3. CT for Technologists

Radiation Safety

CT for Technologists is a training program designed to meet the needs of radiologic technologists entering or working in the field of computed tomography (CT). This series is designed to augment classroom instruction and on-site training for radiologic technology students and professionals planning to take the review board examinations, as well as provide a review for those looking to refresh their knowledge base in CT imaging.

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This material will be reviewed for continued accuracy and relevance. Please go to www.icpme.us for up-to-date information regarding current expiration dates.

Note: Terms in **bold** can be found in the glossary.

OVERVIEW

The skill of the technologist is the single most important factor in obtaining high quality diagnostic images. A successful CT examination is the culmination of many factors under the direct control of the technologist.

CT for Technologists 3 • Radiation Safety introduces the learner to the history of x-ray discovery and its consequent adverse effects, how radiation affects human tissue, how to minimize patient radiation exposure through parameter adjustment, and how to protect the patient as well as the staff, including national initiatives to reduce exposure.

EDUCATIONAL OBJECTIVES

After completing this material, the reader will be able to:

- Discuss the early challenges of x-ray development
- Describe the effects of ionizing radiation on the body
- Explain radiation safety practices in CT
- Assess CT scan parameters that impact patient radiation dose
- Develop and implement reduced-dose CT protocols for adult and pediatric patients

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In addition to managing the 3D Lab at Fairfax Radiological Consultants (FRC), Mr. Jennings oversees CT protocols at six outpatient CT centers. He also serves as Director/Instructor of the GE/FRC *Cardiac CTA for CT Technologists* course.

Mr. Jennings also co-authored with James P. Earls, MD, a 2008 article published in *Radiology* titled: Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: improved image quality and reduced radiation dose.

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Lisa H. Schleelein, MEd, has no conflicts to report.
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3. CT for Technologists

Radiation Safety

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INTRODUCTION

Radiation protection in computed tomography (CT) has always been a concern and remains a topic of great importance. Reports of increased cancer risk for patients who receive CT scans concern both patients and healthcare providers, and pressure is on radiology practices, radiologists, and CT technologists to reevaluate their radiation protection policies. Manufacturers have assisted in attaining this goal with the development of low radiation dose hardware and software, but good radiation protection measures must still be followed by the technologist and radiologist to limit patient radiation dose.

After reading this material, the technologist will have a better understanding of the evolution of x-ray technology, radiobiology, radiation safety practices, scan parameters, and the development of reduced-dose CT protocols for adult and pediatric patients.

Figure 1. (Top) 1920s-era x-ray machine from the museum of Wilhelm Conrad Röntgen.
For more information, click here. Wikimedia

Figure 2. (Bottom) Early x-ray tube from the Museum of Wilhelm Conrad Röntgen.
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HISTORY OF RADIATION PROTECTION

Discovery and Early Experiments

The x-ray was discovered by German physicist Wilhelm Roentgen in 1895, and the discovery became public in 1896. His experiments with an invisible ray that had the ability to image internal structures of the body excited both the scientific and non-scientific communities. For his discovery, Roentgen was awarded the Nobel Prize in Physics in 1901. Unfortunately, little regard to potential health risks was observed during this period of experimentation. This lack of concern was not limited to scientists, as coin operated x-ray machines became a popular form of entertainment for the general public's use until reports of the potential dangers of x-ray surfaced (**Figures 1-5**).

Early Health Risks

Warning signs of radiation exposure appeared as reports of sunburn-like redness on the skin in areas exposed to radiation called skin **erythema**. A notable experience involved an x-ray lab technician named Clarence Dally, who worked for inventor Thomas Edison **(Figure 6)**. Dally was assisting Edison in the development of a fluoroscope tube that provided sharper images than those of the Roentgen fluoroscope. Dally soon reported radiation burns to his hands and face. Despite the adverse side effects, Dally continued to expose his hands during experiments with Edison's fluoroscope. Eventually his hands became cancerous due to repeated x-ray exposure, necessitating multiple surgeries on both hands in an attempt to stop the cancer from spreading to vital parts of his body. Surgeons eventually amputated both arms, but Dally died of metastatic cancer in 1904.

Figure 3. (Top left) Photo of an early x-ray procedure, using a fluoroscope screen, around 1910.
For more information, click here.
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Figure 4. (Top right) GE x-ray machine circa 1945.
For more information, click here.
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Figure 5. (Left) Example of an x-ray machine used to fit shoes circa 1940.
For more information, click here.
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He is the first known death caused by x-ray exposure. Dally's high-profile death alerted many to the potential dangers of x-ray exposure, and x-ray use was largely confined to doctors' offices and hospitals from that point on. Edison was devastated by Dally's death and ceased x-ray experimentation.

Edison himself experienced problems with his eyes that he believed were due to x-ray exposure and thus refused to be x-rayed for any reason for the remainder of his 84 years.[1] See **Figure 7** for an example of radiation necrosis.

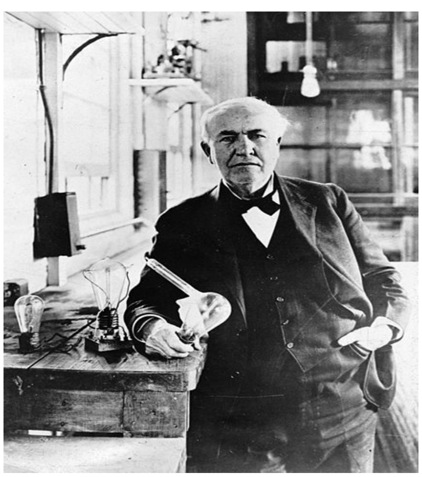

Figure 6. Thomas Edison in his lab.
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Although many scientists dismissed the notion that health risks could be attributed to x-ray exposure, William Herbert Rollins, a dentist from Boston, made great strides in the area of radiation protection in the early years of x-ray. Rollins invented an oral fluoroscope and intra-oral cassette in 1896, eight months after Roentgen's discovery. Rollins became concerned about the effects of x-ray after he developed severe radiation burns on his hand in 1898. In 1901 he published a study on the effects of radiation on guinea pigs, proving that x-ray exposure could be fatal.

Figure 7. Radiation necrosis of the hands.
For more information, click here. Wikimedia

Additionally, Rollins raised concerns about the sensitivity of radiation to an unborn fetus when the fetus of a guinea pig died due to x-ray exposure. Rollins also suggested in 1901 that those working with x-rays wear leaded glasses, enclose the x-ray tube with a lead box, and shield patients with radiopaque material to protect areas not being radiographed. Rollins is also credited with other developments in radiology protection, including collimators and high-voltage tubes to limit radiation dose. He published more than 200 articles warning of the potential dangers of x-ray and was one of the first researchers to recommend x-ray exposure be kept to the lowest dose possible. For many years his suggestions were ignored, but today Rollins is known as the *Father of Radiation Protection*.[2]

Radiation Exposure Guidelines

By 1910, x-ray users commonly used leaded goggles and metal shields as radiation protection measures. Soon after, the first formal radiation protection guidelines began to be issued. In 1915, the British Roentgen Society made recommendations for radiation protection that were simple in nature but important in establishing at least some radiation protection guidelines. These guidelines focused on limiting overexposure and were the first known organized recommendations for radiation protection.[3] In 1922, the American Roentgen Ray Society adopted the radiation protection guidelines of the British Roentgen Society. This year also marked the first of what would become widespread use of film badges to monitor radiation dose to radiation workers.

Tolerance dose

Additional progress in radiation protection was made when German-American physicist Arthur Mutscheller recommended dose guidelines for clinical radiation workers in a 1925 paper titled “Physical Standards of Protection against Roentgen Ray Dangers.” After observing physicians and technicians who worked with radiation, Mutscheller recommended a tolerance dose of 0.2 rem/day. Mutscheller estimated that exposure of 60 rem per month would cause skin erythema. A radiation worker who was exposed to

0.2 rem/day would be exposed to a total of 6 rem/month or 1/10 the amount that would cause erythema over the period of a month. Using Mutscheller's model, the annual tolerance dose for a radiation worker would be approximately 70 rem/year. Mutscheller's tolerance dose was adopted by the International Commission on Radiological Protection (ICRP) in 1931 and in 1936 was lowered to 0.1 rem/day by the U.S. Advisory Committee on x-ray and Radium Protection, for an annual tolerance dose limit of 36 rem/year.[4] (Roentgen equivalent in man [rem] is the former term for the dose equivalent Sievert [Sv]. 100 rems = 1 Sv; see **Table 1** for rem and Sv equivalents).

100.0000 rem	=	100000.0 mrem	=	**1 Sv**	=	1.000000 Sv	=	1000.000 mSv	=	1000000 µSv
1.0000 rem	=	1000.0 mrem	=	**1 rem**	=	0.010000 Sv	=	10.000 mSv	=	10000 µSv
0.1000 rem	=	100.0 mrem	=	**1 mSv**	=	0.001000 Sv	=	1.000 mSv	=	1000 µSv
0.0010 rem	=	1.0 mrem	=	**1 mrem**	=	0.000010 Sv	=	0.010 mSv	=	10 µSv
0.0001 rem	=	0.1 mrem	=	**1 µSv**	=	0.000001 Sv	=	0.001 mSv	=	1 µSv

Table 1. Roentgen equivalent in man (rem) and Sievert (Sv) equivalents.

In 1926, Hermann Muller, a biology professor from New York City, conducted experiments with x-rays and fruit flies. The results of his experiments were published in 1927 in his paper, "Artificial Transmutation of the Gene." Muller found that the offspring of the fruit flies exposed to radiation during the experiments were often genetically deformed, demonstrating that x-ray exposure could cause genetic mutations.[5] Muller was awarded the Nobel Prize in Physiology and Medicine in 1946 for his discovery.
Muller became a vocal opponent of the tolerance dose, which had shaped the recommended dose limits in the early years of radiation protection. Mutscheller's tolerance dose assumed that dangerous levels of radiation dose would be evident in the form of skin erythema. Muller knew from his experiments that the dangers of radiation exposure were often obscured. Despite Muller's opposition, Mutscheller's tolerance dose was the most widely accepted theory for recommended radiation exposure limits until the mid-1950s.

Maximum permissible dose

In 1954, the National Council on Radiation Protection (NCRP) recommended a shift from tolerance dose to a maximum permissible dose. Scientists had noted linear changes in risk for genetic mutations, meaning that the number of mutations increased proportionally to radiation dose. It was also assumed that increases in dose also increased cancer risk.

Figure 8. Underground radiation test site in Nevada.
For more information, click here. Nevada Site Office, U.S. Department of Energy

In 1957, The International Commission on Radiation Protection (ICRP) recommended an annual maximum permissible dose of 5 rem/year for radiation workers. The following year, the NRCP recommended a life-time occupational dose limit of 235 rem for a radiation worker who works from age 18 to 65. The NRCP also recommended a yearly dose limit of 500 millirems (mrem) for the public.[6]

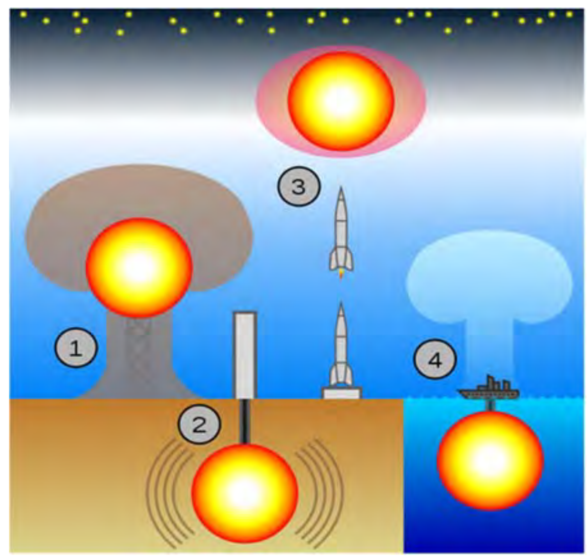

Figure 9. Primary types of nuclear testing.
1) atmospheric 2) underground 3) upper atmospheric
4) underwater.
For more information, click here. Wikimedia

Linear no-threshold model and ALARA

The 1960s marked a time that many Americans were concerned about radiation fallout from nuclear bomb testing during the Cold War with the Union of Soviet Socialist Republic (USSR). In 1957, American biologist Edward B. Lewis from the University of California reported to the powerful Joint Committee on Atomic Energy (JCAE) that although it was difficult to understand the exact effects at lower levels of radiation, it was prudent to assume risks at less than 50 rads. (Rad is the former name for **Gray** (Gy), the absorbed radiation dose; 100 rads = 1 Gray.) Detailed discussion of dose measurement is found later in this material. See **Figures 8** and **9** for related information.

