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"Quantifying the Radiation Imparted to Patients"

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Quantifying the Radiation Imparted to Patients

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INTRODUCTION AND OVERVIEW

The determination and communication to others of the amount of radiation delivered to a patient's body and the biological impact on the patient is often a complex process. There are several reasons for this. One is the variety of radiation quantities and associated units used for this purpose. Another complicating factor is the way in which the radiation is distributed over the patient's body. In diagnostic radiology patients receive radiation from two types of sources. One is an external x-ray beam and the other is a radionuclide within the patient's body. For each of these two sources the distribution of radiation throughout the body has distinct characteristics. In general, there are more radiation quantities that apply to the external x-ray beam. Therefore, much of this discussion will be applied to x-radiation but it will also be pointed out where a specific quantity can be used for the radiation from radionuclides.

The primary objectives of this chapter are to:

1. Develop a conceptual understanding of the various radiation quantities and units
2. Select the appropriate radiation quantity for a specific application
3. Apply the appropriate units and perform conversions as necessary

UNIT SYSTEMS

The complicating factor is that the American society is undergoing a slow change in the units used to express a variety of physical quantities. In everyday life we see this as a change from the conventional British unit system (feet, pound, miles, etc.) to the metric system (meters, kilograms, kilometers). In radiology we are experiencing a change not only to the general metric units but also to the proposed adoption of a set of fundamental metric units known as the International System of Units (SI units). The adoption of the SI radiation units is progressing rather slowly because there is nothing wrong with our conventional radiation units, and the SI units are somewhat awkward for a number of common applications. In this chapter both unit systems are discussed and compared.

QUANTITIES

Radiation quantities used to describe a beam of x-radiation fall into two general categories as shown in Figure 1. One category comprises the quantities that express the *total amount* of radiation or total biological impact and the other comprises the quantities that express radiation *concentration* at a specific point. We need to develop this distinction before considering specific quantities.

A characteristic of an x-ray beam or any other type of radiation emitted from a relatively small source is that it is constantly spreading out or diverging as it moves away from the source. At any point along the beam, the width of the area covered is proportional to the distance from the source. Therefore, the area covered by an x-ray beam is increasing in proportion to the square of the distance from the source.

At any given distance the concentration is inversely proportional to the area covered by the beam, and the area covered by the beam is proportional to the square of the distance from the source. We can conclude that the concentration of radiation is inversely related to the square of the distance from the source. This is commonly known as the inverse square law.

The important thing to realize is that it is the concentration of the radiation and not the total radiation that is reduced by distance from the source. For example, if the size of an x-ray beam (field of view) is such that it does not extend beyond a patient's body, increasing the distance between the x-ray tube and patient will decrease the concentration but not the total amount of radiation entering the body.

We now introduce some quantities and the associated units that can be used to express both the concentration and the total amount of radiation.

PHOTONS

Since an x-ray beam and gamma radiation are showers of individual photons, the number of photons could, in principle, be used to express the amount of radiation. In practice, the number of photons is not commonly used to express radiation delivered to a

