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Radiation exposure and reduction in the operating room: Perspectives and future directions in spine surgery

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Abstract

Intraoperative imaging is vital for accurate placement of instrumentation in spine surgery. However, the use of biplanar fluoroscopy and other intraoperative imaging modalities is associated with the risk of significant radiation exposure in the patient, surgeon, and surgical staff. Radiation exposure in the form of ionizing radiation can lead to cellular damage *via* the induction of DNA lesions and the production of reactive oxygen species. These effects often result in cell death or genomic instability, leading to various radiation-associated pathologies including an increased risk of malignancy. In attempts to reduce radiation-associated health risks, radiation safety has become an important topic in the medical field. All practitioners, regardless of practice setting, can practice radiation safety techniques including shielding and distance to reduce radiation exposure. Additionally, optimization of fluoroscopic settings and techniques can be used as an effective method of radiation dose reduction. New imaging modalities and spinal navigation systems have also been developed in an effort to replace conventional fluoroscopy and reduce radiation doses. These modalities include Isocentric Three-Dimensional C-Arms, O-Arms, and intraoperative magnetic resonance imaging. While this influx of new technology has advanced radiation safety within the field of spine surgery, more work is still required to overcome specific limitations involving increased costs and inadequate training.

Key words: Intraoperative imaging; Ionizing radiation; DNA damage; Genomic instability; Shielding; Distance; Dose reduction; Spinal navigation

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Core tip: Intraoperative radiation exposure is a significant concern for patients, surgeons, and operative

room staff during spine surgery. All surgeons should practice general radiation safety techniques including shielding, distance, and fluoroscopic dose reduction. New imaging modalities and spinal navigation systems have also been developed to mitigate radiation exposure risk. These modalities include CT-based techniques such as Isocentric Three-Dimensional C-arms and O-Arms. Intraoperative magnetic resonance imaging has also been adapted from the neurosurgical field and is another developing imaging technique. Further research is required to overcome the limitations of these novel technologies in regards to costs and training requirements.

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INTRODUCTION

The use of instrumentation and other implants is often necessary for orthopaedic surgical intervention. This is especially true in the field of spine surgery, where anterior and posterior instrumentation is frequently utilized to treat degenerative, traumatic, and neoplastic pathologies. Posterior pedicle screws are the most widely used instruments within spine surgery; however, inaccurate positioning of such constructs can lead to significant intraoperative and postoperative adverse events^[1-5]. Specifically, injury to nearby neurovascular structures can occur, which often results in significant patient morbidity and financial burden on the healthcare system.

In order to ensure accurate placement of spinal instrumentation, intraoperative radiographic images are used to guide and confirm implant location. The use of intraoperative imaging is especially important in minimally-invasive procedures, where instrumentation is inserted percutaneously without the direct anatomic visualization afforded in open procedures. Biplanar fluoroscopy was one of the first real-time intraoperative imaging modalities, and remains the dominant technique amongst orthopaedic and spinal practitioners^[6-8]. However, radiation exposure from intraoperative imaging remains a significant concern for patients, surgeons, and other operative room personnel^[9-13]. In order to mitigate the risk associated with intraoperative radiation exposure, new imaging technologies and personal protective equipment have been developed.

The purpose of this review is to summarize the pathophysiology of intraoperative radiation exposure, discuss effective strategies for intraoperative radiation safety, and to introduce new intraoperative imaging and navigation modalities within the field of spine

surgery.

PATHOPHYSIOLOGY AND EFFECTS OF RADIATION EXPOSURE

During the use of intraoperative imaging, surgical staff and patients are exposed to both direct and scatter radiation. Direct radiation is the radiation absorbed from the beam as it projects from the source. Direct radiation is the predominant source of radiation exposure for the patient and surgeon. Scatter radiation is radiation from the source that is deflected off of a surface, typically the patient in an operative setting. Scatter radiation exposure is the primary form of exposure for operative staff who stand further away from the surgical table. While many different types of radiation exist, the most concerning in regards to the development of pathology is ionizing radiation. Ionizing radiation from intraoperative imaging leads to cellular damage through the induction of direct or indirect DNA lesions and production of reactive oxygen species^[14,15]. The ensuing cellular stress response can lead to cell death *via* replicative or apoptotic mechanisms^[14]. Conversely, if cell death does not occur, the risk of neoplastic proliferation may be increased due to the persistence and replication of cells with DNA lesions and subsequent genomic instability^[15].

