Operative Techniques in
Orthopaedics

Strategies to Minimize Surgeon Radiation Exposure in Spinal Surgery

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For over 100 years, radiation exposure has concerned physicians. Currently, most spine surgeons utilize imaging modalities that rely on radiation in the operating room on a near-daily basis. Recommendations on limits to radiation exposure and ways to minimize that radiation exposure should be familiar to all spine surgeons. Here we review both radiation exposure in the operating room as well as multiple strategies, technologies, and techniques that allow for surgeons to minimize radiation exposure to themselves, their staff, and the patient.
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KEYWORDS radiation, x-ray, surgeon safety, radiation exposure, freehand instrumentation, intraoperative imaging

Introduction

In 1895, Wilhelm Roentgen discovered what came to be known as "X-rays."[1] Despite more than 100 years having passed since this discovery, X-ray imaging remains a cornerstone of intraoperative imaging, particularly in spine surgery. The ubiquity of intraoperative radiography in many fields of orthopaedic surgery has caused many to raise concerns regarding surgeon radiation. This has in turn led to regular use of leaded protective wear in the operating room and the implementation of many other strategies to minimize radiation exposure. The strategies promise to significantly reduce surgeon radiation exposure, and in some cases, to eliminate radiation exposure to the surgeon completely. Here, we detail some of the current most common intraoperative imaging modalities and detail how surgeons might go about minimizing radiation exposure.[2-6]

Terminology

Although some evidence suggests experimentation with X-rays to predate Roentgen, his report of this unique type of radiation was the first formal description and was the first to provide them with a name—"X-radiation" or "X-rays." Almost immediately the medical potential was recognized and the technology was rapidly adopted. The potential complications of this technology were noted almost immediately as well. In 1896, Tarkhanov irradiated frogs and insects and noted that not only was an image generated, but it seemed to also "affect the living function" of the organism as well.[7] Others noted hair loss and skin changes when used on patients.[8] Labeled "Roentgen Rays" in some countries, much of the world called them simply "X-rays."[9] Currently, many practitioners incorrectly refer to the *image* generated from the X-rays as the "X-ray" rather than the more correct term of "radiograph," or even "X-ray picture." Some prominent surgeons have been known to correct trainees who continue to incorrectly refer to the radiographs as the "X-ray" (eg, Dr Lor Randall, UC Davis Department Chair). However, much like languages evolve, the widespread misuse of the term "X-ray" has now led to it being almost universally accepted as referring to the image generated, not the actual radiation. "Radiograph" technically refers to images generated from X-rays only and is not typically used to describe images from a CT study, despite the use of X-ray radiation. Fluoroscopy also utilizes X-ray technology and was first described by Edison as a way to visualize moving tissue in real time. MRI and other forms of imaging are not based on X-ray radiation and should never be called radiographs.

When describing exposure to radiation, care must be taken to use correct units and understand what is being referenced. Strictly speaking, Gray (Gy) is the SI unit of measure for units of

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absorbed dose of radiation, and is equal to 1 J of energy deposited in 1 kg of material. However, because objects vary in their absorption, an "effective dose" needs to be calculated. Thus, an effective dose in humans exposed to radiation relies on a "tissue-weighting factor" and is reported in "roentgen equivalent man" (rem) or Sievert (Sv) (where 100 mrem = 1 mSv). Note that this effective dose (mSv) may differ markedly from the absorbed dose (Gy) in many cases and a simple conversion is not always possible. For example, determining effective dose (mSv) from a computed tomography (CT) scan reported in Gy requires knowledge of variables such as the dose length product (DLP) and the tissue-weighting factor.[10] The dose length product, for example, varies between machines and is often not reported in published papers. Thus, conversion from Gy to mSv is often not possible. The reader should use great care in examining how radiation is reported. Currently, the International Commission on Radiological Protection (ICRP) uses the term "effective dose" when referring to whole-body irradiation and "equivalent dose" when referring to individual organs or tissues.[11] Finally, by convention, Gy has been used when reporting on "deterministic" effects (short-term, immediate effects due to large doses of radiation), while Sievert has been used to report on "stochastic" effects (ie, the long-term carcinogenic damage to tissue from radiation; see below in "radiation limits"). Thus, much of what will be discussed in this chapter will refer to effective dose and will be reported in Sievert (Sv or mSv), the SI unit for effective dose absorbed in humans.[12]