The recommendations Lewis put forth laid the groundwork for the **linear no-threshold model** (LNT) for risk associated from radiation dose. During the 1960s, the JCAE moved slowly to endorse the linear no-threshold model of radiation risk.

Lewis also introduced the **ALARA** principle, which states that radiation dose should be kept As Low As Reasonably Achievable. The ALARA principle remains an important theory and practice in radiation protection today.

In 1964, another important development in radiation protection occurred. The National Academy of Science (NAS) created the Committee on the Biological Effects of Ionizing Radiation (BEIR) to study the biological effects of atomic radiation. Eight years later, British engineer Godfrey Hounsfield and South African physicist Allan Cormack invented computed tomography, the same year the first BEIR report was released.

The BEIR report provided cancer risk rates based on linear extrapolation from the high-dose mortality data of the survivors of the 1945 atomic bombings in Japan. Bomb survivors who received large but varying amounts of radiation were studied for changes in risk based on the amount of radiation they received. Scientists then created statistical models for the risk of effects from radiation at lower levels of exposure. Scientists assumed that radiation at any level posed some risk and increased in a linear manner with exposure increases, that is, a person with twice as much radiation exposure had twice as much cancer risk. It was also assumed that even a tiny amount of radiation exposure posed some risk. The BEIR report also endorsed the ALARA principle that was adopted as a radiation protection recommendation by the International Commission on Radiation Protection.[8]

Although the linear no-threshold model for radiation dose risk assessment remains widely accepted today, some scientists oppose the theory that very low levels of radiation are harmful.

Natural background radiation

The reason for the disagreement about the LNT model lies in the varying degrees of natural background radiation worldwide and lack of corresponding increase in cancer rates in communities with higher-than-normal rates.

The United Nations Scientific Committee on the Effects of Atomic Radiation 2000 (UNSCEAR) report listed Ramsar, Iran as having one of the world's highest natural background radiation levels due to radon-rich hot springs. The average dose per resident of Ramsar is 10mSv or about four times the average worldwide dose. In fact, some residents of Ramsar receive as high as approximately 260mSv natural background radiation annually. A 1999 study by Mortazavi et al reported that the 1800 residents of Ramsar are generally healthy and do not have higher cancer rates despite the increased amount of radiation exposure. The study concluded that the findings in Ramsar were inconsistent with the LNT model.[9]

Hormetic effect

Some scientists have concluded that low doses of radiation are not only harmless but are actually beneficial. This response is called **hormesis**, which is a favorable response or beneficial effect by an agent that can be detrimental at higher doses.

One example of a potential hormetic effect was released by UNSCEAR in 1994. According to the report, atomic bomb survivors who received less than 200 mSv did not have higher cancer deaths than control groups. Also, World War II atomic bomb survivors who received less than 100 mSv had *lower* leukemia mortality rates than an age-matched control group[10].

In 1973, the United States Atomic Energy Commission studied the impact of increased natural background radiation on cancer rates. The study compared six states with the highest natural background radiation levels with all other US states. The study concluded that the six states with the highest level of natural background radiation had 15% *fewer* cancer deaths than the United States average.

More than two decades later, a 1998 study by Jagger compared cancer deaths in the Rocky Mountain states to cancer deaths in the Gulf Coast states. Despite having natural background radiation levels that were 3.2 times greater than in the Gulf Coast states, the Rocky Mountain states had lower cancer mortality rates.[11] Similarly, an Indian study by Nambi and Soman in 1987 found that those living in areas of higher background radiation had lower cancer mortality rates.[12]

A controlled experiment in 1996 by Bhattarcharjee et al also supported the potential hormetic effects of low level radiation exposure. Bhattarcharjee initially exposed mice to very small amounts of radiation for five days and then to a much larger dose of radiation. The mice who received the adaptive radiation dose were compared to a group who received only the higher dose of radiation. The experiment found that 16% of the mice who received the adaptive dose developed thymic lymphoma compared to 46% of the mice who received only the higher dose.[13]

Despite the many examples of potential hormetic effect from exposure to low levels of radiation, the BEIR VII report of 2005 reaffirmed the committee's endorsement of the LNT model for assessing risk of cancer from radiation exposure. The BEIR committee doubted a hormetic effect at low levels of radiation, going on to state that it was unlikely that threshold doses with no risk of cancer exist and that hormetic effects at low levels of radiation exposure remain unproven.[14]

In recent years, radiation safety has become a popular media topic, with patients becoming more concerned about the effects of medical radiation on their health. Currently in the U.S., regulation of radiation dose is dependent on the individual practitioner, so it is especially important that radiology staff have a basic understanding of the potential effects of radiation on the exposed patient. Importantly, imaging staff must adhere to good radiation safety practices by always applying the ALARA principle.

IONIZING RADIATION

There are many forms of electromagnetic energy on the electromagnetic spectrum (**Figure 10**):

- Gamma rays
- Heat waves
- Infrared light
- Microwaves
- Radio waves
- Sound waves
- Ultraviolet light
- Visible light
- X-rays

Not all forms of electromagnetic radiation contain enough energy to ionize an atom. **Ionization** occurs when radiation has enough energy to remove an electron from orbit around the nucleus of an atom, causing the atom to become charged or ionized. Only two forms of electromagnetic radiation can cause ionization: x-rays and gamma rays.

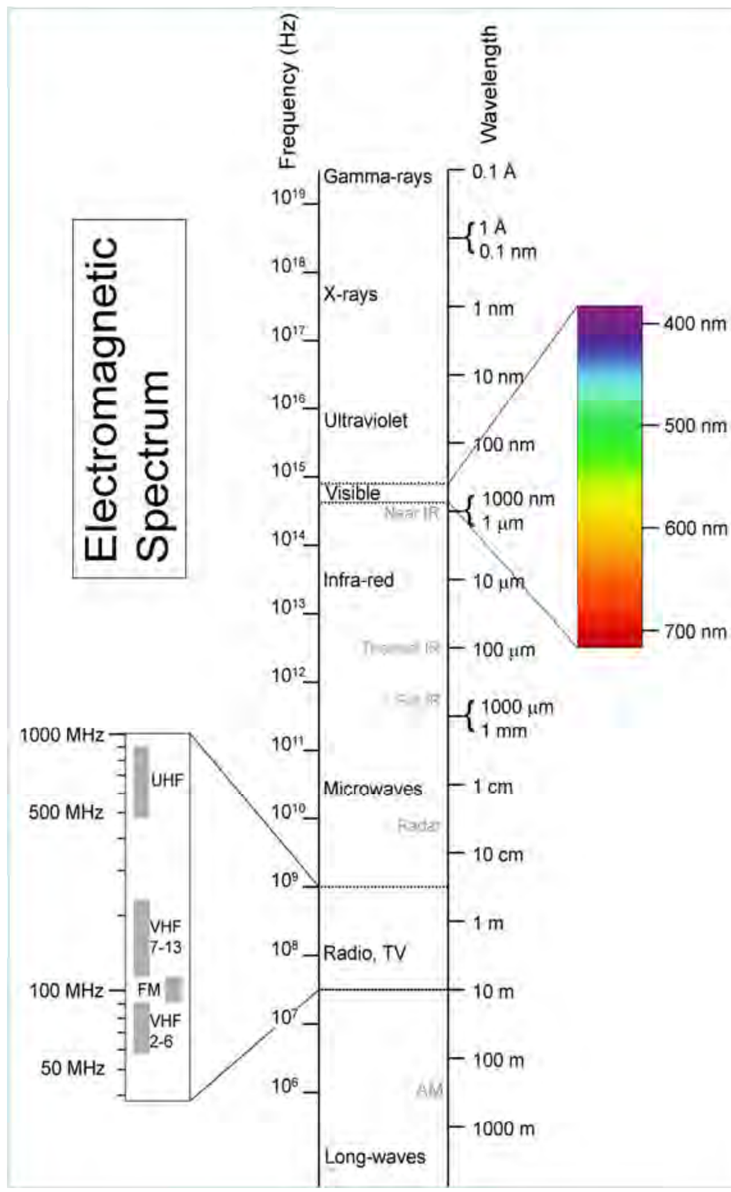

Figure 10. Electromagnetic spectrum.
For more information click here. Wikimedia

X-rays and gamma rays have shorter wave lengths and higher frequency waves as compared to radio waves, heat waves, and light, which have lower frequency and longer wave lengths. These lower frequency forms of electromagnetic radiation can move atoms around or cause them to vibrate but cannot cause ionization by removing an electron from orbit around the nucleus of an atom. Because CT scans utilize x-rays for image formation, the patient is exposed to the higher frequency, ionizing radiation.

Measurements of Dose

The terms used for measurement of radiation depend on what is being measured:

- radiation *emitted* from a radioactive source
- radiation dose *absorbed* by a person
- the biological *risk* to a person exposed to radiation

Each measurement includes terms for both the **International System of Units** (SI) and conventional measurement. SI units evolved from the metric system and are the most commonly used terms world-wide (**Table 2**).

Quantity	SI Unit (Symbol)	Definition	Conventional Unit (Symbol)	Conversion Factor
Activity	becquerel (Bq)	disintegration/sec	Curie (Ci)	1 Bq = 2.7 x 10^{-11} Ci
Absorbed Dose	gray (Gy)	joule/kilogram	rad	1 Gy = 100 rads
Dose Equivalent	sievert (Sv)	joule/kilogram	rem	1 Sv = 100 rems

Table 2. International System and conventional system of units for ionizing radiation.

Radiation emitted from a radioactive source

Emitted radiation is measured using the conventional unit **curie** (Ci) or SI unit **becquerel** (Bq). Radioactive atoms emit radioactivity because the nucleus has too much energy, too much mass, or too many particles to remain stable. The nucleus disintegrates due to its attempt to reach a nonradioactive state. This disintegration releases energy in the form of radioactivity.

The Bq or Ci is a measurement of the number of disintegrations of a radioactive atom over a period of time. One becquerel is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. One curie is defined as a unit of radioactivity, equal to the amount of a radioactive isotope that decays at the rate of 3.7 x 10(10) disintegrations per second. Note that this measurement does not quantify radiation dose to a person.

Radiation dose absorbed by a person

The conventional measurement of *absorbed* dose by a person is **radiation absorbed dose** (rad) or the SI unit gray (Gy). Absorbed dose is the amount of energy deposited per unit of weight of human tissue. One Gy is equal to 100 rad.

Biological risk

A person's biological *risk* from an exposure to radiation is measured in the **roentgen equivalent in man** (rem) in conventional units or the SI unit **sievert** (Sv). One Sv equals 100 rem. Both terms are quantified by using a **quality factor** (QF) that changes based on the form of ionizing radiation the person is exposed to. Alpha and beta particles, gamma rays, and x-rays all have different quality factors.

The formula for determining biological risk is:

$$rem = rad \; x \; QF$$

$$Sv = Gy \; x \; QF$$

The dose from a CT scan is usually expressed in millisieverts (mSv) or 0.001 Sv.

