

Radiation Physics and Safety

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Radiation technology is increasingly involved in the care of breast patients in the modern era, both in the diagnosis of benign and malignant conditions and in the treatment of cancer. Accordingly, surgeons managing breast patients must have a fundamental understanding of radiation physics, its biological effects, and the rationale and methodology used to protect the patient, the surgeon, and allied health professionals from its potentially detrimental effects.

Electromagnetic Radiation

Radiation is a term that encompasses a broad category of energy-containing emissions that have no mass and travel at the speed of light. The electromagnetic (EM) spectrum is made up of subcategories of these forms of energy, the properties and effects of which are dependant upon the wavelength and frequency of the emitted energy. Unlike sound waves (and ultrasound), electromagnetic waves can propagate in a vacuum. The energy contained in the particles (or photons) that are transferred increases with increasing frequency of the waves and, therefore, with decreasing wavelength. On the low-energy (long wavelength/low frequency) end of the spectrum are AM radio waves. In ascending order of energy, next come shortwave radio, FM radio and television, microwaves, radar, infrared, visible light, ultraviolet, x-ray, and finally gamma rays at the high-energy (short wavelength/high frequency) end of the spectrum.

Radiated heat (infrared spectrum) is a relatively low-energy form of EM identical to visible light, but is just at a different wavelength and frequency. In other words, radiated heat is just a different “color” of light, outside of the visible spectrum of humans. We have specialized sensors in our skin to detect this form of EM radiation. We can see EM radiation in the visible spectrum because rods and cones in the retina are sensitive to EM energy in this range. They convert the EM energy to nerve impulses, interpreted by the brain as light and color. Likewise, x-rays and gamma rays are invisible because they are outside of the range that the rods and cones can detect.

Dangers of EM Radiation

All forms of EM radiation, improperly used, can cause harmful effects in humans. In general, radiation at the low and mid range of the energy scale produces damage by transferring heat and is called “non-ionizing” radiation. High energy EM radiation in the form of x-ray and gamma rays is called “ionizing” radiation because it has enough energy to break chemical bonds and create ions in the tissue, thus disrupting the machinery of the cell. The damage ionizing radiation can do to DNA molecules, if not repaired, can lead to genetic mutations and the development of cancer.

Ionizing radiation (x-ray and gamma rays) can cause dose related, potentially reversible changes called “**non-stochastic**” or “deterministic” effects. There is a threshold below which no damage occurs, and the severity of the damage increases as the total dose increases. For example, the skin erythema one sees after a few doses of therapeutic radiation gets progressively worse as the dose increases, potentially leading to ulceration if the dose gets too high. The same changes can be seen with diagnostic x-rays if, for example, a fluoroscope is misused, resulting in unacceptably high doses of skin radiation.

The other form of damage caused by ionizing radiation is called its “**stochastic**” effect, which simply means a “random” effect. This is an “all or none” phenomenon that has no completely safe threshold, is not dose related, and is not reversible. Theoretically, any dose of radiation can cause a stochastic effect, but the probability of the effect occurring increases with increasing dose. One never knows which photon or photons might strike the DNA molecule just right (or, rather, wrong) to cause a cancer, but the probability of the damage occurring increases with every unit of energy delivered. If one develops a cancer because of radiation, it is identical to any other cancer, and its severity is not related to the dose of the radiation that caused it.

All of us are exposed to “background” radiation on a daily basis from cosmic, terrestrial and internal (e.g., ingested strontium) sources. The most common terrestrial exposure comes from radon, a naturally occurring radioactive gas. Depending upon geographic location and altitude, the background radiation may be several hundred millirems annually. Diagnostic x-rays add substantially to that background in many patients.

Production of X-rays

In an x-ray tube a current of electricity is applied to a filament (the cathode) which then gives off electrons. The electrons are accelerated across a vacuum in the tube at a speed (energy level) that is determined by the peak kilovoltage. The electrons then strike a metal target (anode), usually made of tungsten or molybdenum. Here the electrons suddenly decelerate upon colliding with the metal target and, if enough energy is contained within the electron, it is able to knock out an electron from the inner shell of the metal atom. An electron from a higher energy level (orbit) drops into the lower level to fill the vacancy and an x-ray photon is emitted.

mAs and kVp

There are only three factors that are important in generating an x-ray: amperage (mA), voltage (kVp), and time. One ampere is equal to one coulomb/sec, where one coulomb is equal to a specific number of electrons. Therefore, the amperage is merely the number of electrons that pass a fixed point in one second. The amperage and time are usually thought of together and the product of the two is referred to as milliamp seconds (mAs). The mAs controls the number of electrons produced at the cathode and, therefore, at the anode. Thus it controls the quantity of x-rays produced. The mAs has a direct, linear effect on the x-ray intensity and, therefore, determines how dark or light the film is. For example, the same x-ray image is

produced with 100 mA for 1 second, 200 mA for ½ second, or 300 mA for 1/3 second. The mAs in all three examples equals 100.