Radiation Limits

What constitutes "safe" limits of radiation exposure has been an area of concern for many years. Today, there are 2 major advisory bodies that study and address this—the National Council on Radiation Protection (NCRP) and the International Commission on Radiological Protection (ICRP). Both groups have set forth recommendations for the upper amount of radiation that is likely safe:

1) For those that work with radiation, the annual dose should not exceed 20 mSv/y averaged over 5 years and should not exceed 50 mSv/y in any 1 year.
2) For those that do not work with radiation, the annual dose should not exceed 1 mSv/y in addition to background radiation from the earth and in addition to radiation from medical testing.

These limits have been arrived at after years of study and extrapolation. To summarize, these limits are conservative estimates arrived at by examining associations with known exposures to radiation. For example, with exposure to 500 mSv, transient changes to blood cells have been noted[13]; exposure to less than 100 mSv in 1 year has not been associated with any documented deleterious effects.[13] So what constitutes "safe" amounts of radiation? As one might imagine, it is not easy to say. Some have previously espoused the "no radiation is safe" mantra, but this is not helpful in directing medical decisions, where some amount of radiation has proven overwhelmingly helpful in diagnosing and treating patients. To date, literally thousands of lives have been saved due to medical use of radiation (eg, CT scans that detect treatable cancers). Further, some amount of low-level radiation is part of life and something we have deemed acceptable given our lack of correlation with any negative outcomes. For example, background radiation from the earth is around 3 mSv per year depending on where one lives (less at sea level, more at higher elevations); no evidence suggests that those exposed to 3 mSv per year background radiation have any difference outcomes than those exposed to 1 mSv per year from background radiation. Thus, we take flights as needed without excess worry about radiation (a round trip flight from NYC to LA is about 0.1 mSv [or the same as a chest X-ray]). The ICRP and NCRP considered lifetime exposure and a working career of about 30 years in making their recommendations,[5] and these guidelines are continually revised with new data and new imaging modalities. As mentioned earlier, *deterministic* effects are those effects seen in the immediate short term, often due to direct damage of tissue from radiation (eg, damage to skin after radiation therapy is an example). *Stochastic* effects are the long-term changes to genes with radiation exposure (eg, cancers that appear after exposure to ionizing radiation). Both must be considered when determining safe radiation limits, although much of this chapter speaks to stochastic effects.

Although the cause of much confusion and almost always misinterpreted by surgeons when discussing this issue, radiation from medical imaging should not count toward the limits of radiation for the patient. This has been agreed upon by both advisory groups (ICRP and NCRP) and has been explained in a variety of ways.[14] For example, the ICRP reports that: "...medical exposure of patients has unique considerations ... Dose limits are not at all relevant, since ionizing radiation, used at the appropriate level of dose for the particular medical purpose, is an essential tool that will cause more good than harm."[15] Further, the American College of Radiology (ACR) has gone to great length to both agree and help explain this concept.[15-17] As noted above, advanced imaging has saved countless lives, and much of the risk of radiation is theoretical at the lower doses. The ACR points out that "for almost all imaging, benefit outweighs the risk for the patient."[15-17] While current use of imaging seems to fall well below a level that would be considered unsafe (Table 1 shows radiation doses for different activities), patients may still exceed 50 mSv if needed for life saving or altering treatments. As will be discussed at length below, 1 or 2 (or more) O-arm spins in the OR is well worth the radiation to ensure safe placement of spinal hardware. Given the risks of misplaced hardware near the spinal

Table 1 Amount of Radiation for Various Activities

Extremity radiograph; DEXA	0.001
Chest radiograph; Flight (NYC to LA), roundtrip	0.1
Lumbar radiographs	0.7
Thoracolumbar radiographs	1.5
O-arm, spine	2.5
Background radiation, Earth	3
CT, spine	10
CTA for PE	10
Coronary angiogram	5-15