RADIATION QUANTITIES

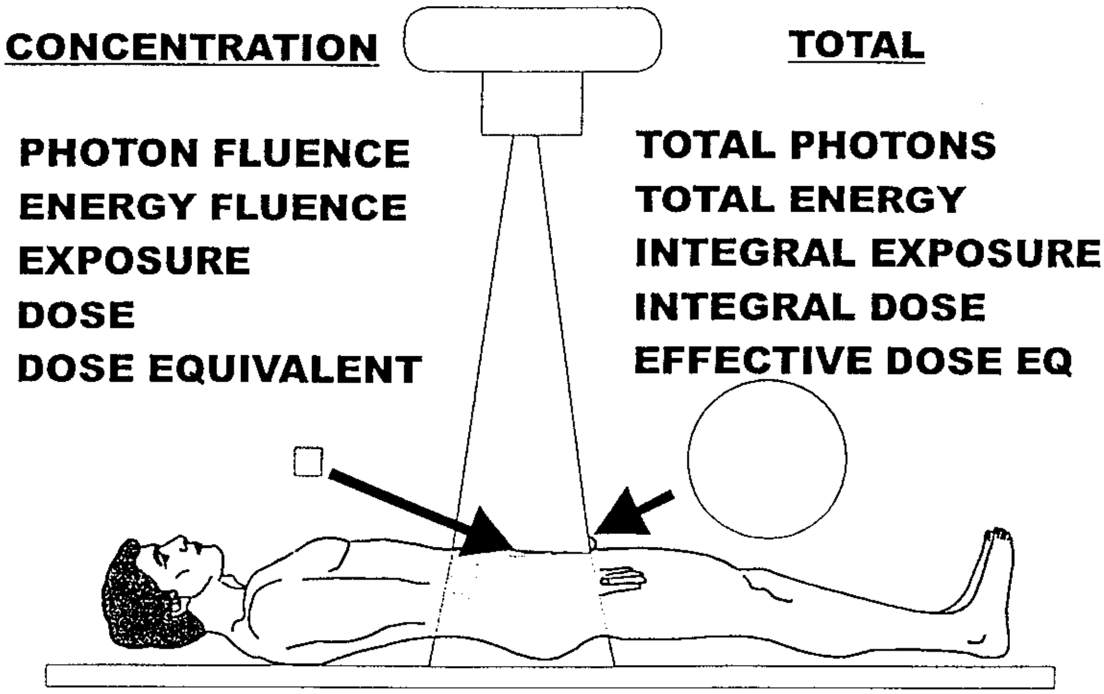

FIGURE 1

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SURFACE EXPOSURE

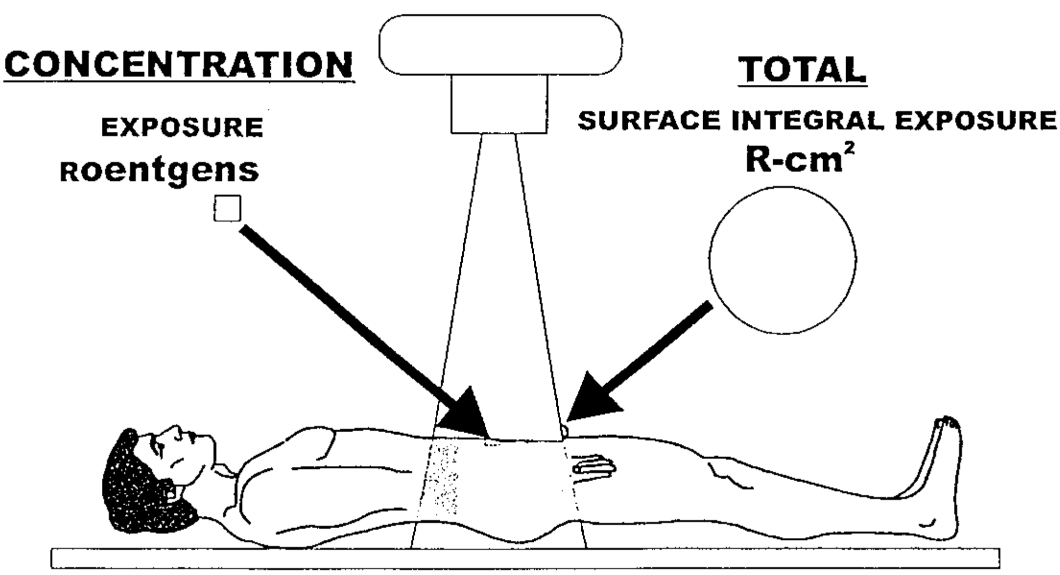

FIGURE 2

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patient. However, the number of photons is a useful quantity for the amount of radiation delivered to an image receptor (radiographic receptor, fluoroscope, gamma camera, etc.). This is because image quantum noise is determined by the quantity of photons used to create an image. Also, it is a useful concept in understanding the nature of radiation and distinguishing between concentration and total radiation. Let us go back to the situation shown in figure 1 and examine the different ways the concentration of radiation delivered to a small area on a patient's body could be expressed.

Photon Concentration (Fluence)

If we draw a 1-cm^2 area on the surface of the patient and then count the number of photons passing through the area during a radiographic procedure, we will have an indication of the concentration of radiation delivered to the patient. During a single abdominal radiographic exposure we would find that close to 10^{10} photons would have passed through our square centimeter. The more formal term for photon concentration is photon fluence.

The photon fluence delivered to an image receptor is the specific quantity that determines the level of quantum noise in the image.

Total Photons

If we count the number of photons entering the total exposed area, we will have an indication of the total amount of radiation delivered to the patient. This quantity depends on the size of the exposed area and the radiation concentration. If the radiation is uniformly distributed over the exposed area, the total number of photons entering the patient can be found by multiplying the concentration (fluence) by the exposed area. Changing the size of the exposed area does not affect the concentration entering at the center of the beam. However, reducing the exposed area does reduce the total number of photons and radiation entering the patient.

