AANA Journal Course 
Update for Nurse Anesthetists 

Radiation Safety for Anesthesia Providers 

Gillian Phillips, CRNA, MS, MSN 
W. Patrick Monaghan, PhD, CLS, SBB 

Many modern diagnostic and surgical procedures rely heavily on the use of ionizing radiation. These procedures include computed tomography, nuclear medicine procedures, interventional radiology, and cardiac catheterization and electrophysiology procedures. Recent trends toward increased patient visits and patients with multiple challenging comorbidities have meant that anesthesia providers are increasingly required to provide services in the ancillary areas using ionizing radiation. As a result, anesthesia providers are at a greater-than-ever risk for excessive radiation doses. 

Introduction 
Many modern diagnostic and surgical procedures rely heavily on the use of ionizing radiation. These procedures include computed tomography, nuclear medicine procedures, interventional radiology, and cardiac catheterization and electrophysiology procedures. Currently, only a handful of sites in the United States, one of which is the University of Florida Shands, Jacksonville, provide a novel type of proton beam therapy using precision high-energy beams of ionizing radiation. Recent trends toward increased patient visits and patients with multiple challenging comorbidities have meant that anesthesia providers are increasingly required to provide services in the ancillary areas that use ionizing radiation. As a result, anesthesia providers are at a greater-than-ever risk for incurring excessive radiation doses. 

An overview of some of the basic principles of radiation biology, radiation physics, and radiation protection and specific guidelines related to radiation exposure and pregnancy are described. The effects of radiation exposure are cumulative and permanent, and an understanding of these principles and practices will help anesthesia providers keep their occupational exposure to a minimum. 

Keywords: ALARA (as low as reasonably achievable), anesthesia provider, electromagnetic radiation, inverse square law, ionizing radiation, radiation safety, x-rays. 

Objectives 
At the completion of this course, the reader should be able to: 
1. Recognize the differences between ionizing and nonionizing radiation and be able to identify the medical imaging modalities using each. 
2. Understand the 4 units used to measure radiation quantity and the definitions of mAs and kV(p) and their influence on the x-ray beam and occupational exposure. 
3. Articulate the concepts contained in the law of Bergonié and Tribondeau and apply the concepts to accurately predict which tissues will be most susceptible to the detrimental effects of ionizing radiation. 
4. Understand the ALARA (as low as reasonably achievable) concept in terms of time, distance, and shielding, and be able to apply the inverse square law to effectively reduce one’s radiation exposure. 
5. State the maximum annual dose of occupational ionizing radiation allowed for anesthesia providers, including pregnant anesthesia providers. 

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6 CE Credits

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Sources of Radiation

Electromagnetic radiation may be divided into 2 broad categories: ionizing and nonionizing radiation. Many types of electromagnetic radiation are harmless and are termed nonionizing. Examples of nonionizing radiation include visible light, infrared radiation, microwaves, radio waves, and certain medical imaging modalities such as ultrasound and magnetic resonance imaging (Figure 1). Ionizing radiation, on the other hand, is of particular concern because it can cause cellular injury. Table 1 is a glossary of common terms used in the discussion of radiation. The term ionization refers to the removal of an electron from an atom, and ionizing radiation is so named because it is capable of removing an orbital electron from matter. Examples of ionizing radiation include x-rays and gamma (γ) rays, as well as alpha (α) and beta (β) particles, the products of certain radioactive decay processes.4

Ionizing radiation comes from many natural and manufactured sources (Figure 2). Natural sources of ionizing radiation include cosmic rays from space, terrestrial radiation (resulting from deposits of uranium, radon, and other radionuclides in the earth), and internally deposited radionuclides (mainly the natural metabolite potassium 40 [40K]). Manufactured sources include nuclear power and industrial sources, certain consumer products (eg, smoke detectors, luminescent watch dials, and television and computer screens), certain medical imaging modalities using radioactive decay processes (nuclear medicine), and x-ray generation (eg, computed tomography, interventional radiology, and electrophysiology and cardiac catheterization procedures).4

During the last 25 years, overall radiation exposure within the US population has more than doubled. During that same period, the percentage of exposure from medical radiation has more than tripled, primarily because of the increased use of diagnostic and surgical procedures using ionizing radiation.5 Trends such as these should serve to remind anesthesia providers of their own vulnerability to the effects of medical ionizing radiation. Table 2 provides a list of the ancillary areas and procedures using ionizing radiation in which anesthesia services are routinely required.

Principles of Radiation Physics

Ionizing radiation may be further classified as particulate...
ALARA: The principle that radiation exposure should be kept as low as reasonably achievable.

Alpha (α) particle: The particulate form of ionizing radiation consisting of 2 protons and 2 neutrons (the helium nucleus); emitted from the nucleus of a radioactive atom during radioactive decay.