All radiation dosages are mSv.

cord or nerve roots, having the patient receive 2.5 mSv or even 5 mSv is well worth the negligible risk. However, it cannot be over emphasized that this concept must be viewed as dynamic in nature, as medical radiation in general is a weak carcinogen and the stochastic effects are not seen for 1-2 decades; thus, as we increase medical imaging now the long-term effects of that are difficult to quantify and will only be revealed once time has passed.[16]

These limits constitute best estimates of safe (or more accurately "low-risk") whole-body exposure, most easily measured and tracked by the surgeon with a dosimeter worn in the operating room. Individual organs vary in their safe upper limits of exposure, mainly due to the characteristics of the tissue; upper annual limits have been set per tissue (eg, 20 mSv for lens of the eye, 500 mSv for skin/hands/feet).[16,18,19] The reader is directed to see excellent discussion by Rehani et al[18] in the ICRP report. It is important to note that while tissues vary in their upper limits, the current upper limits of whole-body exposure have been set with this in mind.[18] Monitoring exposure per area of the body becomes complicated once other factors such as distance from the radiation emitter, use of protective lead, and other factors are considered. We recommend monitoring and limiting total radiation and agree with the ICRP that this is likely safer and easier to track.

Nonetheless, a few general principles should be kept in mind in regard to safe use of fluoroscopy in the operating room. Most radiation to the surgeon is received via scatter; the surgeon's hands should not be in the direct beam from emitter to receiver and the surgeon should remain as far away from the source as possible (Fig. 1). When using fluoroscopy, there are multiple safe practices that should be used. (1) Those in the room should be protected with lead. However, it should be noted that radiation scatter drops precipitously as one moves away from the C-arm. Multiple studies have investigated this. For example, Mehlman and DiPasquale[20] set up an operating room to detect radiation at various points throughout the room. When there was 4000 mrem/min direct beam detection, there was 20 mrem/min at 1 foot away, 6 mrem/min at 2 ft away, and no detection at 3 or 5 feet away. At 6 feet away, they were able to detect 0.025% scatter from the beam. Thus, beyond 6 feet from the C-arm, very little radiation is received. Additionally, leaded gowns shield between 90% and 99% of radiation (depending on thickness, condition, etc.), but are heavy and hot to wear, particularly for cases that may last most of the day (eg, large spine cases, etc.).[5,21] Eyeglasses shield up to 20% of radiation, and up to 70% in some leaded glasses.[5]

One final note should be made about the C-arm machine itself. Most machines have automatic adjustments such that kVp and mAs are optimized. Often times contrast or brightness on the screen itself may be altered to aid in visualization. Dimming the room lights may also help. Other times, when adipose tissue may make imaging difficult, increasing kVp may help; this typically automatically lowers the mA. A more nuanced discussion of machine settings is beyond the scope of this chapter, other than to emphasize that surgeons should think about adjusting things outside of radiation dose first (eg, position, collimation, brightness on screen) before increasing exposure. Interestingly, any tools that can minimize fluoroscopy exposure time are also helpful, including lasers to center the image, and allowing the surgeon to control his own C-arm pedal rather than relying upon the technician.[22]

