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Computed Tomography Intraoperative Navigation in Spinal Surgery: Assessment of Patient Radiation Exposure in Current Practices

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ABSTRACT

Background: Patient radiation exposure associated with the use of computed tomography (CT) navigation during spinal surgeries was widely compared with other intraoperative imaging techniques. The aim of this study is to explore the use of navigation with regard to current spinal surgery practices and the technical limitations of such imaging systems.

Methods: Dosimetric data from 101 patients who underwent intraoperative, CT-navigated spine surgery were retrospectively collected. The study population was divided into 3 groups according to the primary surgical indication. The number of CT image acquisitions per patient, the field length, and the time of exposure per acquisition during a single surgery were compared as well as the radiation dose emitted to patients.

Results: Dose-length products (DLP) per acquisition were 678.52, 656.8, and 649.36 mGy·cm with no significant difference for spinal deformity (SD), degenerative disease (DD), and vertebral fracture (VF) procedures, respectively. Analyzing the number of CT image acquisitions per patient revealed that repeated intraoperative scans were often performed for patients who were suffering from an SD due to technical limitations of the navigation. As a consequence, the cumulative dose was higher in the SD group (DLP total = 1175 mGy·cm) than in the DD (DLP total = 762.74 mGy·cm) and VF (DLP total = 649.36 mGy·cm) groups.

Conclusions: CT navigation is an efficient intraoperative imaging technique that reduces the rate of surgical complications, but its technical limitations lead to an increased risk of patient radiation exposure, especially for complex surgeries where multiple scanning acquisitions are needed.

Clinical Relevance: To avoid patient's overexposure, spine surgeons should minimize the number of intraoperative acquisitions while considering the complexity of the surgery and the limitations of the guidance system. The use of dual guidance systems has also to be considered according to the benefit-risk balance between patient's outcomes and radiation dose exposure.

Level of Evidence: 4.

Lumbar Spine

Keywords: spine surgery, navigation, spine, radiation exposure, intraoperative computed tomography

INTRODUCTION

Intraoperative computed tomography (CT)-based navigation is becoming a standard for spine surgery to increase the accuracy and safety of orthopedic device insertion during the procedure. Navigation provides a serious advantage for achieving good surgical and clinical outcomes after complex surgeries. One of its advantages is to optimize surgical procedures with low rates of postoperative complications and limited radiation dose exposure for patients and surgical teams.[1]

A wide range of spinal procedures, including correction of deformity, minimally invasive fusion, and percutaneous procedures, are performed routinely.[2–4] A CT-based navigation system is more frequently used during minor and low-risk surgeries for which surgeons are completely trained. But, in current practice, navigation has its own limitations, and the risk associated with this kind of technology is overexposing patients to radiation.[5]

Radiation dose exposure associated with the use of intraoperative CT-based navigation was widely explored and compared with other guidance systems.[6,7] However, to our knowledge, there are no data comparing the radiation dose emitted by a navigated system according to different surgical indications. Patient dose exposure is always compared between different imaging modalities, but it has not been clearly assessed given the technical limitations of such guidance systems or the current practices used for different types of indications. The aim of the present study is to report the

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radiation dose emitted to patients during CT-navigated spine procedures according to the current practices of experienced surgeons for the 3 main types of surgical indications (spinal deformities [SDs], degenerative diseases [DDs], and trauma).

MATERIALS AND METHODS

Study Design and Population

This study is an observational study performed in a single French surgical spine institute. Descriptive data collection was performed from 101 consecutive patients who underwent a CT-navigated spine surgery between 11 March 2019 and 19 February 2020. Study population was subdivided into 3 groups considering the surgical indication: SDs, DDs, and vertebral fractures (VFs).

