In the Diagnostic Medical Imaging Radiation Exposure and Risk of Development of Solid and Hematologic Malignancy article, understanding the research used to govern safe radiation exposure doses is crucial. This involves gaining perspective on the spectrum of doses of ionizing radiation from common diagnostic imaging modalities. Moreover, recent initiatives in decreasing radiation exposure are necessary to minimize patients’ exposure, significant risks are found when diagnoses are missed and subsequent treatment is withheld. Therefore, based on epidemiologic data obtained after nuclear and occupational exposures, dose exposure limits have been estimated. A recent collaborative effort between the US Food and Drug Administration and the American College of Radiology has provided information and tools that patients and imaging professionals can use to avoid unnecessary risks posed by diagnostic imaging.
D

oignostic imaging technology has advanced significantly since the introduction of the radiograph by Wilhelm Röntgen in 1895. At that time, little was known about the harmful effects of radiograph beam radiation, and accidental exposures served as hard lessons in the consequences of exposure. Following Röntgen’s development of the radiograph, Thomas Edison attempted to use the radiograph tube to develop an illuminating lamp but soon discovered that his assistant developed alopecia and skin ulcerations and subsequently died of metastatic carcinoma in 1904.

Large single-dose exposures and cumulative exposures have been associated with solid tumors and hematologic malignancy. Over the past 100 years, multiple cohorts of exposed populations have been examined for dose–response relationships between radiation exposure and malignancy, and these historical data have been used to determine harmful and lethal doses and have subsequently helped establish personal and occupational exposure limits.

Since the discovery of radiographs, ionizing (eg, radiography, fluoroscopy, and computed tomography [CT] scan) and nonionizing (eg, ultrasound and magnetic resonance imaging) modalities have emerged. Patient safety remains a priority with these newer imaging modalities. Due to their frequent use and the higher dose of ionizing radiation, CT scans are of the highest concern. Exposure is common, and therefore the at-risk population is large, owing to the fact that 72 million CT scans are performed in the United States each year, and the rate has increased 12% annually from 1993 to 2007. As of 2007, medicine represented the largest source of ionizing radiation exposure to the US population and has been reported to be the single largest manmade population exposure, affecting nearly everyone who seeks medical care. Appearance of this information in popular media created a scare among patients and brought the issue of CT scanning overuse and radiation exposure to the forefront of the medical lay press.

Although associations between ionizing radiation and increasing frequency of CT scanning have been a driving force in minimizing patients’ exposure to ionizing radiation, significant risks occur when diagnoses are delayed or missed and subsequent treatment is withheld due to fears of radiation exposure. Overexposure to ionizing radiation and missed diagnoses have large economic and biopsychosocial consequences, affecting patients, families, and the medical system. Maximizing patients’ benefits and minimizing potential harm involves judicious use of radiological studies, use of nonionizing radiation modalities whenever possible, and properly dosing ionizing radiation when needed to maximize study resolution without delivering excessive radiation doses. This article outlines the research used to govern safe radiation doses, defines recent initiatives in decreasing radiation exposure, and provides orthopedic surgeons with specific techniques that may help decrease radiation exposure in their daily practice.

CURRENT RESEARCH

Several obstacles exist when attempting to study the effects of ionizing radiation on humans. Ionizing radiation is carcinogenic in humans and teratogenic in fetuses. Because there is, by definition, no safe dose to administer for human testing, experimental human study designs are unethical, and information gleaned from animal studies is limited due to their dissimilar genome and physiology compared with those of humans. Therefore, limited pure biologic evidence exists, but animal studies support the view that low-dose radiation acts principally on the early stages of tumorigenesis, and a dose-dependent relationship exists between radiation dose and induction of DNA damage in cells.