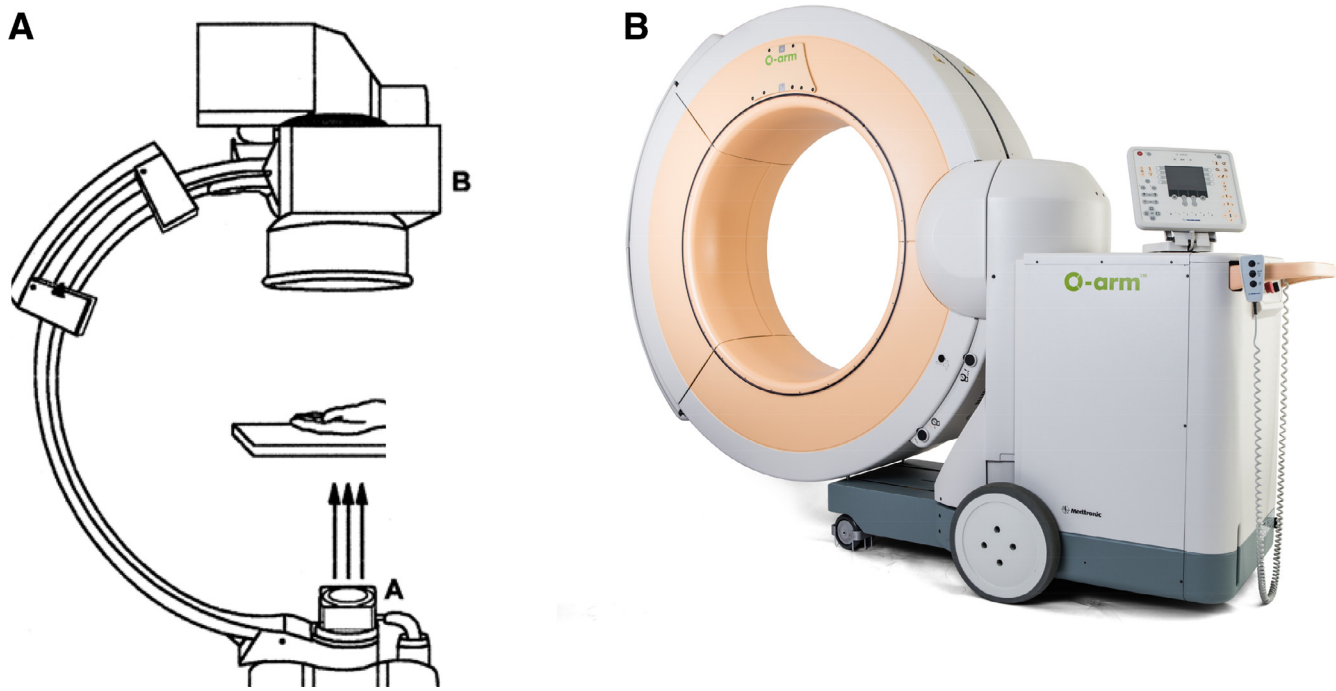

Figure 1 (A) C-arm and (B) O-arm. Note that the C-arm is labeled to demonstrate the Emitter (A) and the image intensifier (B). Many orthopaedic spine surgeons may be more comfortable using C-arm or X-ray while many neurosurgical surgeons may be more comfortable with navigation and O-arm. As surgeons continue to "cross-train" in both specialties, these differences are likely to decrease. Reproduced with permission in modified format from Singer[5] and Medtronic.

Other Intraoperative Imaging Choices

Beyond fluoroscopy, it has become increasingly common to use other imaging modalities in the operating room. First, many surgeons make use of plain films for many aspects of surgery. It is our practice to localize with one plain film to mark the skin and then utilize a second plain film to check our level intraoperatively. This can be done rapidly, with minimal disruption to the field, and provides high-quality imaging to ensure the correct level is identified. Further, the surgeon can step behind a lead shield in a corner of the room or leave the room (depending on the OR) such that little to no radiation is received.

More recently, CT technology has been used in the operating room, with surgeons often utilizing technology like the O-arm,[3] which allows 3D imaging. This can be used in numerous different ways, including in conjunction with navigation technology or even robotic technology. While a standard thoracolumbar CT may be ~10 mSv, an O-arm spin in the OR can be as little as ~2.5 mSv, and as technology improves, there is increasingly lower exposure during these. Our typical preference is to utilize an O-arm spin to check our hardware at the end of a case, after free-hand placement. Then, if small adjustments are needed, we can make them. Even if another O-arm spin is needed at that time, this adds no exposure to the surgeon and only a minimal amount for the patient, as noted earlier.

