Radiation Safety in Nuclear Medicine

A Practical, Concise Guide

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ISBN 978-3-030-16405-8 ISBN 978-3-030-16406-5 (eBook)
https://doi.org/10.1007/978-3-030-16406-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To all selfless and benevolent souls
Who help make the world a better place
to live in!

Preface

Currently, many publications on radiation safety in nuclear medicine are available in the literature. All of them focus on the theory and principles of radiation safety with little attention to practical applications of radiation safety in day-to-day operations of nuclear medicine. The Nuclear Regulatory Commission (NRC) and Agreement States, the Department of Transportation (DOT), and the Environmental Protection Agency (EPA) establish the rules and regulations of radiation safety in the use of byproduct materials. Although nuclear medicine practitioners and technologists are trained in radiation safety and perform routine operations proficiently, they often face situations (spill, accident, shipping, etc.) when they need to seek help and suggestions from Radiation Safety Officer or consult NRC or Agreement States regulations. NRC 10CFR20 for Standards for Radiation Protection and NRC 10CFR35 for Medical Uses of Radioactive Materials are the primary sources of practical information on radiation safety in nuclear medicine. These regulations are quite exhaustive, and direct information on some rules and regulations are elusive and time consuming to retrieve, because they are tethered with several referrals to other parts of 10CFR.

The purpose of this book is to provide a simplified access to and retrieval of all basic information of radiation safety in the practice of nuclear medicine. The chapters are succinct in presentation and content and should be useful for nuclear medicine practitioners and technologists. Much of the information is derived from NRC and Department of Transportation (DOT) regulations and presented as a synopsis but not a substitute for them. The initial chapters (Chaps. 1, 2, and 3) deal with brief discussions of the atomic and nuclear structure, decay equations for radionuclides, interaction of radiations with matter, instruments for measuring radioactivity, and absorbed doses from radiation exposure. Chapter 4 is a gist of 10CFR20, detailing the principles and rules of radiation protection. Regulatory control in nuclear medicine is highlighted in Chap. 5. Regulations controlling the medical uses of radioactive materials in humans as stated in 10CFR35 are presented in Chap. 6. Training and experience requirements, though included in 10CFR35, are separately presented in Chap. 7, because of their unique importance. Emergency procedures involving radioactive spills and accidents are detailed in Chap. 8, management and release of patients administered with radioactive materials in Chap. 9, and radioactive waste disposal in Chap. 10. Transportation of radioactive materials under DOT regulations is discussed in Chap. 11, and a short presentation of biological effects of

radiation exposure in humans is made in Chap. 12. In addition, several appendices with important and pertinent information related to radiation are provided. Once again, the readers are reminded that the book presents only salient points of radiation safety in nuclear medicine, and they need to consult NRC, Agreement States, and DOT regulations for in-depth information for specific situations.

I am ever grateful and thankful to Ms. Margaret Moore, Editor, Clinical Medicine, of Springer Nature for offering the publishing contract and for her encouragement and support in the production of the book. I sincerely thank Mr. Kulandaivalu Devendran of SPi Global Technologies, Chennai, India, and Ms. Sowmya Balagurunathan of Springer Nature for their sincere effort and commitment to bring the book to fruition. Also, special thanks are due to Springer Nature for their perpetual support of publishing all my books without hesitation over four decades.

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Contents

Basic Physics of Radiation Safety

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1.1 Atomic and Nuclear Structure

Atoms are basic components of matter. They are composed of a positively charged nucleus at the center and negatively charged electrons circulating in orbits around the nucleus to neutralize the charge of the nucleus. The dimension of an atom is of the order of 10^{-8} cm (1 Angstrom, Å), and that of a nucleus is of the order of 10^{-13} cm (1 Fermi, F). The nucleus consists of neutrons (no charge) and protons (positively charged), collectively called nucleons. The weight of the atom is mainly due to neutrons (1.6744×10^{-27} g) and protons (1.6721×10^{-27} g), which in turn accounts for the weight of matter. The electrons rotate around the nucleus in different energy shells in increasing order, designated as *K*, *L*, *M*, *N*, etc. These shells have definite capacity to hold electrons dictated by $2n^2$, where *n* is numerical values of 1, 2, 3, 4, etc. for *K*-, *L*-, *M*-, *N*-shells, etc., respectively. Thus, the *K*-shell accommodates 2 electrons, the *L*-shell 8 electrons, the *M*-shell 18 electrons, the *N*-shell 32, etc.

