The AAPM/RSNA Physics Tutorial for Residents

Typical Patient Radiation Doses in Diagnostic Radiology[1]

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LEARNING OBJECTIVES

After reading this article and taking the test, the reader will be able to:

- Identify the main factors that affect patient dose in diagnostic radiologic procedures.
- Recognize the expected and acceptable patient dose levels for the various imaging modalities.
- Identify the expected responses to irradiation in utero.

Factors affecting patient dose in all x-ray imaging modalities include beam energy, filtration, collimation, patient size, and image processing. In conventional radiography, the most important determinant of acceptable patient dose is use of the highest peak kilovoltage that results in diagnostic images. Digital radiography allows a much wider range of exposures than conventional radiography for producing diagnostic images. However, operators must be aware of the subtle differences in techniques used with digital systems to avoid unnecessary increases in patient dose. Low-dose mammography requires lower ranges of peak kilovoltage; different target materials, filters, and screen-film combinations; special attention to breast thickness, composition, and compression during the study; and different standards for grids, magnification, and optical density. Although peak kilovoltage and tube current are important for controlling patient dose in fluoroscopy, collimation, source-to-skin and patient-to–image intensifier distances, and control of beam-on time have perhaps greater importance. Computed tomography (CT) involves greater patient dose than conventional radiography, and, although the primary radiation dose is delivered to smaller volumes, dose calculations must account for dose received by adjacent tissue sections. Many variables are involved in fetal exposure and fetal dose effects, but a solid understanding of them can help in developing responsible patient management practices.

■ INTRODUCTION

Millions of radiologic procedures are performed on patients across the nation each year. A wide range of radiation absorbed doses is delivered to patients by the various diagnostic imaging modalities that use ionizing radiation. Even though these procedures are assumed to produce a net benefit, the potential for radiation-induced injuries to the patient exists. Understanding the typical absorbed doses and the factors that affect them

Abbreviations: AGD = average glandular dose, CTDI = computed tomography dose index, ESD = entrance skin dose, FDA = Food and Drug Administration, MSAD = multiple scan average dose, NCRP = National Council on Radiation Protection and Measurements

Index term: Radiations, exposure to patients and personnel

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therefore becomes very important. The potential exposure of pregnant patients brings an added responsibility of understanding dose effects versus time of irradiation and what courses of action might be required depending on the dose received. As physicians gain more knowledge about the typical dose levels imparted by radiologic procedures and the factors that affect patient dose, the potential for reducing the risk of radiation-induced injuries should rise.

In this article, an explanation of the terms used in identifying absorbed dose lays the groundwork for a discussion of patient dose. Each of the common imaging modalities—conventional and digital radiography, mammography, fluoroscopy, and computed tomography (CT)—is explored in the context of the factors that affect patient dose, as well as what levels of absorbed dose should be expected. The many variables involved in in utero exposure and fetal dose effects are also discussed.

■ ABSORBED DOSE

X rays ionize atoms and molecules in human tissues through the deposition of energy. This ionization is the first step in a series of events that may lead to a biologic effect. *Absorbed dose* is a measure of energy deposited per unit mass and provides a means to gauge the potential for biologic effects. Absorbed dose is measured in units of gray (Gy) or milligray (mGy). One gray is equivalent to an energy deposition of 1 joule per kilogram (J/kg) of tissue. The outdated unit of absorbed dose is the rad, which equals 0.01 Gy. *Absorbed dose rate* is the amount of energy deposited in a given period of time and is typically measured in units of milligrays per minutes or hours.

Entrance skin dose (ESD) is a measure of the radiation dose absorbed by the skin where the x-ray beam enters the patient. ESD can be measured directly with thermoluminescent dosimeters or computed from measurements made with an ionization chamber. *Kerma* (kinetic energy released in matter) is defined as the amount of energy transferred from the incident x rays to charged particles per unit mass in the medium of interest. Kerma includes any energy subsequently given up as photons (ie, bremsstrahlung), but excludes any further energy transfer to other charged particles. *Exposure*, a somewhat outdated concept, represents the amount of energy initially transferred from the incident x rays to charged particles per unit mass of air. Exposure excludes any further energy loss by the charged particles that is subsequently given up as photons or to other charged particles (1).

The unit of *air kerma* is the same as the unit for absorbed dose (ie, gray or milligray), whereas the unit of exposure is the roentgen (R). *Tissue dose* is the product of kerma or exposure and a conversion factor known as the f-factor. For the range of energies encountered in diagnostic radiology, the f-factor is approximately 1.06 for air kerma and 0.93 for exposure (2). The kerma value retains its units, whereas exposure is converted into rads. To determine a true absorbed dose from the factors just described also requires inclusion of the *backscatter factor*, which is the factor by which the radiation dose is increased by radiation scattered back from the body (3). Use of the backscatter factor in calculations of ESD accounts for the radiation scattered back to the surface of the patient. Backscatter factors depend partially on the energy and field size of the x-ray beam, but they are typically in the range of 1.3–1.4 (2).

Organ dose refers to the radiation absorbed dose delivered to the organs of a patient during a radiologic examination. Specific organs of interest include, but are not limited to, active bone marrow, thyroid, breasts, gonads, and the lens of the eye. Dose to the embryo or fetus may also occur during diagnostic procedures, and knowledge of conceptus dose is critical to responsible patient management.

■ DIAGNOSTIC RADIOGRAPHY

Diagnostic radiography typically refers to any of the means used to create a planar image through the use of x rays. In specific terms, ESD in diagnostic radiography is proportional to the tube current, the length of exposure, and the square of peak kilovoltage. The roles of these and other factors are discussed within the context of specific modalities. A fourth factor that applies to all of the modalities is called the inverse square law. The *inverse square law* states that when all other factors are held constant, the dose at any location is inversely proportional to the square of the distance to the source. In other words, if the distance between the source and the location of interest is doubled, the dose will be reduced by a factor of four.