The pathologic effects of ionizing radiation exposure can further be described as either deterministic or stochastic. Deterministic effects are short-term responses observed only after a certain threshold radiation exposure has been reached. These effects are subsequently worsened with any additional exposure past that threshold^[16]. Examples of pathology associated with deterministic effects includes hair loss, skin erythema, skin burns, and cataract formation^[17-19]. As the thresholds for deterministic effects are known in many cases, they can be prevented *via* careful monitoring of radiation exposure levels over short time-periods. More worrisome are stochastic effects, in which incidence increases with exposure without any definitive time period or threshold exposure level^[16]. Stochastic effects are most commonly associated with carcinogenesis and teratogenesis^[17,20-23]. For example, Mastrangelo *et al.*^[21] determined that working as an orthopaedic surgeon was a significant risk factor for tumor development in a survey of cancer incidence amongst 316 hospital employees. The authors cautioned that this increased risk was possibly a result of orthopaedic surgeon radiation exposure along with poor work safety practices.

In order to protect against the dangers of excessive radiation exposure, guidelines are available regarding dosage limits both for those exposed in occupational settings and the general public. The primary international organization producing these guidelines is the International Commission on Radiological Protection (ICRP). The dosage limits are expressed in the units of joules per kilogram, otherwise known as a Sievert

(Sv)^[24]. The Sievert is a measure of the stochastic effects of ionizing radiation, and an exposure of 1 Sv is associated with a 5.5% risk of developing cancer^[24]. Under ICRP guidelines, occupational exposure should be limited to a maximum average of 20 mSv per year over a five-year period, with no exposure greater than 50 mSv in a single year^[24]. For the general public, exposure should be limited strictly to a maximum average of 1 mSv per year over a 5-year period^[24]. These limits can be used as reference points for the evaluation of the safety and efficacy of new imaging technologies and radioprotective techniques.

GENERAL STRATEGIES FOR REDUCING RADIATION EXPOSURE IN SPINAL PROCEDURES

Shielding

In attempting to reduce intraoperative radiation exposure, a variety of simple methods should be employed by all practitioners. One of these methods is shielding, which involves the use of physical barriers to absorb a portion of scatter radiation and prevent it from reaching soft tissues. Shielding for operative room personnel is primarily accomplished by the wearing of lead aprons and thyroid shields, which protect radiosensitive areas from the upper body to the gonads^[18,19,23,25-27]. Other less commonly utilized methods of shielding include lead gloves to reduce hand exposure, lead skirts for operative tables, and mobile shielding screens to provide additional protection to operative room personnel^[28-30]. The literature is overwhelmingly supportive of the utility of shielding, with reported reductions in radiation exposure between 42%-96.9%^[19,27,28,30]. For example, Ahn *et al.*^[27], in a study of three surgeons performing percutaneous endoscopic lumbar discectomies, determined that lead aprons and collars reduced radiation exposure to the upper body and thyroid by 94.2% and 96.9%, respectively. Furthermore, the use of lead aprons was estimated to increase the number of total operations before reaching occupational exposure limits by 5088 procedures.

Distance

An additional method to reduce intraoperative radiation exposure is to feasibly maximize the distance between the patient surface and the surgeon or operative room personnel^[18,30]. This principle derives from the fact that radiation intensity follows an inverse square law, decreasing substantially with increasing distance from the radiation or scatter source. As such, with appropriate shielding, scatter radiation may be reduced to 0.1% and 0.025% of the primary radiation at a distance of 3 feet and 6 feet, respectively^[11]. This principle is further illustrated by Lee *et al.*^[18], in an investigation of scatter radiation doses measured during intraoperative C-arm fluoroscopy. In this study, a chest

phantom on a surgical table was exposed to fluoroscopy while a whole-body phantom was placed in varying positions in the operating room to simulate the surgeon and operative room staff. Measured scatter doses to the whole-body phantom decreased with increasing distance up to 100 cm from the chest phantom device. Kruger *et al.*^[30] provided further recommendations for operative room setup, noting that the image intensifier should be placed on the same side of the operative table as the surgeon so as to increase the distance between the radiation source and operative room personnel.

Fluoroscopic dose reduction techniques

Dose reduction techniques are also an important strategy both in reducing radiation exposure and following the "as low as reasonably achievable" (ALARA) principle. One such technique is the use of fluoroscopy in pulsed and low dose modes^[26,29-31]. Pulsed mode refers to a method where power to the radiation source is applied intermittently producing short pulses of radiation, while low-dose mode reduces the peak kilovolts and miliamperes necessary to create the radiation beam^[26]. Goodman *et al.*^[26], in a study of 316 patients undergoing spinal interventional procedures, determined that the combination of pulsed and low-dose modes decreased average radiation exposure time by 56.7%. The authors also suggested that pulsed modes are most effective in reducing radiation exposure when the surgeon is required to be in closest proximity to the patient. Plastaras *et al.*^[29] examined the effect of pulsed fluoroscopy in conjunction with shielding in patients undergoing interventional spine procedures. The combination of the two methods resulted in a 97.3% reduction in effective dose to all operative room staff. Despite the benefit of radiation exposure reduction, pulsed and low-dose modes exhibit potential disadvantages. Of primary concern is reduced image quality, and as such, the adoption of these fluoroscopy modes is dependent on surgeon acumen and comfort^[26].