No large-scale epidemiologic study of cancer induction by diagnostic radiation is reported in the literature. Therefore, the greatest amount of information regarding human exposure to radiation is from studies of atomic-bomb survivors, which provide the ability to calculate dose-response. Many advantages are found in studying this population: a large number of participants (120,321 in the original Life Span Study [LSS] cohort), inclusion of both sexes, a varied array of dose ranges, and total body exposure, which allows for assessment of cancers at various body sites. Although medical radiation studies, occupational exposures, and environmental studies have also provided some insight, the LSS cohort is the most robust cohort of clinical participants.

Samartzis et al reviewed the LSS cohort to determine threshold exposures for the development of radiation-induced bone sarcoma. They analyzed 80,181 participants and determined a threshold dose of 0.85 Gy using Poisson regression. The most common tumor was pelvic osteosarcoma. Survival in these participants was low, with a 5-year mortality rate of 75%. The same cohort has also been analyzed for increased incidence and radiation threshold of nonmusculoskeletal tumors. Hematologic malignancy rates were higher than those seen in the general population, including leukemia and lymphoma. In total, 34% of leukemia deaths were attributable to radiation exposure in survivors exposed to >0.005 Gy.

A meta-analysis by Daniels and Schubauer-Berigan evaluated 23 pri-
Primary research investigations that assessed occupational protracted exposures to low-dose ionizing radiation and calculated an excess relative risk of leukemia of 0.19 at 0.1 Gy. This is lower than that noted in the LSS cohort but can be explained by differences in exposure types: single-event vs chronic protracted exposure. Further epidemiological data suggest that acute exposures are 2 to 5 times more potent on increased cancer risk in humans than protracted exposures.13

Li et al14 evaluated the LSS cohort for solid and hematologic malignancies and noted an incidence of 17.2% for solid tumors, 0.35% for leukemias, and 0.52% for lymphomas and myelomas. All cancers studied (ie, gastric, lung, colon, liver, female breast, thyroid, bladder, lymphoma, and leukemia) noted a threshold value of 0.005 Gy, with varying increases in relative risk with levels above that threshold. Malignancies most sensitive to radiation dose were those with greater increases in relative risk for dose exposures >0.005 Gy, and included lung, colon, female breast, thyroid, bladder, and leukemia. These data were corroborated by Preston et al,15 who noted that 11% of solid tumors in participants exposed to >0.005 Gy could be attributed to radiation exposure, with increasing relative risk in a dose-response relationship. They also noted a decrease in excess relative risk of 17% per decade increase in age at exposure when controlling for age at diagnosis, and an increase in excess relative risk throughout the study period when controlling for age at exposure, indicating that radiation-associated increases in cancer rates persist throughout life regardless of age at exposure. When evaluating nonsex-specific cancers, no sex differences existed in rates of malignancy.

Studies of the LSS cohort have produced robust evidence that exposure to ionizing radiation >0.005 Gy (5 mSv) confers an increased risk of solid and hematologic malignancy, with a dose-dependent increase in relative risk. Bone tumors have a higher exposure threshold of 0.85 Gy (850 mSv) prior to excess relative risk. Estimates of excess relative risk from the LSS cohort are higher than those from studies examining participants with protracted low-dose exposure, and therefore may lead to an overestimate of the LSS studies on cancer risk. Radiation-associated increases in cancer rates persist throughout life regardless of age at exposure, and earlier exposure is associated with increased excess relative risk of developing radiation-induced malignancy during one’s lifetime. Given these data, risk of malignancy increases in a dose-dependent manner. Therefore, it is important to determine current patient exposures from diagnostic radiology studies and identify potential methods of decreasing patient exposure.