Dose to specific organs may vary substantially with the projection used, such as anteroposterior, posteroanterior, and lateral. Organ absorbed dose may be estimated by using a conversion factor along with a measured value of entrance exposure. Conversion factors for various combinations of projections and organs are available in tabular form in Rosenstein's handbook (4).

• Factors Affecting Dose in Conventional Radiography

Beam Energy and Filtration.—Beam energy primarily depends on the peak kilovoltage (kVp) selected and the amount of filtration in the beam. If all other variables are held constant, ESD will change as the square of the change in peak kilovoltage. The selection of higher peak kilovoltages increases the average energy of the x rays and therefore beam penetrability. As the beam becomes more penetrating, more x rays will reach the image receptor during the same period of time. In practice, this may allow for use of a lower tube current or a shorter exposure, thus reducing the dose to the patient.

Diagnostic radiography units are required by regulations to contain a total filtration (which includes the tube wall and any other added filtration) of at least 2.5 mm of aluminum equivalent if they are operated at tube potentials above 70 kVp (5,6). This filtration preferentially absorbs the low-energy x rays in the beam. Absorption primarily takes place with x rays of less than 40 keV of energy, and virtually all x rays below 10 keV are absorbed (7). Without filtration, this low-energy radiation would most likely be completely absorbed in the patient. Because image formation requires transmission of x rays through the patient to expose the image receptor, low-energy x rays contribute to patient dose without contributing to the image.

In effect, the added filtration serves to further increase the average energy of the beam. In the range of energies of x rays used in diagnostic radiology, however, increasing the average energy of the x-ray beam will decrease the contrast of the resulting image. Therefore, to reduce patient dose, the goal should be to use the highest peak kilovoltage possible that results in acceptable image contrast.

Collimation.—During any radiographic procedure, the area of the patient exposed to the x-ray beam should be limited to the area of clinical interest. Tissues inside the primary beam receive doses that are orders of magnitude higher than doses received by tissues outside the primary beam. By using collimation to expose only the area of clinical interest, one can substantially reduce unnecessary patient exposure.

Use of collimation has another important effect: By reducing the area of the x-ray beam, the amount of scattered radiation that reaches the image receptor is also decreased. The resulting images have better contrast.

Grids.—Grids were introduced into radiography to reduce the amount of scattered radiation that reaches the image receptor. Modern grids do an exceptional job, resulting in images with much improved contrast. Unfortunately, this improved contrast comes at the cost of increased patient dose. A grid also absorbs a portion of the primary x rays—that is, those that would have contributed to exposing the image receptor—and the only way to achieve the degree of exposure required to produce the image is to increase the amount of radiation incident on the grid and therefore the patient. A grid removes a much larger fraction of scattered x rays than unscattered, or primary, x rays, and the doses are typically increased from two to five times those encountered without the use of a grid. This proportion is commonly referred to as the *Bucky factor* and represents the ratio of the dose with a grid to the dose without a grid (8). The higher-quality images achieved with a grid, however, may result in fewer retakes and more accurate diagnoses.

Patient Size.—As the thickness of the area being imaged increases, the amount of radiation incident on the patient increases because adequate x-ray penetration is needed to create an acceptable image. Although the examiner has little or no control over patient size, it is beneficial to know the types of exposures expected for examinations of different anatomic areas and patients of different sizes. Technique charts that display suggested radiographic technique factors for various examinations and patient thicknesses placed near the operator's console may be helpful.

Screen-Film Combinations and Film-processing Conditions.—Most current radiographic intensifying screens are composed of rare earth elements. Previously, calcium tungstate was the most commonly used material. The speed, or overall efficiency, of calcium tungstate screens is often referred to as Par speed and is assigned an arbitrary speed of 100. The speed numbers are relative; that is, a 400-speed system requires only half the dose used with a 200-speed system, which requires half the dose used with a 100-, or Par, speed system. Use of a faster screen-film combination can substantially reduce dose, and modern rare earth screens up to 600 speed may typically be

used (9). Faster systems result in some loss of detail, but if the examination in question permits less detail, the faster system should be used.

The film processor should be functioning according to the film manufacturers' recommendations. If temperature, transport rate, or replenishment rates differ substantially from recommended values, the effects on image quality can be significant. Poor image quality can lead to modification of radiographic techniques, which in turn directly affect patient dose.

• Factors Affecting Dose in Digital Radiography

For this discussion, digital radiography is divided into the categories of computed radiography and direct radiography. Computed radiography refers to imaging systems that use photostimulable phosphor (PSP) plates, which are placed in a cassette similar to screen-film combinations, to capture the latent image. The user inserts the plate into a processor, where it is read, or processed, by a laser that scans the entire surface area and produces an image that may be displayed on a monitor for viewing. Direct radiography refers to imaging systems in which the x-ray beam impinges directly on an image receptor that translates the information into an image, which is then displayed on a monitor without an intermediate step by the operator.

Computed Radiography.—Patient dose in computed radiography is affected by all the factors listed for conventional radiography, as well as other considerations. Typical computed radiography systems operate at a speed equivalent to an approximately 200-speed screen-film combination (10). However, these systems permit a much wider range of exposures for producing acceptable diagnostic images than do conventional screen-film systems. This wide range, or latitude, may allow the operator to use lower peak kilovoltages and tube currents, since the images can be manipulated to adjust contrast and brightness after the image data have been obtained (ie, postprocessing). However, if very low kilovoltages and tube currents are used, substantial levels of noise can be introduced into the image. Overexposures in the traditional film-processing sense are not really possible. Excessively high kilovoltages and tube currents should not be routinely used just to avoid retakes due to possible noise.

