Radiation physics

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Introduction: **Radiation comes in different forms of energy in motion. Doses of radiation and the area of interest are important considerations when imaging patients, particularly during percutaneous procedures.**
Methods: **Reference texts in essential physics, principles of radiation imaging, and radiation dosimetry were reviewed.**
Results: **Dose, exposure to radiation, and total body radiation delivery are reviewed and graphically tabulated.**
Conclusion: **Each institution will monitor radiation dose delivered to the individual; however, individual physicians have the responsibility to protect themselves and their patients against excessive radiation exposure by knowing appropriate dosages and biological risks. (J Vasc Surg 2011;53:6S-8S.)**

ENERGY AND RADIATION

Radiation is energy in movement. Electromagnetic radiation (EMR) refers to energy that travels in the form of waves. Another way of thinking about EMR is as a matterless bundle of energy called a photon. The photon is the "package" of energy that carries the energy through space. The other type of radiation is particulate, in which small particles (electrons, alpha particles) carry the energy. Particulate radiation can emanate from radioactive materials and linear accelerators. Particulate radiation is not effective for imaging due to low penetration of matter.

The characteristics of the various forms of EMR vary according to the wavelength (Fig).[1] It is important to understand that frequency and wavelength are simply inversely proportional. X-rays, for example, have a shorter wavelength (λ) and higher frequency (f) than visible light:

$$v \text{ (velocity)} = f\lambda$$

An inverse relationship also exists between energy from photons and wavelength. Thus, a single x-ray photon carries far more energy (E) than a single light photon.

$$\mathrm{E} = 1.24/\lambda$$

In practical terms, frequency and wavelength are both used sometimes arbitrarily in referring to various components of the EMR spectrum; for example, we talk about "radio frequency," but the wavelength of light.

High-frequency EMR is referred to as ionizing radiation due to the ability to remove an outer electron from an atom. At an atomic level, electrons exist in different shells around the nucleus that correspond to different potential energy levels (eg, K shell, L shell). X-rays are a form of ionizing radiation, as are gamma rays (eg, nuclear energy, cosmic rays). The ability of radiation to ionize is also dependent on the material it interacts with, because different substances have different electron binding energies and different densities.[1] A more thorough discussion of quantum physics and electron energies is beyond the scope of this discussion.

Ionizing radiation has the potential to alter DNA and living tissue. Nonionizing radiation carries less energy and is at the lower end of the electromagnetic spectrum. Nonionizing radiation only energizes electrons to a higher energy state without displacing them. Visible light, radio waves, and microwaves are all forms of nonionizing radiation.

THE PRODUCTION OF X-RAYS

X-rays are produced from electric energy in the form of electrons flowing into the x-ray tube. Electrons are minute particles that possess a negative electric charge. The potential energy of an electron depends on its position in an electric circuit or on its energy level in an atom (electron shell). Within an electric circuit, electrons act as a conduit to transport energy. At the "source" (eg, electric socket), electrons possess a high potential energy that is then lost as the energy is converted into different forms when the electrons reach the "load" (eg, the x-ray tube).

The x-ray tube has a negatively charged cathode that then reuses the electrons by directing them in a beam at the corresponding anode. The anode generates the x-rays as energy is released from the electrons decelerating by corresponding nuclei at the focal spot. The focal spot determines the image quality—with smaller focal spots producing sharper images. The anode, which is composed of a highly stable material such as tungsten, also serves to dissipate some of the heat created.[1]

At an atomic level, x-rays are produced by either the Bremsstrahlung or the characteristic method. [2] Most x-ray photons are created by the Bremsstrahlung (German for "braking radiation") method. Electrons reach the anode material and are deflected by the positively charged nuclei. The loss of kinetic energy with this interaction results in the production of x-ray photons. The highest energy photons are produced by the center of the nucleus, and weaker interactions occur when electrons hit farther away from the nucleus. This process results in the production of a spec-

