Occupational Radiation Exposure to the Surgeon

Gordon Singer, MD, MS

Abstract

Increased use of intraoperative fluoroscopy exposes the surgeon to significant amounts of radiation. The average yearly exposure of the public to ionizing radiation is 360 millirems (mrem), of which 300 mrem is from background radiation and 60 mrem from diagnostic radiographs. A chest radiograph exposes the patient to approximately 25 mrem and a hip radiograph to 500 mrem. A regular C-arm exposes the patient to approximately 1,200 to 4,000 mrem/min. The surgeon may receive exposure to the hands from the primary beam and to the rest of the body from scatter. Recommended yearly limits of radiation are 5,000 mrem to the torso and 50,000 mrem to the hands. Exposure to the hands may be higher than previously estimated, even with the mini C-arm. Potential decreases in radiation exposure can be accomplished by reduced exposure time; increased distance from the beam; increased shielding with gown, thyroid gland cover, gloves, and glasses; beam collimation using the low-dose option; inverting the C-arm; and surgeon control of the C-arm.

As instrumentation and surgical technique advance, surgeons increasingly depend on fluoroscopy for intraoperative imaging. Procedures that often require intraoperative fluoroscopy include fracture reduction, intramedullary rodding, percutaneous techniques requiring cannulated and headless screws, Kirschner wire and external fixator pin placement, hardware and foreign body removal, stability assessment, guidance of bone biopsy, and cyst aspiration. Increased use of fluoroscopy exposes the surgeon to potentially harmful levels of radiation. The surgeon must remain close to the x-ray beam and therefore cannot use distance to reduce radiation exposure. How much radiation surgeons receive is an issue of concern, and how much is considered safe is a matter of periodic revision. Medical physics is rarely taught in surgical programs, and little information is available in the orthopaedic literature. The basic concepts of radiation physics, along with specific exposure information, are critically important to any physician who uses fluoroscopy.

Units of radiation include the roentgen, rad, gray, rem, and sievert. The roentgen, an old unit of measure, is equivalent to a rad. Gray is an SI unit of measurement defined as 1 joule (J) of energy deposited in 1 kg of material. One millilgray (mGy) = 100 millirems (mrem) = 1 millisievert (mSv). Sievert = gray x Wt (where Wt is the radiation weighting factor). For consistency, the units used herein are rem and mrem.

Radiation Sources

Sources of radiation include background (naturally occurring) and artificial (technology based). Background radiation is divided into internal and external exposure. Generally, internal is inhaled (eg, radon gas) or ingested (via food and water). The average annual per capita exposure to ionizing radiation is 360 mrem, of which 300 mrem is from background radiation (Table 1) and 60 mrem is from diagnostic radiographs.

Cosmic Radiation (External)

Naturally occurring sources of radiation include cosmic rays composed primarily of high-energy protons. The amount of cosmic radiation exposure varies with altitude. Exposure at sea level averages 24 mrem/yr. Exposure in Leadville, Colorado, which is 3,200 m above sea level, averages 125 mrem/yr. A 5-hour flight alone averages 25 mrem. Flight crews can average 100 to 600 mrem/yr, depending on altitude and hours of flight.

Spacecraft experience higher radiation levels. The Apollo astronauts received an average dose of 275 mrem during a lunar mission.

Gundersen and Storm reported an increased rate of acute myeloid leukemia in commercial pilots. In their retrospective cohort study involving 3,877 Danish cockpit crew members,

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An average exposure of 40 mrem/yr comes from other internal sources, such as food and water. Food, particularly skeletal muscle, can contain isotopes of potassium. Water may contain absorbed radon gas.¹

### Technology Based

The most common significant source of human-made radiation remains diagnostic radiographs. However, radiation comes from other background sources, as well. For instance, fallout from atmospheric testing of nuclear weapons produces an average dose of 1 mrem/yr. (There were 450 detonations between 1945 and 1980.) Nuclear power, including production, fuel, reactor, and waste materials, produces an average of 0.05 mrem/yr.¹

### Regulatory Agencies

Several agencies have jurisdiction over different aspects of the use of radiation in medicine, and their authority carries the force of law. They can inspect facilities and records, impose fines, suspend activities, and revoke radiation-use authorization.