Studies on Radiation Exposure per Screw Placed

Quantifying radiation exposure is difficult for many reasons. First, as mentioned, the distance from the C-arm or imaging device matters. Second, how we judge radiation exposure can vary—do we use a dosimeter on the patient? The surgeon? The scrub tech? Where should we place it—under or over the lead? Given that lead shields a varying percentage of exposure based on thickness, wear, coverage; and given that staff positions can vary markedly in the OR, it is probably most intuitive to compare overall radiation exposure to the actual surgeon or patient (dosimeter not covered by lead). We recently did an exhaustive review[4] examining radiation exposure per screw to quantify radiation in the OR between various imaging modalities. The data demonstrated that when using the O-arm the surgeon is the safest, as they are exposed to no radiation, always stepping into the hallway for the O-arm spin[4] (Fig. 2). Figure 2 shows radiation exposure to the surgeon between the modalities; Figure 3 shows radiation exposure to the patient for each.

Who Is Most at Risk, Patient or Surgeon?

Given the above-mentioned safe upper limits, it is worth noting that a busy surgeon utilizing fluoroscopy to place screws

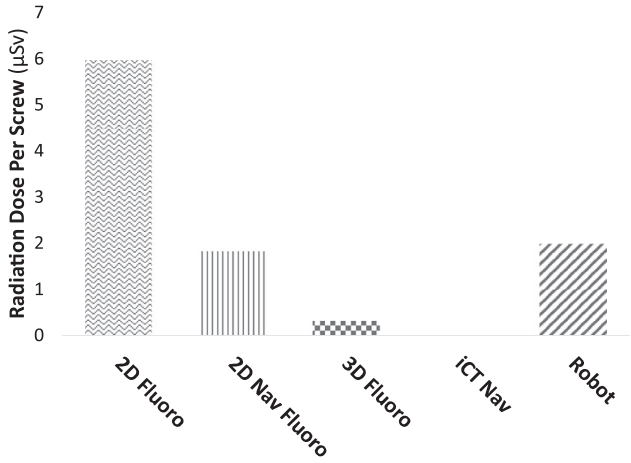

Figure 2 Results from Pennington et al[4] illustrating average radiation exposure to the surgeon per screw placed. In this review, we found that instrumentation using intraoperative navigation exposes surgeons to the lowest amount of radiation. 2D Fluoro, instrumentation using 2D fluoroscopy alone; 2D Nav Fluoro, instrumentation using 2D fluoroscopy and intraoperative navigation based upon preoperative imaging; 3D fluoro, instrumentation using 3D fluoroscopy system; iCT, instrumentation using intraoperative navigation based upon intraoperative acquired CT images; Robot, instrumentation using robotic assistance based upon preoperatively acquired imaging. Used with permission.

(2D fluoro, Fig. 2) could conceivably reach 25-50 mSv in a year, which is at the upper limits of acceptable radiation exposure. For the patient, utilizing intraoperative CT resulted in the most radiation per screw, but likely would remain fairly inconsequential overall as noted earlier. Again, it should be emphasized that current radiation limit recommendations

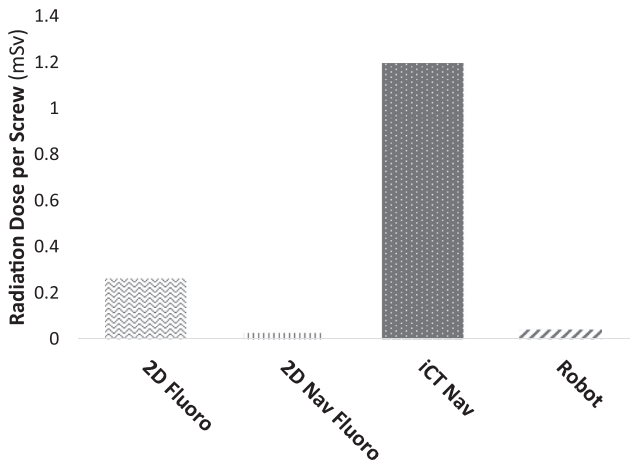

Figure 3 Results from Pennington et al[4] illustrating average radiation exposure to the patient per screw placed. We found that instrumentation using preoperative imaging—2D Nav Fluoro and Robot groups—exposed patients to the lowest amount of radiation of all techniques examined. 2D Fluoro, instrumentation using 2D fluoroscopy alone; 2D Nav Fluoro, instrumentation using 2D fluoroscopy and intraoperative navigation based upon preoperative imaging; iCT, instrumentation using intraoperative navigation based upon intraoperative acquired CT images; Robot, instrumentation using robotic assistance based upon preoperatively acquired imaging. Used with permission.