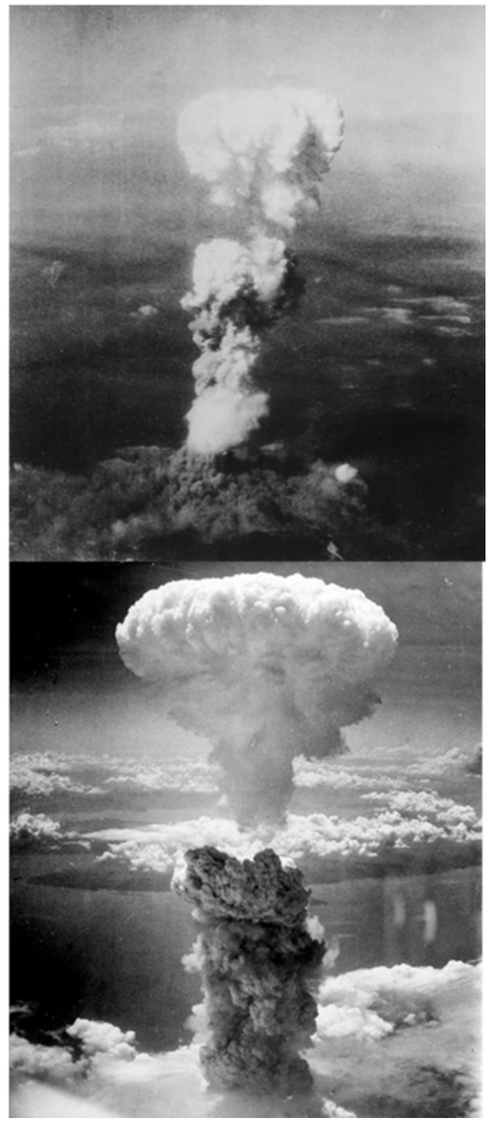

Figure 11. Atomic bombings of Hiroshima (top) and Nagasaki (bottom), Japan in 1945.
For more information click here.
Wikimedia

RADIOBIOLOGY

Radiobiology is the branch of biology that deals with the effects of radiation on living matter. Understanding the effects of radiation a patient receives from a CT scan is complex because of the inability to discern a radiation-induced cancer or mutation from a cancer or mutation from any other cause. For instance, a cancer may not appear for years or even decades, and a genetic mutation could impact offspring generations later. Thus, determining the role of radiation in the mutation of one individual is extremely difficult.

> **Radiobiology is the branch of biology that deals with the effects of radiation on living matter.**

Japanese and Ukrainian Radiation Disasters

To better understand the risk of cancer due to radiation, scientists have studied populations that were exposed to various levels of ionizing radiation and the impact on health. The most extensive data available on the effects of radiation on the human body are on the atomic bomb survivors from Hiroshima and Nagasaki, Japan during World War II in 1945 (**Figure 11**), as well as those affected by the nuclear power plant accident in Chernobyl, Ukraine in 1986.

At high levels of radiation, patients presented with acute illnesses ranging from nausea to death. Scientists found that at higher levels of radiation, the symptoms of the exposed person and prognosis were somewhat predictable. For example, acute exposures of radiation exceeding 500 mSv resulted in acute nausea for most people, while those exposed to less radiation did not experience nausea. Therefore, it was determined that the threshold dose for acute onset of nausea would be 500 mSv. Half of the people exposed to 4000 mSv died within two months, while most people exposed to 10,000 mSv died within two weeks. These acute effects from high radiation dose are termed **non-stochastic effects,** meaning that health effects will vary with radiation dose and for which a threshold is believed to exist (**Figure 12**). As a point of reference, a typical CT scan delivers about 10 mSv per dose and is considered low level radiation.

Comparing the Chernobyl and Fukushima Nuclear Power Plant Disasters

The Chernobyl nuclear accident occurred on April 26, 1986 when a protocol error by workers destroyed a reactor, causing a fire that released high levels of radioactive material. The release caused acute and non-acute illness to those exposed to the increased levels of radiation. More than 100 radiation workers complained of acute radiation sickness, and 30 of those workers died within a few weeks of the accident.

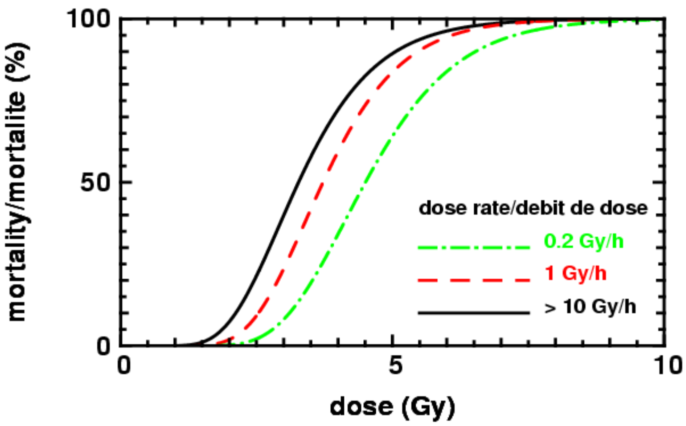

Figure 12. Mortality rates based on radiation dose rate.
The effects of radiation have greater impact on morbidity and mortality when the dose is given quickly, even when the *amount* of the dose is high. For example, the effects of a person receiving a quick radiation dose, like in the case of a nuclear accident, will be greater than a person who receives CT scans over a period of time.
For more information click here. [Wikimedia]

On March 11, 2011 a devastating earthquake and subsequent tsunami damaged a nuclear power reactor in Fukushima, Japan. The damaged reactor leaked **radionuclides** into the atmosphere, causing concerns that the impact on public health could rival the Chernobyl nuclear accident in 1986. Although the *late* effects of the Fukushima nuclear accident will not be known for many years, the *acute* effects do not yet appear to be as impactful as those of the Chernobyl accident (**Figure 13**).

The Chernobyl reactor released the **radioactive isotopes** caesium-134, caesium-137 and iodine-131. Although iodine-131 has a relatively short half-life of 8 days, it had the greatest impact on long-term public health following the accident. In comparison, the half-life of caesium-134 is two years, while caesium-137 has a half-life of 30 years. However, the mode of exposure of the caesium-134 and caesium-137 is strictly external, which lessens their impact.

By 2005, more than 6,000 thyroid cancers in children from Belarus and Ukraine had been diagnosed, and a significant percentage of these cancers were thought to be caused by the Chernobyl accident. Children were at increased risk because iodine-131 is easily transferred to humans through the air and through contaminated milk and leafy vegetables, and the thyroid gland in infants and children is more vulnerable to a radiation-caused cancer than in adults.

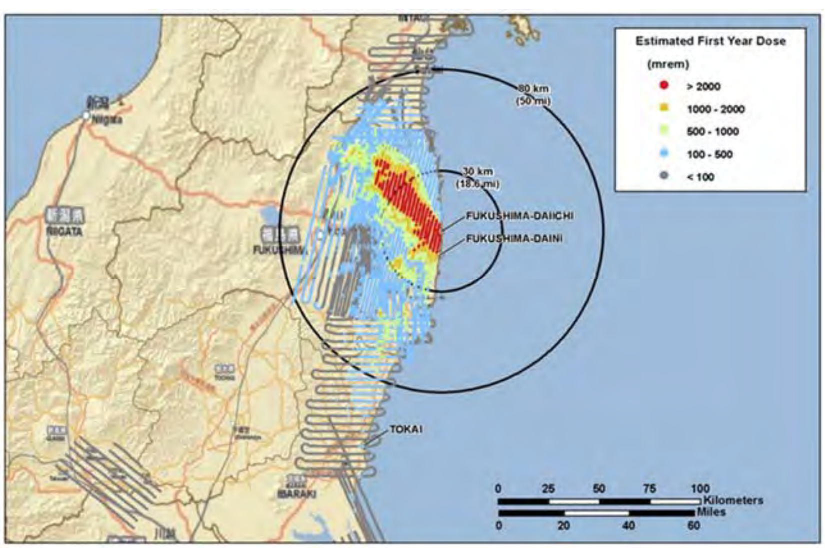

Figure 13. First-Year Radiation Dose Estimate: Fukushima, Japan nuclear incident. For more information, click here. [Wikimedia]

Figure 14. (Top) Measuring radioactivity at the Chernobyl, Ukraine nuclear power plant. *For more information click here.* [Wikimedia]

Figure 15. (Right) Radiation levels in Belarus and Ukraine a decade after the Chernobyl power plant accident.
For more information click here. [Wikimedia]

Beyond radiation workers who became acutely ill or died and children who developed thyroid cancer, the fear of widespread impact on public health of the Ukrainian population and surrounding regions was not realized. Since the meltdown, for example, increases in leukemia have not been documented.[15] See **Figures 14** and **15** for related information.

In contrast, only a few radiation workers received very high radiation levels in Fukushima, and officials report that affected workers have recovered. The same radionuclides as those released in Chernobyl were most concerning to officials: caesium-134, caesium-137, and iodine-131. Understanding the easy mode of transfer of iodine-131 to humans through food, the Japanese government ordered that contaminated food be discarded. In another safety measure, 80,000 residents left their homes in a mandated 20-km exclusion zone around the Fukushima nuclear plant. To further decrease the risk of thyroid cancer, a stable form of iodine was given to residents to prevent the thyroid gland from absorbing radioactive iodine. The Japanese people on average ingest a high level of iodine in their diet, which should also limit the impact of iodine-131 on thyroid cancer rates. Although the full impact of the Fukushima nuclear accident will not be known for years, it appears radiation safety measures gleaned from the Chernobyl experience were integrated into general practice and have had a positive impact in Japan.

Statistical Risks of Developing Radiation-Induced Cancer

The statistical risk of developing a radiation-induced cancer from low level radiation is called a **stochastic effect**. This effect represents the random, statistical nature of how *low level* (non-threshold) radiation impacts cancer risk. That is, the probability of damage increases with dose, yet the probability is still random. At low levels of radiation, the exposed person either develops or does not develop a cancer; there are no *predictable* health effects like nausea, hair loss, etc. These all-or-nothing effects occur at non-threshold levels of radiation, meaning that not all exposed people will develop cancer. Although random in nature, the presumption is that the low levels of radiation received in CT scans can cause cancers as well.

Linear No-Threshold Model

As discussed earlier, the most widely accepted theory regarding radiation exposure is that *no* amount of radiation should be deemed safe and the more lifetime radiation a patient receives, the higher the risk of developing a radiation-induced cancer. The amount of lifetime radiation dose a person receives is termed **cumulative dose.** This concept follows the linear no-threshold model discussed earlier and is used to estimate the long-term biological damage of ionizing radiation exposure (**Table 3**).

Patient Dose	Risk of Radiation-Induced Cancer
5 mSV	1:4000
10 mSv	1:2000
20 mSv	1:1000

Table 3. Example of linear no-threshold concept.

What is a patient's risk of developing a cancer from a typical CT scan? Studies suggest a small but real risk that low level radiation, like that received in CT scans, can cause cancer in some patients. Opinions vary about the rate of radiation-induced cancers resulting from a CT scan with an average dose of 10 mSv and average risk of 1:1000–1:2000. Since a human's lifetime risk of developing cancers from *any* cause is approximately 42%, a typical CT scan increases the patient's risk to 42.1%. The LNT model suggests that higher dose CT exams further increase patient risk, so it is imperative that radiology staff limit the patient's radiation exposure whenever possible by using the ALARA principle.

Interaction of Ionizing Radiation on Cells

Much like an individual's risk of radiation-induced cancers, the effect of ionizing radiation on a given cell in the body is random. When a cell absorbs radiation, one of four effects will occur: (1) the cell could die, which is not a harmful outcome as the body will produce a new cell; (2) the cell could lose its ability to replicate; (3) the DNA of the cell may be altered, which could result in a cancerous growth or a mutation to the DNA code that may impact future generations; and (4) there could be no adverse effect to the cell (**Figure 16**).

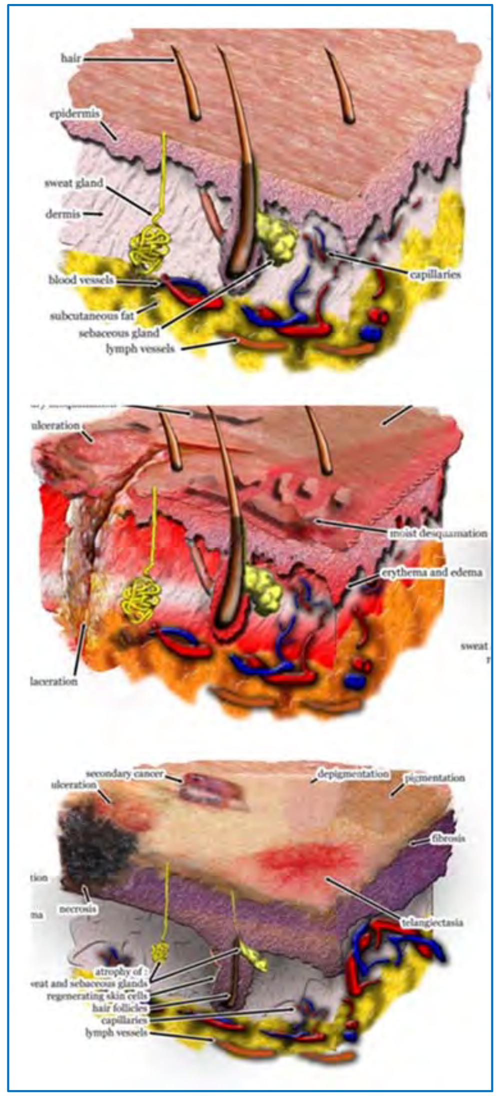

Figure 16. Common effects of ionizing radiation on the skin.
For more information click here.
[Wikimedia]

Some scientists theorize that a cell may be able to repair itself at low levels of radiation exposure. The ability for a damaged cell to self-repair often depends on the level of radiation the cell was exposed to and the cell's inherent sensitivity to radiation. Radiosensitive cells share similar characteristics: they are undifferentiated, highly metabolically active, rapidly dividing, and highly nourished. Highly radiosensitive cells are commonly found in the ovaries, testes, blood, bone marrow, and lymphoid organs. Tissues with low radiosensitivity include muscle, brain, and the spinal cord (**Table 4**).