EXPOSURE

Exposure is the quantity most commonly used to express the amount of radiation delivered to a point, such as the surface of a patient's body as shown in Figure 2.

Units

The conventional unit for exposure is the roentgen (R), and the SI unit is the coulomb per kilogram of air (C/kg):

$$1R = 2.58 \times 10^{-4}\ C/kg$$

$$1C/kg = 3876\ R$$

The reason exposure is such a widely used radiation quantity is that it can be readily measured. All forms of radiation measurement are based on an effect produced when the radiation interacts with a material. The specific effect used to measure exposure is the ionization in air produced by the radiation.

Exposure is generally measured by placing a small volume of air at the point of measurement and then measuring the amount of ionization produced within the air. The enclosure for the air volume is known as an ionization chamber. The use of ionization chambers and other radiation measuring devices is discussed in other chapters.

Exposure is a quantity of radiation concentration. For a specific photon energy, exposure is proportional to photon concentration or fluence exposure and photon. The relationship changes with photon energy because both the number of photons that will interact and the number of ionizations produced by each interacting photon is dependent on photon energy. If we assume a photon energy of 60keV, a 1-R exposure is equivalent to a concentration of approximately 3×10^{10} photons per cm^2.

Application

Exposure is an appropriate quantity for expressing the concentration of x-radiation delivered to the surface of a patient's body. It can be used to compare the

SIE and EXPOSURE DURING FLUOROSCOPY

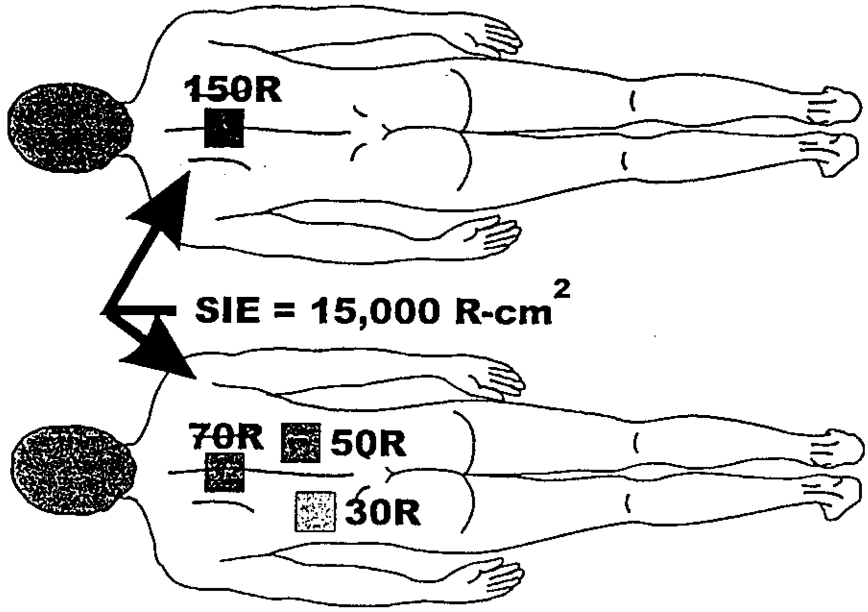

FIGURE 3

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SIE and EXPOSURE DURING RADIOGRAPHY