Anode: The positively charged side of an x-ray tube, which contains the tungsten target.

Atom: The smallest particle of an element that cannot be divided or broken by chemical means.

Becquerel (Bq): The name for the Système International (International System) units of radioactivity, equal to the number of disintegrations per second.

Beta (β) particle: The ionizing radiation with characteristics of an electron; emitted from the nucleus of a radioactive atom during radioactive decay.

Bremsstrahlung x-ray: An x-ray resulting from interaction of the projectile electron with the tungsten target nucleus; braking radiation.

Cathode: The negatively charged side of an x-ray tube, which contains the filament where electrons are “boiled off.”

Characteristic x-ray: An x-ray resulting from interaction of the projectile electron with orbiting electrons of the tungsten target.

Computed tomography: The creation of a cross-sectional “slice” of the body using a rotating fan x-ray beam and computerized reconstruction.

Curie (Ci): A unit of radioactivity; expressed as 1 Ci = 3.7 x 10¹⁰ disintegrations per second = 3.7 x 10¹⁰ Bq.

Deoxyribonucleic acid (DNA): The molecule that carries genetic information necessary for cell replication.

Deterministic effect: A biological response whose severity varies with radiation dose; a dose threshold usually exists.

Direct effect: The effect of radiation that occurs when the ionizing radiation interacts directly with a particularly radiosensitive molecule.

Dose: The amount of radiant energy absorbed by an irradiated object.

Dose equivalent: The radiation quantity that is used for radiation protection and that expresses dose on a common scale for all radiations; expressed in rem or sievert (Sv).

Early effect: A radiation response that occurs within minutes or days after radiation exposure.

Electromagnetic radiation: Oscillating electric and magnetic fields that travel in a vacuum with the velocity of light; includes x-rays, gamma rays, and some nonionizing radiation (such as ultraviolet, visible, infrared, and radio waves).

Electron: A particle with one negative charge; orbits around the nucleus.

Frequency: The number of cycles or wavelengths per unit of time; expressed in Hertz (Hz).

Gray (Gy): The name for the Système International unit of radiation absorbed dose (rad); 1 Gy = 100 rad.

Hard x-ray: An x-ray that has high penetrability.

Indirect effect: The effect of radiation that results from the production of free radicals produced by the interaction of radiation and water.

International System of Units (SI): A standard system of units based on the metric system; it has been adopted, at least in part, by all countries and is used by all branches of science.

Inverse square law: The law stating that the intensity of the radiation at a location is inversely proportional to the square of its distance from the source of radiation.

Ionization: The removal of an orbital electron from an atom.

Ionizing radiation: Radiation capable of ionizing.

Irradiated: A description of matter that intercepts radiation and absorbs part or all of it.

Kilovolt (peak), or kV(p): A measure of the maximum electrical potential across an x-ray tube; expressed in kilovolts; a factor that determines the penetrability of the x-ray beam.

Late effect: A radiation response that is not observed for 6 months or more after the exposure.

Law of Bergonie and Tribondeau: The principle stating that the radiosensitivity of cells is directly proportional to their reproductive activity and inversely proportional to their degree of differentiation.

Linear energy transfer: A measure of the rate at which energy is transferred from ionizing radiation to soft tissue; expressed in kiloelectron volts per micrometer of soft tissue.

Milliampere-second (mAs): The product of exposure time and x-ray tube current; a measure of the total number of electrons coming from the cathode.

Nonionizing radiation: Radiation for which the mechanism of action in tissue does not involve ionization.

Nucleus: The center of an atom containing neutrons and protons.

Occupational dose: The dose received by a person in a restricted area during the course of employment related to assigned duties.

Penetrability: The ability of an x-ray to penetrate tissue; the range in tissue.

Photon: Electromagnetic radiation that has neither mass nor electric charge but interacts with matter as though it is a particle; x-rays and gamma rays.

Planck constant (h): A fundamental physical constant that relates the energy of radiation to its frequency.

Rad (radiation absorbed dose): The unit for absorbed dose; 1 rad = 0.01 Gy.

Radiation: Energy emitted and transferred through matter.

Radioactive decay: A naturally occurring process whereby an unstable atomic nucleus relieves its instability through the emission of one or more energetic particles.

Radiolysis of water: The dissociation of water into other reactive intermediates as a result of irradiation.

Radionuclide: Any nucleus that emits radiation.

Radiosensitivity: The relative susceptibility of cells, tissues, and organs to the harmful action of ionizing radiation.

Rem (radiation equivalent man): The unit for dose equivalent and effective dose; has been replaced with the sievert (Sv) in the Système International system; 1 rem = 0.01 Sv.