Patients from the SD and DD groups underwent a thoracolumbar, lumbar, or lumbosacral open midline access instrumentation of the spine. In those cases, navigation was mainly used for transpedicular screw instrumentation, except for patients who had a spinal decompression without spinal instrumentation, where navigation was used to easily identify the spinal stenosis. Patients in the VF group underwent a bipedicular percutaneous cement augmentation associated with the use of intraoperative navigation for assessing the presence of any vertebral bone fragments or for instrumentation insertion.

Surgical procedures were all performed independently by 1 of the 3 experienced orthopedic spinal surgeons from the site according to their current surgical practices and considering the spinal disease.

Intraoperative Radiation Dose Evaluation

Intraoperative CT image acquisitions were performed using the same AIRO mobile guidance system (Mobius Imaging LLC, Ayer MA 01432, USA associated with the Brainlab image guidance software) with a 120-kV peak x-ray voltage setting up and a helical scanning with 1 slice/mm. Before image acquisition, all the surgical staff left the operative room with the exception of the technician performing the acquisition who was located behind a mobile radiation protective barrier. Thus, radiation exposure of the surgical team could not be assessed in the present study.

For each patient, the number of acquisitions performed during the same spinal procedure was recorded. The number of images, the length of the operative field scanned (cm), the radiation exposure time (seconds), the CT dose index ($CTDI_{vol}$, mGy), and the dose-length product (DLP; mGy·cm) given by the Brainlab guidance system were analyzed for each acquisition. $CTDI_{vol}$ values were determined using the following phantom: Ludlum L-007N polymethyl methacrylate CT dosimetry phantom 32 cm (L-007N32). The total DLP (mGy·cm) per patient was calculated as the cumulative DLP/acquisition in case of multiple acquisitions. Effective doses (E, mSv) were calculated according to the American Association of Physicists in Medicine task group report and recommendations ($E = k \times DLP$; in this study $k = 0.015$ is the given ratio applied for the abdominal and pelvic region).[8]

Statistical Analysis

To assess comparability between the 3 groups, patient demographics were compared using analysis of variance and Student *t* test. Statistical tests were performed using R Studio (version 1.3.959.0 by RStudio, PBC). *P* value of less than 0.05 was considered statistically significant. In case of significant differences found across the groups, only descriptive analysis could be performed in this study to avoid statistical analysis bias due to the difference of the studied population.

Ethics

This study was approved by the local Institutional Review Board. Data were retrospectively collected from patients who gave their inform consent for clinical and medical data analysis.

RESULTS

Description of the Study Population

The study population was composed of 101 patients (25 men and 76 women) aged 13 to 86 years with a median age of 56 years. Among them, 58 patients were treated for an SD, 31 for a DD, and 12 for a VF (Table 1).

Regarding surgical indications, patients with an SD (25 idiopathic scoliosis, 21 degenerative scoliosis, 10 kyphoscoliosis, and 2 segmental kyphosis) underwent an open posterior fusion procedure for transpedicular screw instrumentation, whether or not associated with a pedicle subtraction osteotomy. As per the complexity of their SD, they had a long fusion procedure that targeted 4 to 16 adjacent intervertebral levels. Patients with spinal DD (degenerative disc disease, spondylolisthesis, or spinal stenosis) were treated with a lumbar or thoracic fusion procedure up to 4 adjacent intervertebral levels with or without the use of interbody fusion cage (transforaminal lumbar interbody fusion). Patients from the VF group were treated for an osteoporotic VF

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Table 1. Study groups by surgical indication ($N = 101$).

Surgical Indications	*n*
Spinal deformities	58
Posterior thoracolumbar or lumbar fusion	
Idiopathic scoliosis	25
Degenerative scoliosis	21
Transpedicular osteotomy or pedicle subtraction osteotomy	
Kyphoscoliosis	10
Proximal junctional kyphosis	2
Degenerative Diseases	31
Lumbar fusion	
Anterior lumbar interbody fusion	3
Transforaminal lumbar interbody fusion	21
Lumbar arthrodesis	3
Spinal revision	1
Thoracic herniated disc	2
Decompression without instrumentation	1
Vertebral fractures	12
Vertebroplasty	8
Kyphoplasty	4

requiring a vertebroplasty or kyphoplasty that targeted 1 or 2 vertebrae (Table 1 and Table 2).