Fazel et al16 analyzed utilization data from 952,420 participants aged between 18 and 64 years to determine average annual radiation exposure doses. Median effective dose was 0.1 mSv per participant per year. Cumulative effective doses increased with advancing age and were higher in women than in men. Interestingly, CT scans accounted for 75.4% of exposure, with 81.4% of those being administered in the outpatient setting. In total, 80% of men and 78% of women were exposed to no or low doses (0-3 mSv) of radiation annually. Although a significant minority of participants were exposed to higher doses of radiation, they were typically elderly patients.16 Table 1 shows the average dose of various imaging procedures that use ionizing radiation. Plain radiography creates less exposure than fluoroscopy (continuous radiograph) or CT scanning, with interventional procedures generating the greatest exposures. For comparison, Table 2 lists sources of background radiation and average effective dose.18 Extremity radiography exposes patients to 1/3000 of yearly background radiation and 1/1000 of the radiation exposure of a round-trip transcontinental flight. Fluoroscopic and CT examination exposures are greater.

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**Table 1**

<table>
<thead>
<tr>
<th>Study</th>
<th>Average Effective Exposure, mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myocardial perfusion imaging</td>
<td>15.6</td>
</tr>
<tr>
<td>Chest (noncoronary) CT angiography</td>
<td>15</td>
</tr>
<tr>
<td>Percutaneous coronary intervention</td>
<td>15</td>
</tr>
<tr>
<td>Abdomen CT</td>
<td>8</td>
</tr>
<tr>
<td>Chest CT</td>
<td>7</td>
</tr>
<tr>
<td>Nuclear bone imaging</td>
<td>6.3</td>
</tr>
<tr>
<td>Cervical spine CT</td>
<td>6</td>
</tr>
<tr>
<td>Lumbar spine CT</td>
<td>6</td>
</tr>
<tr>
<td>Pelvis CT</td>
<td>6</td>
</tr>
<tr>
<td>Neck CT</td>
<td>3</td>
</tr>
<tr>
<td>Head or brain CT</td>
<td>2</td>
</tr>
<tr>
<td>Thyroid uptake</td>
<td>1.9</td>
</tr>
<tr>
<td>Lumbar spine radiography</td>
<td>1.5</td>
</tr>
<tr>
<td>Abdomen radiography</td>
<td>0.7</td>
</tr>
<tr>
<td>Mammography</td>
<td>0.4</td>
</tr>
<tr>
<td>Chest radiography</td>
<td>0.1-0.02</td>
</tr>
<tr>
<td>Extremity radiography</td>
<td>0.001</td>
</tr>
</tbody>
</table>

**Table 2**

<table>
<thead>
<tr>
<th>Source</th>
<th>Average Effective Exposure, mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic radiation/ background</td>
<td>3</td>
</tr>
<tr>
<td>Radon gas</td>
<td>2</td>
</tr>
<tr>
<td>Living at plateau/ altitude</td>
<td>+1.5</td>
</tr>
<tr>
<td>Coast-to-coast round-trip flight</td>
<td>+0.03</td>
</tr>
</tbody>
</table>
and, therefore, of higher clinical concern with repeated studies.

Children’s exposure to ionizing radiation is an elevated concern given their developing physiology and increased risk of lifetime malignancy with early radiation exposure. The use of CT scans in children has increased rapidly and has been primarily driven by the speed with which a scan can be performed (within a matter of seconds), which essentially eliminates the need for anesthesia to limit motion during imaging. Adult and pediatric victims of blunt trauma routinely undergo intense imaging in the emergency room and trauma bay to facilitate rapid diagnosis.

To determine pediatric exposure in a cohort of blunt trauma patients, Mueller et al. prospectively studied all pediatric (aged 0-17 years) blunt trauma patients presenting at a major tertiary care urban medical center emergency department. Dosimeters were placed on reproducible anatomical landmarks of all children prior to initial CT evaluation. Mean whole-body effective dose was 17.43 mSv, which falls within the range of historical doses correlated with an increased risk of leukemia and solid tumors. Although an increased risk of future malignancy exists, the emergent nature of obtaining an accurate and rapid diagnosis for the presenting pediatric trauma patient outweighs such future risk because the consequences of misdiagnosis can be immediately fatal.