The United States Nuclear Regulatory Commission (NRC) regulates nuclear material (plutonium and enriched uranium). States typically have an agreement with the NRC to regulate federal guidelines. The NRC regulations for radiation and safety are included in Title 10 of the Code of Federal Regulations, which includes regulations for personnel monitoring, disposal of radioactive material, and maximal permissible doses of radiation to workers and to the public.

Regulatory agencies that determine and enforce standards include the US Food and Drug Administration (FDA), the Department of Transportation, and the Environmental Protection Agency. The FDA regulates radiopharmaceuticals and the performance of commercial radiographic equipment; the Department of Transportation regulates the transport of radioactive material; and the Environmental Protection Agency regulates the release of radioactive materials to the environment.

### Advisory Bodies

Several advisory bodies periodically review the scientific literature and make recommendations regarding radiation safety and protection.³ Although their recommendations do not carry the force of law, they are often the source of federal regulations. The two most widely recognized advisory bodies are the National

### Table 1

<table>
<thead>
<tr>
<th>Source</th>
<th>Average Annual Radiation Exposure (mrem)</th>
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<tbody>
<tr>
<td>Cosmic (external)</td>
<td>27</td>
</tr>
<tr>
<td>Terrestrial (external)</td>
<td>28</td>
</tr>
<tr>
<td>Radon (internal)</td>
<td>200</td>
</tr>
<tr>
<td>Food and water (internal)</td>
<td>40</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1</td>
</tr>
<tr>
<td>Average total (approx.)</td>
<td>300</td>
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</table>

they identified three cases of acute myeloid leukemia compared with the expected number, 0.65—a rate increase of 4.6 times (confidence interval, 0.9 to 13.4). Although the radiation exposure was relatively low (300 to 600 mrem/yr), cosmic radiation at higher altitudes might have 10 to 100 times the energy of gamma radiation.

### Primordial Radiation (External and Internal)

Primordial radionuclides (eg, uranium, thorium, potassium) are terrestrial sources containing radioactive material that have been present on Earth since its formation. Exposure to these radionuclides in the United States can range from 15 to 2,500 mrem/yr (average, 28 mrem/yr). Additional miscellaneous sources of external exposure, including building materials such as concrete and brick, account for approximately 3 mrem/yr.¹

The most common source of internal exposure is radon 222. Inhaled radon gas exerts its effect on the tracheobronchial region. Radon exposure in the United States averages 200 mrem/yr. Doses can be significantly higher if indoor contamination allows levels to concentrate. Radon can enter a building from the underlying soil, water, natural gas, or building materials.
Effects of Radiation

Deterministic Versus Stochastic Effects

Deterministic (nonstochastic) effects of radiation are those in which, below a certain threshold of exposure, there is no increased risk of radiation-induced effects such as cancer or genetic mutation. The assumption is that the rate of injury is low enough that cells may repair themselves. Stochastic effects have no such threshold dose; the assumption is that the damage from radiation is cumulative over a lifetime. Prenatal, intrauterine exposure to ionizing radiation may lead to organ malformation and mental impairment (deterministic effect) as well as to leukemia and genetic anomalies (stochastic effect).

Initial guidelines for radiation exposure either were arbitrary or assumed a deterministic model of exposure. In the 1950s, analysis of Hiroshima and Nagasaki survivors showed a rate of leukemia that followed a stochastic model. S. Upper limits of radiation exposure are now expressed both as a maximum rate per year (deterministic) as well as a lifetime limit (stochastic).

Preconception Paternal Radiation Exposure

Low-level preconception radiation exposure has been evaluated as a risk factor in the development of childhood leukemia in offspring. In 1984, an independent advisory group confirmed a media report of an unusually high incidence of childhood leukemia in the coastal village of Seascale adjacent to the Sellafield nuclear complex in West Cumbria, England. In a case-control study, Gardner reported that the relatively high doses of radiation (quantified by film badges worn by men employed at Sellafield before the conception of their children) increased the risk that their children would develop leukemia. However, Wakeford reviewed the literature and concluded that the body of scientific knowledge did not support Gardner’s conclusion. Yoshimoto et al. reported no increased risk of leukemia in the 263 children conceived shortly after the Hiroshima and Nagasaki bombings whose fathers had received a dose of at least 1,000 mrem (average dose, 25,700 mrem).