Based on patient demographics (Table 2), significant differences were found between the 3 groups ($P < 0.01$) for age, BMI, and the number of instrumented vertebral levels. This difference is explained by the heterogeneity of the SD group, which mixed young idiopathic scoliotic adolescents ($n = 24$, mean age 17 years, mean BMI 21.75 kg/m^2) with older scoliotic or kyphotic patients ($n = 34$, mean age 63 years, mean BMI 24,52 kg/m^2) (results not detailed).

Intraoperative CT Acquisition

Every surgical procedure was performed using the same computer-based navigation system. Settings were automatically defined according to patient's BMI and the operative field of interest identified by the surgical team. During the surgical procedure, CT was first performed after positioning the patient in the final prone position. For each acquisition, the length of the spinal field of interest was analyzed depending on the surgical indication (Table 3). The mean acquisition length of each scanning field was 29.3 ± 5.7, 21.8 ± 3.6, and 21.8 ± 2.9 cm in the SD group, DD group, and VF group, respectively. The mean number of slices per acquisition was 290.9 ± 60.4 slices in the SD group, 218.6 ± 35.8 slices in the DD group, and 219.2 ± 31 slices in the VF group (data not shown). As an assumed consequence, the exposure time during the CT image acquisition was higher in the SD group than in the other 2 groups with a mean exposure time per acquisition of 14.9 ± 2.3, 11.8 ± 1.4, and 11.82 ± 1.2 seconds, respectively.

Radiation Dose Evaluation

Data concerning the radiation dose delivered during each surgery were collected according to those given by the guidance system. The mean $CTDI_{vol}$ value per acquisition was 20.1 ± 6.9 mGy in the SD group, 24.3 ± 6.1 mGy in the DD group, and 24.44 ± 4.6 mGy in the VF group. The mean DLP per acquisition was 674.9 ±233.7 mGy·cm in the SD group, 656.8 ± 187.3 mGy·cm in the DD group, and 649.4 ± 80.2 mGy·cm in the VF group. Calculation of the effective dose per acquisition gave the following values for the 3 groups: 10.1 ± 3.5 mSv in the SD group, 9.8 ± 2.8 mSv in the DD group, and 9.7 ± 1.2 mSv in the VF group.

To assess the total radiation dose delivered during a single surgery, the number of acquisitions performed during the procedure was recorded for the 3 groups. As per the median analysis, 2 acquisitions were done during SD surgeries compared with 1 for the other indications (Table 3). As a consequence, the cumulative DLP per patient is higher for patients treated for a major surgery, with mean values of 1175.3 ± 623.6 mGy·cm in the SD group, 762.7 ± 275.6 mGy·cm in the DD group, and 649.3 ± 80.2 mGy·cm in the VF group. These results lead to an average effective dose received by the patient of 17.6 ± 9.3 mSv in the SD group, 11.4 ± 4.1 mSv in the DD group, and 9.7 ± 1.2 mSv in the VF group.

During each procedure, the surgical staff left the operative room. The radiation dose received by the surgical staff could not be performed in this study in regards to the use of the described guidance system.

Table 2. Patient demographics.

Demographic	Spinal Deformities	Degenerative Diseases	Vertebral Fractures	Total Population	*P* Value
Gender, *n*					
Women	50	19	7	76	NA
Men	8	12	5	25	
Age, y, mean (range)	46 (13–79)	59 (16–84)	72 (51–86)	56 (13–86)	<0.01
Body mass index, kg/m², mean (range)	23.4 (14.9–36.9)	26.3 (20–37)	27.3 (21.1–36.5)	24.8 (14.9–36.9)	<0.01
Vertebral levels treated, mean (range)	9 (4–16)	2 (1–4)	1 (1–2)	NA	<0.01

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Table 3. Radiation exposure data across the groups.