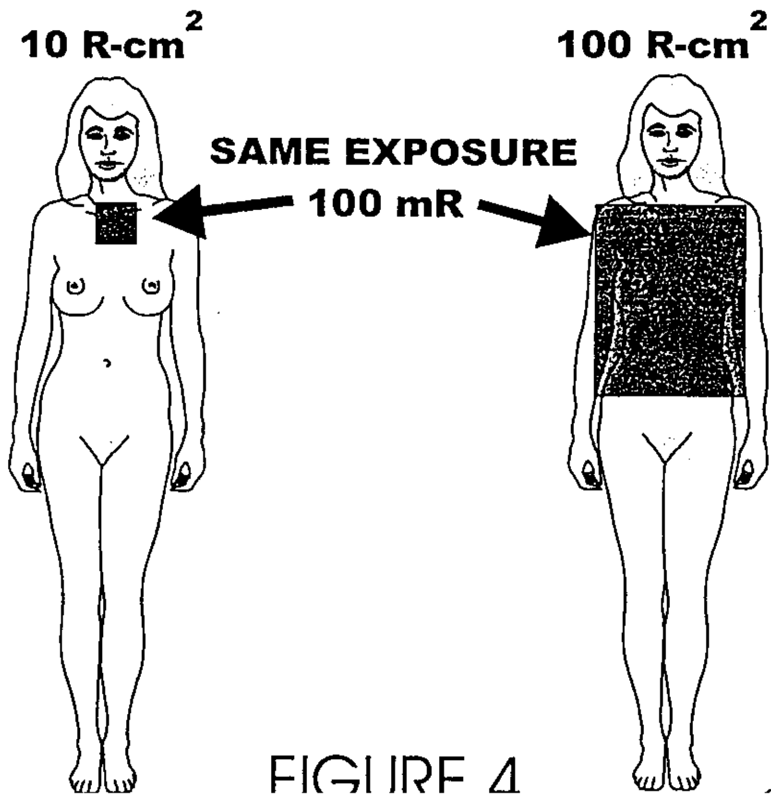

FIGURE 4

amount of radiation delivered by different x-ray procedures. It is also useful in the process of calculating absorbed dose to various points within a patient's body.

Surface Integral Exposure

Since exposure expressed in roentgens or coulombs per kilogram is a concentration, it does not express the total amount of radiation delivered to a body. The total radiation delivered, or surface integral exposure (SIE), is determined by the exposure and the dimensions of the exposed area. It is also referred to as the exposure-area product and is essentially the same as the dose-area product.

The surface integral exposure is expressed in the conventional units of roentgen-cm^2(R-cm^2). If the radiation exposure is uniform over the entire area, the SIE is the product of the exposure in roentgens and the exposure area in square centimeters. If the exposure is not the same at all points in the exposed area, the SIE can be found by adding the exposure values for each square centimeter of exposed surface. Mathematically, this is the process of integrating the exposure over the surface area. The SIE can be measured during x-ray examinations by placing a special type of ionization chamber in the x-ray beam or can be calculated from the x-ray machine output parameters and size of the x-ray beam. The significance of SIE is that it describes total radiation imparted to a patient, whereas exposure indicates only the concentration of radiation at a specific point.

The typical fluoroscopic examination provides an excellent opportunity to compare exposure (concentration) and SIE (total radiation). In Figure 3 two cases are compared. In both instances the beam area was 10cm x 10cm (100cm^2); the total exposure time was 50 minutes at an exposure rate of 3R/min. In both instances the SIE is 15,000 R-cm^2. However, the exposure depends on how the x-ray beam was moved during the examination. In the first example the beam was not moved and the resulting exposure was 150 R. In the second example the beam was moved to different locations so that the exposure was distributed over more surface area and the concentration became less.

Another important example is illustrated in Figure 4. Here we see a radiographic example. Even though the exposure to the surface of the patient is the same the SIE is different because of a difference in the exposed area. Obviously the patient on the right receives much more total radiation.

Application

Surface integral exposure is a very useful quantity for expressing the total radiation imparted to a patient's body.

ENERGY

X-ray and other forms of radiation deliver energy to the body. In principle, the amount of radiation delivered could be expressed in units of energy (joules, ergs, kiloelectron volts, etc.). The energy content of an x-ray beam is rather difficult to measure and for that reason is not widely used in the clinical setting. However, considering the energy delivered by an x-ray beam is helpful in understanding other radiation quantities.

Energy Fluence

Energy fluence (concentration) is the amount of radiation energy delivered to a unit area. The units for expressing radiation energy concentration are either the milijoule (mJ) per square centimeter or erg per square centimeter. For a specific photon energy, fluence is proportional to exposure. The relationship changes with photon energy because of the change in photon interaction rates. However, if we assume a photon energy of 60 keV, the energy fluence for a 1-R exposure is approximately 0.3 mJ/cm^2.

The energy delivered by an x-ray beam can be put into perspective by comparing it to the energy delivered by sunlight . For the x-ray exposure we will use the fluoroscopic factors of 5 minutes at the rate of 3 R/min. This 15 R exposure delivers x-ray energy to the patient with a concentration (fluence) of 4.5 mJ/cm^2 if we assume an effective photon energy of 60 keV.