The total number of protons and neutrons in an atom is called the mass number *A*, and the number of protons is called the atomic number *Z*. The neutron number is denoted by *N*. An atom characterized by a specific number of protons *Z*, neutrons *N*, and mass number *A* is termed a *nuclid*e and denoted by ${}^{A}_{Z}X_{N}$. There exist about 3700 known nuclides of which nearly 288 nuclides are stable and the remainder (~3400) are unstable meaning they break down emitting radiations. These are called *radionuclides*, and the majority of them are artificially produced in a cyclotron or a reactor and decay to stable nuclides by emitting α particles, β^-particles, and/or γ radiations. β^-particles are basically electrons with negative charge (negatron denoted by β^-) or with positive charge (positron denoted by β^+).

The nuclides having the same number of protons are called the *isotopes*, e.g., ${}^{11}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$; those with the same number of neutrons the *isotones,* e.g., ${}^{131}_{53}\mathrm{I}$ and ${}^{132}_{54}\mathrm{Xe}$, each having 78 electrons; those with same mass number are called the *isobars*, e.g., ${}^{90}_{39}\mathrm{Y}$ and ${}^{90}_{40}\mathrm{Zr}$; *isomers* are the nuclides with the same mass number, i.e., the same number of protons and neutrons, but with different energy states, e.g., ${}^{99\mathrm{m}}_{43}\mathrm{Tc}$ and ${}^{99}_{43}\mathrm{Tc}$.

G. B. Saha, *Radiation Safety in Nuclear Medicine*,
https://doi.org/10.1007/978-3-030-16406-5_1

1.2 Radioactive Decay

As mentioned above, radionuclides are unstable and decay by emission of particulate radiations (α and β^-particles), electromagnetic radiations (γ, x-ray radiations), or spontaneous fission depending on the composition of the nucleus. A radionuclide can decay in one step or several successive steps until it reaches the stability. The ratio *N/Z* of a nuclide predicts the stability of a nuclide, and radioactive decay occurs to achieve stability of the nucleus by altering the proton or neutron number, i.e., the *N/Z* ratio of the nucleus. Radionuclides decay by several specific modes, which are discussed below.

1.2.1 Spontaneous Fission

This occurs in only very heavy radionuclides such as ^{235}U, ^{239}Pu, etc., with extremely low probability. These heavy nuclei are dumbbell shaped with a narrow neck in the middle. During the vibrational oscillation of a nucleus, spontaneous fission occurs, and the nucleus breaks up in the neck into two new nuclides of similar or dissimilar mass along with the emission of two or three neutrons. For example, the fission of ^{235}U may lead to ^{99}Mo and ^{134}Sn plus two neutrons, two ^{116}Pd nuclides plus three neutrons, etc.

$$^{235}\mathrm{U} \rightarrow {}^{99}\mathrm{Mo} + {}^{134}\mathrm{Sn} + 2\mathrm{n}$$

Each fission is accompanied by release of about 200 MeV energy as heat.

1.2.2 Alpha (α) Decay

This mode of decay also occurs in heavy nuclides with emission of an α particle, which is basically a helium atom stripped of two electrons from the outer shell of the atom (He^{2+}). For example,

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha$$

The α particles are monoenergetic carrying energy in the order of several MeV. The product ^{234}Th may again decay depending on the energy of the residual nucleus. Because of the heavy mass, the range of α particle in matter is very short, and they cause relatively more radiation damage in human tissues.

1.2.3 Beta (β^-) Decay

Radionuclides having the *N/Z* ratio more than that of nearby stable nuclides decay by β^- emission. In this decay, a neutron in the nucleus is transformed to a proton decreasing the *N/Z* ratio. In the process, a particle called antineutrino $\bar{\nu}$ with negligible mass and no charge is emitted to balance the energy in the decay. For example,