Radiation Oucome Measure	Spinal Deformity	Degenerative Diseases	Vertebral Fractures
Exposure time/acquisition, s	14.9 ± 2.3 (8.6–24.6)	11.8 ± 1.4 (9.4–15.1)	11.8 ± 1.2 (10.4–15)
Acquisition length, cm	29.3 ± 5.7 (13.8–53.6)	21.8 ± 3.6 (15.7–30)	21.8 ± 2.9 (18.3–29.7)
$CTDI_{vol}$ /acquisition, mGy	20.1 ± 6.9 (9.1–50.6)	24.3 ± 6.1 (17.1–50.6)	24.4 ± 4.6 (17.8–33.9)
DLP per single scan, mGy·cm	674.9 ± 233.7 (283.7–1845.8)	656.8 ± 187.3 (409.1–1269.2)	649.4 ± 80.2 (529.2–797.2)
Effective dose/acquisition, mSv	10.1 ± 3.5 (4.3–27.7)	9.8 ± 2.8 (6.1–19.0)	9.7 ± 1.2 (7.9–12)
Total DLP per patient, mGy·cm	1175.3 ± 623.6 (436.4–3393.1)	762.7 ± 275.6 (409.1–1551.7)	649.3 ± 80.2 (529.16–797.3)
Radiation dose received by 1 patient, mSv	17.6 ± 9.3 (6.5–50.9)	11.4 ± 4.1 (6.1–23.3)	9.7 ± 1.2 (7.9–12)

Abbreviations: $CTDI_{vol}$, Computed tomography dose index; DLP, dose-length product.
Note: Data presented as mean ± SD (range).

DISCUSSION

Compared with classical "free-hand" techniques, CT-guided surgeries are safer with low risks of pedicle screw positioning and lead to lower rates of postoperative complications.[9,10] Due to its high precision associated with multiple development in image processing, virtual reality, and robotics, spinal navigation is currently recognized as an essential tool to perform complex spinal surgeries. In some countries, navigation is also used as a pedagogical tool to teach residents in spinal surgery because it allows trainees to visualize the anatomic structures of the spine and to get a real-time appreciation of the pedicle device insertion.[11] In that sense, navigation makes complex spinal surgeries safer and less stressful for the newest generation of surgeons.[12]

Despite its crucial role, intraoperative navigation has technical limitations, and its use should be more considered during spinal surgeries.[5] The risks of such an imaging technique arise from the unjustified or repeated CT image acquisitions, which can leading to overexposing patients to radiation. Before using intraoperative navigation, surgeons have to consider the balance between the real need of an external aid to facilitate the procedure and the risks encountered by the patient associated with radiation dose exposure. Even though the risk ratio for inducing cancer with CT imaging is very low, CT guidance systems have some limitations, and some precautions have to be taken in current practices.[5,13]

Dosimetric Evaluation

The power of the present study is to assess the radiation dose exposure of patients treated with 3 main types of surgical indications from major open posterior fusion surgeries to percutaneous vertebroplasty performed by 3 independent and trained spinal surgeons. According to their respective current practices, intraoperative navigation was used to prevent mispositioning pedicle screws or to easily identify the field of spinal canal requiring a decompression or to improve the insertion of the instrumentation during cement injection. Dosimetric parameters reported in the present study seem to be equivalent than those described in the literature. The overall DLP per acquisition is ranged from 649.4 ± 80.2 to 674.9 ± 232.7 mGy·cm, which is closely similar to the radiation doses previously observed.[7,14] Moreover, the authors demonstrated that the rate of radiation dose emitted to patients per acquisition is under the benchmarks used for diagnostic spine CT images.[15]