The energy delivered by the sun depends on many factors including geographic location, season, time of day, and atmospheric conditions; a typical mid-day summer exposure on a clear day in Atlanta produces approximately 100 $mJ/sec/cm^2$. In five minutes a person would be exposed to an energy fluence of 30,000 mJ/cm^2. We see from this example that the energy content of an x-ray beam is relatively small in comparison to sunlight. However, x-ray and gamma radiation will generally produce a greater biological effect per unit of energy than sunlight because of two significant differences: x-and gamma radiation penetrate and deposit energy within the internal tissue, and the high energy content of the individual photons produces a greater concentration of energy at the points where they are absorbed within individual atoms.

Application

The energy fluence is a useful quantity for comparing an x-ray beam to other sources of energy (sunlight, heat, RF, ultrasound, etc.) delivered to a human body.

Total Energy

The total energy imparted to a body by an x-ray beam is determined by the energy fluence (concentration) and the size of the exposed area. If the radiation is uniformly distributed over the area, the total energy delivered is the product of the fluence and the surface area.

Application

The total radiation energy delivered to a body is a useful quantity because it is reasonably easy to determine and is a general indicator of total biological impact.

ABSORBED DOSE

The human body absorbs most of the radiation energy delivered to it. The portion of an x-ray beam that is absorbed depends on the penetrating ability of the radiation and the size and density of the body section exposed. In most clinical situations more than 90% is absorbed. In nuclear imaging procedures, a large percentage of the energy emitted by radionuclides is absorbed in the body. Two aspects of the absorbed radiation energy must be considered: the amount (concentration) absorbed at various locations throughout the body and the total amount absorbed in all of the body.

