

# Maintaining a Proper Perspective of Risk Associated with Radiation Exposure

Michael A. Thompson

*Division of Medical Imaging and Therapy, University of Alabama at Birmingham, Birmingham, Alabama*

**Objectives:** The objectives of this article are to provide the reader with (a) a brief discussion of actual, perceived, and acceptable risks associated with radiation exposure; (b) a basic review of radiation protection units and a discussion as to how these units are used to estimate risk associated with occupational radiation exposure; (c) a summary of radiation doses required for specific human biologic responses and a comparison of relative doses encountered in a variety of clinical situations; and (d) a practical approach to discussing relative risks associated with medical radiation exposures when patients inquire.

**Key Words:** medical radiation workers; radiation exposure; medical occupational exposure; medical radiation exposure risks

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**R**oentgen discovered x-rays in November 1895, and this historic event was followed by Becquerel's discovery of radioactivity in 1896. Less than 3 mo after their initial discovery, x-rays were used on a human subject at Dartmouth College in New Hampshire. The unregulated use of radiation sources led to many disastrous results, ranging from disfigurement to death (1). The 3-mo span between discovery and the use on humans is in stark comparison with the usual years of testing and clinical trials that are required today before the use of new techniques or new drugs on humans.

It was soon evident that radiation was a double-edged sword, useful with its diagnostic and curative applications but potentially harmful when used in an uncontrolled manner. The potentially harmful effects of radiation were perhaps most evident in early radiologists, whose hands almost always showed signs of severe radiation necrosis as a result of continuously placing their hands in the x-ray beam. Cases like this led to the recognition of the need for the regulation and control of radiation sources and their use, which resulted in the rules and regulations that we work under today.

Early on, it was a recognized fact that exposure to ionizing radiation, either as a radiation worker or as a patient, carried some finite risk of a bioeffect on the individual. The term "risk" is most commonly thought of as a negative impact resulting in personal injury, illness, or death. As men and women of science investigated the nature of radiation, its properties, and its means of inflicting damage to living systems, safety criteria were developed in the form of the "as low as reasonably achievable" (ALARA) concept and the use of time, distance, and appropriate shielding. However, the fact remains that radiation is a form of energy and whenever energy encounters a biologic system, there exists the potential for some type of biologic effect.

As the years have passed, radiation has proven to be a formidable tool in the diagnosis and treatment of disease. The dark, destructive side of radiation was, however, brought to public attention by the Manhattan Project, which brought an end to World War II. Negative public perception has continued to be reinforced by both science fiction writers and accidents such as Three Mile Island and Chernobyl. Recognition of this increased perceived risk and the associated fear on the part of the public, including many health care professionals, led radiologists in the 1980s to drop the term "nuclear" from "nuclear magnetic resonance" and replace it with the term "magnetic resonance imaging" (MRI), so as not to frighten patients. Some institutions have even advertised that their MRI units do not use radiation. (That is untrue, of course, because MRI uses nonionizing radiofrequency radiation to form its images rather than x- or  $\gamma$ -rays.) However, to many, the perceived risk of exposure to low-level radiation tends to be much higher than it should be.

Many individuals do not even realize that radiation is a part of our natural environment. Every day, we are all exposed to high-energy radiation from space (cosmic radiation), radiation from radionuclides formed in the earth's atmosphere (cosmogenic radiation) that eventually finds its way into the water supply and food chain, and radiation from naturally occurring radionuclides (e.g., radon) found in the earth's crust (terrestrial radiation). Additional sources of lower-level radiation exposure include the use of certain consumer products (e.g., lantern mantles, salt substitutes, certain types of pottery, tobacco products, and fertilizers) and the application of certain technologic advancements

For correspondence or reprints contact: Michael A. Thompson, Professor, Division of Medical Imaging and Therapy, University of Alabama at Birmingham, 333 LRC, 1714 9th Ave. S., Birmingham, AL 35294-1270.