In our study, patients with an SD were fused on at least 4 vertebral levels with a maximum of 16 levels compared with a maximum of 4 levels fused in the DD group. For such procedure, a complete mapping of the field of interest is required by the surgeon to properly reduce the SD. The time of radiation exposure is correlated with the acquisition length, patients with an SD are then longer exposed than other patients during each acquisition. Our results show that the radiation dose emitted per slice during each acquisition, which is represented by the mean $CTDI_{vol}$ value, is lower in the SD group than in the others. This could be explained by the fact that the AIRO mobile CT image system is setting up automatically to expose the patient with a dose of radiation according to the as low as reasonably achievable principle. In ourstudy, surgeons first determined the spinal field of interest before scanning. Automatic settings of the AIRO mobile CT image system calculated the radiation dose to be emitted to get a good benefit-risk balance (get more radiologic information with the less radiation dose as possible). In that sense, if the field of interest is longer, the CT image system is expected to automatically adapt the emitted radiation dose to reduce the risks. Furthermore, after this study, we have attempted to reduce by one-third the field of acquisition to a shorter field using a more accurate method consisting of the use of scout view images.

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Percutaneous CT-Guided Procedures

Navigation is a comfortable imaging technique that facilitates the insertion of instrumentation and allows surgeons to get real-time feedback of the procedure. Performing a single acquisition is a way to limit the radiation exposure for patients and to optimize the safety of the spinal surgery. However, the use of such imaging techniques could be discussed for surgeries like vertebroplasty or kyphoplasty. In current practices, VFs are treated under fluoroscopy. In this case, the advantage of fluoroscopy is the possibility to perform a real-time 2-dimensional acquisition during each step of the procedure (devices insertion and balloons insufflation) and to observe immediate cement leakages, which is not possible with navigation. However, it implies an increasing risk of radiation exposures for the patient and the surgical team. In cases of complex VFs with a pedicle injury or a dislocation, navigation is recommended to accurately position the instruments through the pedicles and avoid bone fragment displacements. In this situation, CT-guided navigation alone is an accurate way to control device position but cannot give feedback on the presence of cement leakages or the restoration of the vertebral body during balloons inflation step. The radiation dose exposure must be considered during such procedures, which can be done under dual guidance (CT-guided navigation associated with fluoroscopy during balloon inflation and cement injection).[16] For these reasons, CT-guided navigation is probably not the best indication.

Repeated Intraoperative Acquisitions

In the present study, the average value of the DLP per acquisition appeared to be comparable with those previously described in the literature. However, in current practices, repeated intraoperative CT image acquisitions are often required to achieve the procedure, leading to radiation overexposure for the patient. Our results show that multiple acquisitions are recurrent during major or complex surgeries. This observation is mainly explained by the limitations of the intraoperative navigation system, as follows:

- During a CT-guided procedure, an anatomic reference pin is attached to a spinous process or another anatomical fixed point close to the field of interest at the beginning of the surgery. In case of any movement of the reference array during the procedure, the precision of the guidance system will decrease and lead to less guidance accuracy. Another intraoperative CT image acquisition is then made mandatory to restore the correspondence between the position of the surgical instruments and the computed spinal phantoms of interest.[17,18]
- For long-segment fusion surgeries (eg, thoracolumbar fusion more than 10 levels), a single-CT image acquisition is not sufficient to map the total field of interest. Surgeons have to perform at least 2 scans during the procedure to get an overall visualization of the segments they have to fuse.
- Repeated scanning can be done at the end of the surgical fusion procedure to confirm the good positioning of the instrumentation. Intraoperative navigation is a way for the surgeons to investigate for misposition of the pedicle screws during the surgery or to evaluate the reduction of the SD.