ABSORBED DOSE

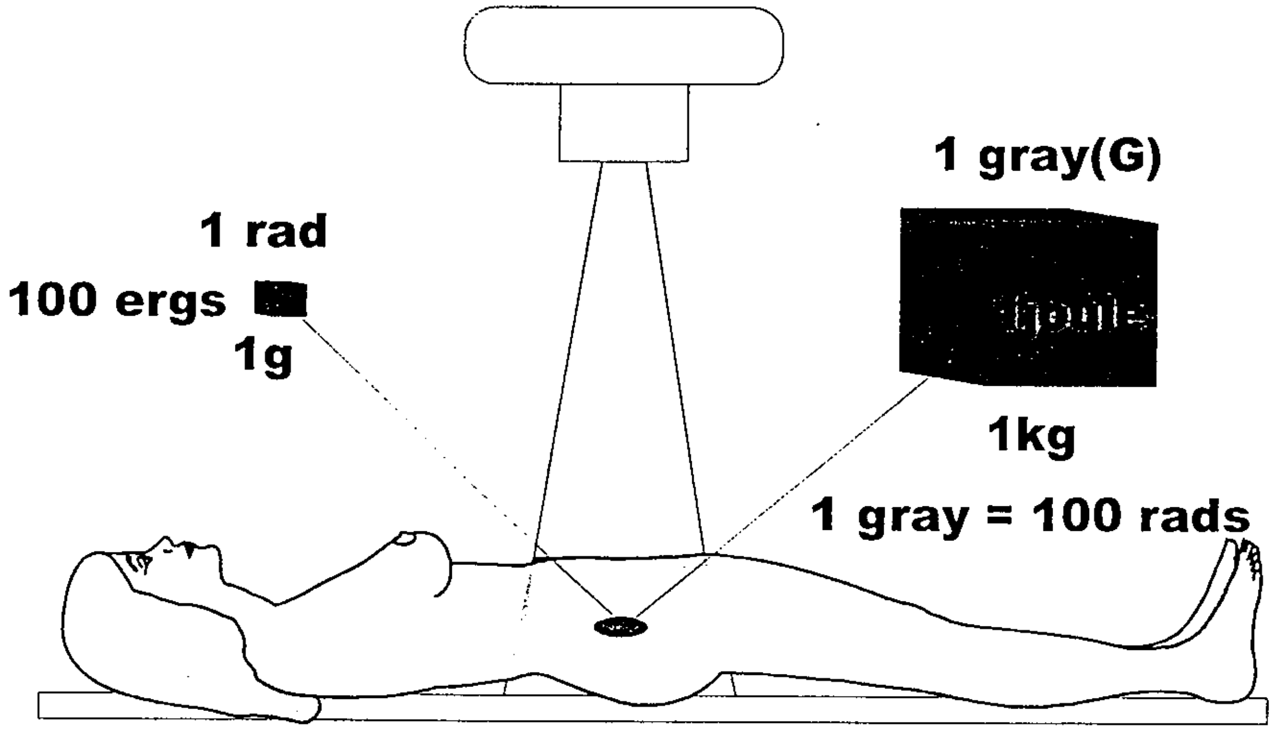

FIGURE 5

COMPUTED TOMOGRAPHY
INTEGRAL DOSE

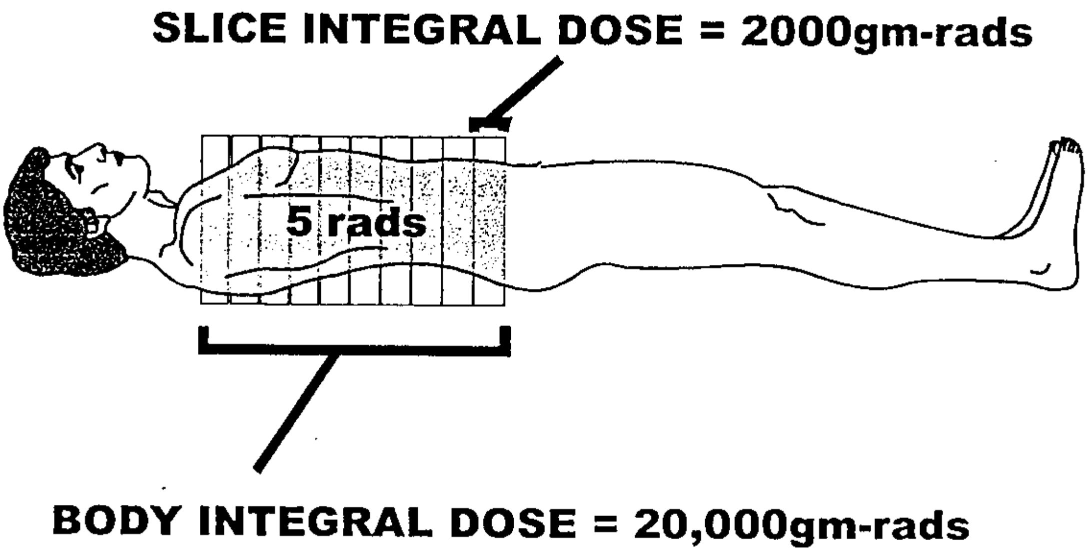

FIGURE 4

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Absorbed dose is the quantity that expresses the concentration of radiation energy absorbed at a specific point within the body tissue as shown in Figure 5. Since an x-ray beam is attenuated by absorption as it passes through the body, all tissues within the beam will obviously not absorb the same dose. The absorbed dose will be much greater for the tissue near the entrance surface than for those deeper within the body. Absorbed dose is defined as the quantity of radiation energy absorbed per unit mass of tissue.

Units

The conventional unit for absorbed dose is the rad, which is equivalent to 100 ergs of absorbed energy per g of tissue. The SI unit is the gray (Gy), which is equivalent to the absorption of 1J of radiation energy per kilogram of tissue. The relationship between the two units is:

$$1 \text{ Gy} = 100 \text{ rads}$$

For a specific type of tissue and photon energy spectrum, the absorbed dose is proportional to the exposure delivered to the tissue. The absorbed dose in soft tissue is slightly less than 1 rad/R of exposure throughout this photon energy range. The relationship for bone undergoes a considerable variation with photon energy. For a typical diagnostic x-ray spectrum, a bone exposure of 1 R will produce an absorbed dose of approximately 3 rads.

Application

Absorbed dose to a specific tissue or organ is the quantity that can be most directly related to biological impact.

Integral Dose

Integral dose is the total amount of energy absorbed in the body. It is determined not only by the absorbed dose values but also by the total mass of tissue exposed.

The integral dose is equal to the total energy imparted to the body less the energy that penetrates or is scattered from the body. Since most of the x-ray energy imparted to a patient's body is absorbed the integral dose and imparted energy are closely related.

The conventional unit for integral dose is the gram-rad, which is equivalent to 100 ergs of absorbed energy. The concept behind the use of this unit is that if we add the absorbed doses (rads) for each gram of tissue in the body, we will have an indication of total absorbed energy. Since integral dose is a quantity of energy, the SI unit used is the joule.

The relationship between the two units is:

$$1 \text{ J} = 1{,}000 \text{ gram-rads}$$

Integral dose (total absorbed radiation energy) is probably the radiation quantity that most closely correlates with potential radiation damage during a diagnostic procedure. This is because it reflects not only the concentration of radiation absorbed in the tissue but also the amount of tissue affected by the radiation.