Scatter radiation: The x-rays scattered back in the direction of the incident x-ray beam; constitutes the primary source of occupational exposure to ionizing radiation.

Sievert (Sv): The Système International unit of dose equivalence; 1 Sv = 100 rem.

Soft x-ray: An x-ray that has low penetrability.

Stem cell: An immature or precursor cell.

Stochastic effects: The frequency or probability of the biologic response to radiation as a function of radiation dose; disease incidence increases proportionally with dose, and there is no dose threshold.

Threshold dose: The dose below which a person has a negligible chance of sustaining specific biologic damage.

Tungsten: A metal element that is the principal component of the cathode and the anode.

Wavelength: The distance between 2 peaks on a sine wave; the length of 1 cycle.

Weighting factor (W): The specific value that accounts for the ability of different types of ionizing radiation to cause varying degrees of biological damage.

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Table 1. Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Irradiated</strong></td>
<td>A description of matter that intercepts radiation and absorbs part or all of it.</td>
</tr>
<tr>
<td><strong>Linear energy transfer</strong></td>
<td>A measure of the rate at which energy is transferred from ionizing radiation to soft tissue; expressed in kiloelectron volts per micrometer of soft tissue.</td>
</tr>
<tr>
<td><strong>Kilovolt (peak), or kV(p)</strong></td>
<td>A measure of the maximum electrical potential across an x-ray tube; expressed in kilovolts; a factor that determines the penetrability of the x-ray beam.</td>
</tr>
<tr>
<td><strong>Ionization</strong></td>
<td>The removal of an orbital electron from an atom.</td>
</tr>
<tr>
<td><strong>Indirect effect</strong></td>
<td>The effect of radiation that results from the production of free radicals produced by the interaction of radiation and water.</td>
</tr>
<tr>
<td><strong>Inverse square law</strong></td>
<td>The law stating that the intensity of the radiation at a location is inversely proportional to the square of its distance from the source of radiation.</td>
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<tr>
<td><strong>Direct effect</strong></td>
<td>The effect of radiation that occurs when the ionizing radiation interacts directly with a particularly radiosensitive molecule.</td>
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<td><strong>Dose</strong></td>
<td>The amount of radiant energy absorbed by an irradiated object.</td>
</tr>
<tr>
<td><strong>Dose equivalent</strong></td>
<td>The radiation quantity that is used for radiation protection and that expresses dose on a common scale for all radiations; expressed in rem or sievert (Sv).</td>
</tr>
<tr>
<td><strong>Early effect</strong></td>
<td>A radiation response that occurs within minutes or days after radiation exposure.</td>
</tr>
<tr>
<td><strong>Electromagnetic radiation</strong></td>
<td>Oscillating electric and magnetic fields that travel in a vacuum with the velocity of light; includes x-rays, gamma rays, and some nonionizing radiation (such as ultraviolet, visible, infrared, and radio waves).</td>
</tr>
</tbody>
</table>

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or wavelike (electromagnetic) and may be analyzed according to 5 physical characteristics: mass, energy, velocity, charge, and origin. There are 2 types of particulate ionizing radiation of interest to anesthesia providers: α and β particles. Used primarily in nuclear medicine imaging and in certain therapeutic procedures, α and β particles present a potential—albeit rather limited—source of ionizing radiation to anesthesia providers. The α and β particles are associated with radioactive decay processes that occur when an atom becomes abnormally excited, resulting in an unstable nucleus. To regain stability, the nucleus spontaneously emits particles and energy.4

An α particle is a positively charged particle emitted specifically during the radioactive decay of some unstable heavy element. Made up of 2 protons and 2 neutrons (essentially the nucleus of a helium atom), its mass is quite heavy. Once emitted, α particles travel with high velocity through matter, but because of their great atomic mass and charge, they readily collide with orbital electrons of matter, resulting in a sudden loss of energy. Because of this energy loss, α particles do not penetrate far into material and can be stopped quite easily (Table 3). In fact, α particles can be stopped by a piece of tissue paper or a layer of dead skin. Therefore, α particles pose little hazard from external exposure, but they can produce massive internal tissue injury if inhaled or digested.4 They are able to deposit intense energy into very small volumes, and they can penetrate up to 50 µm into the pulmonary epithelium when inhaled. Examples include radium, which decays into radon gas, and americium 241 (241Am) found in household smoke detectors.