(e.g., the burning of fossil fuels as an energy source, nuclear power, medical irradiation, air travel) developed to improve the general quality of life. Weapons testing fallout also contributes a small fraction to our exposure to radiation in the environment. All of these radiation sources contribute to what we refer to as background radiation (2), which we know can vary significantly from one location to another. The U.S. Environmental Protection Agency (3) estimates that the background radiation dose to the average person in the United States is approximately 0.36 cSv (360 mrem).

It is important to realize that radiation exposure, whether it originates from the environment or as a result of occupational exposure, is not the only risk factor in our lives, nor is it the most prominent. Several additional risks to our health that are often neglected are listed in Table 1. Also, it is not uncommon for individuals to partake in behaviors that pose significant risk to their lives. Several examples of risky behaviors are listed in Table 2. Generally speaking, the perceived risk, in the minds of those who partake in these behaviors, is much lower than the actual risk. Thus, risk perception to the layperson is very subjective.

Nuclear medicine technologists receive small amounts of radiation each workday. This is referred to as chronic exposure. How does the average staff technologist evaluate his or her risk associated with this type of low-level, chronic radiation exposure? It is important to realize that, since its discovery by Roentgen in 1895, we have learned much about the physical properties of radiation, its modes of interaction in matter, how it inflicts its damage on biologic systems, and the response of the system to this damage. To evaluate the level of risk associated with radiation exposure, all of these factors must be considered. To place this level of risk in proper perspective with other risks in life, one must have an understanding of the nature of the risk, its probability of occurrence, and—if damage does occur—the chance of a perfect repair.

## THE NATURE OF THE RISK

The nuclear medicine technologist works almost exclusively with  $\gamma$ - and x-ray photons, ranging in energy from approximately 60 to 700 keV. This is ionizing radiation, which certainly has sufficient energy to produce ionization events and break molecular bonds. If this energy is deposited in the intercellular fluid, toxic compounds may be

**TABLE 1**  
Common Risk Factors Often Neglected

Risk factor	Nature of risk
Use of pesticides	Chemical toxicity from inhalation, ingestion, or absorption
Obesity	Heart disease
Hypertension	Stroke and kidney damage
Exposure to pollutants	Pulmonary disease, chemical toxicity, and heavy metal poisoning
Lack of exercise	Heart disease and shortened life span

**TABLE 2**  
Behaviors That Pose Significant Risks to Personal Health

Risky behavior	Nature of risk
Use of tobacco	Pulmonary disease
Unprotected sex	AIDS/venereal disease
Alcohol consumption	Cirrhosis
Use of motor vehicles	Injury or death
Use of recreational and prescription drugs	Overdose, chemical toxicity, and death

formed that can be detrimental to cell survival (damage by indirect action). A photon could also directly impact cellular DNA, causing strand breakage (damage by direct action). At low doses, those comparable with natural background levels, the body's natural repair mechanisms usually perfectly repair any damage incurred. At higher radiation doses up to approximately 1 Sv (100 rem), where one might begin to experience symptoms of radiation sickness, damaged cells may either die or be permanently altered. The cells that die will be replaced in time and the body will not suffer from long-term adverse effects. In the case where the cell is permanently altered, it may continue to divide and produce additional abnormal cells. Under the appropriate conditions, these abnormal cells may develop into a radiation-induced cancer (4). The exact risk at very low doses to a specific individual of radiation-induced cancer is not totally understood and is further complicated by many factors, such as the magnitude of the dose, the time span over which the dose was delivered, the general state of health of the individual, the type of radiation to which the individual was exposed, the energy of the radiation, and the area of the body to which the dose was delivered, among others (5). Exposure to ionizing radiation carries the potential to produce a variety of bioeffects (e.g., cataracts, growth impairment, erythema, genetic effects, epilation), most of which are encountered at radiation doses significantly higher than those normally encountered by the average nuclear medicine technologist. Potential cancer induction is perhaps the most commonly discussed health hazard associated with low-level occupational exposure. Because cancer is the second leading cause of death in the United States (6), discussion in this article will be limited to this specific health risk.