The peak kilovoltage (kVp) is the other factor used in obtaining an x-ray. (If anyone cares, a volt is the unit of electrical pressure needed to move one ampere of current through a resistance of one Ohm.) The kVp is the factor that controls the energy of the electrons as they move across the tube during x-ray production and, therefore, the energy of the x-ray beam (or the beam quality). Higher energy electrons produce higher energy (shorter wavelength) x-ray photons. The shorter the wavelength, the easier it is for the x-ray to penetrate tissue. kVp primarily controls x-ray contrast, i.e., the difference in the blacks and whites on the film or image. In a high contrast image there are very few shades of gray between the two extremes. There is a trade-off between penetration and contrast though. The lower the kVp, the better the contrast, but at the expense of penetration. In general, when one lowers the kVp to get better contrast, the mAs must be increased to maintain the same film density.

Modern stereotactic machines have automatic exposure devices, or photo timers, that sense the density of the breast tissue to be penetrated. In the “automatic” mode, the equipment sets the mAs and kVp appropriately. It is essential that one have a skilled technologist to localize the abnormalities in the breast and to make necessary adjustments to improve the quality of images as needed.

In other situations, for example a Faxitron unit in the operating suite for specimen radiographs, a technologist might not be present for the procedure, so it behooves the surgeon to become familiar with the correct settings. The amperage in a Faxitron is set at 0.3 mA, so the only two factors that can be manipulated are kVp and time. If the time is set at 10 seconds, the mAs is 3. For an average sized partial mastectomy specimen, it generally works to set the kVp at 28 and the time at 8 seconds. After the film is acquired (which takes 8 seconds), the image should be scanned with the cursor, avoiding high density areas such as clips and dense cancers. The reading for acquired digital units (ADUs) should be between 6,000 and 8,000. If they are significantly below 6,000, the kVp and time should be increased a bit to get them in the proper range (or decreased if above 8,000). After obtaining the appropriate ADUs, the density and contrast can be manipulated for optimal viewing.

Display of X-ray Images

Whether we are dealing with film-screen mammography, digital mammography, or fluoroscopy, the generation of the x-rays and the transmission through the patient are the same. It is what happens to the x-ray after exiting the patient that differs. The image can be collected on photosensitive film, on a digital imaging plate, or on a fluoroscope.

Film screen mammography

In film screen mammography the x-rays, after passing through the breast, strike a phosphorescent screen in a photographic plate. The phosphor screen emits visible light which then exposes the film. The exposure of the film by light produces a good film with a lower dose than would be required using direct x-ray exposure. The film

is processed chemically, and parts of the film where the x-ray has come through turn black upon development. Areas where the x-rays have been blocked are white.

Digital mammography

In digital mammography the x-ray photons strike a digital detector that converts absorbed energy into an electronic signal. A charge coupled device (CCD) is an integrated circuit containing an array of linked, or coupled, capacitors. The pixels in the CCD collect the electrons as they are created. The number of electrons collected in each pixel depends upon the photon energy, intensity, and the length of time exposed to the light. CCDs with very large area image sensors are used in digital mammography. Images obtained with modern stereotactic equipment are digital and can, therefore, be manipulated for contrast, magnification, black-white reversal, etc., after acquisition without any additional exposure to the patient.

Fluoroscopy

In fluoroscopy the x-rays strike a fluorescent plate that is coupled to an “image intensifier” that is in turn coupled to a CCD video camera. The images are then projected onto a “television” monitor. Some modern image intensifiers no longer use a separate fluorescent screen. Instead, a cesium iodide phosphor is deposited directly on the photocathode of the intensifier tube. The introduction of flat-panel detectors allows for the replacement of the image intensifier in fluoroscopes. Flat panel detectors are considerably more expensive to purchase and repair than image intensifiers, so they are used primarily in specialties that require high-speed imaging, e.g., vascular imaging or cardiac catheterization.