The potential for cell repair is also dependent on the cycle the cell is in during radiation absorption. Cells are least sensitive in the **synthesis phase** and most sensitive during **mitosis**; that is, cells in the synthesis phase during radiation absorption have more time to repair, while those in mitosis have less time to repair.

Care must be taken by the radiology staff to limit radiation to highly sensitive tissues — reproductive organs, breast tissue, thyroid gland, and lens of the eye. Shielding devices should be used whenever possible to limit the risk of radiation-induced cancer.

CT Dose Reports

There are several methods to quantify the amount of radiation dose a patient receives from a CT scan. Some of these methods require the expertise of a radiation physicist. However, radiology staff should have a basic understanding of the dose measurements contained within the dose report and what these measurements represent in terms of patient radiation dose.

Highly Radiosensitive Cells	Low Radiosensitive Cells
Ovaries	Muscle
Testes	Brain
Blood	Spinal Cord
Bone Marrow	Bone
Lymphoid Organs	Cartilage
Lens of Eye	Kidney
Skin	Liver

Table 4. Cell radiosensitivity.

It is important to understand that the measurements contained in a patient's dose report are expressed as dose to a 16cm or 32cm phantom; hence, patient dose is similar to but not exactly the same as the measurements contained within the dose report.

CT Dose Index (CTDI) is a measurement of dose representing the primary beam and scatter from surrounding slices on single slice CT scanners.

CT Dose Index

CT Dose Index (CTDI) is a measurement of dose representing the primary beam and scatter from surrounding slices on single slice CT scanners. Weighted CT Dose Index (CTDIw) represents the weighted sum of two-thirds the peripheral dose and one third-the central dose in a range of 100mm in a phantom.

The advent of multislice scanners brought about another derivative of CTDI: CT Dose Index Volume (CTDIvol). CTDIvol is most useful when comparing the radiation doses of two different scan protocols as it only calculates the dose for a single volume (3D slice). This is reported by most CT systems.

For example, if the CTDIw were 10 and the pitch 2:1, the CTDIvol would be 5. If the technologist adjusts the pitch to 0.875:1, the CTDIvol would increase. To calculate new CTDIvol, divide the CTDIw of 10 by 0.875 for a new CTDIvol of 11.42. Decreasing the pitch increases the radiation dose to the patient:

$$CTDIvol = \frac{CTDIw}{pitch}$$

$$\frac{10}{2} = 5$$

$$\frac{10}{0.875} = 11.42$$

Dose Length Product

The other calculation represented on a dose report is **Dose Length Product** (DLP). The DLP is calculated by multiplying the CTDIvol by the scan length in centimeters. DLP is measured in milliGrays/centimeter (mGy-cm).

Effective Dose

Determining the patient's dose based on the information on a dose report is only an *approximate* dose. When estimating a patient's dose, it is important to understand that regions of the human body vary greatly in sensitivity to radiation, as mentioned earlier. Therefore, the patient's risk for developing cancer or mutations varies depending on the exposed body region. The dose calculation that accounts for the varying sensitivities of different regions or tissues in the body is called **effective dose**.

Region of Body	Weighting Factor
Head *(least sensitive)*	0.0023
Neck	0.0054
Chest	0.017
Abdomen	0.015
Pelvis *(most sensitive)*	0.019

Table 5. Weighting factors by region of the body.

Effective dose can be calculated by multiplying the DLP (mGy-cm) by a weighting factor for the region of the body being scanned and then represented in mSv. The weighting factor is determined by the region of the body's general sensitivity to ionizing radiation (**Table 5**).

For example, two patients are scanned and have identical DLPs of 500 mGy-cm. Patient A undergoes a head CT, while patient B has a CT of the pelvis. Each patient's estimated effective dose is calculated as follows:

Patient A

DLP = 500 mGy-cm x .0023 (head weighting factor)

DLP = 1.15 mSv

Patient B

DLP = 500 mGy-cm x .019 (pelvis weighting factor)

DLP = 9.5 mSv

Although the DLP calculations were the same, the effective dose of Patient B is much higher due to the increased sensitivity of the pelvis as compared to the head.

Multi Scan Average Dose

Another important measurement of dose is **multi scan average dose** (MSAD). Unlike CTDI, MSAD accounts for overlaps or gaps in conventional (axial) scans and pitch (P) during helical acquisitions to provide an accurate per-image dose for a multi scan series.

When calculating MSAD for conventional images with no image overlap, the MSAD would be the same as the CTDI value. Helical scans with a pitch of 1:1 will also have an MSAD that equals the CTDI.

To calculate MSAD, a physicist obtains a CTDI measurement from a phantom and performs one of the following calculations based on the type of scan:

Conventional (Axial) Scan

$$MSAD = \frac{CTDI}{slice\ interval:\ slice\ thickness\ ratio}$$

Helical Scan

$$MSAD = \frac{CTDI}{P}$$

where

$$P = \frac{table\ feed\ per\ rotation}{nominal\ slice\ thickness}$$

Conventional (axial) scan with overlaps or gaps

If the patient is scanned with overlapped or gapped images, the MSAD would be higher than the CTDI:

CTDI = 20.0, Slice Thickness = 5mm, Slice Interval = 3 mm

$$MSAD = \frac{CTDI}{slice\ interval : slice\ thickness\ ratio}$$

$$slice\ interval : slice\ thickness\ ratio\ = \frac{slice\ interval}{slice\ thickness}$$

$$\frac{3mm}{5mm} = 0.6$$

$$MSAD\ = \frac{20.0}{0.6}$$

$$MSAD = 33.33\ mGy$$

Helical scan

When calculating MSAD for a helical acquisition, the pitch must be accounted for in the equation. For helical acquisitions, a pitch of less than one will increase MSAD, while a pitch of more than one will decrease MSAD:

$$MSAD = \frac{CTDI}{P}$$

CTDI =20.0, Pitch = 2:1

$$MSAD = \frac{20.0}{2}$$

$$MSAD = 10\ mGy$$

CTDI= 20.0, pitch = 0.875:1

$$MSAD = \frac{20.0}{0.875}$$

$$MSAD = 22.86\ mGy$$

CT OVEREXPOSURES AND CORRECTIVE MEASURES

Although the cause of most adverse effects, including radiation-induced cancers from CT scanning, may never be determined, radiology staff must thoroughly understand and manage the potential dangers of overexposing patients.

Accidental Overexposures

In January 2008, a two-year-old boy in California had a CT scan of the neck with a reported 151 repeats, resulting in radiation burns on the neck and face from the repeated radiation exposures. The child now has an increased risk of cancer and is likely to develop cataracts within three to eight years after the overexposure.[16]

A study in 2009 of four California hospitals concluded that CT protocols among the hospitals varied greatly in the amount of dose received by study patients. Each hospital sent data on 20-30 adult patients for the 11 most commonly ordered CT procedures, representing 80% of all CT procedures ordered nationwide. The mean age of the patients was 59 years old; 48% of the study participants were female. The study findings revealed much higher effective doses than expected. Equally troubling were the large variations in dose by exam type and by hospital. The investigators found that the **lifetime attributable risk** (LAR) for many of the study patients was much higher than FDA estimates of 1:2000. For example, a young female patient who had a chest CT to rule out pulmonary embolism had a LAR of 1:80 based on her effective dose.

As a result of these startling findings, the researchers recommended: (1) increased standards for monitoring and regulating radiation doses by the FDA; (2) creation of guidelines for repeated CT scans on patients; (3) limits on the per-exam radiation dose; and (4) system-wide tracking of radiation doses on patients at each imaging facility.[17]

In 2009 at another California hospital, it was reported that 206 patients who had had CT brain perfusion scans over an 18-month period were significantly overexposed to radiation during their scans. Upon review, it was noted that the levels of radiation exposure were about eight times greater than usual for a brain perfusion exam. What prompted the review of the CT brain perfusion protocol and scanner was a patient report of hair loss after a scan. It was subsequently learned that almost 80 patients had reported hair loss. In addition, the overexposed patients were placed at increased risk for developing cataracts and cancer. The cause of the error was that the technical parameters for the perfusion scan had been increased to improve image quality but had also significantly increased radiation dose.

FDA and ACR Responses

In response to the 2009 incident, the Food and Drug Administration (FDA) recommended guidelines for sites performing brain and heart CT scans:

- Facilities assess whether patients who underwent CT perfusion scans received excess radiation.
- Facilities review their radiation dosing protocols for all CT perfusion studies to ensure the correct dose is planned for each study.
- Facilities implement quality control procedures to ensure that dosing protocols are followed every time and the planned amount of radiation is administered.
- Radiologic technologists check the CT scanner display panel before performing a study to make sure the amount of radiation to be delivered is at the appropriate level for the individual patient.
- If more than one study is performed on a patient during one imaging session, practitioners should adjust the dose of radiation so it is appropriate for each study.[18]

The American College of Radiology (ACR) supported the FDA recommendations and also offered guidelines for radiology practices, recommending that no imaging procedures be performed without a clear medical benefit that outweighs the risk. The recommendations also state that the "as low as reasonably achievable" policy should be followed to ensure patient safety.

The ACR also urged radiology practices to implement low dose protocols by participating in the *Image Gently* and *Image Wisely* initiatives.[19] (The Image Gently campaign offers guidance for pediatric low dose imaging techniques, as well as information for pediatricians, radiologists, technologists, and parents. Specific information about this campaign is provided in the pediatric section of this unit.)

The Image Wisely Campaign

The Image Wisely campaign is a collaborative initiative of the ACR, the Radiological Society of North America (RSNA), the American Society of Radiologic Technologists (ASRT), and the American Association of Physicists in Medicine (AAPM). Image Wisely urges radiology practices to[20]:

- Optimize scan protocols to only utilize enough radiation to produce quality diagnostic images.
- Convey the principles of the *Image Wisely Program* to the entire imaging team to ensure that the facility optimizes its use of radiation when imaging patients.
- Communicate optimal patient imaging strategies to referring physicians and be available for consultation.
- Routinely review protocols to ensure that the goal of utilizing the least amount of radiation to produce quality diagnostic images is being met.
- Demonstrate to patients that they "image wisely" by taking the *Image Wisely* pledge, obtaining ACR accreditation (or equivalent), and participate in a Dose Index Registry.

The Dose Index Registry (DIR) is a data registry that allows imaging facilities to compare their dose indices for all CT exams to other facilities regionally and nationally. The participating facilities receive periodic feedback in the form of reports from the ACR. The collected data are also used to establish national benchmarks for CT dose indices. In January 2012, the ACR announced that the DIR had recorded 1,000,000 patient doses from over 300 participating facilities.[21]

For additional information on the *Image Wisely* initiative, go to www.imagewisely.org.

Dose Notifications and Alerts

In October 2010, the CT Group of the X-ray Imaging Section of the Medical Imaging & Technology Alliance (MITA), a division of the National Electrical Manufacturers Association (NEMA) published new U.S. technical standards called XR-25, *Computed Tomography Dose Check*). These standards require compliant CT scanners to alert users when doses in CTDIvol or DLP may exceed pre-assigned values. These values can be pre-set by the manufacturer or adjusted by the CT site. The goal of this requirement is to limit overexposures to patients. A pop-up window appears on the CT monitor asking the technologist to confirm that the parameters are correct when dose values are exceeded.

