

Radiation Safety and Physics

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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 dependent 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 it 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. The highest energy emissions that can do the most harm, x-rays and gamma rays, are not detectable because humans have no receptors that are sensitive to their frequency.

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-rays, gamma rays, and even very high energy ultraviolet 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 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 actually 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. There are traces of radioactivity in granite, so some buildings emit low levels of radiation. The stone used to build the United States Capitol is laced with uranium. It is said that if the Capitol building were a nuclear reactor facility it would not pass licensing inspection! The most common terrestrial exposure comes from radon, a naturally occurring radioactive gas. Depending upon geographic location and altitude, the background radiation varies but averages about 3 mSv 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 voltage differential between the cathode and the anode (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, the number striking 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 $\frac{1}{2}$ second, or 300 mA for $\frac{1}{3}$ second. The mAs in all three examples equals 100. The peak kilovoltage (kVp) is the other factor that is important in obtaining an x-ray. (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. The 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. The effect of mAs on the image is linear, but the effect of kVp is more complex and is neither linear nor exponential. 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.

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

Older radiation terminology that has been abandoned in most other countries is still sometimes used in the United States, so we will include it for the sake of completeness. A Roentgen refers to the amount of radiation that is generated in air and is defined as 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 is a measured dose that refers to the amount of radiation absorbed in tissue. It is used to quantify the dose given to tissue that can cause non-stochastic changes. One rad equals the absorption of 100 ergs of energy in one gram of tissue. The rem, or radiation “equivalent” in man, takes into account the type of radiation and the impact it has on a particular tissue. The international system (SI) has replaced old terminology everywhere except in the United States where it is rapidly changing as well. The gray (Gy) has replaced the rad and is equivalent to 1 joule/kilogram of tissue.

The Sievert (Sv) has replaced the rem. Gy is multiplied by a factor that takes into account the type of radiation (alpha particle or x-ray) and the sensitivity of the tissue in order to determine the “equivalent” dose in Sv. Alpha particles have a quality factor of 3 and pose a higher risk than x-rays. The quality factor for both gamma and x-rays is 1, so for practical purposes, Gy and Sv are the same when dealing with x-rays of the breast. In estimating the probability of a future stochastic event, an “effective” dose is calculated that takes into account the absorbed dose throughout the body, the relative harmfulness of the type of radiation, and the sensitivity of the organs. Effective dose is expressed in Sv. The Roentgen measures exposure, i.e., how much radiation is emitted; rad and gray measure absorbed doses; rem and Sv are used to estimate risk. It is not important to remember the scientific definitions of Roentgen and rad, but one should be aware that 1 gray equals 100 rads. (Most 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 such as the size and density of the tissue, 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 or with very specific instructions to the radiology technologist if a hand controlled device is used. Rather than keeping the fluoroscope on during manipulation of the wire and catheter, if the wire goes in without resistance, the surgeon should insert it to 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 (usually 19 plus or minus one centimeter, depending on the size of the patient) and another “tap” done to confirm the position. Minor adjustments can be made and a final “tap” confirms the final location. Some difficult cases require continuous fluoroscopy to manipulate the wire or catheter, and in those instances fluoroscopy should be used as much as necessary to make the procedure safe. With a little practice, though, one should be able to get the fluoroscopic time below 3 seconds in the majority of cases.

Distance

The exposure rate from radiation decreases exponentially 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 mrads/hour radiation at a distance of one meter from the source, the radiation at 2 meters would be 2.5 mrads/hour ($\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$). 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.

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 specimen radiography unit, 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 0.05 Sv per year. The sum of the dose to individual organs or tissues must not exceed 0.5 Sv per year. The dose to an extremity (arm below the elbow or leg below the knee) also must not exceed 0.5 Sv per year. The lens of the eye is limited to 0.15 Sv per year. Pregnant women are limited to 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.

The Fukushima nuclear disaster understandably caused widespread concern and confusion as to the danger of high levels of radiation. Acute whole body exposure to high doses of radiation can cause acute radiation sickness and even death, and those who survive are at high risk for ultimate stochastic events such as cancer. The highest dose reported at the Fukushima nuclear plant was 1Sv/hour and was recorded on March 27, 2011. Two workers were hospitalized on March 24 with burns to their legs and were reported to have received a *localized* dose to the legs of between 2 and 3 Sv. A typical daily fraction for treatment of breast cancer is 1.8 Gy, and in special circumstances single dose fractions in other parts of the body may be as high as 8 Gy. If the reported high radiation dose at Fukushima was localized, it is likely that the burns suffered by the radiation workers were thermal and related to hot water in their boots rather than to radiation.