There is no practical method for measuring integral dose in the human body. However, since most of the radiation energy delivered to a body is absorbed, the integral dose can be estimated to within a few percent from the total energy delivered to the body.

Computed tomography can be used to demonstrate integral dose; as illustrated in Figure 6. We begin with a 1-slice examination and assume that the average dose to the tissue in the slice is 5 rad. If there are 400 g of tissue in the slice, the integral dose will be 2,000 gram-rad. If we now perform an examination of 10 slices, but all other factors remain the same, the dose (energy concentration) in each slice will remain the same. However, the integral dose (total energy) increases in proportion to the number of slices and is now 20,000 gram-rad. In this example we made the simplifying assumption that no radiation is scattered from one slice to another. In reality, some radiation is exchanged between contiguous slices but that does not affect the concept presented.

Application

Integral dose is a useful quantity for expressing the total radiation imparted to the patient's body.

BIOLOGICAL IMPACT

It is sometimes desirable to express the actual or relative biological impact of the radiation. It is necessary to develop a distinction between the biological impact and the absorbed energy (dose) because:

1. all types of radiation do not have the same potential for producing a biological effect
2. all tissues do not have the same sensitivity to radiation

For example, 1 rad of one type of radiation might produce significantly more radiation damage than 1 rad of another type. Also 1 rad of radiation delivered to one type of tissue (gonads) will have a greater biological impact than 1 rad delivered to another tissue (muscle).

Therefore, to develop a relationship between the biological impact of radiation and the physical dose, characteristics of both the radiation and the tissue must be considered.

Dose Equivalent

Dose equivalent (H) is the quantity commonly used to express the undesirable impact of radiation on persons receiving occupational or environmental exposures and patients undergoing diagnostic examinations.

Personnel exposure in a radiation facility is often determined and recorded as a dose equivalent.

Dose equivalent is proportional to the absorbed dose (D), the quality factor (Q), and other modifying factors (N) or the specific type of radiation. Most radiations encountered in diagnostic procedures (x-ray, gamma, and beta) have quality and modifying factor values of one. Therefore, the dose equivalent is numerically equal to the absorbed dose. Some radiation types consisting of large (relative to electrons) particles have quality factors greater than one. For example, alpha particles have a quality factor value of approximately 20.

The conventional unit for dose equivalent is the rem and the SI unit is the sievert (Sv). When the quality factor is 1, the different relationships between dose equivalent (H) and absorbed dose (D) are:

$$H(rem) = D(rad)$$
$$H(Sv) = D(Gy)$$

Dose equivalent values can be converted from one system of units to the other by:

$$1 \text{ Sv} = 100 \text{ rems}$$

Among the three quantities: exposure, absorbed dose, and dose equivalent, each expresses a different aspect of the radiation, However, they all express radiation concentration. For the types of radiation used in diagnostic procedures, the factors that relate the three quantities have values of approximately one in soft tissue. Therefore, an exposure of 1R produces an absorbed dose of approximately 1 rad, which, in turn, produces a dose equivalent of 1 rem.

Application

Dose equivalent is a useful quantity for comparing the biological impact of different types of radiation.

TOTAL BODY DOSE

The dose absorbed in the total body is a useful concept for certain applications but is generally a difficult quantity to determine. It is sometimes used to express radiation safety limits or action levels for personnel working in radiation environments and general population exposure from background radiation. It has limited applications for patients undergoing diagnostic procedures.

A major factor in the use of whole body dose is the distribution of the radiation throughout the body. Radiation exposure from the general environment (background radiation) exposes the whole body with a relatively evenly distributed dose throughout the body. Some occupational exposure conditions might deliver radiation to the whole body. However, when personal shielding devices such as lead aprons are used the radiation to the body is not evenly distributed.