Clearly, obstacles exist in conducting meaningful research in this field despite its ubiquitous importance. Again, because it is unfeasible and unethical to conduct directed human research by exposing participants to radiation, studies largely comprise epidemiologic data from atomic-bomb survivors (eg, the LSS cohort), occupational exposures, and observational studies. All methods have strengths and weaknesses. Although the LSS cohort includes patients of varying ages and both sexes, exposures are estimated and acute exposures may overestimate the effect that would be seen with protracted low-dose exposures. Observational studies typically have fewer participants and smaller exposures, but dosimetry allows for more accurate and precise dose measurements. Experimental designs in animals are limited by the genetic and physiologic differences between humans and animals. Regardless of research methodology, it is accepted that ionizing radiation is carcinogenic and that a dose–response relationship exists between exposure and several types of malignancy.

**Future Direction**

It is in the best interest of physicians and patients to minimize exposure to ionizing radiation. However, studies requiring the use of ionizing radiation are clinically necessary and allow for rapid, accurate diagnosis of various disease entities and traumatic conditions. Therefore, future research should be directed toward reducing ionizing radiation as much as is clinically reasonable. As technology emerges, practice guidelines should be updated based on scientific study of new imaging modalities and scanner protocols. Joint efforts between the American College of Radiology and the US Food and Drug Administration, called Image Wisely (in adults) and Image Gently (in children), have initiated educational efforts of patients, families, radiologists, and radiology technicians in an attempt to eliminate unnecessary radiation exposure in patients and health care workers. Minimizing excessive radiation exposure involves using a dose as low as reasonably achievable to obtain proper resolution and therefore prevent the need for repeat imaging. Lead shielding of radiosensitive body parts, collimation (restricting beam area), patient positioning, exposure time during fluoroscopy, and appropriate safety training of all radiology technologists are also imperative.

Research and development of new technology has the potential to achieve higher image resolution with minimal radiation dose. For example, diagnostic workup of certain bony hip abnormalities requires 3-dimensional rendering of bony structures. Previously, routine pelvic CT scans were used to obtain these images, and orthopedic surgeons analyzed bony structures while the increased radiation dose used to obtain soft tissue resolution was wasted.

Early intraintitutional collaboration between treating orthopedic surgeons and radiologists led to the development of low-dose CT scanning protocols that allow the surgeon to gain comprehensive diagnostic information while using minimal radiation exposure. According to personal communication with D. Gallagher, RT, in 2011, this has led to a pelvic CT scanning protocol that gains 3-dimensional imaging of a CT scan while using 2.5 mSv, or the equivalent dose of 4 to 6 pelvic radiographs. This underscores a vital need for an open dialogue between treating physicians, radiologists, and patients and their families regarding the goals of diagnosis and treatment. In addition, early private-sector research has developed CT scanning protocols that minimize radiation by 40% while maintaining a similar level of diagnostic resolution. This leads to more desirable software and equipment that can competitively enter the market, further driving industry research and innovation that benefits patients.

Additional future areas of research should include practical and accessible methods of image portability. A universal imaging display language and accessible electronic medical records would eliminate the need for repeat imaging if patients do not possess their imaging studies. A complete log of cumulative year-to-date and lifetime radiation exposures would allow patients and physicians to make more informed decisions “on the margin” regarding the risk–benefit ratio of further imaging, given the patients’ cumulative dose from multiple studies across multiple practitioners.