There are two important values in XR-25 [22]:

- Notification Value: A value of CTDIvol (measured in mGy) or DLP (measured in mGy-cm) used to trigger a notification to the technologist when the value would likely be exceeded by the prescribed scans.
- Alert Value: A value of CTDIvol (measured in mGy) or DLP (measured in mGy-cm) used to trigger an alert when the scanner projects that the prescribed scans within an ongoing examination would result in a cumulative dose index value that exceeded the user-configured alert value.

In April 2011, The American Association of Physicists in Medicine (AAPM) recommended notification and alert values for XR-25 to limit overexposures to patients from CT scans (**Table 6**). The AAPM cautioned against setting levels too low for notification and alert values. Because one-third of the U.S. population is currently considered obese, the AAPM cautioned that if levels were set too low, the technologist may become de-sensitized to the alert or notification. Although the values would result in some overexposures, the AAPM believes extreme overexposures would be less likely if technologist does not see the pop-up warning on a routine basis.[23]

CT Scan Region	CTDIvol Notification Value
Adult Head	80 mGy
Adult Torso	50 mGy
Pediatric Head <2 yrs old	50 mGy
Pediatric Head 2-5 yrs old	60 mGy
Pediatric Torso <10 yrs old (16-cm phantom)	25 mGy
Pediatric Torso <10 yrs old (32-cm phantom)	10 mGy
Brain Perfusion	600 mGy
Cardiac (retrospective gating)	150 mGy
Cardiac (prospective gating)	50 mGy

Table 6. Notification Values recommended by the AAPM Working Group on Standardization of CT Nomenclature and Protocols.

In 2013, NEMA issued XR-29, the *MITA Smart Dose* or *Standard Attributes on Computed Tomography (CT) Equipment Related to Dose Optimization and Management*. The key dose optimization features of XR-29 produce high-quality diagnostic images while ensuring patient safety:

- DICOM Dose Structured Reporting. This standard recommends that patient dose be recorded in a standardized electronic format. This information can be included in the patient report, which promotes establishment of diagnostic reference levels and facility dose management and quality assurance.
- Pediatric and adult reference protocols. These are pre-loaded protocols on a CT scanner that serve as a baseline for various clinical tasks.
- CT Dose Check. This incorporates dose notifications and dose alerts that warn operators and physicians when dose exceeds established thresholds (current XR-25).
- Automatic Exposure Control (AEC). This is a CT scanner function that automatically adjusts radiation dose levels based on patient size and pre-set quality standards.[24]

On April 1, 2014, President Obama signed into law the Protecting Access to Medicare Act of 2014. Beginning January 1, 2014, providers will be assessed a 5% penalty for any exam acquired with a CT system that does not meet MITA Smart Dose XR-29-2013 standards. The penalty will increase to 15% in 2017.[25]

TECHNOLOGIST-CONTROLLED SYSTEM FACTORS

There are many technical and non-technical factors under the control of the CT technologist that impact radiation dose.

The technologist should always adhere to the ALARA principle to limit patient exposure to ionizing radiation. However, it is important to understand that this principle does not imply that the technologist should use the lowest dose at any cost. A balance must be found between radiation dose and image quality. This balance can only be determined by the radiologist and technologist working in tandem.

> **The ALARA principle does not imply that the technologist should use the lowest dose at any cost.**
>
> **Determining the highest amount of image noise that is acceptable to the radiologist is the most important factor in implementing reduced dose protocols.**

Successful implementation of reduced dose protocols requires the input of the radiologist to advise when the scan parameters have been adjusted to a level that negatively impacts the diagnostic quality of the CT image. The technologist's knowledge of the technical parameters is also vital for striking the correct balance between dose reduction and image quality. A scan with technical factors set too low may result in images that are too noisy and may impact the ability of the radiologist to diagnose subtle abnormalities.

Unlike a diagnostic x-ray, a CT scan with technical parameters set too high will not negatively impact the quality of the scan. In fact, the scan will have very low image noise and still be an excellent diagnostic tool. However, the excess radiation dose that the patient receives will likely increase the risk of developing a radiation-induced cancer compared to a patient who was scanned using appropriate technique.

Determining the highest amount of image noise that is acceptable to the radiologist is the most important factor in implementing reduced dose protocols. There are many technical factors that impact image noise and therefore affect the amount of radiation dose the patient receives.

Password Protection Limited to Authorized Users

Once a site has developed low dose protocols, it is recommended that the protocols be locked using a password. The password allows only authorized users to override the scan protocols in the CT scanner. It is recommended that sites only grant access to the password to one or two users so that changes can easily be tracked. Using a password would allow all scanning technologists to override *parameters* on a CT scan but not be able to change the *protocols*. This simple step prevents an unauthorized technologist from making changes that would impact the scan protocols for the entire CT staff.

ALARA Principle

As discussed previously, the ALARA (As Low as Reasonably Achievable) principle is a basic radiation protection philosophy that offers guidance to x-ray technologists from all specialties including computed tomography. Simply stated, the technologist should strive to keep radiation dose as low as possible while maintaining diagnostic quality. In other words, an exam that utilizes too much radiation may be of excellent diagnostic quality but also exposes the patient to excessive radiation does not follow the ALARA principle. Neither does an exam with a dose so low that diagnostic capability is hindered. In order to conform to the ALARA principle, a proper balance must be maintained, with the technologist exposing the patient to only enough radiation to acquire diagnostic-quality images. Following the ALARA principle is particularly important in CT as the radiation dose is significantly higher than for most diagnostic x-ray exams.

Automatic Exposure Controls/Dose Modulation

Automatic exposure controls (AECs), also known as **dose modulation**, vary in application by manufacturer. Some manufacturers allow the technologist to set threshold noise factors to adjust to varying patient sizes. The noise factor will remain constant, but the mAs will vary based on the size of the patient, ie, smaller patients require lower mAs to meet the threshold noise factor, while larger patients require more mAs. This results in less radiation dose to the smaller patient and more dosage to the larger patient. Other scanners automatically adapt to attenuation values of the body tissues that are being imaged to achieve lower radiation doses.

Another advantage of utilizing AECs is that the mAs constantly adjusts throughout the exposure based on the region that is being scanned. For example, a chest (lung) exam requires less exposure than scans of the abdomen or pelvis. To maintain the threshold noise factor set for the procedure, the mAs will be lower for the chest than for the abdomen or pelvis, while maintaining good image quality throughout both regions of the body. If a manual technique is utilized, the mAs will remain constant and need to be set based on the body part requiring the most mAs to maintain an acceptable image noise throughout the scan. This results in more radiation dose than necessary for those regions not requiring as much mAs. Therefore, the technologist should use AECs whenever possible to limit patient radiation dose. The radiologist should assist the technologist in setting the noise factors for each protocol based on diagnostic capability. The noise factor should be set to the highest amount of acceptable noise for each CT protocol to maximize radiation dose reduction but still result in a diagnostic image.

Studies have shown using dose modulation decreases dose for CT chest by 18-26% and an average of 43% for adult abdomen and pelvis exams.[26]

Tube Current

Tube current (mA) and scan time (tube current plus scan time = mAs) should be evaluated in tandem when evaluating the amount of radiation dose a patient will receive. For example, an mA of 400 with a 1-second scan time and an mA of 200 with a 2-second scan time each calculate to 400 mAs. Therefore, mAs is the factor requiring adjustment to impact the radiation dose. For example, doubling the mAs will double the patient dose, while cutting the mAs in half will lower the dose by 50%. In most cases, mAs is the best parameter to change to impact image noise as increasing the number of x-ray photons will decrease image noise. Hence, a scan with increased image noise may require an increase in mAs to decrease noise, resulting in an increase in patient radiation dose.

Tube Voltage

Adjustments to kVp (kilovolt peak), the maximum tube voltage from the cathode to the anode, will impact the radiation dose given to the patient. Unlike mAs, the effect of kVp is not proportional. The radiation dose will change in proportion to the square of the kVp. Small changes to kVp have a large impact on radiation dose, when mAs is not adjusted. In most CT exams, kVp is usually set at 120 and other factors are manipulated. However, smaller adult patients or children can be scanned at 100 kVp without decreasing image quality, with the added benefit of decreased radiation dose; a reduction of kVp from 120 to 100 will reduce the dose by approximately 40%. Increasing the kVp for imaging structures with metallic hardware has been found to increase image quality but at the expense of substantially increased dose if all other technical factors remain the same.

Pitch

Increasing the **pitch** (P) or table speed decreases the patient radiation dose. If all other technical factors remain the same, an increase in pitch will increase image noise, due to fewer x-ray photons striking the detectors. Fewer photons will be absorbed by the patient as well, resulting in less radiation dose. A pitch of less than 1:1 will have the opposite effect on image noise and patient dose. In this case, more photons will be absorbed by the patient and strike the detectors, resulting in less image noise and radiation dose to the patient.

Understanding the effect of pitch on radiation dose is explained by calculating **effective mAs,** which reflects the average absorbed dose in a scan volume when pitch is adjusted.

$$Effective\ mAs = \frac{mAs}{P}$$

For example, for Patient A, 400 mAs with a pitch of 0.875:1 is used; for Patient B, 500 mAs with a pitch of 1.5:1. We might expect that Patient A would receive a lower dose of radiation. However:

Patient A
400 mAs , 0.875 :1 pitch

$$Effective\ mAs = \frac{400}{0.875}$$

$$Effective\ mAs = 457$$

Patient B
500 mAs, 1.5 :1 pitch

$$Effective\ mAs = \frac{500}{1.5}$$

$$Effective\ mAs = 333$$

Even though the mAs is greater for Patient B, the *effective mAs* is lower than Patient A due to increased pitch. Thus, the radiation dose for Patient B was 27% less than that for Patient A.

Slice thickness

Slice thickness directly impacts radiation dose on conventional (axial or transverse) scanning techniques. Thinner slices result in an increased number of exposures within the **scan range**. For helical scans, however, thinner slices do not result in increased dose, which is discussed later in this unit.

However, in both conventional and helical scanning, thinner slices increase image noise creating an indirect effect on dose. Increasing mAs may help compensate, but remember that increasing mAs will increase patient dose. Thicker slices require fewer exposures during conventional scanning for the same scan range, resulting in less radiation dose to the patient. Thicker slices also result in less image noise and, therefore, lower mAs may be used.

In both conventional and helical scanning, thinner slices increase image noise creating an indirect effect on dose.

Interval

On conventional scanning, smaller intervals or increments (the amount the table moves during each rotation) increase the number of exposures and therefore increase the radiation dose. Larger intervals decrease the number of exposures, resulting in less radiation dose. Helical scan intervals have no impact on dose as they are a form of image reconstruction so do not expose the patient to additional radiation.

Image Filters

The reconstruction image filter has no direct impact on dose. However, much like slice thickness, the filter may increase image noise when reconstructing images in a more detailed filter. More mAs may be required to compensate for the increased noise. Again, if mAs is increased, the radiation dose is increased. Using a smoother filter will create less image noise and perhaps allow lower mAs and radiation dose.

Figure 17. Isocentering of wrist in x-, y-, and z-axes. *Courtesy of NYU Langone Medical Center.*

Conventional vs Helical Acquisition

All other parameters being the same, conventional scanning results in less radiation dose than helical scanning. In helical scanning, the outside borders along the z-axis of the x-ray beam have reduced intensity called the **penumbra**, the nonuniform, nonuseable portion of the x-ray beam. Conventional scanning uses all of the beam, resulting in no wasted radiation during image acquisition.

Single vs Multidetector Systems

On single detector systems the whole beam, including the penumbra, is utilized in image formation. If the penumbra were used on multidetector systems, the outside detectors would receive the penumbra, resulting in narrow and noisy images. To compensate, the x-ray beam is increased to expose an area outside the detector arrays, ensuring the outer detectors are not exposed by the penumbra. The penumbra is not used and therefore considered wasted radiation. Limiting the effect on radiation dose of the penumbra can be accomplished by using all detector elements in the z-direction and the largest fan beam thickness of the CT scanner.

All other parameters being the same, conventional scanning results in less radiation dose than helical scanning.