The issue of health risks associated with low-level occupational exposure is further clouded by the fact that there are other agents in our environment that are carcinogenic, such as certain pesticides, tobacco products, air pollution, certain chemicals, food additives, and others that have yet to be identified. Another way of saying this is that there are no forms of biologic injury, including cancer induction, that are unique to exposure to ionizing radiation.

## A PRACTICAL METHOD FOR RADIATION RISK EVALUATION

Does a tool exist that would provide a method to estimate the level of risk associated with occupational exposure?

Unlike the subjective estimate of the chance of being involved in an automobile accident, radiation workers have formally defined units of dose equivalent, a unit of radiation protection that takes into account that some forms of radiation are more biologically damaging than others. One may first determine the exposure (in coulombs/kg of air or roentgens) using a detector such as an ionization chamber. From this measurement, absorbed dose (in gray or rad) is determined by multiplying the exposure by an appropriate f-factor (7). Absorbed dose to an individual may also be inferred by measuring the absorbed dose delivered to a personnel dosimeter worn by the individual. The dose equivalent (in sievert or rem) is then obtained by multiplying the absorbed dose by a quality factor (Q-factor) (8,9). Recommended values for Q-factors are shown in Table 3. The unit of dose equivalent is the unit used in radiation protection and in which occupational dose limits are expressed. In general, the higher the dose equivalent received, the greater the associated risk. This relationship between occupational dose and risk stresses the importance of the implementation of the ALARA concept through the use of time, distance, and appropriate shielding.

In 1994, the U.S. Nuclear Regulatory Commission (NRC) adopted the concept of the total effective dose equivalent (TEDE), which was defined as the sum of the effective dose equivalent (EDE) from internal exposure and the deep dose equivalent (DDE) from external exposure. That is,

$$\text{TEDE} = \text{EDE} + \text{DDE}.$$

To accurately assess relative risk, one must look at the TEDE, which takes into consideration the dose from both internal and external radiation sources. Safety procedures enforced in most nuclear medicine departments make the chance of internal contamination of personnel very unlikely. In this case, the TEDE is essentially equal to the DDE, as estimated by the dose measured by a personnel dosimetry device.

### RISK ESTIMATE DETERMINATION: ITS BASIS AND METHOD OF EXPRESSION

Over the past 40 y, several national and international scientific organizations have been involved in the study of radiation effects on human subjects. Some of the subjects

**TABLE 3**  
Recommended Quality Factors for Various  
Types of Radiation

Type of radiation	Q
X-rays, $\gamma$ -rays, $\beta$ -particles, and electrons	1
Thermal neutrons	5
Neutrons (other than thermal), protons, $\alpha$ -particles, and multicharged particles of unknown energy	20

Q = quality factor.  
Data obtained from (8).

studied included early radiologists, the radium dial painters, Marshall Islanders exposed to atomic weapons testing fallout, uranium miners, radiation accident victims, radiation therapy patients, and Japanese atomic bomb survivors. It must be emphasized that the groups of individuals studied were not part of a controlled experiment. Therefore, conclusions drawn for risk estimates of low-level radiation exposure are possibly subject to some degree of error and interpretation of the data. Studies of the human data lead to several generalizations regarding radiation carcinogenesis (10):

- a single exposure to ionizing radiation can be sufficient to elevate cancer incidence years after the exposure;
- there is no 1 type of cancer unique to radiation;
- the risk of any type of cancer induction is increased with increases in radiation dose;
- the bone marrow, thyroid, and breast were identified as being especially radiosensitive;
- the most prominent type of cancer, most strongly linked to radiation exposure, was leukemia (with a 2 to 7-y latent period);
- the age of the individual at the time of irradiation is very important; immature tissues have a higher level of risk of cancer induction as a result of radiation exposure than mature tissues;
- the percentage increase in cancer incidence per unit of absorbed dose varies with the organ and type of cancer;
- from the safety perspective, based on these generalizations, it is best to assume a linear, nonthreshold dose-effect relationship, which is a more conservative approach.