In contrast, Shu et al. found a positive correlation between paternal preconception radiographic exposure and infant (aged <18 months) leukemia. In a study of 250 patients and 361 control subjects, the authors identified a statistically significant (P < 0.01) risk for development of acute lymphocytic leukemia in the offspring of fathers exposed to two or more radiographs of the lower gastrointestinal tract and lower abdomen (odds ratio, 3.78; 95% confidence interval, 1.49 to 9.64).

Current recommendations for maximum radiation exposure do not separate gonad exposure levels from those of the torso (Table 2). Studies evaluating the risk of paternal exposure are limited by their retrospective nature, the self-reported occupation and exposure level, and the difficulty in obtaining dosimetry data. Until a definitive study is performed, surgeons in their reproductive years are encouraged to keep exposure to their gonads to a minimum.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Maximum Permissible Annual Dose (rem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupational Total (whole body) dose</td>
<td>2 or 5*</td>
</tr>
<tr>
<td>Dose to the eye</td>
<td>15</td>
</tr>
<tr>
<td>Dose to the thyroid gland</td>
<td>30</td>
</tr>
<tr>
<td>Total dose to an individual organ (excluding the eye)</td>
<td>50</td>
</tr>
<tr>
<td>Dose to the skin or extremity (eg, hands)</td>
<td>50</td>
</tr>
<tr>
<td>Minor (aged &lt;18 years)</td>
<td>10% of adult</td>
</tr>
<tr>
<td>Dose to embryo or fetus</td>
<td>0.5 over 9 months</td>
</tr>
<tr>
<td>Nonoccupational (Public) Individual members of the public</td>
<td>0.1 per year</td>
</tr>
<tr>
<td>Unrestricted area</td>
<td>2 mrem/hr</td>
</tr>
</tbody>
</table>

* The International Commission on Radiological Protection recommends a maximum of 2 rem/yr; the National Council on Radiation Protection and Measurements recommends a maximum of 5 rem/yr.
Maximum Allowable Radiation Dose

It is widely agreed that a dose as low as is reasonably achievable is best. One should strive for the minimum of radiation exposure, regardless of maximum recommended guidelines.

The NRC has established "Standards for Protections Against Radiation" (Title 10, Part 20) Taking into account social and economic factors, the commission established maximum allowable limits of radiation for workers and the public. The NRC has different standards for controlled areas, where occupational workers are present, and uncontrolled areas, where exposure to nonoccupational workers or to the public occurs. The NCRP has recommended maximum annual exposure in areas adjacent to x-ray rooms of 5 rem (5,000 mrem) for occupational workers and 0.1 rem (100 mrem) for uncontrolled areas.

Determination of Maximum Radiation Dose

Current levels of maximum radiation dose are based on acceptable levels of calculated risk. Acceptable risk is defined by comparing risk of cancer death in radiation workers to the risk of fatal accidents in other so-called safe industries. The lifetime risk of accidental death in safe industry is (5 x 10^-4/yr) x (30 yr) = 1.5 x 10^-2, or 1.5%. In comparison, the so-called natural risk of cancer mortality in the United States is estimated at 16%.

Levels of exposure were then chosen so that the risks are comparable. Specifically, assuming an average work span of 30 years and a maximum exposure of 1 rem/yr (as opposed to 5 rem/yr), exposure would be 30 rem over a life span. Using an estimated risk of 4 x 10^-4 rem for cancer mortality and assuming 1 rem/yr of exposure, the risk of radiation-induced cancer mortality would be (1 rem/yr) x (30 yr) x (4 x 10^-4 rem) = 1.2 x 10^-2. The risk of fatal cancer for a radiation worker who is exposed to 1 rem/yr over 30 years results in a 1.2% increased risk of premature death.

If one were exposed to the maximum recommended dose of 5 rem/yr to the torso, the mortality rate would be significantly higher.