Isocenter Positioning

Improper patient centering within the gantry significantly increases surface radiation dose to the patient. **Isocentering** should be used to increase image quality and decrease patient dose (**Figure 17**).

Li et al conducted an isocenter study published in the *American Journal of Radio*logy in February 2007. A 32cm CTDI phantom was scanned in three positions: isocenter, 30mm below isocenter, and 60mm below isocenter. CTDIs were then estimated in each position using a 10cm pencil ionization chamber (pencil-shaped probe). Sixty-three patients were scanned utilizing automatic centering software that estimated the amount a patient was off-center and the percentage of dose increase due to the off-centering.

The study showed that 95% of patients were not centered properly, for a mean dose increase of 13%. Patients off-centered by 30mm had a 12-18% increase in dose, while those off-centered by 60mm had a 41-49% increase in radiation dose. Because of the significant impact of isocentering, technologists should strive for accurate positioning to decrease patient radiation dose.[27]

MANUFACTURER-DEPENDENT VARIABLES

CT scanners vary in the capabilities of hardware that may impact radiation dose to the patient. The scanner's geometry, efficiency of detectors, and beam filtration, including **bowtie filters**, impact the amount of radiation dose a patient will receive.

Efficiency of Hardware

Detector efficiency

The effect of detectors on patient dose is determined by the ability of the detector to capture photons and convert them into a usable signal. Solid state detectors are superior to xenon gas detectors in capturing and converting photons and are therefore the material of choice in most modern CT scanners. Detectors with poor efficiency provide photon-starved images, resulting in the need for increased tube current and increased radiation dose to the patient to compensate for the inefficiency of the detectors.

Data acquisition system

The amount of electrical noise in the **data acquisition system** (DAS) may also impact the amount of noise on an image. After a photon is captured by a detector, the DAS converts the photon into an electrical signal. The efficiency of the electrical systems in the DAS impacts the amount of electrical noise after the conversion. Systems with lower efficiency may require higher tube current to compensate for the resulting increase in image noise.

Figure 18. Axial image of the mid-liver. (Top) Before iterative reconstruction. (Bottom) After iterative reconstruction. Notice the noise in the top image has been decreased on the bottom image. *Courtesy of NYU Langone Medical Center.*

Pre- and postpatient collimation

Pre- and postpatient collimators are additional system components that impact patient radiation dose. Prepatient collimation decreases the amount of wasted radiation (penumbra) outside of the detector coverage. Increased width of detector collimation increases geometric efficiency and improves dose efficiency. Postpatient collimators impact image quality but do not decrease patient dose. Postpatient collimators prevent scatter radiation from entering the detectors, sacrificing dose efficiency while improving image quality.

Beam filtration

Beam filtration impacts radiation dose by increasing the overall energy of the beam by filtering out low energy photons. Low energy photons will not penetrate the patient and reach the detectors, thus having no impact on image formation. However, these nonpenetrating photons do increase radiation dose to the patient. Some CT scanners incorporate bowtie filters that decrease dose to the periphery of the patient by removing photons that would not positively impact image quality.

Iterative reconstruction techniques

Most CT scanner manufactures have developed software that decreases the radiation dose to the patient. This technology, which utilizes **iterative reconstruction** (IR), produces less image noise. As compared to the more commonly used **filtered back-projection** (FBP), iterative reconstruction techniques generate images with significantly lower noise. By lowering the mAs, IR can generate images of similar diagnostic image quality to FBP but at a reduced radiation dose (**Figure 18**).

Hounsfield used iterative reconstructions as the initial form of image reconstruction in the 1970s, but the reconstructions were very complex and time-consuming, making the extensive reconstruction time ill-suited for clinical practice.

As an alternative, for years CT scanners incorporated filtered back-projection for image reconstructions. FBP directly calculates an image in one reconstruction step, a simple and fast computation. However, FBP is extremely sensitive to artifacts and noise; therefore when mAs is lowered, the result is a noisy, potentially nondiagnostic image. Thus, manufacturers looking for a new way to decrease radiation dose turned to Hounsfield's "old" technology—iterative reconstruction. Technological advances have increased the speed of iterative reconstruction, allowing clinically useful images and significantly less radiation dose.

Among its complex mathematical computations, iterative reconstruction employs a correction loop that decreases image noise while maintaining spatial resolution at lower doses than FBP. Manufacturers vary in the manner that iterative reconstruction computations are employed, but the result is decreased noise artifact and lower patient radiation dose.

PROTECTING THE PATIENT

There are many technical and non-technical factors that impact radiation dose to the patient that must be addressed when developing protocols to reduce radiation dose. When developing these protocols, it is important to always be mindful of the ALARA principle.

> **Determining the amount of image noise that is acceptable is an important step in reducing dose.**

Lowering Radiation Dose

Noise variables of CT exams

First, determining the amount of image noise that is acceptable is an important step in reducing dose. Protocols should be set with technical factors that maximize dose reduction while still maintaining diagnostic image quality. Exams such as CT angiograms, sinus studies, and orthopedic studies can tolerate increased image noise without impacting the diagnostic capability of the scan. Evaluations of the brain, liver, and kidney, however, require low contrast detectability to visualize subtle abnormalities.

Any time an exam requires low contrast detectability, it is important to limit the amount of image noise. As we have learned, exams that require lower image noise will need increased mAs, thus increasing the radiation dose to the patient. The technologist must work closely with the radiologist to fine-tune each protocol. As always, technical parameters should be set at a level that maximizes the diagnostic capability at the lowest radiation dose to the patient.

Multiple series exams and delayed imaging

When implementing reduced dose protocols, the radiologist should alert the technologist when multiple series and delayed imaging (time after the IV contrast is injected) are required. Providing clear instructions of when delayed imaging is needed will limit the number of unnecessarily delayed contrast series and therefore decrease patient dose. Some multiple-series exams are unnecessary and may double the patient’s radiation dose due to lack of clear communication among the imaging team members. Specific guidelines should be developed based on the symptoms of the patient. The technologist should be alerted when additional imaging series may be unnecessary.

For example, CT urograms have been performed in many different ways, including up to four series (unenhanced, arterial, venous, and delayed nephrographic phases). Many centers have elected to reduce the radiation dose by eliminating the arterial and venous phases. A single postcontrast delayed phase is performed using a multiphase contrast injection protocol to ensure adequate renal enhancement and contrast excretion.

Protocols should also provide the required scan ranges (z-axis) for each procedure. Adhering to proper scan ranges is an easy way for the technologist to decrease the radiation dose to the patient.

Multiplanar reconstruction

Another effective way to decrease patient radiation dose is utilization of multiplanar reconstruction (MPR) instead of direct imaging in two planes. Some CT procedures require both axial and coronal views. If a patient is scanned in the axial plane with subsequent coronal MPR reconstructions, radiation dose will be decreased significantly compared to scanning the patient in both axial and coronal planes, eg, for a sinus exam when two planes are necessary. Also, axial lumbar retro-reformations of the spine can be generated with a smaller field of view from routine abdominopelvic acquisitions to save the patient from a second exposure.

Communication

Despite significant advances in technology that limit patient radiation exposure, effective communication by the technologist with the patient remains an important part of CT dose reduction. The technologist should provide clear instructions to the patient before starting a CT procedure. No matter how routine the exam seems to the technologist, the patient may not fully appreciate their own role. The patient should understand the breathing instructions and the importance of remaining still. If an IV contrast agent is administered, the patient should be made aware of the sensations likely to be felt during the injection phase. Pediatric and geriatric patients may require more instruction.

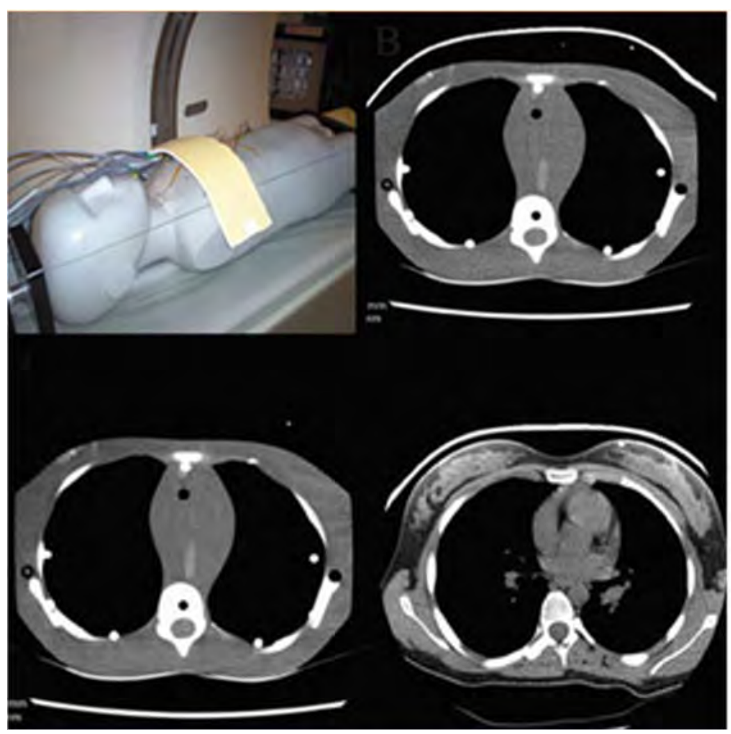

Figure 19. Example of a breast bismuth shield. Top right and bottom left images are of a phantom, while bottom right is a patient scan.
For more information click here. [Medscape Today]

Effective communication by the technologist with the patient remains an important part of CT dose reduction.

Non-English-speaking patients may require the assistance of an interpreter. No matter the circumstance, it is important the patient understands the instructions and potential physical sensations to limit repeat exposures.

Shielding Devices

The technologist should use shielding whenever possible. Lead aprons can be used outside of the scan range to cover radiosensitive organs such as breasts, thyroid cartilage, and genitals. In-plane bismuth shields decrease radiation to organs within scan range while maintaining acceptable image quality. In-plane bismuth shields *filter* radiation rather than *blocking* the x-ray beam completely like lead shields. In-plane shields are commonly used on breasts, thyroid cartilage, and the eyes (**Figure 19**). Studies have shown covering sensitive body areas with a shield of bismuth, a metal that is 85% as dense as lead, can reduce radiation to the breast by 26-52% depending on the thickness of the shield.

However, use of bismuth shields is somewhat controversial as the shields can reduce the SNR of the resulting images. If the scan technique is then changed to compensate for the signal changes, there may be little net benefit to the patient. All technologists or others in the scan room during scan acquisition must wear lead shielding and remain as far away as possible from the gantry to limit x-ray exposure.[28]

Minimizing Risk to Pregnant Patients

The CT technologist must ask all women of childbearing age about the potential for pregnancy and the date of their last menstrual period. If the patient's menstrual period is late, it is assumed that she is pregnant until proven otherwise. The safest time to scan a female patient of childbearing age is within ten days of the onset of their last menstrual period when the probability of pregnancy is much less likely.

Stages of pregnancy

During the early stages of pregnancy, the effect of ionizing radiation on the embryo is random but can result in death and subsequent miscarriage. Within the first two weeks of development, an embryo is comprised of just a few cells. Therefore, damage to just one of the cells may be fatal. However, embryos that survive are not at increased risk for developmental deformities.

Throughout the remaining of the first and majority of the second trimester, the potential for deformity caused by radiation is increased, peaking at weeks 8–15. After week 15 of pregnancy, radiation exposure to the fetus is not believed to increase the risk of deformity.[29]

The risk of radiation-induced cancer to the embryo/fetus throughout the three trimesters of pregnancy is not known. The assumption is that the risk is similar or slightly greater than that for a young child. However, the risk to a young child is much greater than for an adult, and extra precautions must be taken with pregnant patients.

Benefit vs risk

The decision to scan a pregnant patient should be made after careful counsel among the patient, the referring physician, and the radiologist. Sometimes ultrasound or MR imaging will be adequate. However, in some cases the benefit of having the CT scan may outweigh the risk to the embryo/fetus, as with potentially life-threatening conditions such as abdominal trauma or pulmonary embolism.

If the decision is made to proceed with a CT scan, the abdomen of the mother provides some protection to the embryo/fetus, but abdominal and pelvic shielding and dose reduction techniques should be used when possible.