exclude radiation for medical purposes, so it is helpful to consider the risk and benefit for the patient in this scenario. Given the need for accurate hardware placement, and that a large, instrumented spinal surgery is a "rare" event (even if a patient has 2-3 in a lifetime), receiving radiation up to the limits for radiation workers in a year is likely of little harm. Theoretically, if a patient was also a radiation worker with significant exposure, then dosing could reach more predictably harmful levels. Further, radiation exposure in pediatric patients undergoing multiple procedures becomes complicated and more difficult to interpret. Our data[4] and this chapter refer to adult exposure to radiation only.

Strategies to Minimize Radiation

Overall, various techniques may be utilized to decrease radiation exposure. First, the surgeon and patient should recognize the radiation exposure; it may even be helpful for the patient to have a small handout to explain the radiation exposure and risks, or at minimum have a short discussion with the surgeon or surgeon's staff about this. Empirically, patients seem to understand the role of radiation in optimizing hardware placement. The patient should also be educated about how little the radiation is from plain films, both immediately postoperatively and in follow-up. Second, the surgeon should make efforts to be sure his OR team is safe. This includes utilizing proper use of radiation per above as well as making sure appropriate shielding is utilized as needed. At only 6 feet away from the C-arm, there is a precipitous drop in radiation[23,24]; the surgeon can help educated staff about positioning as staff can often position themselves beyond this area (eg, the anesthesiologist, circulating nurse, etc.). Finally, the surgeon should optimize safety for staff and patient while in the operating room. This may be done in a variety of ways. One option would be to utilize navigation rather than fluoroscopy for guidance. Another option, our preferred method, is to place hardware with free-hand technique, and then utilize O-arm to check the hardware. This gives a near fool-proof image confirming hardware placement, and minimizes exposure to the surgeon, allowing the surgeon to also operate without a heavy lead apron. Additionally, prior studies have suggested that for certain levels (eg, C2 pedicle screws) instrumentation accuracy may be just as high or higher when using the free-hand techniques as compared to using intraoperative navigation.[25]

To conclude, we recommend that all trainees learn the basics of free-hand placement from the occiput to pelvis. To maximize both accuracy and efficiency in the OR, preoperative studies should be reviewed to be sure they are adequate, and notes should be made as to what instrumentation should be used and in what size. Any anatomic abnormality should be noted and discussed preoperatively to plan surgery, and then again at the timeout to be sure all members are aware. For example, for cervical cases, the vertebral arteries should always be examined on the preoperative MRI (seen as the dark flow-voids on T2 imaging). Vertebral artery abnormalities are fairly common and can almost always be identified preoperatively.[26-29] At times 1 artery may already be occluded, or very small. In some cases, angiography may be helpful to delineate contribution of each vertebral artery, particularly in cases where the artery is to be sacrificed (eg, tumor cases). Although the balloon occlusion test has been popular in the past, our radiology colleagues typically do not perform this, but instead perform an angiogram and have a full discussion with the surgeon about the blood flow, contribution, and what risk sacrificing the artery confers. We have found this method to be useful. Surgeons and trainees should recognize any vertebral artery variation from normal, paying particular attention to where the artery is at each level and where its course brings it closer to our operative field.