The β particles are also emitted during the radioactive decay of an unstable atom, but compared with α particles, they are relatively light, with an atomic mass approaching zero. The β particles may carry a +1 or −1 charge. Positively charged β particles are called positrons. Negatively charged β particles are usually called electrons because they have the exact same mass and charge as electrons. The only difference between a negatively charged β particle and an electron is the origin. A negatively charged β particle is emitted from within the nucleus, whereas an electron orbits around the nucleus. Because of their low mass, β particles have a longer range in matter than do α particles and may traverse up to 2 cm of tissue. A thin sheet of plastic, aluminum, or even a short span of air (10-100 cm) can stop β particles.4 Examples of the use of β particles of interest to anesthesia providers include positron emission tomography scanning and strontium 90 (90Sr) used in radiation therapy

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**Table 2. Ancillary Areas and Procedures Using Ionizing Radiation: Potential Sources of Ionizing Radiation for Anesthesia Providers**

<table>
<thead>
<tr>
<th>Cardiac catheterization laboratory</th>
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<tbody>
<tr>
<td>Angioplasty and/or stent insertion for coronary stenosis</td>
</tr>
<tr>
<td>Diagnostic cardiac catheterization</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Computed tomography</th>
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</thead>
<tbody>
<tr>
<td>Assessment of the airway (neck or thoracic tumors)</td>
</tr>
<tr>
<td>Assessment of bony trauma (especially the spine)</td>
</tr>
<tr>
<td>Imaging of brain tumors or cerebral hemorrhage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrophysiology laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardioversion</td>
</tr>
<tr>
<td>Permanent pacemaker insertion</td>
</tr>
<tr>
<td>Radiofrequency catheter ablation</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Interventional radiology</th>
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</thead>
<tbody>
<tr>
<td>Balloon angioplasty of cerebral vasospasm</td>
</tr>
<tr>
<td>Carotid cavernous fistula and vertebral fistula treatment</td>
</tr>
<tr>
<td>Catheterization of ducts, vascular lesions, and tumors for regional delivery of chemotherapy</td>
</tr>
<tr>
<td>Embolization or embolectomy of vascular lesions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nuclear medicine</th>
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</thead>
<tbody>
<tr>
<td>Positron emission tomography</td>
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<tr>
<td>Single photon emission computed tomography</td>
</tr>
<tr>
<td>Ventilation-perfusion scan</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiation therapy</th>
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</thead>
<tbody>
<tr>
<td>Electron beam radiation therapy (usually intraoperative)</td>
</tr>
<tr>
<td>Gamma-knife surgery (eg, for brain tumors and arteriovenous malformations)</td>
</tr>
<tr>
<td>Proton beam therapy (eg, for brain tumors and prostate carcinoma)</td>
</tr>
</tbody>
</table>

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![Figure 2. Natural and Manufactured Exposure Sources of Ionizing Radiation Contributing to the Collective Dose for 2006](image-url)
(intraoperative plaque insertion) for cancer of the eye.

The 2 main types of electromagnetic ionizing radiation are γ-rays and x-rays. All electromagnetic radiation travels at the speed of light ($3 \times 10^8$ m/s) and may be visualized as 2 perpendicular sine waves traveling in a straight line (Figure 3). Because of this arrangement, electromagnetic radiation is unable to bend around corners and behaves as a wave and as a particle. As a wave, it is characterized by the equation $c = f\lambda$, where $c$ is the speed of light, $f$ is frequency, and $\lambda$ is wavelength. Wavelength ($\lambda$) is defined as the distance from one wave peak to the next and represents 1 cycle. Frequency ($f$) is the number of cycles that occur per second and is measured in Hertz (Hz). As a particle, electromagnetic radiation is termed a photon (a packet or “quanta” of energy having no mass) and has energy calculated by the equation $E = hf$, where $E$ is energy, $h$ is the Planck constant, and $f$ is frequency. In either case, it is the frequency that determines the energy of the radiation and the potential for cellular damage. Frequency and wavelength are inversely related. Higher frequencies—and shorter wavelengths—result in higher energy radiation (more particlelike), whereas lower frequencies—and longer wavelengths—result in lower energy radiation (more wavelike).

Just as the only difference between β particles and electrons is their origin, the only difference between γ rays and x-rays is in their origin. The γ rays are a type of electromagnetic radiation emitted during radioactive decay and usually accompany emission of α and β particles because after the process of emitting an α or a β particle, the nucleus still exists in an excited state; γ-ray electromagnetic energy is emitted as the nucleus returns to a stable state. Because of their high energy and absence of mass, γ rays are highly penetrating and may be stopped only by dense materials such as lead and concrete.