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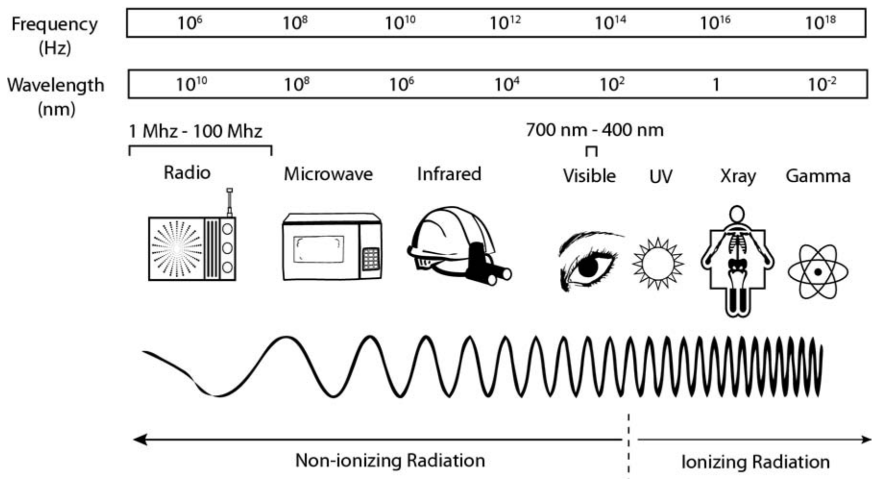

Fig. The electromagnetic spectrum. Higher-frequency radiation, such as x-rays, carry more energy than lower frequencies and can penetrate tissue.

trum of different energy photons. Some of the lower-energy photons are ultimately filtered out. Characteristic x-ray photons are produced by high-speed electrons in the beam colliding with the orbital shell electrons of the anode material. An orbital shell electron is dislodged and subsequently replaced by an electron from a higher-energy shell level. This process results in a net production of an energy photon with energy equal to the difference between the two shells. Depending on which shells and what anode material are involved, specific "characteristic" energy photon spikes are produced.

An important concept is that the radiation emitted from the cathode becomes less concentrated as it travels further. This concept is sometimes referred to as the inverse-square law, in which the radiation concentration (C) is equal to the inverse square of the distance (d) from the beam; for example, if the operator triples the distance to the radiation source, the exposure is reduced by ninefold.[3]

$$\text{The inverse} - \text{square law: } C = 1/d^2$$

THE INTERACTION BETWEEN RADIATION AND MATTER

All forms of energy used in medical imaging, with the exception of ultrasound, are a type of radiation. Radiation interacts with the human body in a way that creates information. The trajectory of radiation is straight until it interacts with matter. Matter both absorbs and scatters radiation. A fundamental principle of physics is that energy can neither be created nor destroyed, only converted from one form to another. The fundamental units of energy are presented in Table I. When x-rays are used to image the human body, electric energy from a source is converted into x-rays and subsequently transformed into light, heat, and chemical energy.

The biologic effects of radiation are deterministic or stochastic. Deterministic effects occur above a certain threshold and are the result of cellular death. As the most superficial structure encountering the x-ray beam, the skin is particularly vulnerable to radiation. Skin erythema and desquamation are deterministic effects of differing severity. Other examples are hair loss, cataracts, and sterility. The threshold for these adverse biologic events is measured in grays (Gy). In general, 2 Gy is the threshold above which deterministic effects are more likely to occur.[4]

Table I. Energy terminology

Term	*Description*
Joule	Fundamental unit of energy[a]
Electron volts	Unit of energy[b]
Watt (J/s)	Power (rate of energy transfer)
Angstrom, nanometer	Measure for smaller wavelengths (eg, 1Å = 10^{-10}m)
Voltage	Potential energy
Ampere	Current (electron flow in a circuit)

[a] Typically used for large amounts of energy.
[b] Used for smaller amounts of energy.

Lower doses of radiation can result in stochastic effects, such as cancer and genetic mutations.[4] As a form of ionizing radiation, x-ray photons have the ability to eject electrons from the atomic structure. In living tissue, this may translate to breaks in DNA molecules. The cumulative breaks in DNA may exceed the body's ability to repair itself, leading to mutations. Stochastic effects are more likely with higher, cumulative doses of radiation but do not have a certain threshold. Certain organs, such as bone marrow and breast, are more vulnerable to radiation-induced cancer.