Authors Recommendations

To the best of our knowledge, no diagnostic reference levels are explicitly defined regarding the use of CT image intraoperative navigation during spine surgery. Recommendations for such imaging technique are based on guidelines given for diagnostic routine CT images. Every center equipped with an intraoperative CT technology is responsible for assessing the benefit-risk balance associated with such technology in terms of radiation dose and protection. The power of the present study is to describe some dosimetric parameters according to 3 surgical indications and surgeons' current practices. Dosimetric data presented here are dependent on the setting up of the machine, so the presented thresholds cannot be applied widely. However, considering the radiation doses emitted to the patient and the surgical team, authors can make some recommendations on the basis of their current practices for the use of intraoperative navigation depending on the surgical indication.

Surgical experience and training are also 2 key factors for the success of complex procedures.[19] Some non-navigated spinal surgeries can be performed in good conditions with low risk of intraoperative complications.[20,21] In the case of complex pathologies (scoliosis, hyperkyphosis, trauma, etc), navigation has a crucial role for surgeons in order to facilitate the procedures and decrease the risks, particularly for surgeons with limited experience. Nonetheless, the radiation dose emitted to patient and surgical team has to be

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considered even if the radiation exposure is known to be largely less than the dose emitted with conventional fluoroscopic C-arm navigation. We recommend the use of intraoperative navigation for complex surgeries such as long-segment fusion (scoliosis and hyperkyphosis), difficult situations of short-segment fusion (high-grade spondylolisthesis, vertebral dislocation, etc), or high-risk pathologies (VFs with bone fragment displacement, metastatic tumor resection, etc). Regarding the surgical indication, we highly encourage spinal surgeons to minimize the number of CT image acquisitions performed during the procedure, taking care to consider the limitations of the guidance system (loss of accuracy, long scanning length, etc). Acquisitions should be limited to the field of interest, which can be easily defined using a preoperative CT image view. These recommendations should not limit the use of navigation but minimize the radiation dose risks while ensuring the procedure will have good outcomes.

Limitations

This descriptive study is based on data collection from 101 patients consecutively included from a single center. The population was divided into 3 groups depending on the initial diagnosis. Significant differences were found between these 3 groups based on demographic data. This is assumed to be consistent with a detailed subgroup evaluation. The SD group is composed of adolescent patients with idiopathic scoliosis (mean age, 17.6 years) and older patients (mean age, 62.9 years) who suffered from degenerative scoliosis or kyphoscoliosis. In this way, even if the performed surgical procedures are closely similar, this patient group is still heterogeneous and is not comparable with others. While the cohorts presented in this study remain heterogeneous, they fit with the types of population groups that might be encountered in private or academic practice. Even though the SD group is composed of 2 subgroup of patients with different ages and curve types, many of these cases are performed by a single deformity surgeon in a group and therefore has a practical real-world application.

The present study is based on a retrospective database performed by 3 independent and fully experienced spine surgeons working in a single center. The usefulness of the CT image navigation was discussed according to their current practices, which did not represent the worldwide process used during every surgery done. However, this study can provide some guidelines and considerations regarding the use of such technologies. Radiographic parameters described here were collected from only 1 CT image navigation system. Patient radiation exposure could only be assessed in the present study due to current site practices requiring the surgical team to leave the operative room during the scanning sequence. Settings of the machine are specific to 1 manufacturer and should be compared with other systems of acquisition. Moreover, during some surgical processes, especially for percutaneous procedures, surgeons are obliged to use 2 intraoperative imaging systems (C-arm navigated or non-navigated fluoroscopy), which considerably increase the radiation dose and risks. These risks have to be assessed in the future. A multicenter, multivariate, and prospective study performed for each spinal surgical indication is needed to assess the radiation dose emitted to patients.

CONCLUSION

CT image navigation systems allow spinal surgeons to improve their skills and manage more complex pathologies. Even if navigation technologies are safer and more accurate than free-hand procedures or conventional C-arm fluoroscopy systems, it introduces significant radiation risks to be considered when planning the surgery. Radiation exposure associated with the use of navigation systems is higher for patients with an SD than with a trauma or a DD because of repeated CT image acquisitions due to the complexity of the surgery (higher number of instrumented vertebra or higher risks for losing accuracy).

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