Direct Radiography.—As with computed radiography, direct radiography possesses a wide dynamic range and postprocessing capability. When used properly, these capabilities may allow reduction in patient dose, but use of unnecessarily high kilovoltages and tube currents can also increase patient dose. Ease of image processing with direct radiography might lead to other improper use, for example, when spot images are obtained. In traditional screen-film radiography, for each spot image or group of images acquired, the operator must remove the exposed cassette and process the film. This method is relatively labor intensive and involves a period of waiting before the images may be viewed. To produce spot images in direct radiography, the operator simply pushes a button and the image can be viewed immediately. This extreme convenience could lead unwary operators to acquire more images than are actually needed (thus increasing patient dose) unless they are cautioned to avoid this extremely poor clinical practice.

• Patient Doses in Diagnostic Radiography

Whenever patient doses are discussed for a given type of examination, all relevant variables should be identified, including projection type and thickness of the body area being imaged. Table 1 presents guidance levels for ESDs for a typical adult patient for various diagnostic radiographic examinations performed with a 400-speed screen-film combination. A *guidance level* is a value that is typically derived from a population dose survey and represents the third quartile in the range of doses observed. Because the guidance level dose corresponds to the 75th percentile, 75% of individuals receive a dose less than this value. This also implies that dose reduction should be possible for the 25% of individuals whose doses exceed the guidance value (11).

■ MAMMOGRAPHY

Although the factors described for diagnostic radiography also apply to mammography, they have quite different parameters because of the tissue being imaged. In mammography, the term *average glandular dose* (AGD) is used to describe the dose to the breast tissue considered to be at greatest risk, that is, the glandular tissue (14). This descriptor, which represents organ dose for the breast, replaces other traditional measured values such as skin dose and midplane breast dose because it is widely believed to be more representative of the risk to the patient.

Table 1
Diagnostic Radiography ESD Guidance Levels

Examination	Projection	Patient Thickness (cm)	Entrance Dose	
			mrad	mGy
Chest (non-grid)	PA	23	14	0.14
Chest (grid)	PA	23	20	0.20
Chest (grid)	LAT	30	75	0.75
Abdomen (KUB)	AP	23	500	5.00
Lumbar spine	AP	23	500	5.00
Lumbar spine	LAT	30	1,500	15.00
Thoracic spine	AP	23	350	3.50
Thoracic spine	LAT	30	1,000	10.00
Cervical spine	AP	13	120	1.20
Full spine	AP	23	290	2.90
Skull	PA	20	250	2.50
Skull	LAT	15	150	1.50
Pelvis	PA	23	500	5.00
Hip joint	AP	21	500	5.00
Foot	...	8	35	0.45

Note.—AP = anteroposterior; KUB = kidney, ureter, bladder; LAT = lateral; PA = posteroanterior. Adapted from references 11–13.

• Factors Affecting Dose in Mammography

Beam Energy.—Small differences in beam energy used in mammography greatly affect the resulting dose to the patient. The mammographic range of peak kilovoltages is much lower than that used for all other applications of radiography because high contrast is needed to image tissue of similar density. Within the useful range of approximately 24–30 kVp, however, higher peak kilovoltage selections still require less output in milliampere seconds (mAs) and therefore result in lower dose. In recent years, most mammographic procedures have been performed at or near 25 kVp. Newer screen-film combinations can maintain relatively high image contrast in the range of 25–28 kVp; thus, higher peak kilovoltages can be used and dose can be reduced.

Target Material.—Different target materials yield x rays of different energies; thus, patient dose is also affected when different target materials are used. The traditional target material for screen-film mammography is molybdenum, which emits characteristic x rays of approximately 18 and 20 keV. Recently, rhodium has been introduced for imaging thick or dense breasts; rhodium emits characteristic x rays of approximately 23 keV. The shift in x-ray energy of more than 3 keV provides a more energetic, penetrating beam. Tungsten has also been employed as a mammography target material. Although tungsten offers no useful characteristic x rays in the mammography range, it provides a bremsstrahlung spectrum that can be shaped with filters. As with rhodium, tungsten provides a more energetic beam to penetrate thick or dense breasts.

Filter Material.—Filters are used in mammography to shape the x-ray energy spectrum. The filters absorb low-energy x rays that do not contribute to image formation and high-energy x rays that would degrade image contrast. The traditional filter for screen-film mammography is molybdenum, which selectively filters out a high percentage of x rays with energies greater than 20 keV. Rhodium, which has also been used as a filter material, selectively filters out x rays with energies greater than 23 keV. These two different energies represent the binding energy of the K-shell electrons in the two materials. This binding energy is referred to as the K-absorption edge of any given element. Use of a rhodium filter rather than a molybdenum filter results in a more penetrating x-ray beam and can provide a substantial dose reduction when imaging thick, dense breasts.

Grids.—Grids are used in mammography to reduce the amount of scattered radiation that reaches the image receptor. High-quality images are very important in mammography because the tissue of concern has a composition similar to that of surrounding tissue. The Bucky factor for mammography grids is usually in the range of 2–3 (8).

Magnification.—Magnification can be an excellent tool for imaging very small breast lesions, but it also increases the AGD. The amount of magnification usually ranges from 1.5 to 2.0 times. Magnification is achieved by moving the breast farther away from the image receptor and closer to the x-ray tube, which increases the dose to the breast according to the inverse square law. In addition, performing magnification mammography requires removal of the grid. These two factors result in an AGD for a magnification view that is approximately twice that incurred for a nonmagnification view.