Although γ rays pose the greatest threat from external exposure, they can also produce massive internal tissue injury if inhaled or ingested in the form of α-

### Table 3. General Classification of Ionizing Radiation
(Adapted from Bushong.4)

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Symbol</th>
<th>Type</th>
<th>Mass</th>
<th>Charge</th>
<th>Shielding material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>α</td>
<td>Particle</td>
<td>4</td>
<td>+2</td>
<td>Paper, skin, clothes</td>
</tr>
<tr>
<td>Beta minus</td>
<td>β−</td>
<td>Particle</td>
<td>1/1,836</td>
<td>−1</td>
<td>Aluminum, plastic</td>
</tr>
<tr>
<td>Beta plus</td>
<td>β+</td>
<td>Particle</td>
<td>1/1,836</td>
<td>+1</td>
<td>Aluminum, plastic</td>
</tr>
<tr>
<td>Gamma</td>
<td>γ</td>
<td>Wave</td>
<td>0</td>
<td>0</td>
<td>Lead, concrete</td>
</tr>
<tr>
<td>X-ray</td>
<td>X</td>
<td>Wave</td>
<td>0</td>
<td>0</td>
<td>Lead, concrete</td>
</tr>
</tbody>
</table>

### Figure 3. The Electromagnetic Radiation Wave
Electromagnetic waves transport energy through space and are characterized by sinusoidal perpendicular electrical and magnetic fields. Wavelength ($\lambda$) is measured from peak to peak (1 cycle). Frequency ($f$) is the number of cycles per second.
and β-particle emitters. Examples of diagnostic imaging devices using γ-ray emission include single photon emission computed tomography scans; cardiac scans of this type involve the release of a single γ ray from the radiotracer technetium (Tc-99m) attached to the cardiac-tissue-seeking molecule sestamibi. Other examples of the diagnostic use of γ rays may be found in pulmonary ventilation-perfusion scans, which use the inhaled radiotracer xenon 133, and in the thyroid uptake of iodine 123.

To reiterate, the only difference between γ rays and x-rays is how they are generated. Whereas γ rays are emitted from the nucleus during radioactive decay, x-rays are produced artificially within an x-ray machine. Electrons are “boiled off” from a heated filament within the cathode (the negative side of the x-ray machine), focused into a small area, and projected at approximately one-half the speed of light toward a rotating tungsten target called the anode (the positive side of the x-ray machine). Negatively charged electrons are naturally attracted to the positive neutrons within the tungsten nucleus and may interact in 1 of 2 ways to produce x-rays:

1. Electrons may lose energy as they pass near the nucleus and slow down, emitting an x-ray in the process. This process is termed Bremsstrahlung—“braking x-rays.”

2. Alternatively, the incoming electrons can remove an inner (K-shell) electron from the tungsten, leaving an empty space. This highly unstable situation is corrected when an outer-shell electron drops into the space.6 The excess energy is released through the emission of a “characteristic x-ray.”

A useful tool in visualizing an x-ray beam is to imagine it as a light source. Imagine you are standing 2 feet from a wall while shining a flashlight at it. You see a focused bright area with defined edges. As you slowly back away from the wall, you see the lighted area becoming larger, and, as it does, the relative intensity of the light dims and the edges become softer and less defined. Like light, x-rays diverge from a point of origin, namely, the x-ray cathode. And like light, x-rays obey the inverse square law, which states that the intensity of a beam is inversely proportional to the square of its distance from the source (Figure 4).4 Put another way, an object twice the distance from the radiation source will receive one-quarter the amount of radiation exposure. Tripling the distance from the radiation source, and the object will receive one-ninth the amount of radiation exposure. This valuable concept will be revisited later.

**Definitions and Units of Radiation Quantity**

There are 4 units used to measure radiation quantity (Figure 5):

- **Roentgen (R)** is the unit of radiation exposure or intensity in air and is applicable only to γ rays and x-rays. The output intensity of an x-ray imaging device is measured in milliroentgen (mR).

- **Rad (radiation absorbed dose)** refers to the quantity of radiation received by an individual. The rad is used for any type of ionizing radiation (α- and β-particles and γ rays and x-rays) and any exposed matter (eg, humans and animals).4

- **Rem (radiation equivalent man)** is the unit of occupational radiation exposure. Some types of radiation produce more damage than others (eg, α particles more than x-rays), and this term accounts for the differences by expressing the biological effectiveness of the radiation as the “effective dose.” Linear energy transfer is used to describe the amount of energy lost by the ionizing radiation and transferred to matter (eg, an anesthesia provider). Photons (such as x-rays and γ rays) have much less linear energy transfer than, eg, α particles, and therefore do relatively less harm. The specific value that accounts for the ability of different types of ionizing radiation to cause varying degrees of biological damage is termed the weighting factor (WR). An equivalent dose for any type of ionizing radiation may be calculated by using the appropriate weighting factor (WR) in the following equation: Equivalent Dose (rem) = Absorbed Dose (rad) × WR. For example, the WR for x-rays, γ rays, and β particles = 1; therefore, for these types of ionizing radiation, 1 rad = 1 rem.6 By comparison, the WR for α particles is 20; therefore, for α-particle radiation, 1 rad = 20 rem.
The curie (Ci) is a unit of radioactive material and not the radiation emitted by that material. A curie is defined as the quantity of radioactive material in which \(3.7 \times 10^{10}\) atoms disintegrate per second.\(^4\)

Since 1981, all countries—except the United States—have adopted Le Système International d’Unités (the International System, or SI). In the International System, the gray (Gy) is equivalent to the rad, and 1 Gray = 100 rad; the sievert (Sv) is equivalent to the rem, and 1 Sv = 100 rem; the becquerel (Bq) is equivalent to the curie, and 1 curie is equivalent to \(3.7 \times 10^{10}\) becquerel.\(^4\) Because these terms are often used interchangeably, we have included them for completeness.