TERMINOLOGY

The terminology for measuring radiation quantities is confounded by two different nomenclature systems, the conventional and International System of Units (SI). Be-

Table II. Measurements of radiation

Radiation quantity	*Description*	*Conventional units*	*SI units*
Exposure	Radiation concentration present in field	Roentgen (R)	Coulombs/kg
Surface integral exposure	Total dose in radiation field	Roentgen-cm^2	
Absorbed dose	Radiation concentration absorbed by patient	rad	Gray (Gy)
Integral dose	Total body radiation absorbed by patient	gram-rad	Joules (J)
Equivalent dose	Biologic impact of radiation	rem	Sieverts (Sv)
Effective dose	Organ-specific impact of radiation	rem	Sieverts (Sv)

cause SI units have not supplanted the conventional system, both are mentioned here. A true respect for the potential risks and benefits of using ionizing radiation in the vascular surgical practice necessitates a thorough knowledge of the terminology (Table II).

Radiation field (exposure). This can only be quantified within an air ionization chamber. As air is exposed to radiation, the amount of air ionization is measured. The amount of ionization depends on the concentration of the radiation (distance from beam) and the amount of photon energy. The unit of exposure is measured in roentgens (R). The exposure is defined strictly for air as the interacting medium. There is a way to quantify different radiologic procedures called the "entrance skin exposure," meaning the exposure at the location in space where the central beam of radiation enters the patient. Exposure can easily be measured and compared between facilities.

Surface integral exposure. The total radiation delivery to the body is called the surface integral exposure (SIE) and is measured in R-cm^2. Therefore, even though two individuals are exposed to the same radiation concentration, the SIE will be greater in the individual with a larger surface area exposure. For example, 100 mR of delivered radiation could mean 10 R-cm^2 in the individual exposed to a narrower beam vs 100 R-cm^2 for a larger beam area. Collimation of the x-ray beam will therefore reduce the surface integral exposure.

Absorbed dose. This is the energy that is deposited in the absorbing medium (ie, the skin or an organ) and was measured traditionally as the rad (radiation-absorbed dose). When SI units are used, the absorbed dose is measured as a gray (Gy), with 1 Gy = 100 rad. The absorbed dose of radiation depends on the tissue density and depth, with more superficial structures absorbing more of the radiation. Bone and soft tissue have very different profiles of radiation absorption.

Integral dose. The integral dose is the cumulative absorbed dose in all the tissues and therefore corresponds with the amount of potential radiation tissue damage. Integral dose is measured conventionally as grams of tissue—rad. Integral dose is calculated as an extrapolation from radiation delivery (exposure) because there is no gauge to directly measure radiation absorption in the body.

Equivalent dose. This term describes the biologic effect of radiation, now measured in the SI unit of the sievert (Sv). Conventionally, it was measured in rem (roentgen equivalent in man), with 1 Sv = 100 rem. The equivalent dose represents the product of the absorbed dose (in rads or Gy) and weighting factors (W_R) accounting for the fact that different types of radiation have different effects on tissue. The type of radiation used in medical imaging has a $W_R = 1$. Therefore, for medical radiation exposures (eg, x-rays and gamma rays), the sievert and gray are about equal (equivalent dose = absorbed dose). For highly ionizing particles (eg, alpha particles), the equivalent dose more accurately reflects the tissue damage that can occur.

Effective dose. Effective dose is a term that quantifies the stochastic effects as measured in sieverts. It takes into account that different organs and tissues have different sensitivities to the radiation that is being absorbed. For example, the gonads are more radiosensitive than the liver. The organ-weighing factor (W_T) relates to that organ's specific risk associated with cancer development and genetic defects as a result of the radiation exposure. The equivalent dose for that organ is multiplied by the weighting factor to give the effective dose. Importantly, the effective dose from various imaging modalities (fluoroscopy, computed tomography, nuclear medicine) as well as from everyday background radiation (radon, cosmic radiation) can be quantified and compared.[1,2,4]

CONCLUSIONS

Each institution will have a mechanism to monitor the radiation dose delivered to the individual; however, individual physicians have the responsibility to protect themselves and their patients against excessive radiation exposure. The amount of radiation absorbed by an individual's tissues corresponds with the risk of developing biologic effects. Therefore, it is important to quantify the radiation exposure, the absorbed dose, and the biologic effects and risks.

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