Radiation Terminology

In the United States older radiation terminology that has been abandoned in most other countries is still utilized to a large degree. A Roentgen refers to the amount of radiation that is generated in the air and is defined as (if anyone cares) the amount of radiation required to liberate positive and negative charges of one electrostatic unit in 1 cc of air at standard temperature and pressure. One Roentgen equals 2.58×10^{-4} coulomb per kg of air. The rad is the “radiation absorbed dose” and refers to the amount of radiation absorbed in tissue. One rad equals the absorption of 100 ergs of energy in one gram of tissue. The rem, or radiation equivalent in man, refers to the amount of energy absorbed by human tissue. For our purposes, Roentgen, rad and rem can be considered to be essentially the same. The international system (SI) has replaced old terminology everywhere except in the United States. The gray (Gy) has replaced the rad and is equivalent to 1 joule/kilogram of tissue. The Sievert (Sv) has replaced the rem. One Sv equals one gray multiplied by a radiation weighting factor r_W , determined by the radiation type, part of the body radiated, and even the species. The Roentgen measures exposure, i.e., how much radiation is emitted; rad, gray, rem, and Sv measure radiation dose, i.e., how much radiation is absorbed. It is not important to remember the definitions, but one should be aware that 1 gray equals 100 rads. (Many radiation oncologists now refer to treating the breast with 50 or 60 Gy as opposed to 5000 – 6000 rads.) One Sv equals 100 rem.

Reducing Radiation Exposure

There are 3 ways to reduce radiation exposure in patients and personnel: 1) time, 2) distance, and 3) shielding.

Time

Whereas the amount of time an individual exposure requires is largely determined by uncontrollable factors, the number of exposures to which the patient and personnel are exposed increases the total time of exposure. Limiting the number of exposures obviously limits the total amount of radiation exposure. One area in which surgeons have direct control over the time of exposure is in the use of fluoroscopy to insert venous access devices. One should always strive to keep exposure to a minimum according to the ALARA (as low as reasonably achievable) principle, because a stochastic effect of radiation could occur at any time. The fluoroscope “on time” should be controlled with a foot pedal by the surgeon. Rather than keeping the fluoroscope on during manipulation of the wire and catheter, the surgeon should insert the wire the appropriate distance then “tap” the pedal to take a snapshot of the location. If the location is good, the sheath can be passed over the wire and the catheter can then be inserted to a predetermined length and another “tap” done to confirm the position. Minor adjustments can be made and a final “tap” confirms the final location. Although some difficult cases require continuous fluoroscopy to manipulate the wire or catheter, with a little practice one can easily get the fluoroscopic time below 5 or 10 seconds in the majority of cases.

Distance

The exposure rate from radiation decreases with the square of the distance from the source. The relationship between exposure and distance is called “the inverse square law” and is governed by the formula $R = (1/d)^2$ where R equals the amount of radiation and d equals the distance from the source of radiation. For example, if one receives 10 mrad/hour radiation at a distance of one meter from the source, the radiation at 2 meters would be 2.5 mrad/hour ($1/2 \times 1/2 = 1/4$). The primary concern for personnel is radiation scattered from the patient, and that dose is quite small. At a distance of 1 meter from the patient, an unshielded person in the room would get approximately 1/1000 the dose the patient gets. Again, fluoroscopy is an example of a time when the surgeon can have a direct impact on the amount of radiation the patient receives. One should remember that the source of the radiation in a C-arm comes from beneath the patient and the image intensifier is on top of the patient. Therefore, by keeping the image intensifier as close to the chest as reasonably achievable, the source of radiation is as far from the patient’s skin (in back) as possible, thus limiting the total dose received.

Shielding

The final way to protect patients and personnel is the proper use of shielding. In stereotactic procedures, wearing an apron is not necessary since the surgeon and technologist can stand behind a leaded glass partition some distance from the radiation source while taking images. The radiation received there is negligible. When using a Faxitron for specimen radiography, the shielding in the unit reduces radiation outside to a negligible amount. When performing fluoroscopy, however, it

is necessary to wear an apron containing at least 0.5 mm of lead. This apron will stop 75% of 100 kVp x-rays and 99.9% of 75 kVp x-rays. Overall, it reduces radiation exposure by about 95%. In addition to lead, effective radiation shields include steel, concrete, and leaded windows.