Breast Thickness and Tissue Composition.—The thickness of a breast and composition of breast tissue have a substantial impact on patient dose. Large breasts or those composed of dense tissue are more difficult to penetrate, and a higher-energy x-ray beam and longer exposures are required to obtain acceptable images. Thus, patients with such breasts receive a higher AGD, and patients with smaller breasts or breasts composed of more adipose tissue receive a reduced AGD.

Mammographic technique charts that display suggested technique factors for various breast thicknesses and compositions should be available near the operator's console and can be helpful.

Compression.—Compression is another important tool in mammography. In addition to providing the benefits of better imaging geometries, compression results in a lower AGD to the patient. The lower dose is a direct result of an effective reduction in the thickness of breast tissue that the x-ray beam must penetrate. Compression also creates a more uniform object, resulting in a more uniform exposure to the breast and image receptor.

Image Optical Density.—Optical density (OD) refers to the darkness, or density, of the exposed film. If a greater optical density is required, more exposure will be needed to create the image. In past years, the typical density of an image of the mammography accreditation phantom was approximately 1.4. The recent trend of producing darker films, typically with optical densities of 1.6 and above, has resulted in increased AGD to patients.

Screen-Film Combinations and Film-processing Conditions.—Screen-film combinations of various speeds can be used in mammography. Because great detail is needed in mammograms, the relative speeds used are typically slower (usually 100–180) than those used in general radiography. Choosing a slower screen-film combination results in a higher AGD.

Film-processing conditions are important in mammography, since the images must depict small objects and objects with low subject contrast to be acceptable. Manufacturers' recommendations for film-processing conditions should be strictly followed. Deviation can lead to use of improper exposure techniques, thereby increasing the dose to the patient.

Another consideration in mammography is the length of the film-processing cycle, which can be standard or extended. Standard processing usually consists of a 90-second cycle time, with a developer immersion time of approximately 23 seconds. Extended-cycle processing has a longer cycle time of about 3 minutes, with a developer immersion time of approximately 45 seconds (15). In theory, extended-cycle processing should permit a decrease in dose required to produce acceptable images from the single-emulsion films used in mammography. However, not all mammography film is compatible with extended-cycle processing.

• Dose Estimation in Mammography

The AGD may be determined from measurements of skin entrance exposure and beam quality. Beam quality, which represents the penetrability (or energy) of the x-ray beam, is quantified by the half-value layer (HVL). AGD for a given breast thickness is the product of entrance exposure and a conversion factor based on the half-value layer and peak kilovoltage of the exposure in question. To evaluate the AGD delivered by mammography systems, images are obtained of the American College of Radiology accreditation phantom, which simulates a 4.2-cm-thick compressed breast of 50% glandular and 50% adipose tissue (16).

• Patient Doses in Mammography

The range of AGDs incurred with modern mammography equipment is approximately 100–300 mrad (1–3 mGy) for a single craniocaudal view. The regulatory limit established by the Food and Drug Administration (FDA) under the Mammography Quality Standards Act (MQSA) is 300 mrad (3 mGy) (17). Data collected in the annual MQSA inspections show that the average AGD was 160 mrad (1.6 mGy) in 1997 (18).

■ FLUOROSCOPY

Fluoroscopy is used to create real-time images for diagnosis and to guide other medical procedures. Modern fluoroscopic x-ray equipment is subject to strict governmental regulations, but these regulations do not guarantee that radiation is safely used on patients nor that the physician operators and support staff are protected from risk of radiation-induced injury. Information gathered earlier this decade revealed infrequent, but sometimes severe, cases of radiation-induced burns in patients who underwent lengthy, fluoroscopically guided procedures (19). These cases prompted the FDA to issue an advisory warning to health care facilities to ensure that practitioners undergo appropriate training in radiation safety management (20).

● Factors Affecting Dose in Fluoroscopy

Beam Energy and Tube Current.—As mentioned, beam energy (peak kilovoltage), as well as tube current (milliamperes), play an important role in the dose received by the patient. Higher peak kilovoltages, which mean a more energetic x-ray beam, result in a more penetrating beam and allow the tube current to be reduced. Lower peak kilovoltages require a substantially higher tube current to produce acceptable images and result in a higher dose to the patient, if all other factors remain constant. The drawback to using a high-energy beam is loss in image contrast. Maintaining the highest peak kilovoltage that will provide acceptable image contrast leads to lower patient doses.

Collimation.—Fluoroscopy collimators are important in considerations of patient dose. Because extended "beam-on" times may be used in fluoroscopy, areas adjacent to the location of clinical interest can receive substantial doses. This potential overexposure is easily remedied by using the smallest field possible to image only the area of interest. Proper collimation also reduces the contribution of scattered radiation and leads to higher-quality images.

Source-to-Skin Distance.—The dose rate of a fluoroscopic x-ray beam as it exits the x-ray tube is extremely high. Increasing the source-to-skin distance reduces the dose to the patient according to the inverse square law. If the inverse square law is applied to some equipment in common clinical practice, such as mobile C-arm units, we see that dose rates may increase as much as four to nine times those reported under "normal" conditions. Maintaining the maximum possible distance between the x-ray source and the patient is one of the most effective means of reducing patient dose and minimizing potential adverse biologic effects and exposure risks.

Patient-to–Image Intensifier Distance.—The distance between the patient and image intensifier also has a substantial effect on patient dose. By decreasing the distance that the x-ray beam travels after exiting the patient to reach the image receptor (ie, the image intensifier), the dose rate of the x-ray beam can be reduced. Reduction in dose rate results in a lower cumulative dose to the patient. However, minimizing this distance also means that a larger fraction of scattered radiation will contribute to the image, possibly degrading image quality. When an x ray changes direction because of a scatter interaction, it will not diverge as far from its original path if it has only a short distance to travel. Conversely, the farther away the image receptor is from the point of scatter, the more likely it is that the x ray will diverge and not reach the image receptor. It is widely accepted, however, that minimizing patient-to–image intensifier distance is the most preferred scenario and will result in the lowest patient dose.