Annual Whole Body Limits

Recommended limits have been revised downward at least five times since 1934, when the initial recommended annual maximum was 60 rem. From 1960 to 1991, the maximum was 5 rem. In 1991, it was reduced to 2 rem by the NCRP, but it remains at 5 rem for the NCRP. The newer recommendation is based on new risk models, revised dosimetry techniques, and additional follow-up from survivors of the atomic bombs at Hiroshima and Nagasaki.

Limits for Specific Organs

Specific maximum doses have been established for individual organs and for pregnant women (Table 2). The maximum dose to the fetus of a pregnant worker may not exceed 0.5 rem (500 mrem), the equivalent of one hip radiograph, over the 9-month gestation. No more than 0.05 rem (50 mrem) is allowed in any one month. Average exposures for various radiographic and fluoroscopic procedures are listed in Table 3.

Exposure to the Orthopaedic Surgeon

Exposure to the surgeon typically comes from primary radiation or scatter. Primary refers to radiation in the path between the x-ray generator and the image intensifier. Scatter is radiation produced from interactions of the primary beam with objects in the path, such as the patient, the operating table, and instruments. The radiation the patient receives from the primary beam is much greater than the amount of radiation from scatter. The surgeon's hands are at marked risk for primary exposure and always should be kept out of the beam. An additional potential source of radiation is leakage from radiation passing through the x-ray machine.

Table 3

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Radiation to Patient (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest radiograph</td>
<td>25</td>
</tr>
<tr>
<td>Dental survey</td>
<td>150 per view x 3 views = 450</td>
</tr>
<tr>
<td>Hip radiograph</td>
<td>500 to 600</td>
</tr>
<tr>
<td>Mammogram</td>
<td>170 per view x 3 views = 510</td>
</tr>
<tr>
<td>Computed tomography, wrist</td>
<td>700</td>
</tr>
<tr>
<td>Computed tomography, hip</td>
<td>1,000</td>
</tr>
<tr>
<td>Barium enema (diagnostic)</td>
<td>1,300 per min x 3.5 min = 4,550</td>
</tr>
<tr>
<td>Cerebral embolization</td>
<td>1,000 per min x 34 min = 34,000</td>
</tr>
<tr>
<td>(interventional procedure)</td>
<td></td>
</tr>
<tr>
<td>Cardiac catheterization</td>
<td>2,000 per min for fluoroscopy x avg</td>
</tr>
<tr>
<td>Fluoroscopic imaging, regular C-aro</td>
<td>50 min = 100,000</td>
</tr>
<tr>
<td>Fluoroscopic imaging, mini C-aro</td>
<td>50,000 per min for cineangiogram x 1</td>
</tr>
<tr>
<td></td>
<td>Total fluoroscopy + cineangiogram = 150,000 per study</td>
</tr>
<tr>
<td></td>
<td>1,200 to 4,000 per min (lower for extremity and higher for pelvis)</td>
</tr>
</tbody>
</table>
tube housing. Proper monitoring and maintenance of equipment should minimize leakage.

The exposure rate to the patient from a regular C-arm is approximately 1,200 to 4,000 mrem/min of fluoroscopy use. The exposure rate is lower for the extremity and higher for the pelvis. The exposure rate for scatter from a regular C-arm is approximately 5 mrem/min at 2 ft from the beam and 1 mrem/min at 4 ft. More recent mini C-arms have double the exposure of older models. Although the kilovolt level is about the same (60 to 70 kV), the current has been increased from 50 to 100 JJA which has improved image quality. Exposure differs only slightly from manufacturer to manufacturer.

Exposure During Intramedullary Nailing

Sanders et al. studied exposure to the hands and thyroid glands of surgeons performing intramedullary nailing of tibial and femoral fractures. Redding and locking femoral fractures required an average of 6.2 minutes of fluoroscopy time and resulted in an average exposure of 100 mrem per operation (16 mrem/min).

Millner et al. evaluated radiation exposure to the hands and thyroid glands of surgeons during intramedullary nailing of femoral and tibial fractures. Average fluoroscopy time was 4.6 minutes, with an average dose of 127 mrem to the dominant index finger of the primary surgeon (27.6 mrem/min) and 119 mrem to the dominant index finger of the first assistant. Maximum recommended yearly exposure to the hand is 50,000 mrem (approximately 394 locked nailings per year). Additionally, a phantom leg was used to simulate exposure to the thyroid gland for both shielded and unshielded conditions at different beam configurations and distances. The greatest exposure to the thyroid gland was with the beam in the lateral position and the surgeon on the side of the x-ray generator.