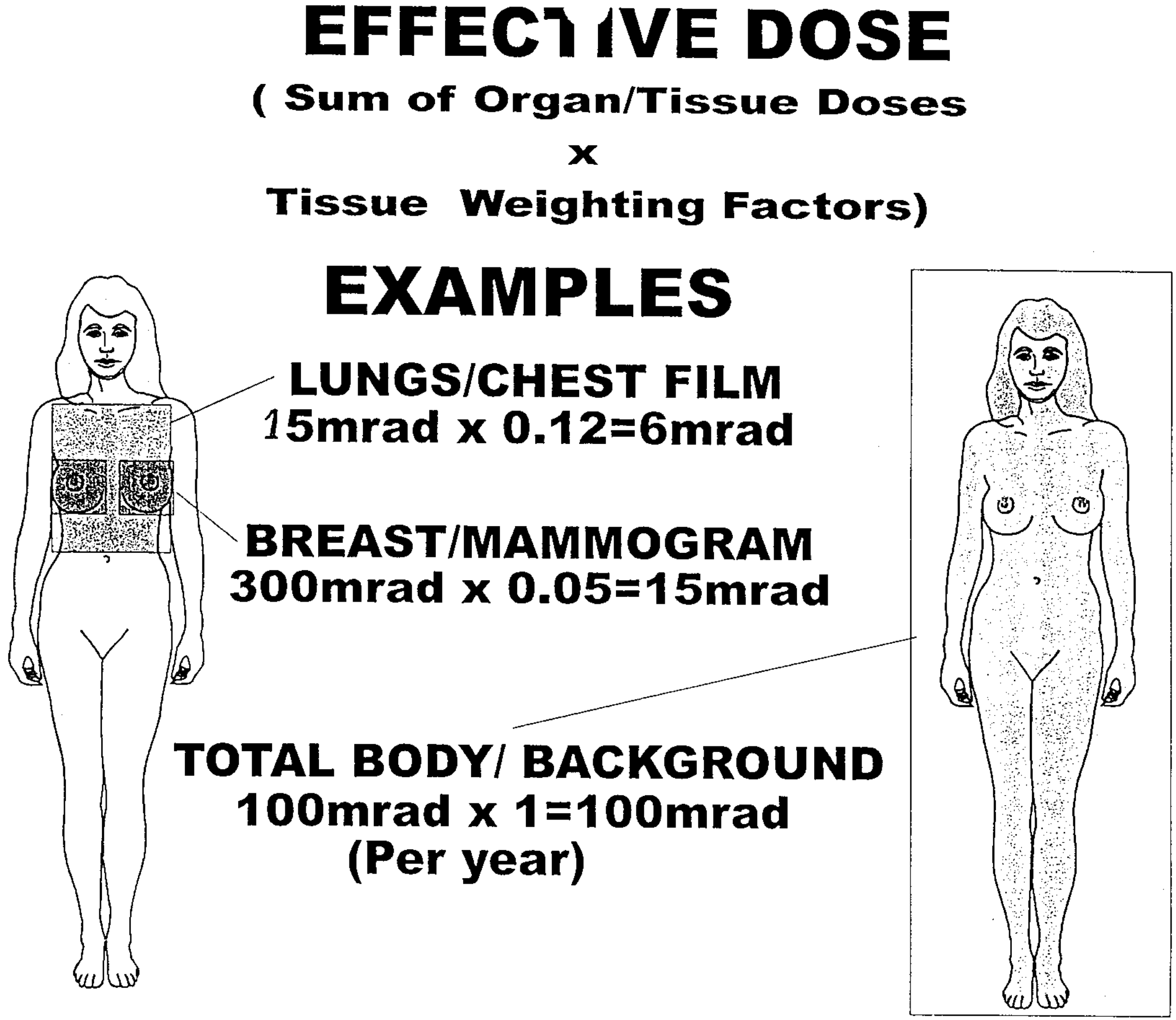

FIGURE 7

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Effective Dose

Not all tissues in the body have the same sensitivity to radiation with respect to the production of undesirable effects. Therefore, in order to assess the total biological impact of radiation the distribution of the radiation absorbed by the tissue (dose) and the relative sensitivities of the tissues must be taken into consideration.

Effective dose is the quantity that takes into consideration the distribution of the radiation throughout the body and the different sensitivities of the tissues exposed.

The effective dose for the total body is the sum of the doses in various exposed organs or tissues multiplied by the weighting factor for the specific organ or tissue. The weighting factors established by NCRP 116 for an average adult body are:

Tissue	Weighting factor
Gonads	0.20
Breast	0.05
Red Bone Marrow	0.12
Lung	0.12
Thyroid	0.05
Bone Surface	0.01
Bladder	0.05
Liver	0.05
Esophagus	0.05
Colon	0.12
Stomach	0.12
Skin	0.1
Remainder	0.05
Total	**1.00**

Application

Effective dose is a useful quantity for expressing the total biological impact by radiation delivered to a body when it is not uniformly distributed.