Other dose reduction techniques include intermittent fluoroscopy and last image hold^[30,32]. Intermittent fluoroscopy refers to applying fluoroscopy only for short time periods, while last image hold displays the last collected image even when fluoroscopy is not being applied^[32]. These methods allow for both reduced total fluoroscopy time and the ability to better plan surgical approaches through image review. Finally, collimation can be utilized to reduce radiation dose. Collimation refers to narrowing the radiation beam over the area of anatomic interest, thus reducing radiation exposure by subjecting less total body area to interaction with radiation^[26,31].

INTRAOPERATIVE THREE-DIMENSIONAL IMAGING AND SPINAL NAVIGATION SYSTEMS

Spinal navigation systems have been developed with

the goals of increasing the accuracy of instrumentation placement and reducing operative radiation exposure. Navigation technologies are comprised of many different components that must act in concert. Typically, an imaging mechanism is used to collect radiographic images that are then imported into a computer workstation that creates a three-dimensional (3D) reconstruction of the anatomy of interest^[33]. This computer system interacts with a specialized optical camera and surgical tools to guide real-time insertion of instrumentation without the need for repetitive collection of fluoroscopic images^[33].

Since its inception, navigation has shifted from utilizing preoperative images to using intraoperative 3D imaging modalities^[34]. These imaging modalities are more frequently used because, unlike with preoperative imaging, they do not require as significant a degree of the time-consuming process of anatomic registration^[17]. Furthermore, intraoperative imaging is a better representation of surgical anatomy than preoperative studies, as preoperative images do not reflect anatomic shifts and variations due to surgical positioning^[35-40]. Multiple intraoperative imaging modalities can be used in conjunction with navigation systems, including computed tomography (CT) and magnetic resonance imaging (MRI) based approaches.

Isocentric 3D C-arm

Isocentric 3D C-arms are CT based systems that collect images from a 190° screening arc^[36,41,42]. Up to 200 fluoroscopic images are collected at equidistant angles which are then utilized by navigation systems to create a 3D reconstruction of the relevant spinal anatomy^[41,43]. In one pass, these modified C-arms can collect images from a 12 cm³ anatomical space^[44]. Furthermore, the surgeon and surgical staff can step outside of the operating room during image acquisition, possibly reducing unnecessary radiation exposure^[45,46].

In regards to radiation exposure, prior investigations have exhibited reduced fluoroscopy time and radiation doses with the use of Isocentric 3D C-arms compared to standard fluoroscopy^[41,45,46]. Kim *et al.*^[45] performed one such study in 18 cadaveric spines undergoing minimally invasive transforaminal lumbar interbody fusion (MIS TLIF). The authors demonstrated that while the navigation group had greater setup time (9.67 min vs 4.78 min), the overall fluoroscopy time was lower compared to the standard fluoroscopy group (28.7 s vs 41.9 s). Radiation exposure, measured in millirems (mREM), was also lower in the navigation group (undetectable vs 12.4 mREM). Furthermore, in a subsequent series of 18 patients undergoing MIS TLIF, the navigation group had lower overall fluoroscopy time (57.1 vs 147.2 s). Smith *et al.*^[46] noted similar findings in an investigation of 4 cadavers in which lumbar pedicle screw placement was attempted. Compared to standard fluoroscopy, isocentric C-arm use was associated with lower total mean radiation exposure to the surgeon's torso (0.33 mREM vs 4.33 mREM). The

advantages of isocentric 3D C-arm use also extend past limiting radiation exposure, as multiple studies have indicated equivalent or superior accuracy of pedicle screw placement when compared to standard fluoroscopic methods^[36,44,46,47].

O-arm

The O-arm (Medtronic, Fridley, Minnesota) is a cone-beam, CT-based intraoperative imaging modality that can produce a 360° scanning arc^[8]. O-arm devices can acquire up to 750 images in a single scan, and these images can be utilized with navigation systems to create 3D anatomical reconstructions^[7,48,49]. The O-arm also is programmed with preset modes that optimize kilovoltage and milliamperage settings for various patient sizes and anatomical regions^[25,48,49]. Similar to the isocentric 3D C-arm, the O-arm can possibly reduce radiation exposure by allowing the surgical staff to exit the operating theatre during image acquisition^[49].

