to facilitate estimation of radiation doses from radiopharmaceuticals [9].

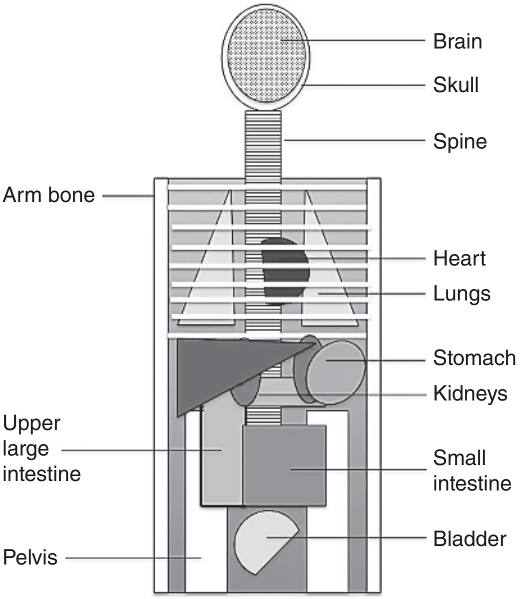

Figure 1.2 The MIRD adult phantom used to estimate radiation doses to organs from radiopharmaceuticals (not all organs are shown). Other phantoms are available for newborns through 15-year-old children as well as for a pregnant female adult, and dynamic phantoms that take into account excretion of radioactivity from the bladder. *Source:* Adapted from Snyder et al. [6].

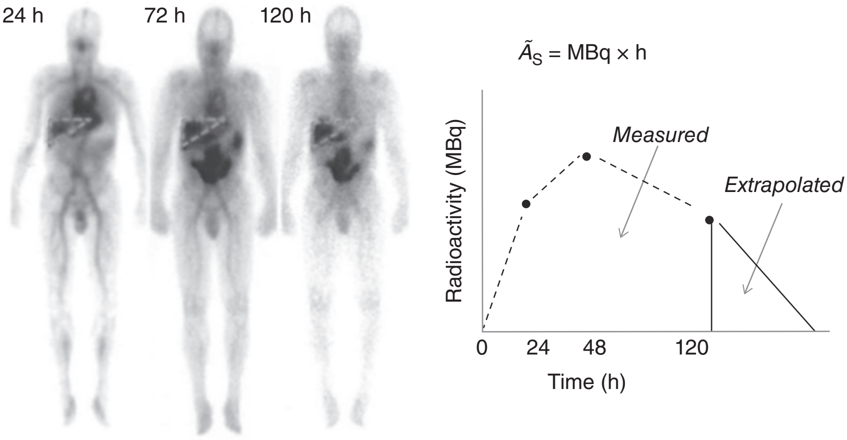

Figure 1.3 Estimation of cumulative radioactivity ($\tilde{A}_S$) in a source organ (i.e. liver; broken triangle on image) from administration of a radiopharmaceutical by quantitative gamma camera imaging and region-of-interest (ROI) analysis (left panel). The cumulative radioactivity from the last time point for which there is a measurement is estimated by extrapolation. The total $\tilde{A}_S$ (right panel) is used to estimate radiation doses from radiopharmaceuticals using the MIRD formalism. Source: From Wiseman et al. [8]. Reproduced with permission from Society of Nuclear Medicine and Molecular Imaging (SNMMI) publication.

Table 1.4 Radiation doses from a nuclear medicine bone scan using ^{99m}Tc-MDP.

Organ	Radiation dose (mSv MBq^{-1})	Dose for 740 MBq[a] (mSv)
Bone	0.0630	46.6
Brain	0.0017	1.3
Heart	0.0012	0.9
Kidneys	0.0073	5.4
Liver	0.0012	0.9
Lungs	0.0013	1.0
Spleen	0.0014	1.0
Whole body	0.0057	4.2

[a] Usual administered dose of radioactivity.

1.2.2 Radiation Doses and Increased Use of Medical Imaging

Natural radiation exposure mainly from radon gas present in the environment is responsible for most of the radiation dose exposure of the general population, accounting for an annual dose of about 3 mSv. However, since 1980, there has been a rapid increase in the use of medical imaging procedures in the United States, such that the dose from medical imaging now accounts for an additional 3 mSv per year, representing about half of the total radiation dose to individuals [10]. In 1980, medical imaging only accounted for one quarter of the total radiation dose to individuals. The increased utilization of medical imaging is due to major advances in imaging technology, which allow more applications (e.g. CT colonography, PET scans, myocardial perfusion imaging, and others). Nonetheless, it has been suggested that there may be overutilization of medical imaging, since in some cases, imaging procedures have not yielded additional information that changed patient management [11]. The most rational approach is to judiciously use imaging whenever it will yield diagnostic information that significantly improves patient care.

1.3 Summary

Medical imaging technologies include X-ray, CT, mammography, SPECT and PET, MRI, and US. Billions of imaging procedures are performed annually around the world to diagnose a wide range of diseases and health conditions, as well as monitor response to treatment. Only MRI and US do not use ionizing radiation. However, the risk of cancer development from medical imaging procedures is very low. Radiation doses from radiological procedures that employ X-rays are measured using phantoms of the body and dosimeters. Radiation doses from nuclear medicine procedures need to take into account the decay properties of the radionuclide, the pharmacokinetics of the radiopharmaceutical, and the geometry of organs in the body. Increased utilization of medical imaging due to advancements in technology has increased the annual radiation exposure of the population over the past 40 years. Judicial use of imaging to maximize impact on patient care is warranted to minimize radiation doses.

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