According to the International Commission on Radiological Protection (ICRP), the annual occupational effective dose limit is 5,000 mrem/y (50 mSv/y), whereas the cumulative effective dose limit is 1,000 mrem \(\times\) age (10 mSv \(\times\) age).\(^7\) So, for a 35-year-old person, the cumulative lifetime effective dose should be no greater than 35,000 mrem or 350 mSv. The risk of fatal cancer increases by about 0.04% \(\times\) the lifetime rem exposure. To put this in perspective, for a person who reached his or her annual effective dose of 5,000 mrem/y for the next 10 years (highly unlikely), this dose would translate into a dose of 50 rem total. The person’s added risk of fatal cancer is therefore 50 \(\times\) 0.04%, or 2%. If the risk of fatal cancer in the United States is 20%, this person’s risk would increase from 20% to 22%. Other limits set out by the ICRP include equivalent annual doses to the lens of the eye—15 rem (150 mSv) and for the thyroid, skin, hands, and feet—50 rem (500 mSv). The ICRP also states that exposure to the embryo or fetus shall not exceed 500 mrem (5 mSv) for the total gestational period or 50 mrem per month.\(^7\)

Two important terms used to describe the x-ray beam are milliampere-seconds (mAs) and kilovolt (peak), or kV(p). X-rays are generated when electrons are boiled off from a heated filament within the cathode, and this is expressed in mAs. X-ray quantity is directly proportional to mAs so that when mAs is doubled, the number of electrons striking the tungsten target is doubled, and the number of x-rays emitted is also doubled. Just as mAs describes the quantity of x-rays, kV(p) describes the quality of the x-rays. Ohm’s law describes the volt, as in kV(p), as the pressure or intensity of the flow of electrons. As voltage (ie, kV(p)) increases, the penetrability or “hardness” of the x-ray beam increases because of increased intensity of electron flow from the cathode toward the anode. Conversely, as kV(p) decreases, penetrability decreases and the beam becomes “softer.”\(^4\)

Alterations in kV(p) and mAs are made by radiologic technologists to compensate for certain patient-related factors such as body weight and habitus, the thickness of the body part to be imaged (eg, hip vs ankle), and the atomic number of the body part (reflective of the elemental composition/mass density of that body part, ie, bone vs soft tissue vs lung). Each factor requires more or less x-ray quantity, ie, mAs, and/or penetration, ie, kV(p), to generate the optimal x-ray image. Some alteration in kV(p) and mAs is also necessary depending on how the x-ray beam is projected or oriented relative to the patient. In the posterior-anterior view with the patient supine, the

Figure 5. The 4 Units of Radiation Quantity: Roentgen, Rad, Rem, and Curie.\(^4\)
The x-ray beam is projected from below the table through the patient’s back and out through to the front, whereas in the lateral view (with the patient still supine), the x-ray tube is rotated 90° so that the x-ray beam enters from the right side of the patient and exits out the left (Figure 6). The tissue thickness that the x-ray beam must traverse increases as the x-ray tube is rotated from posterior-anterior to oblique to lateral, requiring increases in mAs and kV(p) to generate an optimal image. So why should anesthesia providers care about these patient-related factors? Because any factor requiring increased mAs or kV(p), eg, a large patient, thick body part, or extreme angulation of the x-ray beam as in the lateral projection, results in increasing dose to the patient (or anyone else in the path of the primary x-ray beam). Of far greater concern is the fact that with increased kV(p) comes increased scatter radiation from the patient, and scatter radiation is the predominant source of radiation exposure to anesthesia personnel.4

**Principles of Radiation Biology**

Ionizing radiation is of concern to anesthesia providers because it causes ionization of matter (the loss or gain of electrons). Ionization may subsequently result in one or more of the following: the production of reactive oxygen species, including ions and free radicals; the breakage—or production—of chemical bonds; cross-linkage between molecules; or, most important, damage to molecules that regulate vital cellular processes (eg, DNA, RNA, and proteins).4