Such positioning exposed the thyroid gland to a maximum of 3.32 mrem/min, or 15.3 mrem for the average 4.6 minutes of intramedullary nailing. The maximum recommended exposure to the thyroid gland is 30,000 mrem/yr (1,960 locked nailings per year). Use of a lead thyroid gland shield reduced exposure by a factor of 70.

Radiation Exposure to the Hands

Goldstone et al. evaluated radiation exposure to the hands of orthopaedic surgeons performing a variety of internal and external fixation procedures under fluoroscopy. Sterilized TLDs were attached with sterile strips to the middle finger under a sterile glove. Nine different surgeons of varying experience performed a total of 44 procedures. Exposure to the hands during a single procedure ranged from undetectable to a maximum exposure of 570 mrem for a dynamic hip screw. Exposure varied substantially not only between cases but also between surgeons.

Noordeen et al. studied 78 orthopaedic trauma procedures performed by five different surgeons and reported a maximum monthly hand exposure of 395 mrem. That rate is equivalent to a yearly exposure to the hands of 4,740 mrem, approximately one tenth the yearly maximum recommended dose to hands.

Arnsztin et al. used a cadaver hand to measure radiation exposure at 15 cm and 30 cm from the beam to simulate exposure to the surgeon's hand and eyes. Exposure was 100 times greater in the beam than at 15 cm, and the authors strongly recommend that the surgeon carefully avoid placing his or her hand in the beam at all times. Coning down the image to half the area reduced the exposure by half.

Rampersaud et al. evaluated radiation exposure to the spine surgeon during pedicle screw fixation in a cadaver model. A surgeon wore TLDs on multiple digits. The hand exposure rate averaged 58.2 mrem/min. Radiation exposure was approximately 10 times higher in spine surgery compared with other musculoskeletal procedures; exposure rates are higher for larger specimens. Radiation was reduced most notably when the primary beam entered the cadaver opposite the surgeon because that positioning increased the distance from the source.

Exposure to the Hands From Mini C-Arm Fluoroscopy

Data indicate that exposure to the hands during mini C-arm fluoroscopy is higher than predicted. Radiation exposure to the hands was measured using TLDs on the non-dominant index finger of five hand surgeons during surgery of the finger, hand, and wrist. Eighty-seven dosimetry rings were analyzed. Surgeons' hands were exposed to an average of 20 mrem per case (SD, 12.3 mrem). The data indicate that surgeons sometimes allow their hands direct exposure from the x-ray beam, in addition to the unavoidable exposure from scatter. Although the exposure rate of the mini C-arm is approximately 10% that of the large C-arm, surgeons work much closer to the beam; as a result, their hands may be exposed to increased amounts of radiation.

Surgeons used an average of 51 seconds of fluoroscopy time per case (SD, 37 sec/case). No correlation existed between exposure dose and fluoroscopy time across all surgeons ($r^2 = 0.063$). Surgeons' hands are sometimes close and sometimes far from the beam during a procedure. As a result, the exposure rate was too variable and not useful as data. Each surgeon had a different mean radiation exposure, but this was not statistically significant ($P = 0.177$) because of variability in the data. Type of fluoroscope and level of surgical difficulty did not correlate with exposure dose.
Radiation to the Orthopaedic Team

Mehlman and DiPasquale evaluated exposure to operating room personnel during simulated surgery using a pelvic phantom as a target. Exposure was measured for the surgeon, first assistant, scrub nurse, and anesthesiologist, and exposure rate (mrem/min) was determined for each position. Direct beam contact resulted in 4,000 mrem/min. The surgeon, who was 1 ft away, received 20 mrem/min of whole body exposure and 29 mrem/min to the hands. The first assistant, who was 2 ft away, received 6 mrem/min of whole body exposure and 10 mrem/min to the hands. No exposure was detected at either the scrub nurse position (3 ft away) or the anesthesiologist position (5 ft away). Scatter is 0.1% of the beam energy at 3 ft from the beam and 0.025% at 6 ft. Therefore, the minimum distances up to which protective apparel is required are at least 6 ft for the large C-arm and 3 ft for the mini-C-arm. Staff and hospital regulations may differ.