Although not meant to be exhaustive, a few notes on technique for free-hand placement of hardware are listed here. At C1, free-hand posterior lateral mass screws are relatively safe. Personal preference dictates whether the C2 nerve root is taken, as data are weak in favor or against this.[30,31] Our experience has taught us that telling the patient to expect posterior skull numbness and then systematically taking the C2 root with the DRG allows a well-controlled and successful procedure. Others claim this leads to bothersome numbness[32] or even pain[33]; we take great care to bipolar the free nerve end and remove the DRG and typically do not get complaints of any pain. The "football shape" of the C1 lateral mass is recognized, and the posterior most point is used as a starting point, taking care to point slighting superior and slightly medial. Setting a drill guide to 16 mm or 18 mm after marking the start point often allows a safe and reliable hole for the screw. Often times, we can make this bicortical, although the internal carotid artery (ICA) should be viewed preoperatively to be sure this is not at undue risk. Preoperative CT scans aide tremendously in getting these lengths correct (Fig. 4A and B).

For C2 placement, the preoperative imaging is critical. We recommend CT and MRI so that both the boney tunnel for the pedicle screw as well as the vertebral artery can be visualized. Although there are a variety of methods to instrument C2, including pedicle screws, "parsicle screws," pars screws, and translaminar screws, we prefer a pedicle screw if there is an adequate boney tunnel and no contraindications for placement. For example, if a patient has one functioning vertebral artery, a pedicle screw should not be placed on that side. If a pedicle screw cannot be placed, typically a translaminar screw can safely be placed. For the pedicle screw, our preference is to be sure the CT is examined in multiple planes while changing the gantry to optimize bone tunnel visualization. We prefer to stay high (superior) when choosing our start point on the posterior aspect of the C2 posterior ring (Fig. 4C), as this helps avoid misplacement and breach in the superior direction. After feeling the medial aspect of the pedicle, we use the tap to slowly drill our hole, cheating toward the thick cortical bone that is medial rather than the thinner bone and vertebral artery that lie lateral (Fig. 4C and D). Keep in mind that measuring this screw on preoperative CTs will often measure "slightly short" as most imaging programs do not account for measurement in more than 1 plane. Often around a 24 mm or 26 mm in length is appropriate with this method.