Cellular DNA is composed of atoms and molecules held together by various electron interactions resulting in the characteristic double helix structure. Ionizing radiation can cause disruption of these bonds directly or indirectly.4 The “direct effect” occurs when ionizing radiation interacts directly with a single bond within an atom or molecule, causing disruption of that bond. The principal effect of ionizing radiation on human tissue, however, is through the “indirect effect.” Because much of the human body is made up of water, ionizing radiation may interact with a molecule of water (termed radiolysis) to form a reactive oxygen species. Reactive oxygen species are highly reactive intermediates including ions and free radicals that can subsequently disrupt bonds in neighboring atoms and molecules through a domino effect. The damage to the DNA may now result in 1 of 3 things:

1. Enzymes may be unable to repair the damage, and the cell simply dies (apoptosis).
2. Enzymes may accurately repair the damaged DNA with no adverse effects.
3. Enzymes may inaccurately repair the damaged DNA, resulting in chromosomal aberrations, and these genetically mutated cells will be retained throughout subsequent cellular divisions.4 Under certain circumstances, these cells may eventually become cancerous.

To produce a radiation response in humans within a few hours to months, the dose must be substantial. Such a dose is termed early or deterministic, meaning that the severity of symptoms is proportional to the dose, and
usually there is a threshold dose below which there is no observable effect.\textsuperscript{4,6,8} Cataracts and skin injury (e.g., sunburn) are examples of early radiation exposure. The second type of radiation response in humans is termed \textit{late effect} and results from repeated low doses of radiation over long periods, the kind most likely to be seen in occupational exposure. Late radiation exposure is termed \textit{stochastic}, meaning the incidence of the biological response is a function of the radiation dose and increases proportionally with increased dose. The severity of that response, however, is independent of the dose. Furthermore, there is no known threshold dose below which there is no observable effect.\textsuperscript{4,6,8} Examples include radiation-induced malignancy (e.g., leukemia) and genetic effects. Because there is no known threshold dose, the key to reducing late effects is to minimize radiation exposure. There are simple yet effective ways to minimize exposure, which will be discussed later.

Tissue Radiosensitivity

In 1906, 2 French scientists, Jean Bergonié and Louis Tribondeau, arrived at the theory that tissue radiosensitivity was a function of the metabolic state of the tissue being irradiated. This theory came to be known as the law of Bergonié and Tribondeau. Simply put, it states the following:\textsuperscript{4}

- Stem cells are the most radiosensitive.
- Younger tissues and organs are more radiosensitive.
- The more mature a cell, the more resistant to radiation it is.
- As the cellular metabolic activity increases, radiosensitivity also increases.

- As the cellular proliferation rate increases, radiosensitivity also increases.

From this law, an accurate prediction may be made about which types of tissues and organs are likely to be most radiosensitive (Figure 7). Sperm, bone marrow, lymph and thyroid tissue, the optic lens, and intestinal epithelium with their relatively high rates of metabolic activity and cellular proliferation are considered highly radiosensitive, whereas mature bone and cartilage, which heal very slowly because of low metabolic rates, are categorized as fairly radioresistant.

Because the age of a biological structure is one determinant of its radiosensitivity, we may conclude that humans will become less radiosensitive throughout the lifespan. As expected, humans are most sensitive before birth. Following birth, sensitivity decreases until maturity. In old age, however, humans again become somewhat more radiosensitive, presumably because with advanced age, the body becomes less efficient at repairing itself following cellular damage.\textsuperscript{4}

Radiation exposure during pregnancy is always of particular concern because of stem cell differentiation, increased metabolic demands, and rapid cellular proliferation of the rapidly developing fetus. As expected, the developing human is most sensitive to the lethal effects of ionizing radiation during the first trimester, particularly the first 14 days after conception.\textsuperscript{4} During this period, the radiation-exposed embryo survives undamaged or is resorbed—termed “all or none.” During the period of organogenesis (approximately 2 to 8 weeks after fertilization or 4 to 10 weeks after the last menstrual period), lethality is rare, but the embryo may be injured as a result
of radiation exposure. The major effects of radiation damage during this period are congenital malformations, particularly microcephaly, mental retardation, and gross eye abnormalities.8,9 After approximately 20 to 25 weeks of gestation, the fetus is relatively resistant to the teratogenic effects of most commonly encountered levels of ionizing radiation.9

Radiation Safety Practices
The basic principle for radiation safety practice lies in the ALARA pneumonic: “as low as reasonably achievable.” A simple yet effective way to promote ALARA is through the prudent use of time, distance, and shielding.4,8,10
• Time. Keep time spent near the radiation source to a minimum. This may seem like an obvious precaution, yet it is easily forgotten. Radiation exposure is cumulative and permanent and should therefore command a healthy respect. Similar to switching a light on and off, radiation is produced only when the x-ray beam is on. Objects do not “glow” or emit radiation once the x-ray beam is turned off.
• Distance. This factor uses the inverse square law to advantage. Simply doubling a person’s distance from the x-ray source decreases exposure to one quarter of the original dose, and tripling the distance decreases exposure to one-ninth of the original dose.4 The American College of Cardiology recommends maintaining a 3- to 6-ft distance from the radiation source at all times.8