Inverted C-Arm Fluoroscopy

The C-arm is typically used with the x-ray tube (radiation source) below and the image intensifier above. As the beam goes through the patient, the energy is attenuated. For hip and long bone fracture fixation, the surgeon should be on the side of the patient opposite the C-arm, where scatter exposure is reduced. One method of reducing fluoroscopic time is to use the C-arm in the inverted position, which allows the surgeon to more easily position the area for imaging. More accurate positioning can reduce the number of repeat images.

Tremains et al. compared radiation exposure using the large C-arm in the standard position, with the x-ray tube and image source near the floor (Fig. 1, A), to the inverted C-arm position, with the image intensifier beneath the extremity (Fig. 1, B). They measured radiation to a phantom hand as well as to the simulated surgeon’s head, chest, and groin for each of three imaging configurations. In the inverted position, the hand is farther from the x-ray source. The inverted position exposed the phantom hand to less than half the level of radiation of the standard C-arm position. The inverted position exposed the simulated groin to about 15% of the radiation and the head to two thirds of the radiation of the standard position. The exposure to both patient and surgeon was less primarily because the distance from the extremity to the beam source was increased. The authors concluded that using the C-arm in the inverted position significantly (P < 0.0001) reduced radiation to both the patient and the surgeon.

Radiation Protection

The four principal methods to reduce radiation exposure from scatter are decreased exposure time, increased distance, shielding, and contamination control. Additional methods include manipulating the x-ray beam, such as with collimation. Reducing fluoroscopic time directly reduces exposure for both patient and surgeon.

Distance

Increasing distance from the beam greatly reduces exposure. At a distance of 1 m from the patient and at 90° to the beam, the intensity is 0.001 (0.1%) of the patient’s beam intensity. Doubling the distance reduces the amount of exposure by a factor of four: at 2 m, the exposure is 0.00025 (0.025%), one fourth of that at 1 m. The NCRP recommends that person-
nel stand at least 2m away from the x-ray tube and the patient.

**Shielding**

Shielding typically is done with a lead gown. Lead is the most common material used because of its high attenuation properties and low cost. The typical thickness of a lead gown is 0.25 mm to 0.5 mm; thickness of 1 mm is available for high-exposure areas (eg, cardiac catheterization laboratory). More than 90% of radiation is attenuated by the 0.25-mm thick apron. Thickness of 0.35 mm gives 95% attenuation and thickness of 0.5 mm gives 99% attenuation, but they weigh 40% and 100% more, respectively; than the 0.25-mm thick apron. Areas not protected by the apron include the extremities, eyes, and thyroid gland. Pregnant women should monitor exposure with a badge outside the lead apron and should wear a second badge inside the apron over the abdomen to monitor fetal exposure.

Glasses provide about 20% attenuation. Leaded glasses attenuate x-rays 30% to 70%, depending on the amount of lead. Thyroid gland shields 0.5 mm thick attenuate radiation by approximately 90%. Women are encouraged to shield their thyroid glands because women are more likely than men to develop radiation-induced thyroid gland tumors.

**Contamination Control**

**Monitoring of Equipment**

Most hospital radiology departments annually test radiographic equipment and lead aprons. Fluoroscopy equipment is tested for accuracy of voltage and current and for leakage from the x-ray generator. Lead aprons are tested with fluoroscopy to identify holes and leaks.

**Exposure Reduction Techniques**

X-rays are electically generated electromagnetic waves that are absorbed and subsequently magnified by the image intensifier. Increasing the current in the generator produces more photons per unit of time and, therefore, more radiation. Increasing the voltage (beam energy) results in greater transmission and, therefore, less absorption of x-rays through the patient. An increase in voltage, with a corresponding lower current, results in less radiation exposure but also in less contrast in the resulting image. The generator voltage and current are automatically adjusted to provide the best image with the lowest radiation dose.