$$^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + \beta^- + \bar{\nu}$$

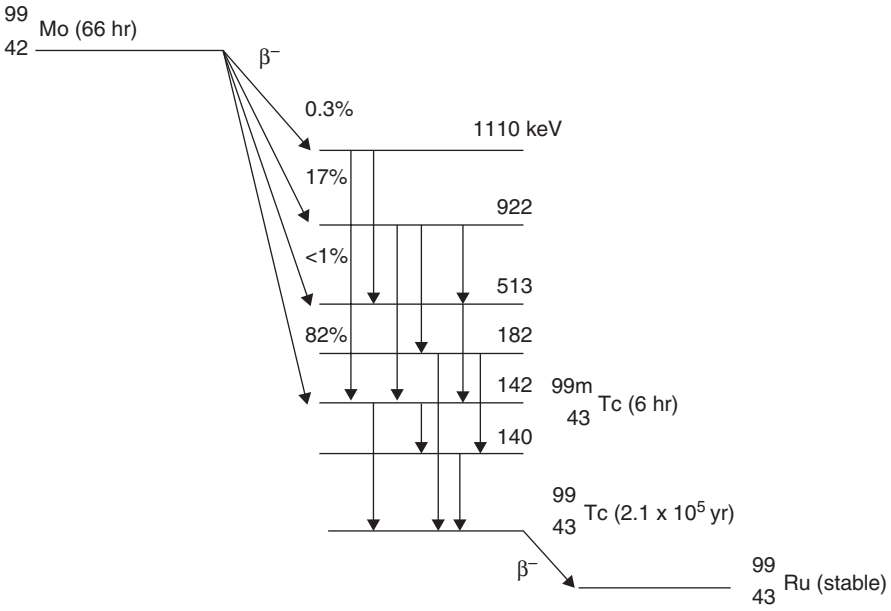

Fig. 1.1 Decay scheme of ^{99}Mo. Approximately 87% of the total ^{99}Mo decays to isomer ^{99m}Tc and 13% to the ground state ^{99}Tc. (Reprinted by permission from Springer Nature, *Physics and Radiobiology of Nuclear Medicine* by Saha GB, 2013)

Note that the β^- particle is an electron which arises from the conversion of a neutron to a proton in the nucleus. The difference between the rest mass of the parent radionuclide and the rest masses of the daughter nuclide plus β^- particle is called the *transition* or decay energy, $E_{max,}$ which is shared between the β^- particle and antineutrino. From a cohort of radionuclides, β^- particles are emitted with a spectrum of energy, carrying a fraction of E_{max} to maximum E_{max}. The average energy of β^- particles in the spectrum is about one-third of E_{max}.

If the product nucleus has still enough energy after β^- particle emission, further emission of particles and/or γ rays can follow. So the decay of radionuclides is illustrated by decay schemes to illustrate these transitions. The decay scheme of ^{99}Mo is shown in Fig.1.1.

1.2.4 Positron (β^+) Decay

When the *N*/*Z* of a radionuclide is relatively lower than that of the close stable nuclide, the radionuclide decays by emitting a β^+ particle to reach a stable nucleus, accompanied by a neutrino ν emission for energy conservation. In the process, a proton is converted to a neutron which is heavier than a proton by an electron rest mass (0.511 MeV). This additional rest mass plus that of β^+ particle equals to at least 1.022 MeV, which the parent radionuclide must have, as a minimum, as transition energy to decay by β^+ emission. The transition energy in excess of 1.022 MeV is

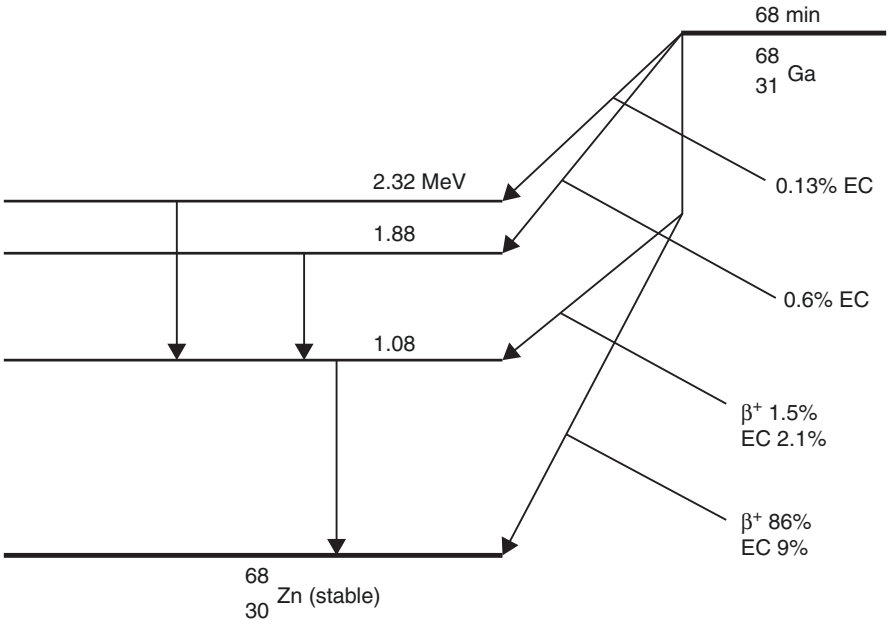

Fig. 1.2 Decay scheme of ^{68}Ga. Positrons interact with medium and are annihilated to produce two 511 keV photons. Electron capture is an alternative process to positron emission determined by the characteristics of the radionuclide. (Reprinted by permission from Springer Nature, *Physics and Radiobiology of Nuclear Medicine* by Saha GB, 2013)

shared by the β^+ and the neutrino ν as kinetic energy, and like β^- particle, the β^+ particle energy is variable. An example is