Image Magnification.—The ability to create a magnified image can be very useful and in some circumstances might be considered necessary. In almost all cases, image magnification results in higher patient dose. Magnification may be accomplished by two means: geometric and electronic. Geometric magnification is accomplished by moving the image intensifier farther away from the patient, by moving the x-ray source closer to the patient, or both. All these choices reflect an increase in dose because of the reasons just described. In electronic manipulation of the image intensifier, the size of the x-ray beam may be restricted to impinge on only a portion of the image intensifier, and the resulting image will be magnified to fill the entire display area. This technique usually produces an increase in patient dose, although to a smaller degree than geometric magnification.

Grids.—Use of grids in fluoroscopy reduces the amount of scattered radiation that reaches the image intensifier and yields images with improved contrast. Patient doses, however, often increase by a factor of two or more. In some cases, grids may be removed without a substantial loss in image contrast, for example, when the patient is small (because little scatter is generated) and when the patient-to–image

Table 2
Potential Effects in Skin from Single Exposures

Effect	Dose		Onset	Peak
	rad	Gy		
Early transient erythema	200	2	Hours	~24 h
Main erythema	600	6	~10 d	~2 wk
Temporary epilation	300	3	~3 wk	NA
Permanent epilation	700	7	~3 wk	NA
Dry desquamation	1,000	10	~4 wk	~5 wk
Moist desquamation	1,500	15	~4 wk	~5 wk
Late erythema	1,500	15	~6–10 wk	NA
Dermal necrosis (phase 1)	1,800	18	>10 wk	NA
Dermal atrophy				
Phase 1	1,000	10	>14 wk	NA
Phase 2	1,000	10	>1 y	NA
Skin cancer	Unknown	Unknown	>5 y	NA

Note.—NA = not applicable. Adapted from reference 21.

intensifier distance is sufficiently large (because less scatter will reach the image intensifier).

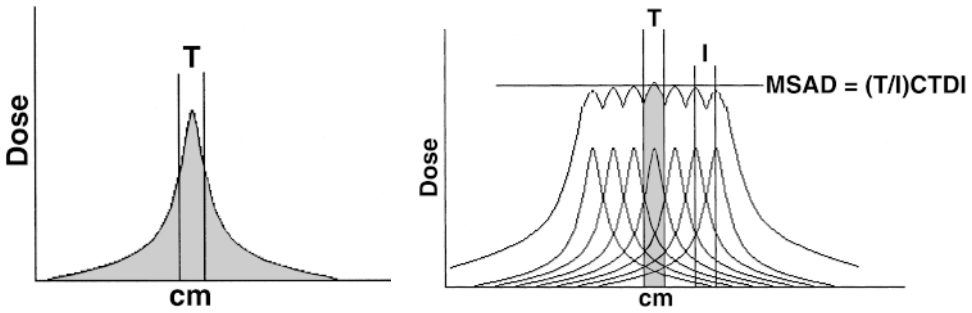
Patient Size.—Thicker patients or dense areas within a patient cause more of the x-ray beam to be absorbed or scattered. To maintain acceptable image brightness, contrast, and detail, the peak kilovoltage and tube current must be increased. Higher peak kilovoltage and higher tube current mean a higher dose to the patient. The backscatter factor also contributes to an increased ESD in thicker patients. Operators should realize that ESD accumulates more rapidly in thick patients, making them more susceptible to radiation burns.

Beam-on Time.—The amount of dose delivered to the patient is directly proportional to the amount of time that the x-ray source is energized, creating a real-time image. Substantial reductions in dose may be gained by being aware of the amount of time spent with the x-ray beam on. Use of systems that continue to display the last image after the beam has been disengaged may help reduce beam-on time. Use of short intermittent exposures rather than extended continuous exposure also reduces patient dose. Ultimately, keeping beam-on time to a minimum is the most effective way to reduce the dose to the patient. It is advisable to maintain written records of beam-on times for patients. These records may prove useful if a patient dose must be estimated or for the analysis of trends in the use of fluoroscopy.

• Patient Doses in Fluoroscopy

The dose rate to the patient is greatest at the skin where the x-ray beam first enters the patient. Although most literature has begun to report dose rate in milligray per minute, existing regulations still specify limits in terms of an exposure rate (roentgen per minute). The entrance exposure limit for standard operation of a fluoroscope is 10 R/min (100 mGy/min) (5). Some fluoroscopes are equipped with a high-output or "boost" mode, and the limit for operation in this mode on state-of-the-art equipment is 20 R/min (200 mGy/min) (5). There is no limit on entrance exposure rate during any type of recorded fluoroscopy, such as cinefluorography or digital acquisitions.