On the basis of currently available data, the NRC adopted the following risk value as reported in the *National Research Council BEIR V Report* (11): "The risk value for an occupational dose of 1 cSv (1 rem) total effective dose equivalent (TEDE) is 4 in 10,000 of developing a fatal cancer, or 1 chance in 2,500 of fatal cancer per cSv (rem) of TEDE received." Because of the uncertainties in the data, risk estimates may be higher or lower for low-level occupational exposures (12). This risk factor could be decreased by a factor of 2 or more if the 1-cSv dose is delivered over a long period of time, as in the case of a chronic exposure. Using the linear dose-effect relationship concept, this would imply that a technologist who received 2 cSv (2 rem) in 1 y incurs 4 times the risk as another technologist who receives an occupational dose of only 0.5 cSv (0.5 rem). Thus, the radiation risk incurred by a worker depends on the magnitude of the radiation dose received.

With current regulatory safeguards in place, it is rare that a radiation worker exceeds 5 cSv (5 rem) as an annual occupational dose. A review of whole-body dosimetry reports from several sources (the Medical Center and radiation safety personnel) at the University of Alabama yielded the average occupational doses shown in Table 4. Also, according to the *BEIR V Report* (11), approximately 1 of 5

adults (20%) will die of cancer as a result of causes other than occupational radiation exposure. These other causes include smoking, alcohol, drugs, pollution, food additives, natural background radiation, and genetic traits. Extending this concept to a population of 10,000, 2,000 (20%) would be expected to die of cancer, even with no occupational exposure. With the addition of 4 deaths as a result of occupational exposure, the number expected to die from cancer would be 2,004, or 20.04% of the original 10,000, as a result of an annual dose of 1 cSv (1 rem). It is of interest to note that the average measurable dose of radiation workers reported to the NRC in 1993 was 0.31 cSv, which correlates closely with the occupational doses shown in Table 4.

As the reader considers these risk estimates, it is important to emphasize the following points:

- risk estimates described here are based on high-dose and high-dose-rate data—the validity of its extrapolation to provide risk estimates associated with low-level chronic doses is uncertain;
- risk estimates described here are based on total-body radiation doses—identical doses to limited areas of the body can yield very different biologic effects;
- the chance that a particular individual will get cancer as a result of occupational exposure is made even more uncertain by the laws of probability, in addition to other risk factors for cancer induction (e.g., smoking, drugs, relative state of health, stress, alcohol, exposure to chemicals);
- although genetic effects are often linked to radiation exposure, there is no direct evidence of radiation-induced genetic effects in humans even at high doses (13);
- sterility does not occur in humans at doses less than approximately 2 Gy (200 rad).

Another method used to compare risk estimates is to look at the average number of days of life lost as a result of exposure to a specific health risk. Most of the data and statistical results quoted are results of studies conducted by

**TABLE 4**

Typical Average Annual Occupational Radiation Doses of Various Personnel at UAB Medical Center in 2000

Personnel	Dose*
Radiologic technologists	0.3 (300)
Nuclear medicine technologists	0.3 (300)
Radiation therapy technologists	0.12 (120)
Radiation therapy nurses	0.12 (120)
Radiation safety technicians	0.24 (240)

\*Data are expressed as approximate values in cSv, with mrem in parentheses.

UAB = University of Alabama.

Data based upon a review of whole-body film badge reports by the UAB Radiation Safety Officer.

**TABLE 5**  
Estimated Loss of Life Expectancy As a Result of Certain Health Risks

Health risk	Estimated life expectancy loss (average)
Smoking 20 cigarettes per day	6 y
Overweight by 15%	2 y
Alcohol consumption (U.S. average)	1 y
All accidents	1 y
Home accidents	74 d
Medical radiation	7 d
Occupational exposure	
0.3 cSv/y from 18 to 65 y of age	15 d
1.0 cSv/y from 18 to 65 y of age	51 d

Data adapted and used with permission of Cohen (14).