Acute *whole body* radiation is a different matter altogether. Whole body acute doses below 0.25 Sv are well tolerated and cause no acute symptoms. At doses around 1 Sv some people experience nausea, anorexia and potential damage to the bone marrow. As the dose increases, the nausea, vomiting, diarrhea and hematopoietic damage become worse, along with acute hair loss and hemorrhaging. If the Fukushima workers received whole body doses of 2-3 Sv, they would have certainly had significant radiation related symptoms. Fifty percent of people exposed to 5 Sv of acute whole body radiation die within 30 days despite treatment. Acute doses above 6 Sv cause the above symptoms plus central nervous system impairment and probable death.

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 less than 0.3 mGy. The average glandular dose (AGD) of a two-view 2D mammogram is almost 10 times as

much, or around 2.74 mGy. The AGD of a typical 3D mammogram is about 3.74 mGy, 37% higher than 2D. Multiple factors determine the AGD of a mammogram. As discussed above, as the mAs increases, the dose to the breast increases in a linear manner. The dose also increases with increasing kVp, but 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. The AGD of digital mammography is lower than film screen mammography, and 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, 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. As the equipment has become better, diagnostic radiation doses have come down. With modern equipment, the mean glandular dose (MGD) for a two-view digital mammogram is approximately 2.74 mGy. The MGD for 3D mammography (tomography) is approximately 37% higher, or 3.74 mGy. Regardless of whether calcifications are discovered on 2D or 3D screening mammography, further evaluation with full field and magnification views are necessary to adequately characterize the calcifications. Since magnification views bring the breast closer to the x-ray source and further away from the receptor, the dose is higher than for standard views, adding significantly to the total dose. Although the dose from stereotactic biopsy is less than with full field mammography, frequently multiple scout images are obtained before the calcifications are located and properly positioned. Screening and diagnostic mammography leading to stereotactic biopsy can result in a total dose to the breast of 0.02 Gy. How likely is it that this dose of radiation could be harmful to the patient?

Harmful Effects of Radiation

Ionizing radiation can induce cancer if it breaks a DNA bond and the damage goes unrepaired. If the damage occurs in a somatic cell, the cancer will be induced in that organ but it will not be hereditary. If the damage occurs in a germ cell, it will be passed to all progeny and will increase the likelihood of a hereditary form of cancer. The grade of the cancer will be the same whether the damage to the DNA occurs after a limited exposure to radiation or after prolonged exposure over a number of years. It is a random occurrence and is not dose related. The only impact increasing doses of radiation has is to increase the probability of a stochastic event. It does not change the characteristics of the resultant cancer.

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 are no direct data that low doses of radiation have caused these theoretical problems. Many people 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 round trip 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 reports are the most authoritative sources for radiation risk estimation and radiation protection regulations in the United States. The BEIR VII Report (Phase 2) was released in March, 2006, and the BEIR VIII report is at least several years away. Extrapolating from BEIR VII data, the 0.02 Gy dose for a screening and diagnostic mammogram coupled with a stereotactic biopsy might be expected to produce about 30 excess breast cancers per 100,000 exposed women of varying ages. CT scans give high doses of radiation. The Food and Drug Administration (FDA) estimates the effective dose of CT scans varies between 1 and 10 mSv depending on the size, age, and tissue sensitivities of the patient. According to the FDA, a 10 mSv effective dose would be expected to lead to one additional cancer per 2,000 CT scans. Considering that approximately 100,000,000 CT scans will be performed in this country in 2018, that translates to 5,000 to 50,000 deaths caused by CT scans! It behooves all medical professionals to follow the ALARA principle and keep radiation doses as low as reasonably achievable.

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 at collar level 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 May, 2018) 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 FDA once considered 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 are advised to obtain updated information from the FDA to be certain regulations are not pending that would make it 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. A physicist usually has to perform at least annual inspections to determine proper functioning of the equipment.

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