The literature regarding the use of O-arm imaging is mixed in terms of its efficacy in radiation dose reduction. Multiple studies have determined that while O-arm imaging reduces radiation exposure to operative room personnel, it increases the radiation exposure to the patient^[7,17,25,48-50]. Tabaraee *et al.*^[50] demonstrated such findings in a cadaveric study investigating the insertion of 160 pedicle screws under either C-arm or O-arm imaging. In the operative room staff, O-arm imaging led to undetectable levels of radiation exposure while C-arm imaging was associated with an exposure of 60.75 mREM. The opposite correlation was seen in cadavers, where the use of the O-arm modality was associated with higher mean radiation doses compared to the use of conventional C-arm fluoroscopy. Mendelsohn *et al.*^[17] confirmed this association in a matched cohort analysis of 146 patients undergoing posterior pedicle screw insertion. In the 73 patients undergoing a procedure with O-arm imaging, the observed radiation dose in patients was 8.74 times greater than that of the OR staff. Those patients also experienced a higher mean effective dose of radiation (1.09 mSv) compared to published radiation dosages for patients undergoing pedicle screw insertion using standard C-arm fluoroscopy following MIS (0.611 mSv) or open (0.393 mSv) techniques. The results of these studies indicate that any practitioner considering the use of O-arm imaging must weigh the benefit of reduced radiation exposure to operative staff with the limitation of increased radiation exposure to patients.

Intraoperative MRI

Intraoperative MRI is a developing technology in the field of spine surgery that has the potential for significant reductions in intraoperative radiation exposure both for patients and surgical personnel. Intraoperative MRI has been adapted from the field of neurosurgery, and it involves the use of ultra-high field 3T MRI scanners^[51]. Within the spine literature, few studies exist regarding the safety and efficacy of intraoperative MRI. Woodard

et al.^[52], in a case series consisting of both cervical and lumbar procedures, demonstrated that intraoperative MRI could feasibly be used for localization and confirmation of neural decompression. Similarly, Choi *et al.*^[53] conducted a study utilizing intraoperative MRI for surgical site localization and confirmation of decompression in 89 patients undergoing percutaneous endoscopic lumbar discectomy. The authors concluded that intraoperative MRI was successful in detecting inadequate intraoperative decompression, especially in cases of highly migrated or segmented discs. While this initial data is promising, further work is required to definitively determine the efficacy of procedures utilizing intraoperative MRI.

Limitations to the adoption of intraoperative 3D imaging

While the data supporting the use of intraoperative 3D imaging modalities and navigation systems is promising, these techniques have not yet achieved widespread adoption. Estimates of the percentage of spine surgeons who routinely utilize navigation systems are in some instances as low as 11%^[54]. In attempting to identify impediments to adoption, multiple studies have been undertaken to survey the opinions of practitioners in the field of spine surgery^[54,55]. These investigations consistently identify increased cost, lack of adequate training, and increased associated operative times as factors precluding the use of navigation systems^[54,55]. Costs associated with buying and implementing new imaging and guidance technologies can be burdensome, especially to single-physician and small-group practices. Furthermore, concerns regarding inadequate training extend not only to the surgeon, but to members of the entire operative staff who must adjust to an unfamiliar operative workflow with the introduction of new imaging systems. Worries about increased operative time are also logical, especially during the initial phase of navigation system adoption when surgical teams are at the beginning of their learning curve. However, recent studies have noted no significant differences in operative time in navigated and non-navigated procedures^[44,50]. Nonetheless, manufacturers and proponents of new imaging and navigation systems must still work to overcome the disadvantages of cost, training, and the learning curve to ensure greater adoption of this technology within the field of spine surgery.

CONCLUSION

Radiation exposure is a significant concern for patients, surgeons, and operative room staff. Exposure to ionizing radiation from conventional fluoroscopy is associated with a number of pathologies, the most worrisome being the development of malignancy. As such, radiation safety must be a priority in the operative setting. All practitioners, irrespective of their practice setting, can and should employ the safety principles of

shielding, distance, and dose reduction. Furthermore, practitioners should also consider the use of new navigation systems with alternative imaging modalities such as isocentric-3D C-arm, O-arm, or intraoperative MRI. While these systems may be associated with reductions in radiation exposure to operative staff, they also have significant limitations pertaining to cost, training requirements, and operative times. Further work is still required within the field of spine surgery to improve radiation safety and to further increase the adoption of new imaging modalities.

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