A typical fluoroscopic entrance exposure rate for a man of medium build is approximately 3 R/min (30 mGy/min) (8). Dose rates of up to 50 R/min (500 mGy/min) and higher may be encountered during recorded interventional and cardiac catheterization studies, such as those that involve a series of multiple, still-frame image acquisitions. A very long examination involving 30 minutes of fluoroscopy time could result in doses of <90–1,500 rad (900 mGy to 15 Gy). Although a dose of 90 rad (900 mGy) will most likely produce no apparent effects, 1,500 rad (15 Gy) can cause severe skin burns that develop slowly and may take months to heal. Dermal atrophy may develop after several months and become more severe after a year. At doses in excess of about 1,800 rad (18 Gy), more severe skin burns involving dermal necrosis may slowly evolve over many months (21). Physicians must know how to minimize radiation doses to patients to avoid short-term (<2



1. **2.**

Figures 1, 2. **(1)** Schematic illustrates the profile of radiation dose delivered during a single CT scan. The CTDI equals the shaded area under the curve divided by the section thickness (*T*). **(2)** Schematic illustrates the profile of radiation dose delivered during multiple CT scans. *T* represents section thickness, and *I* represents the interval between sections. The MSAD includes the contributions of neighboring sections to the dose of the section of interest.

years) radiation-induced injuries (eg, burns) and long-term (>2 years) harm (eg, cancer). Table 2 summarizes the deleterious effects associated with given doses.

■ COMPUTED TOMOGRAPHY

CT uses x rays to produce diagnostic images in a manner that differs significantly from that in conventional radiography. One main advantage of CT is its ability to provide superior images of low-contrast subject material. A disadvantage that we must accept, however, is that CT delivers higher doses than we are accustomed to in conventional radiography. The majority of the dose from a single scan is delivered to the thin volume of tissue (usually 1–10-mm thick) exposed to the primary beam. Tissue outside the defined volume also receives dose from scattered radiation, as well as from any part of the primary beam that diverged from the intended thickness.

The two main variables used to describe doses received from CT are *computed tomography dose index* (CTDI) and *multiple scan average dose* (MSAD) (22). Both variables may be reported as a surface dose, at a depth no less than 1 cm, or at some point inside the patient, usually the midline. The CTDI represents the dose from a single scan and results from absorption of the x-ray beam over a range of distance of plus or minus the product of seven and the section thickness, centered on the location of interest. This value is then divided by the intended section thickness to obtain a CTDI (5). The following equation represents the CTDI for a single section:

$$\frac{1}{T}\int_{-7T}^{7T} D(z)\,dz,$$

where T = section thickness, z = the position along the axis normal to the scan plane, and $D(z)$ = the dose at a given position. Figure 1 demonstrates that the dose profile from a single CT scan does indeed spread beyond the intended section thickness. The area beyond the section thickness is referred to as the *penumbra*.

The MSAD represents the dose to a specific section location resulting from the scan at that location as well as from adjacent scan locations. The penumbra from adjacent sections may contribute to the dose received by the section of interest. By definition, the MSAD equals the CTDI for the seven contiguous sections above and below the section of interest if the interval between sections is equal to the section thickness (22). Figure 2 demonstrates the additive effect of penumbra from adjacent sections.

● Factors Affecting Dose in Conventional CT

Beam Energy and Filtration.—Just as in diagnostic radiography, the energy of the x-ray beam in CT has a direct effect on dose. The higher the beam energy for an otherwise constant exposure, the higher the dose. Most CT scanners operate at 120–140 kVp. Use of the most appropriate peak kilovoltage for a given examination is important to keep patient doses reasonable. The type of filter placed in the x-ray beam also plays a major role in the resulting beam energy in CT. These filters may be shaped to present different thicknesses at different points across the x-ray beam. The filter used for a specific CT examination is usually determined by the manufacturer and can reduce the ratio of surface dose to midline dose.

Collimation (Section Thickness).—Collimation of the x-ray beam plays a significant role in determining patient dose in CT. Effective methods of using pre-patient collimators are available

to confine the beam to the section thickness intended at the area of interest. By restricting the beam in this manner, the amount of radiation absorbed by tissue adjacent to that being imaged is kept to a minimum. Another set of collimators may be positioned post-patient, or predetector, to reduce the amount of scattered radiation that reaches the detectors. This technique produces images with better contrast resolution and may indirectly affect patient dose.

Number and Spacing of Adjacent Sections.—Patient dose in CT is affected by the number and spacing of adjacent sections. When more sections are scanned, more total volume of tissue is irradiated. The MSAD may increase because of the penumbra resulting from scattered radiation and possibly beam divergence. As the ratio between section thickness and section interval increases, the MSAD increases because of increasing contributions from neighboring sections.

Image Quality and Noise.—Two of the most significant factors affecting image quality are statistical noise and the loss of image contrast as a result of scattered radiation. Generally speaking, anytime a decrease in noise is desired, the dose used to acquire the image will increase. This is simply a matter of statistics, and the same relationship exists for all radiographic modalities. Although detector collimators help increase image contrast, this improvement usually comes at the cost of increased patient dose. To maintain acceptable levels of noise, the peak kilovoltage and tube current used to acquire the image may need to be increased.

● Factors Affecting Dose in Spiral CT

Spiral CT (ie, continuous scanning of the patient while the couch is moved through the scanner) is becoming commonplace in radiology departments. The advantages of being able to scan a large volume of tissue in a relatively short time are well documented. Although the variables discussed for traditional CT also apply to spiral CT, another important factor, the scan pitch, must also be considered.

Pitch is a ratio and is defined as the distance the patient couch travels during one 360° gantry rotation divided by the section thickness. If the couch travels 10 mm during one rotation and the section thickness is 10 mm, the pitch is one. A schematic illustrates pitch in Figure 3. The larger the pitch, the more tissue can be imaged during the same scan interval.

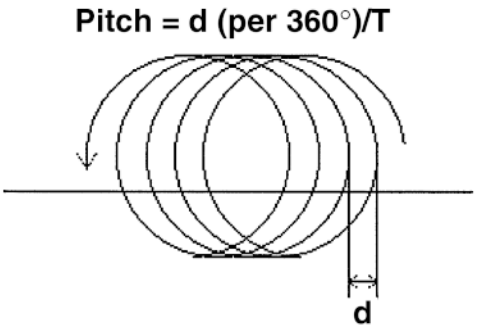


Figure 3. Schematic illustrates spiral CT pitch. *T* represents section thickness, and *d* represents the distance the patient couch travels during one 360° rotation of the gantry.