Occupational Dose Limit

The National Council on Radiation Protection and Measurement (NCRP) and the Nuclear Regulatory Commission (NRC) set the allowable limits that radiation workers in the United States, including health care personnel may receive. The maximum whole body permissible limit is 5 rem (0.05 Sv) per year. The sum of the dose to individual organs or tissues must not exceed 50 rem (0.5 Sv) per year. The dose to an extremity (arm below the elbow or leg below the knee) also must not exceed 50 rem (0.5 Sv) per year. The lens of the eye is limited to 15 rem (0.15 Sv) per year. Pregnant women are limited to 0.5 rem (0.005 Sv) over the course of the pregnancy, because the fetus is assumed to be more sensitive to radiation. Working full time in a stereotactic unit should pose no problem, since the negligible radiation exposure will not approach any of these levels. With proper shielding a pregnant person can even work in fluoroscopy. It is highly unlikely the dose under the protective apron to the abdomen of a technologist will ever approach the recommended maximum dose limit.

Diagnostic Radiation Doses

Typical doses that are encountered in diagnostic radiology relating to patients with benign and malignant breast disorders are as follows. The radiation absorbed from a chest x-ray is around 30 mrad. The average glandular dose (AGD) of a mammogram is 10 times as much, or around 300 mrad. Most physicians, including radiologists and the physicians who order the test are unaware that a CT of the chest delivers between 2 and 5 rads to the female breast, depending upon the size and density of the breast!

Multiple factors determine the average glandular dose (AGD) of a mammogram. As discussed above, as the mAs increases, the dose to the breast increases. The relationship between kVp and breast dose is more complex and is not linear. It requires much more radiation to penetrate a large breast than a small one, so the larger the breast, the higher the radiation dose. Likewise, it requires much more radiation to penetrate dense breasts as opposed to fatty breasts. When doing stereotactic exposures, the exposure time for elderly patients with small, fatty-replaced breasts is a fraction of a second. Conversely, the exposure time for young women with large, dense breasts sometimes seems to last for an interminable number of seconds. The other variable in film screen imaging is the optical density of the film. That is not a consideration in digital images. Whether digital imaging substantially reduces the dose of radiation is controversial, but some studies show a 25% or so reduction in radiation exposure compared to film screen mammography. It is important to note that post-acquisition changes in contrast, magnification, and black/white reversal do not increase the dose the patient receives.

Radiation Doses in Breast Patients

Although there is wide variability in the amount of radiation a patient receives (as outlined in the previous section), it is useful to consider some typical patient doses and ask what the potential for harm is with those doses. In general, we are not as concerned about the amount of diagnostic radiation a cancerous breast receives, since the breast will usually be removed or treated with doses of therapeutic radiation that will render the diagnostic radiation dose negligible. Occasionally, however, some patients with small, low-grade or non-invasive cancers receive neither mastectomy nor radiation. In addition, we must be concerned about the non-cancerous breast that receives diagnostic evaluation and stereotactic biopsy. It is not uncommon for both breasts to undergo diagnostic evaluation and stereotactic biopsy, so we will consider a scenario where both breasts are evaluated but only one is treated.

On average one could expect a screening mammogram to generate a dose of about 300 mrad/view which would give a total dose of at least 0.6 rads to the breast for two standard views, assuming none of the films had to be repeated. If an abnormality is detected and the patient is referred to a specialized diagnostic unit, the screening MLO and CC views are frequently repeated for another 0.6 rads. Straight lateral, straight lateral magnification, and CC magnification views are frequently done, along with several cone compression views. It would not be uncommon for the breast to receive 3 rads (0.3 Gy) of screening and diagnostic radiation. If the patient needs a stereotactic procedure, the dose of each exposure is significantly reduced because of the small aperture of the window, but it averages at least 50 mrad/exposure. (In pregnant patients the dose the fetus receives is minimal). A fortunate patient (with an experienced tech) might receive just one scout view, a stereo pair prior to needle insertion, a pre-fire stereo view, a post-fire stereo view, and a final exposure to check clip placement. Add at least another 0.4 rads to the total, but the technologist usually has to perform multiple exposures to properly locate the lesion on the scout so a whole rad would not be uncommon. If the patient has breast cancer she might get a CT scan of the chest for another 2 to 5 rads. (Perhaps we should accept a normal chest x-ray with its 15 - 30 mrad dose as adequate to exclude metastasis, particularly in young patients in whom the breast tissue is much more sensitive to radiation.) If a port is inserted for chemotherapy, a heavy-footed surgeon could easily add another 1 rad with fluoroscopy. Before we know it, particularly in a young patient with large, dense breasts, we could easily reach 10 rads to the benign breast. How likely is it that this dose is harmful?