Ionizing radiation can be scattered off objects such as patients and is most likely to present a problem under certain conditions. Increased scatter should be expected if the patient is large, if the body part being imaged is thick (eg, hip vs wrist), if the elemental composition of the tissue is relatively dense (eg, bone vs lung), if the kV(p) is high (eg, 110 kV(p) vs 50 kV(p)), or if angulation of the x-ray tube is extreme (eg, lateral vs posterior-anterior projection).4,8 Occupational exposure is predominantly due to scatter radiation, and distance is the best protection.
• Shielding. Like visible light, ionizing radiation travels in a straight line and cannot bend around corners. If possible, shielding material should be positioned between the radiation source and the provider. Shielding material may be as simple as a concrete wall or a mobile lead shield, or it may include protective apparel such as a lead apron. Lead aprons usually contain 0.5 mm of lead, which should reduce occupational exposure to approximately 25% of the original dose. For example, at 100 kV(p), roughly the energy of the beam used for a chest x-ray, the intensity of the beam will be attenuated by 55%. At 75 kV(p), the energy used for an x-ray of the hip, a 0.5-mm lead apron will attenuate the intensity of the x-ray beam by as much as 88%.4 Although often heavier, wraparound lead is superior to a one-piece apron. One-piece aprons are adequate while facing the radiation source, but they provide no protection if facing away from the source. The advantage of wraparound lead is that it provides protection from all angles and obviates the need to always know where one is standing relative to the radiation source.

Pregnant anesthesia providers should always wear wraparound lead. The ICRP states that for a pregnant provider, wraparound lead aprons shall contain 1.0 mm of lead protection at the level of the fetus. The ICRP also states that the fetal dose limit shall be less than 5 mSv (500 mrem) for the entire gestational period with an operational dose limit of less than 0.5 mSv/mo (< 50 mrem/month).5,7 Pregnant providers should be given 2 film badges to more accurately monitor their radiation dose. One badge should be worn outside the lead at the level of the collar as usual. The other should be worn under the lead at waist level to determine how much radiation actually reached the fetus. Readings for anesthesia providers are expected to be minimal and under-the-lead readings should be less than 10% of the collar (over-the-lead) readings. It has been determined that low doses of ionizing radiation do not impair fertility and that for most of her prereproductive life, a woman is actually less sensitive to the genetic effects of radiation than a man. There is a 5% natural incidence of congenital abnormalities.4

In addition to wearing a lead apron, it is advisable to wear a thyroid shield. Thyroid tissue is highly radiosensitive because of its high metabolic rate.4 Thyroid collars usually contain 0.25 mm of lead. The lens of the eye is also sensitive, and lead eyeglasses should be considered for providers who spend a fair amount of time in the electrophysiology or cardiac catheterization laboratory. Eyeglasses containing 0.5 mm of lead offer 4 times the protection of regular eyeglasses.10 Plastic lenses offer no radiation protection.

Summary
Current trends toward increased diagnostic and therapeutic uses of ionizing radiation show no signs of abating. As such, anesthesia providers may expect to spend more time working in the ancillary areas using ionizing radiation. It is imperative that anesthesia providers understand the basic concepts of radiation safety to keep their occupational exposures to a minimum. When one considers the fact that radiation exposure is permanent and cumulative, prudent providers would do well to heed the general admonition represented by ALARA when dealing with occupational radiation exposure.

Current educational research in using the training module described by Phillips et al3 has addressed at least 2 main concerns for anesthesia providers. Recent data have shown that this module improves the “knowledge gap” of radiation safety and clinical anesthesia practice.3 Furthermore, it has served to stimulate individual anesthesia providers toward an increased awareness of
current radiation practice and its effect on their clinical practice milieu.

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AUTHORS
Gillian Phillips, CRNA, MS, MSN, is a staff nurse anesthetist with the JLR Medical Group in Orlando, Florida. She is a certified registered radiologic technologist in radiography and has advanced certification in cardiovascular interventional technology and magnetic resonance imaging. At the time this course was written, Phillips was a graduate student in the Nurse Anesthesia Program at the University of North Florida, Jacksonville, Florida. Email: gillianphillipsrn@gmail.com.

W. Patrick Monaghan, PhD, CLS, SBB, is a professor in the Brooks College of Health at the University of North Florida, Jacksonville, Florida.

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