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + \beta^+ + \nu$$

When positrons travel through matter, they interact with atomic electrons and annihilate each other to produce two annihilation radiations of 0.511 MeV, which are emitted in opposite direction. Positron-emission tomography is based on the detection of these two annihilation radiations in coincidence to form images of tissues or organs. The decay scheme of ^{68}Ga is illustrated in Fig. 1.2.

1.2.5 Electron Capture

When a radionuclide has relatively lower *N/Z* compared to nearby stable nuclides and also less than 1.022 MeV in transition energy, then it decays by electron capture (EC) by capturing an electron from the outer shell, normally *K*-shell, along with emission of a neutrino. In the process, a proton is transformed into a neutron. Note that electron capture can also occur in the nuclides having greater than 1.022 MeV transition energy, but the probability decreases with increasing energy. An example is

$$^{111}_{49}\mathrm{In} \rightarrow {}^{111}_{48}\mathrm{Cd} + e^- + \nu$$

The hole created on the orbit is filled in by the transition of an electron from the upper shell, and the difference in energy between the two orbits appears as a characteristic K x-ray, in a situation similar to internal conversion of γ rays discussed below. ^{68}Ga decays 13% by electron capture, as shown in Fig. 1.2.

1.2.6 Isomeric Transition

Radionuclides can exist in different states of excitation energy, the majority of which are very short-lived (nanoseconds to femtoseconds), and some are long-lived (seconds to million years). These nuclides are called isomers. An isomer disposes of excitation energy by decaying from an upper excited state to a lower energy state with emission of a γ ray (electromagnetic radiation), and the process is called isomeric transition. When the half-life of an isomer is relatively long, it is called the metastable state and denoted by m. The decay of metastable ^{99m}Tc is given below and illustrated in Fig. 1.3. An example of isomeric transition is

$$^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$$

As an alternative to γ ray emission, the γ ray can eject an electron from the nearest K-shell by transferring all its energy. The electron is called the conversion electron and carries the energy equal to $E_\gamma - E_{b,}$ where E_γ and E_b are the energy of the γ ray and the binding energy of the electron in the shell, respectively. The hole in the K-shell is filled by the transition of an electron from an upper shell (L-, M-shells, etc.), and the difference in energy between the two shells appears as the so-called characteristic K x-ray, L x-ray, etc. The process is called the internal conversion and is illustrated in Fig. 1.4. It should be understood that for a given number of isomeric transitions, some transitions will be by γ ray emission, and the remaining transitions will be by internal conversion. The ratio of internal conversions to γ ray emissions is called the conversion coefficient. Thus, if 315 transitions of the total isomeric

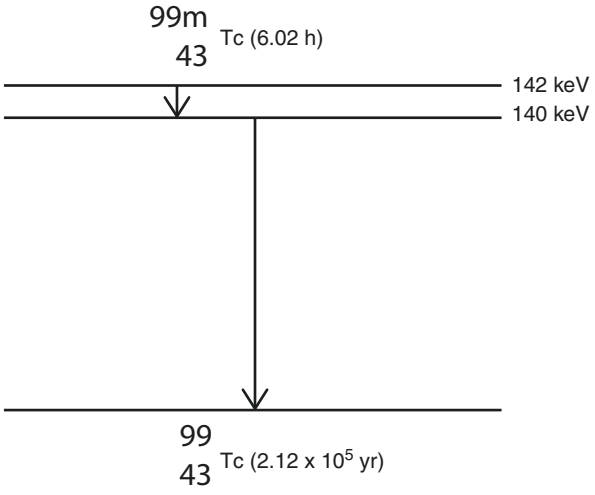

Fig. 1.3 Isomeric transition of ^{99m}Tc. (Reprinted by permission from Springer Nature, *Physics and Radiobiology of Nuclear Medicine* by Saha GB, 2013)