Cohen (14). The results of some of his extensive studies are provided in Table 5. It is noted in Table 5 that a radiation worker who receives an annual occupational exposure of 0.3 cSv (0.3 rem) would, on average, lose 15 d of life expectancy, whereas other commonly accepted activities result in significantly higher risk estimates. It should be stressed that these are only estimates because of the large number of variables that come into play. It does, however, provide us with a starting point for consideration.

It should also be noted that it is the official position of the Health Physics Society (15), the nonprofit scientific organization dedicated to radiation protection, that risk estimates of radiogenic health effects, primarily cancer in humans, as a result of low-level exposure below 10 cSv (10 rem) are speculative. Quantitative risk assessment should be limited to doses at or above 5 cSv (5 rem) per year or 10 cSv (10 rem) as a lifetime dose.

#### RISK ESTIMATES AND THEIR RELATION TO TEDE LIMITS

As soon as the link between cancer induction and high doses of ionizing radiation was strengthened by studies of irradiated human populations, there came a shift in radiation protection philosophy. For several years, occupational dose limits had been based on those doses that prevented the manifestation of clinically observable radiation effects, such as erythema. In 1994, a new risk-based system (8) was adopted. Thus, as the knowledge base of radiation health effects expanded, it permitted the evolution from a system based on the prevention of injury to one based on risk reduction. Under this new system, TEDE limits have been established to accomplish 3 goals: to avoid immediate injuries to tissues by keeping occupational dose limits low; to keep the risks of the incidence of fatal cancers, severe genetic effects, and fatal accidents among radiation workers at levels no greater than the risk of a fatal accident for a worker in a “safe” industry; and to keep the level of risk associated with occupational exposure as low as reasonably achievable, taking into account social and economic factors.

It must be reemphasized that determination of risk estimates is influenced by many variables (16), and values used in this article are always subject to change. This uncertainty makes the implementation of the ALARA concept in the workplace through the use of time, distance, and appropriate shielding a prudent technique to reduce the risk of detrimental health effects.

### TERATOGENIC RISK ASSOCIATED WITH OCCUPATIONAL EXPOSURE

Radiation is a known teratogen (i.e., an agent known to cause birth defects). Other known teratogens include alcohol, rubella, smoking, and mercury. The specific effect of radiation on an embryo or fetus depends on 2 factors: the stage of development and the radiation dose delivered (5). Potential biologic effects include embryonic, fetal, or neonatal death; growth retardation; malformations; congenital defects; and cancer induction.

A radiation dose of 5–15 cGy (5–15 rad) during the preimplantation stage (from conception to 10 d after conception) can result in prenatal death; an in utero dose of 10 cGy (10 rad) in the first 2 wk can result in a spontaneous abortion (note: the natural occurrence of spontaneous abortion is 25%–50%). Radiation doses delivered to the developing fetus during the stage of organogenesis (through the sixth week after conception) may result in developmental abnormalities (e.g., multiple organs, microcephaly, and hydrocephaly). A dose of 10 cGy (10 rad) may produce only a 1% increase in the natural rate of occurrence of these abnormalities. A radiation dose delivered during the fetal or growth stage (from wk 6 to birth) generally tends to result in diminished growth and development. Fetal doses as low as 1–2 cGy (1–2 rad) have been associated with a slight increase in childhood malignancies, especially leukemia (17,18), from a natural occurrence rate of 3.6 per 10,000 to 5 per 10,000.

It is the position of the National Council on Radiation Protection and Measurements (19) that fetal risk is consid-

ered negligible at doses of 5 cGy (5 rad) or less when compared with other risks of pregnancy, and the risk of malformations is significantly increased above control levels only at doses above 15 cGy (15 rad). It should be noted, however, that current radiation protection standards restrict occupational radiation dose to a developing fetus to 0.5 cSv (0.5 rem) during the gestation period, equally divided over the gestation period, not to exceed 0.05 cSv (0.05 rem) per month.