Minimizing Risk to Children

The reason pediatric patients are at increased risk for developing radiation induced cancers are twofold. First, organs in children are still developing and therefore more sensitive to the effects of radiation as compared to adults. Second, because the life expectancy of a child is greater than that of an adult, a cancer has more time to develop, and radiation-induced cancers may take decades to appear.

A 2001 study by Brenner et al showed that 600,000 abdomen and head CT scans performed annually on patients ≤15 years could lead to 500 deaths from radiation-induced cancers.[30]

At the 2001 conference of the Society of Pediatric Radiology, a 200% increase in pediatric CT scans was reported in just a few years. The study noted a lack of attention to the hazards of ionizing radiation exposure in children and the need to adjust dose based on body size.[31]

A more recent study in 2011 by Kocher et al reported an increase in CT scans ordered by emergency departments. Although the greatest increase in CT scans was for elderly patients, pediatric use of CT grew almost 500%. Among patients younger than 18 years, the use of CT increased from 1.1% of all CT exams in 1996 to 5.2% of all exams in 2007.[32]

Image Gently campaign

Knowing the risk to pediatric patients, CT staff must be cautious about overexposing this radiosensitive population and special pediatric protocols must be implemented. Due to their smaller size, pediatric patients require less radiation exposure than adult patients. Radiology practices can obtain technical guidance from the *Image Gently* campaign, an initiative of the Alliance for Radiation Safety in Pediatric Imaging, which provides pediatric radiation safety materials for physicians, technologists, radiation physicists, and parents. The *Image Gently* initiative has developed protocol algorithms to assist the radiology practice with pediatric CT techniques by utilizing a **mAs reduction factor** (mAs RF). The mAs RF is a numeric value of less than 1 that is multiplied by the baseline adult head, chest and abdomen mAs values used by the radiology practice.

Developing pediatric protocols

Image Gently recommends radiology practices work with a radiation physicist to establish adult protocols within the recommendations of the American College of Radiology CTDIvol values for adult head and abdomen exams. The ACR CTDIvol reference value for an adult head is 75 mGy, and an adult abdomen is 25 mGy. The radiation physicist determines baseline values are within range by measuring the CTDI on phantoms. If baseline protocols are greater than the ACR CTDIvol reference values, the mAs should be lowered until the CTDIvol is at or lower than the recommended value.[33]

Once the adult protocols are within the ACR reference CTDIvol values, pediatric protocols can be developed. The following example demonstrates how mAs RF is calculated.

If the baseline abdomen mAs is 100, what would the adjusted protocols be for a 5-year-old patient and a15-year-old patient using *Image Gently* protocols?

5-year-old patient
mAs RF = 0.59

100 mAs x 0.59 = 59 mAs

15-year-old patient
mAs RF = 0.76

100 mAs x 0.76 = 76 mAs

Use of automatic exposure controls or dose modulation software can also significantly decrease radiation dose to the pediatric patient. In a study of pediatric chest CT scans, Alibek et al found an average of 30% dose reduction when dose modulation was used as compared with standard body weight-adapted protocols. [34]

Non-technical factors when imaging children

Beyond developing pediatric-safe protocols, the CT technologist should take extra precautions to limit radiation exposure to young patients. Effective age-appropriate communication about the need to hold still during the potential sensations caused by the administration of iodinated contrast may limit the need for repeat exposures.

It is vital that the technologist works efficiently to limit the time young patients wait on the table to minimize the chance of patient movement. Gentle immobilization techniques may be beneficial for some exams. Pitch or rotation time can be adjusted but may only reduce scan time slightly, so the child's compliance is required. Also, increasing the pitch or decreasing the rotation time will adversely impact additional images if the child moves during scan acquisition as the per-image time will decrease. Thus, adjusting pitch or rotation time is not the preferred solution when the likelihood of motion artifact is increased, as it often is with pediatric patients.

The technologist must also shield this radiosensitive group whenever possible to decrease the risk of radiation-induced cancers. In–plane bismuth shields reduce dose while maintaining acceptable image quality. Studies have shown that bismuth shields reduce breast exposure by 29% and orbit exposure by 34% in pediatric patients. Family members or technologists who remain in the scan room during scan acquisition must wear lead shielding and stay as far from the gantry as possible to limit radiation exposure. [35]

For additional information on the *Image Gently* initiative, go to www.imagegently.org.

Exam-Specific Techniques to Minimize Radiation Dose

Cardiac CTA

Heart disease remains the number one cause of death for Americans, as well as the number one cause of disability.[36]

Cardiac CT angiography (CTA) imaging has become a reliable tool for the detection of coronary artery disease, as well as for determining whether further intervention such as cardiac catheterization is needed. However, if low dose imaging techniques are not utilized, radiation dose levels for CTA can reach 20 mSv per exam or greater.

Between February and December 2007, the PROTECTION I study collected cardiac CTA data from 50 hospitals worldwide. The median effective dose of the 1,965 cardiac CTA procedures was 12 mSV per exam, less than a thallium stress test, which can deliver up to 22 mSV per exam.

However, the results revealed a broad discrepancy in dose ranges. The median dose ranged from a low of 2.1 mSV to a high of 21 mSv per exam. The investigators concluded that the variable radiation differences were due to a lack of low dose imaging strategies at the hospitals with higher exposure rates.[37]

Electrocardiographic gating

CT scanner manufacturers have developed techniques for optimal imaging of the coronary arteries. The best quality imaging of the heart usually occurs during **diastole**, also known as the resting phase when there is the least cardiac motion. **Systole** is the phase of most cardiac motion and is therefore not desirable for cardiac imaging. In order to successfully image the coronary arteries, **electrocardiographic gating** (ECG) must be utilized (**Figure 20**). ECG is a means by which to synchronize heart beats to obtain an image during diastole, when the heart is resting. ECG leads are placed on the patient's torso, allowing synchronization of the patient's cardiac cycle during image acquisition. Cardiac gating is used to improve temporal resolution and minimize imaging artifacts caused by cardiac motion.

Figure 20. Illustration of normal sinus rhythm for a human heart as seen on ECG. *For more information, click here.* [Wikimedia]

Prospective and retrospective triggering

Prospective triggering is a cardiac scanning technique that results in lower radiation doses than other cardiac imaging techniques. Prospective triggering uses the ECG signal to control scanning, while the heart is scanned axially in a step-and-shoot format. The first portion of the heart is scanned during a user-determined percentage of the diastolic cycle. The table is moved to the next position and when the ECG signal is again in diastole, the next image is acquired. Three to four separate acquisitions are usually required to image the entire heart. Studies have shown the radiation dose falls in the range of 1-3 mSv using prospective triggering.[38]

Prospective triggering should not be used on patients with rapid heart rates or arrhythmias as images may be of poor quality due to inability to reconstruct all phases of the cardiac cycle.[39]

Retrospective triggering utilizes helical scanning and is a better imaging technique for patients with rapid heart rates or arrhythmias due to the ability to reconstruct all systolic and diastolic phases. However, this technique emits a higher radiation dose than prospective triggering. One technique to lower doses with retrospective gating is electrocardiographic gating dose modulation, which lowers mAs when the patient's heart is in systole, with a resultant significant decrease in radiation dose.

Takakuwa et al compared doses of 267 patients who had retrospective coronary CTA exams with and without the use of ECG dose modulation. The exams that did not utilize ECG dose modulation delivered an average dose of 18 mSv, while the exams that did employ this dose modulation strategy delivered an average dose of 8.75 mSv.[40]

The role of heart rate

In cardiac imaging, the lowest radiation doses are attained at lower heart rates when prospective triggering technique is most successful. Oral or IV **beta blockers** can be administered to lower heart rate to an optimal level of 50-60 beats per minute (bpm). Patients should also abstain from caffeine or nicotine the day of the cardiac CTA to keep the heart rate as low as possible.

Recently, the Department of Radiology of Capital Medical University in Beijing, China conducted a study comparing dual source coronary CTA (DS-CTCA) to retrospective ECG gating on patients with heart rates greater than 70 bpm. One hundred patients with heart rates between 70 and 110 bpm were studied; 50 patients were scanned utilizing DS-CTCA technology and the other 50 utilizing retrospective gating. The results of the study, released in November 2010, revealed that the image quality was *slightly better* with DS-CTCA but with a significant average radiation dose savings of 57%, an average dose of 5.1 mSv per exam.[41]

Low dose CT lung screening

Although CT has received a lot of attention for its potential to increase cancer risk, a recent study demonstrated the positive impact of CT scans on patient health. Low dose CT lung screening exams are usually performed on patients with increased risk for lung cancer, like family history of lung cancer, smoking history, and age. Lung cancer claims more lives in the United States than all other cancers; in fact, lung cancer claims more than the next three cancers combined.[42] CT lung screening exams are performed without the use of iodinated contrast using mAs levels lower than a standard CT chest exam. Lung tumors are high-contrast structures in comparison to air-filled lungs, so increased image noise has minimal impact on the ability of the radiologist to diagnose small tumors. The CT technologist and radiologist should develop a low dose protocol that maintains diagnostic quality while minimizing radiation dose.

The National Lung Screening Trial (NLST) was conducted to determine whether low dose CT lung screening exams could reduce mortality from lung cancer. More than 50,000 patients with high lung cancer risk factors were enrolled in the trial conducted at 33 medical centers in the United States. Half of the participants underwent low dose CT lung screening exams, while the other half had chest radiographs. The study was conducted from 2002 and 2004, with deaths from lung cancer calculated at the end of 2009.

NLST found that CT lung screening diagnosed more than three times more lung cancers than conventional chest radiographs. More importantly, the low dose CT lung screenings literally saved lives; the mortality rate for the patients diagnosed with lung cancer by chest radiograph was 20% higher than the participants who had low dose CT lung screening exams. An added benefit for participants receiving lung CT was a 7% *decrease* in deaths for reasons other than lung cancer. Patients with smoking history are also at increased risk for coronary artery disease and emphysema, both of which may be evident on a lung screening study. Once these patients were identified, immediate medical intervention may have accounted for the 7% decrease in non-lung cancer deaths.

The National Lung Screening Trial also evaluated patient radiation dose exposure for the 26,000 participants who received low dose CT lung screening exams. The trial concluded that effective doses of 1.5 mSv can be obtained on CT lung screening exams while maintaining adequate diagnostic capability. The average effective dose for a standard chest CT is approximately 7 mSV; thus CT practices should strive to set mAs levels much lower for a screening lung CT than for standard chest CT.[43]

Low dose abdomen and pelvis CT for Crohn's Disease

Patients with Crohn's disease are often diagnosed at an early age, requiring significant follow-up diagnostic testing. A CT scan of the abdomen and pelvis may expose a patient to an effective dose of more than 20 mSv. In 2012, researchers in Ireland published findings showing that low dose software using iterative reconstructions decreased radiation doses by 32-65% on CT enterography exams, with doses as low as 1 mSv. CT may have some advantages for Crohn's patients due to increased temporal and spatial resolution as compared to MRI enterography. Limiting radiation dose is essential for patients with Crohn's disease due to the number of follow-up procedures required and an existing increased risk of developing small bowel lymphoma or other bowel malignancies in this patient population.[44]

PROTECTING THE CLINICAL STAFF

Occupational Radiation Guidelines

Limiting radiation exposure to the technologist, radiologist, and other healthcare workers is critical. The same principles of radiation risk to patients apply to the radiology team. While lead-lined walls protect the technologist from radiation scatter during the CT exam, the technologist and other staff should stay out of the exam room during imaging if possible. If it is necessary to remain in the exam room during image acquisition, the technologist must wear lead shielding and remain as far from the gantry as possible. The **inverse square law** states that the further one is away from the x-ray source, the less intense the x-ray beam becomes (**Figure 21**).