Harmful Effects of Radiation

The National Academy of Sciences (NAS) periodically evaluates and reports on the biological effects of ionizing radiation, primarily by long term follow-up of survivors of Hiroshima and Nagasaki. Other radiated populations followed include patients from Nova Scotia and Massachusetts who received large amounts of chest fluoroscopy in following tuberculosis over a number of years, and patients in Rochester, New York who were treated with radiation for post-partum mastitis. The health impact of various levels of radiation is assessed. It should be remembered that

the risk of radiation exposure has been extrapolated from data in patients who had high doses of radiation, assuming that the risk is linear and that there is no threshold dose. There is no direct data that low doses of radiation have caused these theoretical problems. Most of you have seen the familiar estimates that the mortality risk of a single mammogram in a 45 year old woman is comparable to the chance of dying as a result of a plane trip from New York to Los Angeles, driving roundtrip in a car from New York to Boston, smoking 3 cigarettes, or simply being alive for 15 minutes at age 60. Those calculations came from the NAS 1990 BEIR V Report (Biological Effects of Ionizing Radiation). The BEIR series of reports are the most authoritative basis for radiation risk estimation and radiation protection regulations in the United States.

The BEIR VII Report (Phase 2) was released in March 2006 and estimated the lifetime attributable risk (LAR) of a breast dose of 10 rads (0.1 Gy). The LAR (incidence) for a woman 50 years old who receives 0.1 Gy to both breasts is 70 additional breast cancer cases per 100,000. The risk in our theoretical patient would be half that, or about 1 in 3000 since we assume one breast has either been removed or subjected to therapeutic doses of radiation. We can extrapolate this risk down to 50 mrad (0.0005 Gy) to determine the risk of each stereotactic exposure we make. The dose of a single stereotactic exposure at age 50 gives an LAR of 0.175 additional cases per 100,000 women. Ten stereo exposures would give an LAR of 1 or 2 additional cases per 100,000. For younger women, the risk is substantially higher, perhaps 12 or so per 100,000 for 10 stereo exposures. Although these numbers are small when compared to the baseline risk (over a lifetime) of 12,000 breast cancers per 100,000 women, they still behoove us to apply the ALARA principle at all times.

Regulatory Compliance

Health care workers exposed to ionizing radiation who are likely to exceed 10% of the allowable doses are required to monitor their exposure by wearing badges that detect the amount of radiation received. If only one badge is assigned by the radiation safety officer, when doing fluoroscopy and wearing a lead apron, the badge should be affixed to the collar on the outside of the apron. If a second badge is assigned, it should be worn at the waist beneath the apron. It is not necessary to wear badges when doing stereotactic biopsies, because the dose of radiation the physician receives is negligible.

Currently (as of August, 2007) stereotactic biopsy does not fall under the regulations imposed by the Medical Quality Standards Act (MQSA), so most of the monitoring is done at a state level. The Food and Drug Administration (FDA) is considering bringing stereotactic biopsy under the umbrella of MQSA which would change the regulatory landscape enormously. Unless that happens, compliance issues are largely handled by the individual state in which the procedure is done. Surgeons who are contemplating purchasing stereotactic equipment would be well advised to monitor closely the actions of the FDA to be certain regulations are not passed that would make it quite difficult for them to use the equipment.

In general, the vendors that sell the equipment provide the necessary information for meeting regulations. An installation project manager helps with the design and layout of the room, and a shielding plan is submitted to the state radiation control authorities for approval. After installation, a physicist then inspects the equipment and evaluates collimation, calibration, camera sensitivity and noise, image quality and artifacts. After passing this inspection, the equipment is ready for use. The physicist usually has to perform at least annual inspections to determine proper functioning of the equipment.

Additional AMA-PRA Category 1 CME Credit in Radiation Physics

In order to become accredited in stereotactic biopsy by the combined American College of Surgeons/American College of Radiology program, it is necessary to obtain 4 hours of AMA-PRA category 1 credit in radiation physics. These hours can now be obtained by completing an online program sponsored by the American College of Surgeons Commission on Cancer. The program is presented by Robert J Pizzutiello, Jr., MS, FAAPM, FACMP, president of Upstate Medical Physics, Inc., Rochester, New York. It is available at <http://www.facs.org/cancer/webcast/index.html>.

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