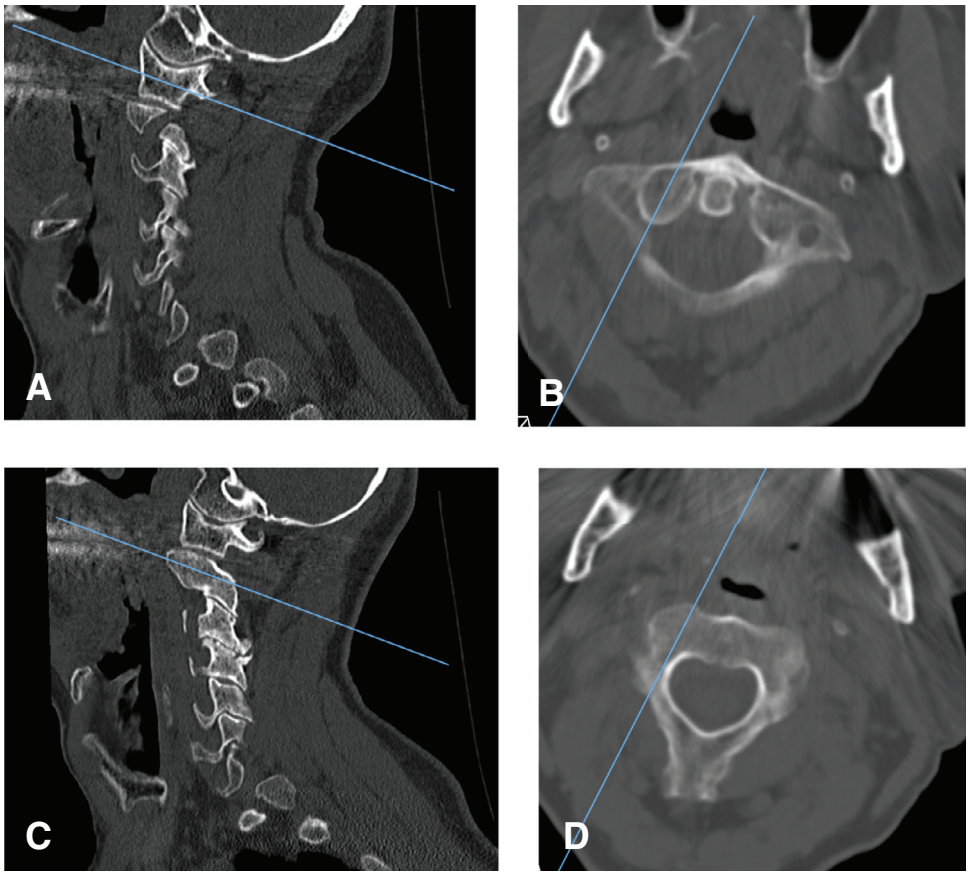

Figure 4 Preferred free-hand trajectory for C1 (A,B) and C2 (C,D) screw placement. Note the "football" shape of C1 and placement of long axis on the axial view (B). Also note risk of internal carotid injury with bicortical screw placement and need for good pre-op imaging review to assess risk. Demonstrated in (C) is our preferred superior start point when placing C2 screws. In (D), the classic pedicle screw trajectory along the medial wall is demonstrated.

At C3-6, lateral mass screws are typically used and again, utilizing preoperative imaging is helpful. While these are often 14 mm in length using the traditional Magerl technique,[34] which employs an inferomedial to superolateral trajectory, at times 12 mm may be necessary. At C7, we typically do not instrument, although pedicle screws could be placed here if needed. Again, imaging should be interrogated to be sure the vertebral artery is not in the transverse foramen at C7. Due to its transitional nature, placement of hardware here is often not helpful.

When placing thoracic screws, there are multiple high-yield references in the literature to guide free-hand placement.[35] In general, trainees should become accustomed to thinking about (1) the plane of the lamina and how the trajectory is near 90 degrees to this surface, (2) the transverse plane, and how from T12 to T1 screws become increasingly "more medialized" (the transverse angle increases), and (3) the starting point, which should never be medial to midpoint of the SAP.[36,37] If these 3 steps are thought about with each screw placement and the pre-op axial CT is visualized on the screen intraoperatively at each level, free-hand placement of thoracic screws becomes straightforward. We also typically (1) remove a small amount of the superior level IAP to aid visualization, (2) visually reference the contralateral TP for rotation, and (3) reference the confluence of TP/SAP and lamina as another way of triangulating our trajectory. We use intraoperative electrophysiological monitoring (IOM) throughout and typically run a motor after placement of each screw at cord level.

Finally, lumbar screws are often easier for most surgeons, as the TP is often large and can be used along with the pars to locate the ideal starting point. While there is a change in transverse trajectory and start point from L1 to L5 (more medialization as start point moves slightly inferior), most of these are placed below cord level (L1/L2), and a free-running EMG as well as stimulation of screws after placement are helpful. For sacral screws, S1 screws are typically placed with a classic inferolateral starting point, while our preferred method of pelvic fixation is S2 alar-iliac (S2AI) screws when possible. Full reviews of placing the S2AI screws have been published previously.[38-41] Utilizing the posterior superior iliac spine (PSIS) as well as the greater trochanter are both methods to help localize direction. Often a flat plate obturator oblique and iliac oblique can be used to be sure the screw did not enter the sciatic notch (iliac) and to visualize the screw in the iliac bone (obturator).[38]

Future Directions

Spine surgery is rapidly changing. Although various advanced imaging modalities now exist to optimize hardware placement

and osteotomy cuts during surgery, radiation exposure has become of increasing concern, particularly for the surgeon, who is exposed daily. By utilizing methods of either free-hand technique (with an O-arm spin to check placement with the surgeon outside of the room) or various forms of navigation (including various robotic systems that include navigation platforms), safety, efficiency, and efficacy can be optimized while protecting the surgeon, staff, and patient from excess radiation. Although current guidelines make exceptions for "medical imaging" when discussing limits of radiation, most patient exposure to radiation from spinal procedures stays well below the amount of radiation needed to cause any known adverse outcome. Surgeons should remain cognizant of both the benefits and potential dangers when utilizing any advanced imaging before, during, or after spinal procedures.

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