For a spiral CT examination performed with a pitch of one, the dose to the patient should be comparable with that delivered in a traditional CT study of the same volume of tissue. The patient dose is proportional to 1/pitch, so as the pitch is increased, the dose at any point along the volume of tissue being imaged decreases. Similarly, if the pitch is decreased, the dose will increase. This latter concept might be compared with scan overlap in traditional CT.

● Patient Doses in CT

The two doses most commonly reported for CT are those delivered during head scans and body scans. The FDA requires manufacturers to report CTDI derived from imaging 16- and 32-cm-diameter phantoms for head and body scans, respectively (5). These standards are also used to report MSAD. In general, the MSAD ranges are 4–6 rad (40–60 mGy) for head scans and 1–4 rad (10–40 mGy) for body scans (22). Patient dose is also incurred during acquisition of a scout scan. The CT scanner is used to acquire a scout planar image similar to that obtained in radiography. A scout scan usually results in a surface dose of approximately 100 mrad (1 mGy) (22). Table 3 summarizes some manufacturers' published values of CTDI in the center position of a 16-cm-diameter head phantom, which was imaged with standard head techniques.

■ IN UTERO EXPOSURE IN DIAGNOSTIC RADIOLOGY

Whenever a patient of childbearing age needs a radiologic procedure, certain patient safety measures should be taken. If the patient is or could reasonably be pregnant, the examination should not be performed unless the need is great. If the examination must be performed, the following precautions should be used:

Table 3
Published Values of CTDI from Manufacturers

Manufacturer	Model	Head CTDI	
		mrad	mGy
Elscint (Rockleigh, NJ)	Twin	3,200	32
GE Medical Systems (Milwaukee, Wis)	HiSpeed Advantage	4,000	40
Philips Medical Systems North America (Shelton, Conn)	Tomoscan SR 7000	5,300	53
Picker International (Cleveland, Ohio)	PQ 2000 Mark II	4,200	42
Siemens Medical Systems (Iselin, NJ)	Somatom Plus 4	7,300	73
Toshiba America Medical Systems (Tustin, Calif)	Xpress SX	6,600	66

Source.—Adapted from reference 22.

(*a*) the patient's abdomen should be shielded if the type of examination permits, (*b*) fluoroscopy time should be limited to an absolute minimum, and (*c*) the number of radiographs or scans should be reduced to as few as necessary.

Once an exposure of a pregnant patient has taken place, fetal dose can be estimated to determine what, if any, additional risk may be present for the developing fetus and if any further action should be taken.

• Factors Affecting Fetal Dose in Diagnostic Radiology

Direct (inside Field of View) Exposure.—If a fetus is located within the field of view of a particular examination, such as studies of the abdomen, pelvis, and lumber spine, it is exposed directly to primary beam radiation. This situation typically results in the highest fetal doses. In these instances, a shield is usually of limited value because it cannot cover the area being imaged.

Indirect (outside Field of View) Exposure.—When a fetus is positioned outside the field of view, such as during examinations of the skull and extremities, the bulk of the exposure received is from indirect scattered radiation from the maternal tissues. This situation usually results in lower fetal doses than incurred during a direct exposure. The actual dose varies depending on the distance between the fetus and the primary x-ray field. Unfortunately, a shield has limited value in this case as well because most of the fetal dose results from internal scatter in the mother.

• Fetal Dose Estimation in Diagnostic Radiology

To provide a reasonable estimation of fetal dose, one must know the output intensity (measured in exposure or air kerma) of the x-ray equipment for radiographic exposures and entrance exposure (or air kerma rate) for fluoroscopic exposures, along with the conditions of the examination. The half-value layer is also used to determine beam penetrability. Information about the conditions of the procedure includes the location and number of views taken and the radiographic exposure factors. For fluoroscopic procedures, the beam-on time and the number of digital or cassette spot images taken, with the related exposure factors, are needed. The required information about the patient includes the fetal age at the time of exposure, the patient's size or thickness, and the depth of the fetus. It is also important to know the orientation of the patient in relation to the x-ray tube.

Direct (inside Field of View) Exposure.—Once the facts about the examination are known, calculations are performed by using measured values of exposure or air kerma, along with the specific technique factors used, to obtain a maternal entrance exposure. This entrance exposure is then used to calculate the dose at the depth of the fetus by using either published depth-dose (23–25) or tissue-air ratio tables (26,27). This procedure is applicable to both radiographic and fluoroscopic exposures.

Indirect (outside Field of View) Exposure.—The calculation method used for indirect exposures differs somewhat from that employed for direct exposures. The maternal entrance exposure is determined on the basis of the same information, and then published scatter factors are applied to account for the location of the fetus relative to the location of the examination (28). The distance between the fetus and the area being imaged is a significant factor affecting fetal dose for an indirect exposure.

Early Pregnancy.—Report 54 from the National Council on Radiation Protection and Measurements (NCRP) (29, Table 4) is particularly useful for calculating fetal doses for many common views for an exposure during early pregnancy. These data include fetal dose from both direct and indirect exposures. The adjustments for depth and distance from the x-ray field are already incorporated in the conversion factors. These factors are based on half-value layer and convert directly from maternal entrance exposure to fetal dose. However, use of this method is limited to average-sized women whose exposure took place early in pregnancy.