One of the easiest ways to reduce exposure is to use the low-dose option available on some C-arms;20 exposure to both. Patient and surgeon is thereby reduced by approximately 20%. The low-dose option is useful except when maximum resolution is needed, such as in intra-articular fracture reductioTL With the C-arm, the laser guide can be used to center the area of interest and thereby reduce wasted, off-center images.

Collimation reduces the size of the beam, thus reducing the area of the primary beam and the amount of scatter exposure to the surgeon. Because area, and therefore exposure, is proportional to the radius squared, collimation can markedly decrease exposure. In addition, because the outer periphery usually is not the focus of interest, collimation helps reduce radiation dose.

Additional Exposure Reduction Techniques

**Sterile Disposable Protective Surgical Drapes**

Sterile disposable surgical drapes and shields are available for interventional procedures. King et al.7 reported on the effectiveness during abdominal procedures of using a sterile protective surgical drape composed of bismuth. During clinical application, exposure to the radiologist was reduced twelvefold for the eyes, twenty-fivefold for the thyroid gland, and twenty-ninefold for the hands. Although this approach may be useful in some orthopaedic procedures, it has not been studied.

**Sw-gon Control of Fluoroscopy**

Noordeen et al.4 evaluated exposure to five different orthopaedic surgeons with either technician or surgeon control of the x-ray unit. They reported a statistically significant (P < 0.05) reduction in exposure with surgeon control of the foot pedal. Fluoroscopy during the first month was controlled by the technologist and in the second month by the surgeon operating a foot pedal. When the foot pedal was controlled by the technologist, three of the five surgeons were exposed to more than one third the maximum amount of radiation recommended by international guidelines.14 Computer-assisted robotic surgery also has the potential to reduce surgeon exposure to radiation scatter.

**Sterile Protective Gloves**

Sterile protective gloves typically are made from lead or tungsten. Wagner and Mulhern22 evaluated gloves from four different manufacturers and reported that forward scatter back scatter, and secondary electrons reduced their effectiveness. Those additional sources of radiation scatter increased the amount of exposure to the hands by about 15%. Taking into account the scatter as well as the different types of gloves, the authors reported a large variation in attenuation properties, from exposure reduction of only 7% to almost 50%. At higher energy levels, the gloves were even less effective. Wearing protective gloves might give a false sense of security that could increase the risk of the surgeon placing his or her hand directly in the beam.

**Summary**

Orthopaedic surgeons are increasingly using fluoroscopy to perform com-
plex procedures and are necessarily exposing themselves to more radiation than previously. Hands are at the highest risk for exposure. Exposure rates for the orthopaedic surgeon using a regular C-arm are estimated to be as high as 20 mrem/min to the torso and 30 mrem/min to the hand. Assuming an average fluoroscopy time of 5 minutes for an intramedullary rod procedure, this yields an exposure of 100 mrem to the torso and 150 mrem to the hands per case. When the torso is protected and the hands are not, the exposure rate to the surgeon would be 10 mrem to the torso and 150 mrem to the hand per case. With a limit of 5 rem/yr to the torso (NCRP guideline) and 50 rem/yr to the hand, the surgeon could perform 500 cases per year (torso exposure limit) or 333 cases per year (hand exposure limit). A limit of 2 rem/yr to the torso (ICRP guideline) would allow 200 cases per year to reach maximum exposure.

With the C-arm, radiation to the hands averages 20 mrem per case. Although the exposure rate of the mini C-arm is about 10% that of the large C-arm, exposure to the hands is similar to that of the large C-arm because the surgeon works much closer to the beam and to scatter.

Precautions should be taken to reduce exposure as much as possible. Potential decreases in radiation exposure can be accomplished by decreased exposure time; increased shielding with gown, thyroid gland cover, gloves, and glasses; beam collimation; using the low-dose option available on some C-arm units; inverting the C-arm; and surgeon control of the C-arm.

References

Addendum

Radiation protection of staff in fluoroscopy

Wearing your dosimeter

Wellspan Health personnel monitored for radiation exposure receive a single dosimeter \textit{that must be worn at or near the collar.} It is important that the dosimeter is placed outside of any protective equipment that is worn (lead aprons or thyroid shield). Readings at this position provide an estimate of radiation exposure to the eyes.