### RADIATION RISK ASSOCIATED WITH DIAGNOSTIC MEDICAL STUDIES

On occasion, a patient may express concern regarding the amount of radiation that he or she will receive as a result of a specific nuclear medicine study. When this occurs, the technologist may have less than 5 min to provide a coherent and logical answer. Technical responses should be avoided. The technologist can reasonably say that the dose received from a nuclear medicine procedure is comparable with that received in x-ray procedures. A comparison of average patient radiation dose from various nuclear medicine and radiographic procedures can be found on the Health Physics Society's Web site (20).

This article has stressed the importance of the magnitude of the dose equivalent in the evaluation of the potential risk. The greater the dose equivalent to the individual, the greater the potential risk. The patient radiation dose varies from one study to another, as indicated in the typical values shown in Table 6. Even though patient dose varies significantly, several important points should be stressed to the patient if questions arise:

- the importance of the risk versus benefit decision made by the patient's physician in ordering the test;
- for the benefit of the patient, radiation doses are mostly delivered to only a limited area of the body or to a limited number of organs;
- radiation doses delivered to individual organs do not

**TABLE 6**  
Typical Patient Radiation Effective Dose Associated with Select Nuclear Medicine Tests

Study	Radiopharmaceutical	Median activity (MBq)	cSv/MBq	Median body dose cSv
Bone	<sup>99m</sup> Tc-MDP	555	$1.9 \times 10^{-4}$	0.10
Brain	<sup>99m</sup> Tc-HMPAO	555	$3.5 \times 10^{-4}$	0.19
Cardiac	<sup>99m</sup> Tc-MIBI	740	$4.6 \times 10^{-4}$	0.34
	<sup>201</sup> Tl-thallous chloride	55.5	$5.7 \times 10^{-3}$	0.32
Hepatobiliary	<sup>99m</sup> Tc-DISIDA	277.5	$4.3 \times 10^{-4}$	0.12
Inflammation	<sup>67</sup> Ga-citrate	148	$7.0 \times 10^{-3}$	1.04
Liver/spleen	<sup>99m</sup> Tc-SC	55.5	$5.1 \times 10^{-4}$	0.03
Lung perfusion	<sup>99m</sup> Tc-MAA	74	$4.1 \times 10^{-4}$	0.03
Lung ventilation	<sup>133</sup> Xe gas	370	$3.8 \times 10^{-5}$	0.014
Renal	<sup>99m</sup> Tc-MAG3	277.5	$1.9 \times 10^{-4}$	0.05
Thyroid	<sup>123</sup> I-Nal	3.7	$8.1 \times 10^{-4}$	0.003

Adapted from Lombardi (21).

Patient doses were determined using median recommended activities found in package inserts for each product.

exceed effective dose limits of 50 cSv (50 rem) for individual organs (below this dose limit, the risk of adverse biologic effects is considered minimal);

- clinically observable health effects as a result of whole-body irradiation typically do not occur at doses below 0.50 Gy (50 rad), where changes in blood count are first noted;
- nausea and vomiting are first noted at acute doses of approximately 1 Gy (100 rad).

Based on our current knowledge of radiation biology, the doses delivered, and the precautions taken, the great benefit derived from an accurate medical diagnosis far outweighs the low level of risk associated with diagnostic tests that use ionizing radiation.

## CONCLUSION

Although the risk of detrimental health effects, specifically increased incidence of cancer, and genetic effects associated with the medical uses of ionizing radiation is relatively small, the uncertainty in determining risk estimates demands continued vigilance on the part of the nuclear medicine technologist. As radiation workers become more accustomed to working with radiation sources, they may tend to become more cavalier about radiation exposure. Each nuclear medicine technologist should constantly use his or her knowledge of radiation protection to implement the ALARA concept to ensure the safety of patients and department personnel.

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