Computed Tomography.—Two predominant methods are used to estimate fetal dose from a CT examination. The free-in-air technique and the standard-phantom technique both require a measurement of CTDI. For the free-in-air technique, an equivalent CTDI (not the strict definition [5]) is measured in air, and for the standard-phantom technique, the CTDI is measured in the center of an acrylic phantom of 160-mm diameter. These values are then used with published dose conversion factors to estimate the absorbed dose to the fetus (2). With these two methods, fetal dose can be estimated based on direct or indirect exposure, the cumulative effect of many scans is accounted for, and the conversion factors incorporate the distance between the conceptus and each particular scan.

• Fetal Doses in Diagnostic Radiology

Some procedures have relatively low maternal exposures and are located at sufficient distance from the fetus that they result in very little, sometimes immeasurable, fetal exposure. Skull and other head examinations; cervical spine, chest, and extremity examinations; and mammography fall into this category. Table 4 provides estimated doses to the uterus from typical diagnostic procedures. However, any procedure that incorporates fluoroscopy can vary greatly from these values.

Table 4
Estimated Doses to the Uterus from Diagnostic Procedures

Examination	Absorbed Dose	
	mrad	mGy
Upper gastrointestinal series	100	1
Cholecystography	100	1
Lumbar spine radiography	400	4
Pelvic radiography	200	2
Hip and femur radiography	300	3
Retrograde pyelography	600	6
Barium enema study	1,000	10
Abdominal (KUB) radiography	250	2.5
Hysterosalpingography	1,000	10
CT		
Head	~0	~0
Chest	16	0.16
Abdomen	3,000	30

Note.—KUB = kidney, ureter, bladder. Adapted from reference 2.

• Recommendations Following Exposure

In 1977, NCRP Report 54 recommended: "The risk [of abnormality] is considered to be negligible at 5 rad (50 mGy) or less when compared to other risks of pregnancy, and the risk of malformations is substantially increased above control levels only at doses above 15 rad (150 mGy). Therefore exposure of the fetus to radiation arising from diagnostic procedures would very rarely be cause by itself, for terminating a pregnancy" (29). Table 5 presents recommendations for continuing a pregnancy after radiation exposure as a function of gestational age and dose.

• Malformations and Induction of Childhood Malignancy

When a patient undergoes diagnostic x-ray procedures and subsequently finds that she is pregnant, the immediate concern is about abnormalities in the developing fetus. Animal data suggest that doses of 5–10 rad (50–100 mGy) received before embryonic implantation may result in prenatal death. Small head size (microcephaly) has been the primary anomaly observed in children of survivors of the nuclear bombing of Hiroshima and Nagasaki, who sustained in utero radiation exposure. The most sensitive period for this effect is 2–15 weeks after conception. In fetuses who receive in utero radiation exposure during the latter half of this period (ie, at 8–15 weeks), severe mental retardation and intellectual deficits are also of concern at doses as low as 10 rad (100 mGy) (2). However, the doses received during radiologic procedures are typically orders of magnitude lower than those delivered to experimental rats and mice and nuclear bombing survivors. Table 6 presents the effects of prenatal exposure as a function of gestational age.

Radiation-induced childhood malignancy caused by in utero radiation exposure is also a concern. Data suggest that a fetus exposed in

Table 5
Continuing a Pregnancy after Radiation Exposure as a Function of Gestational Age and Dose

Gestational Age	Fetal Absorbed Dose <5 rad (<50 mGy)	5–15 rad (50–150 mGy)	>15 rad (>150 mGy)
<14 d (<2 wk)	Recommended	Recommended	Recommended
14–56 d (2–8 wk)	Recommended	Maybe consider termination (in presence of other severe risks)	Maybe consider termination (in presence of other risks)
57–105 d (8–15 wk)	Recommended	Maybe consider termination (in presence of other risks)	Higher risk conditions exist, but termination is not necessarily recommended
>105 days (15 wk to term)	Recommended	Recommended	Recommended

Source.—Adapted from reference 2.

Table 6
Effects of Radiation Exposure on Prenatal Development

Gestational stage	Days after Conception	Fetal Dose rad	Fetal Dose mGy	Observed Effect
Preimplantation	0–14	5–10	50–100	Animal data suggest possibility of prenatal death
Major organogenesis	8–56	20–25	200–250	Animal and NBS data suggest that this is the most sensitive stage for growth retardation
	14–105			NBS data indicate small head size; those exposed before 8 wk did not display any intellectual deficit even with small head; most sensitive time for induction of childhood cancer
Rapid neuron development and migration	56–105	>10	>100	Small head size, seizures, decline in IQ points: 25 points/100 rad (1 Gy)
After organogenesis and rapid neuron development	105 to term	>10	>100	Associated with increased frequency of childhood cancer
		>50	>500	Severe mental retardation observed at 16–25 wk

Note.—NBS = nuclear bombing survivor from Hiroshima and Nagasaki.

utero to 1 rad (10 mGy) during the 1st trimester would be 3.5 times more likely to develop childhood cancer (30). In the unexposed population, the frequency of childhood cancer is one in 1,500 or 0.07%. Because the natural frequency is so low, 3.5 times that value is still quite low ($3.5 \times 0.07\% = 0.25\%$), which leaves a high probability of 99.75% that the child exposed in utero will not develop childhood cancer (2). However, there is substantial uncertainty and a fair amount of controversy surrounding risk factors such as these. Other publications contain much more information on this subject matter (31,32).

■ CONCLUSIONS

When used under properly controlled conditions, radiation is a safe and indispensable tool for medical diagnoses. Proper radiation safety management should ensure that practitioners are knowledgeable about typical patient doses that are imparted in each type of radiologic examination and about the factors that affect these doses. By understanding the factors that affect patient doses, practitioners can help keep doses as low as possible while still creating diagnostic quality images.

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