**Minimizing Radiation Exposure: Practical Considerations**

Through the use of advanced diagnostic technology, improved operating room
instrumentation, proper safety principles, and rational decision making, orthopedic surgeons can decrease the amount of radiation exposure to themselves, patients, and ancillary medical staff. The easiest and least expensive way to reduce radiation exposure in the operating room is to use standard radiation safety precautions. This involves using the low-dose or pulsed fluoroscopy (rather than extended exposures) to obtain an adequate quality image, which has been shown to dramatically reduce exposure to ionizing radiation.26 Similarly, a mini C-arm fluoroscopy unit can be used in lieu of a standard C-arm for intraoperative extremity fluoroscopy when feasible, which releases a lower dose of ionizing radiation.27 Also, the effective dose received by the operating room staff or patient can be dramatically reduced if they are located at least 36 inches away from the beam.28 Therefore, it is recommended that all nonessential staff remain at least 36 inches away from the radiation source during fluoroscopic exposure. Proper safety equipment, including radiation safety gowns, thyroid shields, gloves, and radiopaque glasses, should be used habitually.29

Advances in surgical instrumentation can also lead to less ionizing radiation in the operating room. For instance, a large number of fluoroscopic images are often required to appropriately place interlocking screws through an intramedullary device via the perfect circles technique. However, several readily available devices largely decrease the need for fluoroscopy for this surgical technique, including a mechanical aiming arm, which affixes to an intramedullary nail proximally and allows for accurate placement of distal interlocking screws.30,33 In addition, techniques using computer navigation and electromagnetic field guidance have been developed to eliminate the use of fluoroscopy for interlocking screw placement.32

Computer navigation has also been well described for several orthopedic procedures. This technology allows for increased surgical precision with less reliance on intraoperative fluoroscopy use and, therefore, decreased radiation exposure. Studies have shown that navigation can dramatically reduce fluoroscopy time during spine surgery when pedicle screw instrumentation is performed.33,34 In addition, navigation has also been described for retrograde drilling of osteochondral lesions, eliminating the need for fluoroscopic radiation.35 This reduction in intraoperative fluoroscopy use is particularly important when dealing with pediatric patients, and posterior spinal fusions with pedicle screw instrumentation and osteochondral lesion drilling are common procedures in the pediatric population that would benefit greatly from a reduction in ionizing radiation exposure.

Finally, patients’ exposure to ionizing radiation can be reduced through rational clinical decision making. Surgeons must ask themselves, “Is this radiograph really necessary?” Some recent publications have suggested that radiography use can be limited without negative diagnostic or clinical consequences. For instance, the standard workup for nonaccidental trauma involves a skeletal survey of the entire body and a follow-up survey a few weeks after the initial encounter. Sonik et al16 reported that no new fractures of the skull, spine, or pelvis had been detected in the follow-up survey based on their series and data from the literature. From this, it can be inferred that routine repeat imaging of the skull, spine, and pelvis is unnecessary unless a high clinical suspicion of injury exists; this is especially important because these anatomic areas receive the highest amount dose exposure, compared with the extremities. Another example is the use of immediate postoperative pelvis radiographs following total hip arthroplasty. The standard practice in many institutions is to obtain an immediate radiograph of the pelvis in the operating room or recovery room to rule out dislocation or periprosthetic fracture. Ndu et al37 reported that, in a series of 632 recovery room radiographs following total hip arthroplasty, 17% of radiographs were inadequately performed. In addition, only 1.9% (12 of 632) identified technical issues, of which only 0.3% (2 of 632) required intervention; 1 was a dislocation diagnosed by clinical examination prior to the radiograph being taken.37 Based on these data, immediate postoperative radiographs may be avoided given the unnecessary economic and health burden associated with their use.

**CONCLUSION**

It is important to balance the immediate, frequently substantial clinical need for radiological studies and procedures against the rare but significant risk of cancer that would not be evident for years, if at all.6 Current research and policies by radiological societies and governmental organizations have brought these concerns to the forefront. Future research should focus on developing technology that allows for improved diagnostic accuracy with less radiation, as well as developing systems-based approaches to image and medical record portability to eliminate duplicate imaging studies. For the time being, orthopedic surgeons should use the techniques outlined in this article to minimize radiation exposure to themselves, patients, and medical staff.

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**MAY 2012 | Volume 35 • Number 5**

**CME ARTICLE**

**MEDICAL IMAGING RADIATION EXPOSURE | FABRICANT ET AL**

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