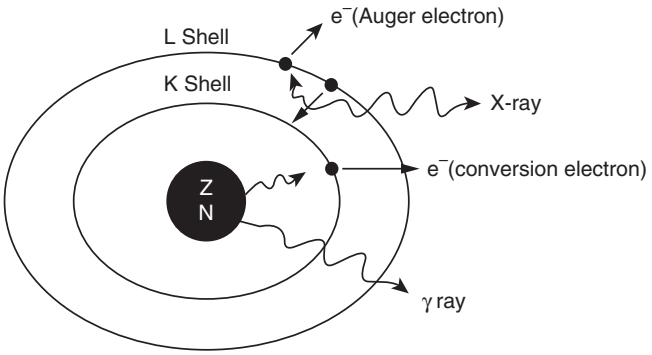

Fig. 1.4 Illustration of internal conversion process. The excitation energy of the nucleus is transferred to a *K*-shell electron, which is then ejected with kinetic energy equal to $E_\gamma - E_B$, and the *K*-shell vacancy is filled by an electron from the *L*-shell. The energy difference between the *L*-shell and *K*-shell appears as the characteristic *K* x-ray. Alternatively, the characteristic *K* x-ray may transfer its energy to an *L*-shell electron, called the Auger electron, which is then ejected. (Reprinted by permission from Springer Nature, *Physics and Radiobiology of Nuclear Medicine* by Saha GB, 2013)

transitions occur by internal conversion and the remaining 523 transitions by γ ray emission, then the conversion coefficient is 315/523 = 0.6.

The characteristic x-rays behave like γ rays, and some of them can eject an electron from an upper shell, similar to internal conversion, if energetically possible. This process is called the Auger process, and the ejected electron is called the Auger electron. The fraction of characteristic x-rays that are not used in the auger process is called the fluorescence yield, and the fraction that undergoes the Auger process is called the Auger yield. The Auger process increases with increasing atomic number of the medium.

1.3 Radioactive Decay Equation

Radioactive decay is random, and the time of decay of an individual radionuclide cannot be ascertained. So we can only assess the average decay of a cohort of radionuclides. The rate of decay of a radionuclide is given by

$$\frac{dN}{dt} = \lambda N \tag{1.1}$$

where N is the number of radionuclides present in the sample and λ is the decay constant. On integration, Eq. (1.1) becomes for decay over time t

$$A_t = A_0 e^{-\lambda t} \tag{1.2}$$

where A_0 is the original activity and A_t is the activity at time t. The semilogarithmic plot of radioactivity against time of decay is shown in Fig. 1.5. The radioactive

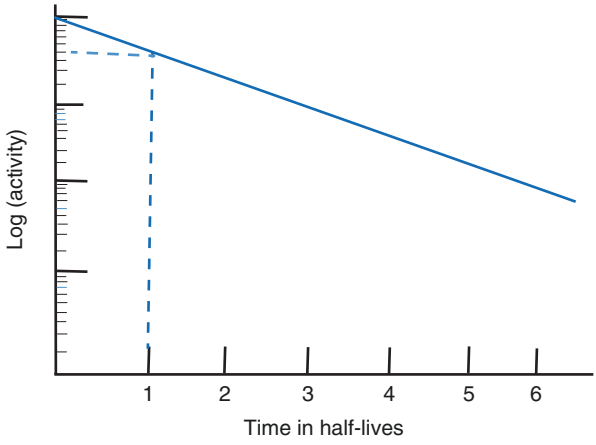

Fig. 1.5 Semilogarithmic plot of radioactivity versus time of decay

decay is characterized by a half-life, $t_{1/2}$, which is defined by the time a radionuclide decays to one half of the initial activity. It is related to the decay constant λ by

$$\lambda = \frac{0.693}{t_{1/2}} \tag{1.3}$$

The half-life of a radionuclide can be determined by plotting the measured activity on a log scale and the decay time on a linear scale. From the straight line plot, one chooses an activity at a time point and then half the chosen activity at its corresponding time. The difference between the two time values is the half-life of the radionuclide.

Another important parameter is the mean life τ, which represents the average life of a cohort of radionuclides. It is given by the reciprocal of decay constant λ:

$$\tau = \frac{1}{\lambda} = \frac{t_{1/2}}{0.693} \tag{1.4}$$

In one mean life, the activity of a radionuclide is reduced to 37% of its initial value.

1.3.1 Successive Decay Equation

Equation (1.2) describes the decay of a radionuclide to a nuclide, which may be stable or radioactive. If the decay product nuclide is radioactive, it grows by the decay of the parent nuclide and also decays by itself, and hence the decay equations are different.

When a parent radionuclide p decays to a radioactive daughter nuclide d, which decays to another nuclide, i.e., $p \rightarrow d \rightarrow$, the equation for the growth of d is given by

$$\frac{dN_d}{dt} = \lambda_p N_p - \lambda_d N_d \tag{1.5}$$