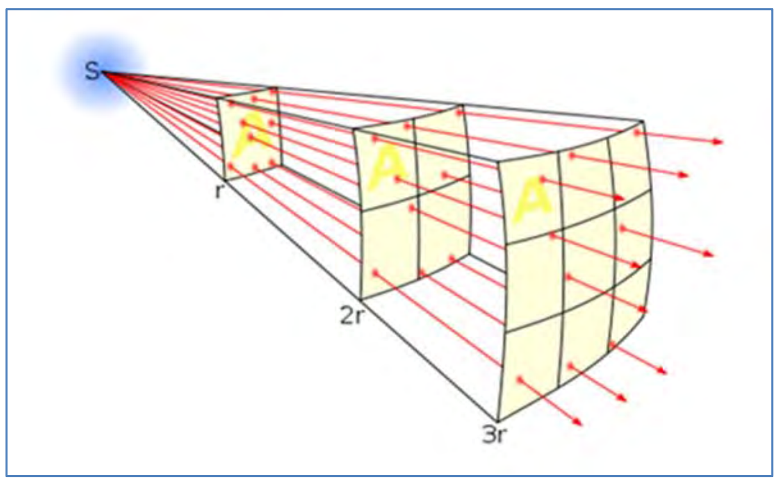

Figure 21. Illustration of the inverse square law. S represents an ideal source of electromagnetic radiation and A (note all three sets of yellow squares) represents an arbitrary segment of the surface of a sphere of radius (r). *For more information, click here.* Wikimedia

Current occupational guidelines for occupational radiation exposure include[45]:

1. Total effective dose equivalent of 5 rems (0.05 Sv) to the whole body or deep-dose equivalent to any individual organ other than the lens of 50 rems (0.5 Sv). Deep-dose is measured at a tissue depth of 1 cm.
2. Lens dose equivalent of 15 rems (0.15 Sv). The lens dose equivalent is measured at a tissue depth of 0.3 cm.
3. Shallow dose equivalent of 50 rems (0.50 Sv) to the skin or to any extremity. Shallow dose is measured at a tissue depth of 0.007 cm averaged over 10 cm2.

Role of the Radiation Safety Officer

Occupational exposure to radiation is regulated by the National Council of Radiation Protection and the U.S. Food and Drug Administration. The NCRP regulates radiation monitoring of all personnel working with ionizing radiation in the workplace. In the radiology setting, this includes technologists, radiologists, nurses, physicists, other physicians, biomedical repair personnel, and others.

Non-stochastic effects occur at higher levels of radiation where illness can be predicted, while stochastic effects are based on statistical risk and are considered all-or-nothing events.

Radiation monitoring is the responsibility of the Radiation Safety Officer. Beyond monitoring, the safety officer is responsible for counseling and educating those who are exposed to ionizing radiation on the job. The Radiation Safety Officer must also ensure that all personnel understand radiation safety and protection. A successful radiation protection program will limit the risk of stochastic effects to personnel to that of the risk of a non-radiation worker; in other words, there should be a zero-tolerance policy regarding stochastic effects. A well-implemented program will also prevent the occurrence of non-stochastic effects. Remember that non-stochastic effects occur at higher levels of radiation where illness can be predicted, while stochastic effects are based on statistical risk and are considered all-or-nothing events, that is, the exposed person will either become ill or not.

Radiation Safety Monitoring

Radiation monitoring of individual employees is accomplished by use of personal monitor badges (**Figure 22**). The badges are usually placed at the collar but may be worn at the belt as well. The badge should be placed *outside* of a lead shield to quantify the exposure to non-protected areas of the body. The *annual* limit of dose allowed by the NCRP for radiation workers is 0.5 Sv.

Figure 22. Example of employee radiation safety badge.

Pregnant employees

Pregnant employees require an additional monitor badge that should be annotated to identify it as a monitor for the fetus. This monitor should be worn at the level of the naval and should be placed *behind* the lead shield when worn by the pregnant employee. Due to the increased sensitivity to radiation by the fetus, the *fetal* dose allowed is only 0.05 Sv or 5 mSv annually.

Exceeding Occupational Radiation Limits

Radiation workers who exceed annual limits of radiation will not be allowed additional occupational exposure for the remainder of the calendar year. Only occupational exposure is tabulated in the exposure limits. Therefore, a radiation worker's radiation exposure received from personal medical exams such as x-rays or CT scans will not count toward their annual occupational exposure.

SUMMARY

Exposure to excessive radiation often has detrimental effects on humans, ranging from erythema to acute radiation syndrome leading to death. Latent effects of ionizing radiation such as cancer can take decades to develop. Manufacturers have developed software to decrease radiation dose, but the technologist must also limit dose by adhering to the ALARA principle. The technologist must also understand the impact of each of several technical factors on patient radiation dose. This responsibility is one of the defining elements of the technologist's professional status. The goal must always be to obtain the best quality scans while exposing the patient to the minimum amount of radiation. In order to attain this goal, the technologist and radiologist must work in tandem to develop and implement exam-specific protocols that lower radiation dose while maintaining acceptable image quality. By implementing radiation safety measures, radiology practices will protect both patients and staff, while providing diagnostic-quality CT images.

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GLOSSARY

automatic exposure controls (AEC)
a device that automatically adjusts the tube current relative to the patient attenuation; also known as *dose modulation*

becquerel (Bq)
the activity of a quantity of radioactive material in which one nucleus decays per second. *Becquerel* is the SI term; *Curie* is the conventional term. Named for Henri Becquerel, who shared a Nobel Prize with Pierre and Marie Curie in 1903 for their discovery of radioactivity.

beta blocker
a class of drugs used to manage cardiac arrhythmias, cardioprotection after myocardial infarction (heart attack), and hypertension

bowtie filter
filters that decrease dose to the periphery of the patient by removing photons that would not positively impact image quality

CT Dose Index (CTDI)
defined by the US Department of Health and Human Services (HHS) as the average dose imparted by a single axial acquisition to a standard 100-mm pencil chamber dosimeter inside a PMMA phantom over the width of 14 CT slices

cumulative dose
total amount of radiation dose a person receives over a period of time

curie (Ci)
a unit of radioactivity equal to the amount of a radioactive isotope that decays at the rate of 3.7 x 10(10) disintegrations per second. Curie is the conventional term; *becquerel* is the SI term. Named for Marie and Pierre Curie.

data acquisition system (DAS)
the electronics positioned between the detectors and computer responsible for collecting image data

diastole
the period of time when the heart refills with blood after systole (contraction); the resting phase

dose length product (DLP)
measure of total radiation exposure for a CT study

effective dose
a measure of the effect that a radiation dose to part of the body will have on the whole organism. Effective dose accounts for the varying radiosensitivities of organs or regions of the body.

effective mAs
reflects the average absorbed dose in a scan volume when pitch is adjusted;
Effective mAs = mAs / pitch

electrocardiographic gating (ECG)
a means by which to synchronize heart beats to obtain an image during diastole, when the heart is resting; used to improve temporal resolution and minimize imaging artifacts caused by cardiac motion

erythema
abnormal redness of the skin, caused by local congestion of the capillaries, as in inflammation

filtered back-projection (FBP)
method of image reconstruction that uses a basic numeric approach; multiple beams are passed through an object, creating multiple projections which are then back-projected. The resulting images are calculated to create a single object image.

gray (Gy)
the SI derived unit of absorbed radiation dose of ionizing radiation, defined as the absorption of one joule of ionizing radiation by one kilogram of tissue. Named for the British physicist Louis Harold Gray

hormesis
the hypothesis that low doses of ionizing radiation (within the region and just above natural background levels) are beneficial, stimulating the activation of repair mechanisms that protect against disease that are not activated in absence of ionizing radiation

International System of Units (SI)
the modern form of the metric system and generally a system of units of measurement devised around seven base units and the convenience of the number ten

inverse square law
the principle that the further one is away from the x-ray source, the less intense the x-ray beam becomes

ionization
occurs when radiation has enough energy to remove an electron from orbit around the nucleus of an atom, causing the atom to become charged

isocentering
centering the patient vertically at the intersection of the gantry axis of rotation as defined by the gantry's positioning lights. Improper isocentering increases patient radiation dose.

iterative reconstruction (IR)
the process of passing images through numerous software filters and noise-reducing calculations to reduce image noise, allowing for diagnostic-quality images at lower radiation doses

lifetime attributable risk (LAR)
the amount or proportion of incidence or risk of disease or death in individuals exposed to a specific risk factor that can be attributed to exposure to that factor; the difference in the risk for unexposed versus exposed individuals

linear no-threshold model (LNT)
a model used in radiation protection to estimate the long term, biological damage caused by ionizing radiation

mAs reduction factor (mAs RF)
a numeric value of less than one that is multiplied to a site's baseline adult head, chest, and abdomen mAs values when developing pediatric techniques

mitosis
the process by which a cell separates the chromosomes in its nucleus into two identical sets, in two separate nuclei

multi scan average dose (MSAD)
the average radiation dose over the central scan of a CT study consisting of multiple parallel scans; dose measurement similar to but more accurate than CTDIvol

non-stochastic effects
the severity of health effects which vary with radiation dose and for which a threshold is believed to exist; skin erythema and radiation-induced cataract formation is an example of a non-stochastic effect

penumbra
the nonuniform, nonuseable portion of the x-ray beam

pitch
the distance the patient table travels in the time it takes the tube to complete one full 360° rotation divided by the slice width

quality factor (QF)
the factor by which the absorbed dose (rad or gray) must be multiplied to obtain a quantity that expresses, on a common scale for all ionizing radiation, the biological damage (rem or sievert) to the exposed tissue

radiobiology
the branch of biology dealing with the effects of radiation on living matter

radiation absorbed dose (rad)
the measure of absorbed dose by a person or the amount of energy deposited per unit of weight of human tissue; *rad* is the conventional term; *Gray* is the SI term.

radioactive isotope
an element that has radioactive qualities, eg, caesium-134, caesium-137, and iodine-131

radionuclides
an atom with an unstable nucleus caused by excess energy

roentgen equivalent in man (rem)
a person's biological risk from radiation exposure is measured in rems; *rem* is the conventional term; *sievert* is the SI term.

scan range
the entire area being scanned on the patient

sievert (Sv)
radiation dose equivalent. Sv is the SI term; rem is the conventional term. Named for Rolf Maximilian Sievert, a Swedish medical physicist renowned for work on radiation dosage measurement and research into the biological effects of radiation.

stochastic effects
effects produced at random without a threshold dose level, the probability of occurrence being proportional to dose and severity being independent of dose; in radiation safety, the main stochastic effects are carcinogenesis and genetic mutation; the statistical risk of developing a radiation-induced cancer from low level radiation

synthesis phase
also known as "S phase," occurs during the interphase of a cell cycle between the G1 and G2 stages; DNA molecules "unzip" and each old strand attracts free nucleotides forming complementary new strands, leaving two strands of DNA identical to the original strand of DNA

systole
contraction of the heart muscle; phase of the heart beat with the most motion

tolerance dose
the amount of radiation that may be received by an individual within a specified period with negligible results

ABBREVIATIONS OF TERMS

AAPM	American Association of Physicists in Medicine
ACR	American College of Radiology
AEC	automatic exposure controls
ALARA	as low as reasonably achievable
ASRT	American Society of Radiologic Technologists
Bq	becquerel
BEIR	Committee on the Biological Effects of Ionizing Radiation
bpm	beats per minute
Ci	Curie
CTA	CT angiography
CTDI	CT Dose Index
CTDIvol	CT Dose Index Volume
CTDIw	weighted CT Dose Index
DAS	data acquisition system
DICOM	Digital Imaging and Communications In Medicine
DIR	Dose Index Registry
DLP	dose length product
DS-CTCA	dual-source coronary CT angiography
ECG	electrocardiogram or electrocardiac gating
FBP	filtered back-projection
FDA	Food and Drug Administration
Gy	gray
ICRP	International Commission on Radiation Protection
IR	iterative reconstruction
JCAE	Joint Committee on Atomic Energy
kVp	peak kilovoltage
LAR	lifetime attributable risk
LNT	linear no-threshold model
mAs	tube current (mA) x scan time
mAs RF	mAs reduction factor
mGy	milliGray; 0.001 Gy
mGy-cm	milliGrays per centimeter
MITA	Medical Imaging and Technology Alliance
MPR	multiplanar reconstruction
mSv	millisievert; 0.001 Sv
MSAD	multi scan average dose
NAS	National Academy of Science
NCRP	National Council on Radiation Protection
NEMA	National Electrical Manufacturers Association
NLST	National Lung Screening Trial
P	pitch
QF	quality factor
rad	radiation absorbed dose
RF	reduction factor
rem	roentgen equivalent in man
RSNA	Radiological Society of North America
Sv	sievert
SI	International System of Units
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation