Journal of Digital Imaging (2020) 33:1136–1143
https://doi.org/10.1007/s10278-020-00324-2

ORIGINAL PAPER

Evaluation of Software-Based Metal Artifact Reduction in Intraoperative 3D Imaging of the Spine Using a Mobile Cone Beam CT

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Published online: 6 July 2020

Abstract

The aim of our study was to evaluate whether software-based artifact reduction can achieve an improved image quality, using intraoperative 3D imaging in spinal surgery. A total of 49 intraoperative 3D image datasets of patients, who underwent surgery with pedicle screw placement, were retrospectively evaluated. The visibility of anatomical structures and the diameter of the pedicle screws were examined, with and without the application of the artifact reduction software. All software prototypes can improve the visibility of anatomical structures ($P < 0.01$), except MAR (metal artifact reduction) combined with IRIS (iterative reconstruction in image space) ($P = 0.04$). The algorithms MAR and MAR-2 can reduce the blooming artifacts significantly ($P < 0.01$), but SL (Shepp & Logan) cannot ($P = 0.08$–0.988). In summary, software-based artifact reduction for intraoperative 3D datasets can improve the current image quality. Additional information regarding the implant placement and the fracture reduction is therefore generated for the surgeon.

Keywords Intraoperative 3D imaging · Cone-beam CT · Artifact reduction · Spinal surgery · Pedicle screw

Introduction

The incidence of spinal fractures in western countries is around 64 per 100,000 inhabitants [1]. Elderly patients ≥ 65 years are increasingly affected [2]. In about 20% of all cases, the cervical spine is affected; the remaining 80% are related to injuries of the thoracic and lumbar spine [3].

The dorsal instrumentation of the spine using pedicle screws is the gold standard at present, especially not only in the stabilization of fractures but also in many congenital (e.g., scoliosis—spinal deformity in which a sideways curvature of the spine is caused by a defect present at birth) and degenerative diseases (e.g., spondylosis–osteoarthritic degeneration of the vertebral column) of the spine [4]. The pedicles are located in the immediate, topographic vicinity of the spinal cord, and the nerve roots. This determines the vulnerability of these structures due to incorrectly placed screws. Despite this critical anatomical constellation, neurological complications with 0.19% per screw are comparatively rare. However, transitory neurapraxia, which is defined as temporary loss of motor and sensory function due to blockage of nerve conduction lasting an average of 6 to 8 weeks, is observed more frequently than a permanent neurological deficit [5]. Also, depending on the height, the viscera of the neck (esophagus and trachea), thorax (lung), or abdomen (intestines) are located directly ventral to the anterior cortex of the vertebral body. If the anterior cortex is perforated by the screw tip, injuries to numerous organs and blood vessels are possible. Nevertheless, reports of such incidents with severe consequences are rare in the literature [6–8].

Intraoperative imaging is regularly used to avoid screw malpositions. The intraoperative assessment of implant placement with conventional fluoroscopy alone can be challenging. Studies carried out on cadaver models have already shown that, even under optimal conditions, the assessment of the implant position, even in other body regions, using conventional fluoroscopy is often insufficient [9–11]. Depending on the literature, malpositions of pedicle screws are indicated with 3 to 55% [12]. The current gold standard for preoperative

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planning and postoperative assessment of reduction and implant placement is computed tomography (CT) [13].

Studies dealing with postoperative revision rates in dorsal instrumentation of the spine have already shown that the use of intraoperative cone-beam CT has a positive effect on screw placement. Intraoperative malalignments could be detected and corrected immediately due to the additional information provided by the 3D datasets [14–16].

Due to metal artifacts, however, the image quality is significantly reduced, especially in the context of a dorsal instrumentation of the spine (Fig. 1). This therefore has an adverse effect on the assessment of screw positioning [17]. A hardware- or software-based solution to improve the image quality of mobile C-arms while maintaining low radiation dose and high mobility compared to CT would therefore be highly advantageous. Several publications deal with artifact reduction in the field of CT [18], but nothing has been published about the reduction of metal artifacts in the field of mobile C-arms with 3D function (cone beam CT).

The aim of this study was to evaluate whether software-based algorithms can effectively reduce artifacts and thus improve image quality in intraoperative 3D image datasets with pedicle screws acquired by a cone beam CT.

Materials and Methods

Subjects

Patients, who underwent surgery with pedicle screw placement between 2009 and 2013 at the BG Trauma Center Ludwigshafen, were analyzed for the presence of intraoperative 3D scans and corresponding postoperative CTs. If both criteria were met, the corresponding patient was included in the study. The examination of the image datasets was performed retrospectively.

All included 3D scans were acquired using an Arcadis Orbic 3D made by Siemens (Erlangen, Germany). The corresponding computer tomographies were obtained using an Aquilion 32 made by Toshiba (Nasu, Japan).

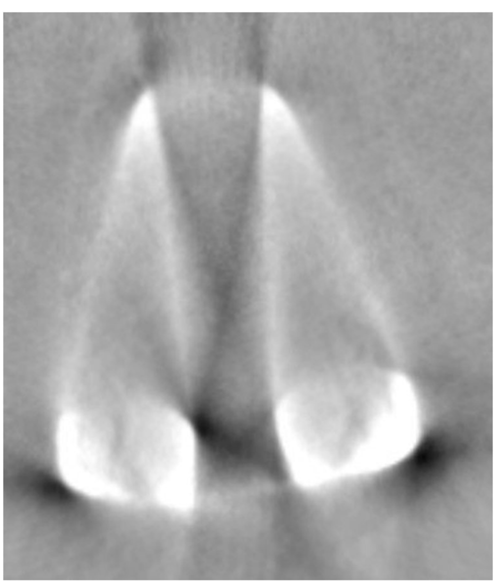

Fig. 1 Screenshot of a 3D scan using CBCT after pedicle screw placement in the lumbar spine showing resulting artifacts

Software

A selection of three programs was provided by the manufacturer of the mobile 3D C-arm: "metal artifact reduction" (MAR), "metal artifact reduction 2" (MAR-2), and "Shepp & Logan" (SL) (Fig. 2). The function "iterative reconstruction in image space" (IRIS) was also offered and can be used as an "Add-on" for the other programs. The three programs mentioned above were all evaluated with and without the additional use of IRIS during the application. These are presented within the study as six individual programs. In the figures, the activation of the IRIS function is marked with a "+."

All software algorithms mentioned have already been used in computed tomography, but an implementation in the mobile C-arm has not yet been carried out. Therefore, an independent software prototype, which not only included the known algorithms but also allowed a retrospective application on 3D image datasets of a mobile C-arm, was used to perform the artifact reduction and thus to improve of the image quality.

In the following sections, the individual software algorithms on which the software prototype of this study is based are described in detail.

SL

The basis of software-based artifact reduction is SL. Its principle is defined by the convolution kernel and the filtered back projection invented by Shepp and Logan [19]. The filtered back projection is not explicitly designed for the reduction of image artifacts caused by metallic elements. However, the known subtle image enhancements have been integrated into this algorithm to achieve the best "cone beam computed tomography" (CBCT) standard image quality. Apart from the transition to a volume size of 512^3 voxel with a voxel size of approximately 0.25 mm (CT has approximately 0.5 mm), the so-called cosine-weighting for the correction of obliquely incoming cone rays is included, as well as the "Parker-Weighting" for the compensation of redundancies caused by lateral cone rays. The convolutional kernel serves to parameterize the filtering, which reduces the "smear artifacts." The realization and implementation of this method were only possible with the new and faster generation of graphics cards.

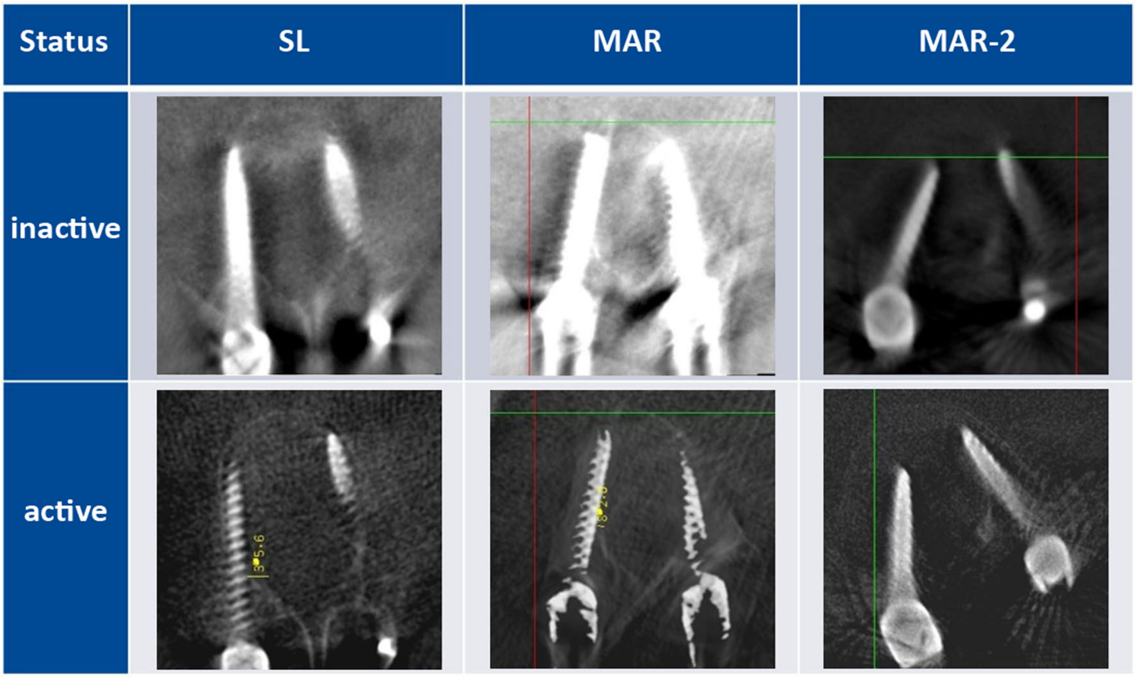

Fig. 2 Comparison of screenshots of a 3D scan using a CBCT after pedicle screw placement with representation of the image quality before ("inactive") and after application of SL, MAR, and MAR-2 ("active")

MAR

The purpose of this method, especially in the reduction of metal artifacts, is to improve the visualization of tissue close to metallic screws in 3D datasets. In the affected image areas, either brightening or darkening can often be observed, making the assessment difficult or even impossible for the clinician.

In the MAR technique, the flat projections obtained, when using the C-arm, are first reconstructed into a volume block consisting of voxels. This volume is called "the mask volume." Metal objects are now specifically detected in this "mask volume" using 3D segmentation. The physical basis of this segmentation is the detection of high-density values in the reconstructed volume dataset. These detected dense 3D structures are now projected onto each individual detector image and thus generate "metal shadows" there. The areas affected by metal shadows are removed and replaced by values interpolated between the edges of this shadows. This method is sometimes referred to as "Inpainting." This results in further projections, which now serve as input data for a new projection (without metal). In this second, improved volume, the previously segmented metal structure is faded in again [20].

Meilinger et al. (2011) were able to develop a similar method, whereby the "inpainting" is realized with adequate attenuation coefficients of tissue (or water) [21].

MAR-2

MAR-2 is an extended version of MAR based on the "frequency split metal artifact reduction" (FSMAR) published by Meyer et al. (2012) [22]. It became evident that sometimes in the case of pedicle screws, e.g., in the lateral projections, there is still a modulation of the signal intensity (physically corresponding to the detected X-ray energy) in detector areas covered by metal. There is therefore no ideal X-ray shadow behind the screw. Therefore, only low-frequency detector signals were specifically interpolated in the MAR-2 method and the higher-frequency detector signals were classified as appropriate and used originally. "Frequency" here refers to the "spatial frequency" (image modulation) in the shadow area of the projection.

IRIS

In the preliminary stages of the development of the software prototype, it was already known that the SL algorithm reduces image interference while at the same time artificially smoothing out (rounding off) geometric edges in scanned objects. Due to this fact, the method IRIS was introduced. It aims to detect object edges and to preserve the high-frequency 3D intensity transitions at these edges, while still smoothing high-frequency "clean" interference [23]. IRIS is not a stand-alone artifact reduction method but can be used in addition to the three previously described SL, MAR, and MAR-2.

Radiological Analysis

Plane Selection

The images in the region of each pedicle screw were analyzed using a defined image plane found using a standardized protocol. The criterion was that the selected plane cuts the affected pedicle screw in a longitudinal direction, where the diameter was largest, in order to visualize the implant in full length. To achieve an axial representation of the final plane, the rotation around the screw axis was carried out until as many spinous processes as possible are displayed simultaneously.

Assessment and Classification of Image Quality by Visibility of Anatomical Structures

In the selected plane, the visibility of the following structures was evaluated: medial pedicle wall, lateral pedicle wall, anterior side of the vertebral body, and posterior side of the vertebral body (Fig. 3). The overall quality of the image was evaluated according to the number of visible structures. If no or only one structure could be delimited, the image was classified as not assessable (class 1). An image with two or three visible structures was classified as having limited assessability (class 2). If all four structures could be depicted in the picture, it was considered to be completely assessable (class 3).

This evaluation was performed for CBCT only.

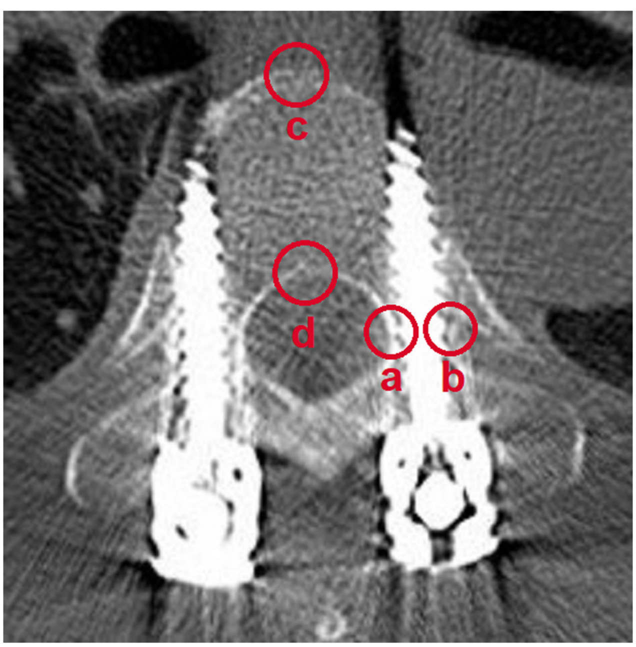

Fig. 3 Screenshot of a postoperative CT showing a vertebral body in the region of the upper thoracic spine after pedicle screw placement with marked anatomical structures suggested for the evaluation of image quality: (a) medial pedicle wall, (b) lateral pedicle wall, (c) anterior side of the vertebral body, (d) posterior side of the vertebral body

Assessment and Evaluation of Image Quality by Screw Diameter

For additional validation of the measurement, the diameter of the screw at the point of greatest expansion was measured and then compared with the actual diameter known from the OP protocol. A high deviation of the diameters was regarded as another factor for poor image quality, as anatomical structures could be concealed by the blooming artifact. The cause of this artifact is that the high-density value of such metal objects as pedicle screws coupled with the use of smoothing filter kernels results in saturated pixels, due to which these structures can seemingly appear larger than their real size.

This evaluation was carried out for CBCT and compared to postoperative CT.

Statistical Analysis

The Wilcoxon signed-rank test was used to compare the average image quality and the deviation of the measured and physical screw diameter.

A value of $P < 0.05$ was considered as statistically significant. All statistical analyses were performed with SPSS v. 22 (SPSS, Chicago, IL, USA).

Results

Descriptive Statistics

A total of 49 patients could be enrolled in this study. They were on average 55.3 years old. A total of 55.1% of them were male. The average body weight was 76.4 kg. A total of 48.3% of the patients were assigned to BMI group 2, 27.65% to BMI group 3, 13.8% to BMI group 4, and the remaining 10.3% were distributed among the BMI groups 1 and 5.

A total of 229 pedicle screws were examined in the study. A total of 64 (27.9%) of the screws were located in the cervical spine, 92 (40.2%) in the thoracic spine, and 73 (31.9%) were found to be in the lumbar spine.

Image Quality

Without artifact reduction, the average image quality was found to be 1.7 for the stated three classes for image quality. The precise distribution according to the anatomical area of the spine is shown in Fig. 4 and is represented by the blue-colored bar. The best assessable vertebrae were T2, T1, and C6 (in descending order). The least assessable vertebrae were

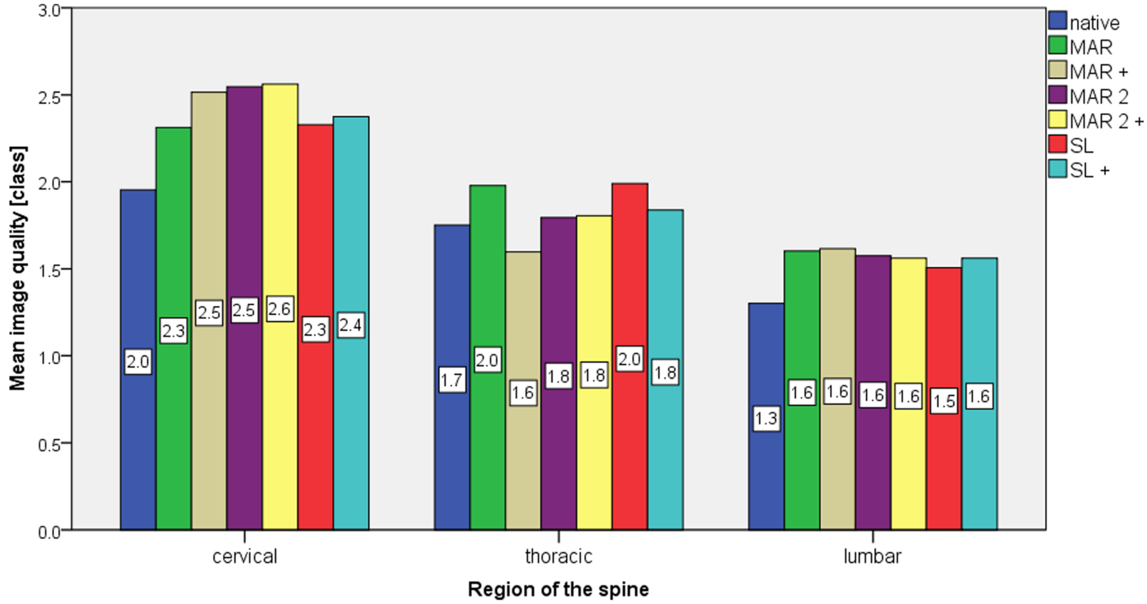

Fig. 4 Mean image quality before and after artifact reduction using all 3 software algorithms with and without the application of IRIS (+) in different spinal regions presented as a bar chart

T9, L5, and T11. The difference between normal weight (BMI group 2) and slight overweight (BMI group 3) only resulted in poorer assessability in the thoracic region. In the other anatomical regions, the BMI had no relevant influence on the assessability.

Artifact Reduction According to Visibility of Anatomical Structures

Image quality after artifact reduction for individual anatomic subgroups is shown in Fig. 4. All programs could improve the image quality to at least 1.9 on average. The program MAR could even improve the quality to 2.0. P was < 0.01 for all methods except for MAR + IRIS ($P = 0.04$).

Artifact Reduction According to Deviation of Screw Diameter

The deviation of screw diameter after artifact reduction comparing to the image quality of a CT is shown in Fig. 5. The programs MAR and MAR-2 can reduce the blooming artifacts significantly ($P < 0.01$ for both). SL is not able to reduce the artifacts significantly, as P is 0.08 with IRIS and 0.988 without IRIS. IRIS introduces more blooming artifacts when used in combination with MAR-2.

Discussion

The main finding of the presented study is that software-based artifact reduction can be used in a clinical setting and appears to deliver improved image quality. Regarding the visibility of bony structures, all programs show an advantageous result. For the reduction of the blooming artifacts, only the programs MAR and MAR-2 can achieve higher quality images. SL does not appear to be appropriate for this purpose. The activation of IRIS as an additional function is not always beneficial. This can lead to interference with the individual algorithms, as illustrated by the example of the MAR-2 method, since the original dataset is modified by IRIS. In this case, the blooming effect next to the pedicle screw was increased, but the assessment of the anatomical structures of the vertebral body was

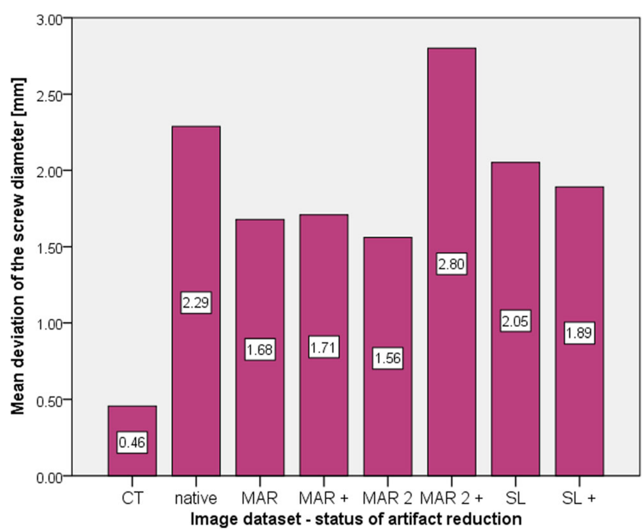

Fig. 5 Deviation between actual and measured screw diameter before ("native") and after artifact reduction (SL, MAR, MAR-2 with/without IRIS) using CBCT compared to CT presented as a bar chart

not compromised. On the contrary, the average image quality was improved by reducing other metal artifacts such as beam hardening. However, from our point of view, in marginal cases, where the implant is located directly at the cortical line, the assessability can be restricted. Since there were virtually no implant misalignments in our datasets, this aspect cannot be adequately assessed and should be investigated in a further study.

At present, there are no studies that explicitly focus on the reduction of metal artifacts in cone beam CT scans of pedicle screws. However, an investigation dealing with such metal artifacts in the context of computed tomography was carried out by Wang et al. (2013). In the study, it was shown that the contrast between the pedicle screws and the bony structures is significantly lower if the images were reconstructed using the standard software for conventional polychromatic images of the manufacturer (GE Advantage, GE Medical Systems). In contrast, image quality was significantly improved when the monochromatic reconstruction method was applied. Furthermore, both the evaluation of artifacts and the diagnostic value of the images improved when energies above 100 keV were used for the scans. Based on these results, the authors recommend the use of the additional "Metal Artifacts Reduction Software" (MARS) algorithm for monochromatic image reconstruction in CT, whereby particularly meaningful images can be obtained in an energy range from 110 to 140 keV [18].

The presented study deals with a different type of cross-sectional imaging. However, similar to our investigation, it shows that software-based reduction of metal artifacts can improve the quality of sectional images.

Another study on metal artifacts in computed tomography was published by Kidoh et al. (2014), specifically focusing on artifacts from metallic dental implants. The artifact reduction method was based on the standard "filtered back projection algorithm" with the addition of O-MAR (Metal Artifact Reduction for Orthopedic Implants). The study demonstrated that O-MAR could significantly improve line artifacts ($P < 0.01$). On the other hand, the new reconstruction method showed a slight but statistically significant degradation of the image sharpness and naturalness of the textures compared to the standard version ($P < 0.01$). Accordingly, the authors assigned a supporting role to the new algorithm and recommend its use in addition to the normal, standard reconstructed images [24]. This study demonstrates that metallic artifacts are also a problem in the region of the facial skull. These can also be successfully addressed by software-based artifact reduction.

The methods for the reduction of metal artifacts in intraoperative 3D imaging which are discussed in the context of this study are still being evaluated and continuously further developed by research groups focusing on this topic. One of the reasons for this is that although the current methods (e.g., MAR and MAR-2) can reduce artifacts well, such methods often go hand in hand with the introduction of new artifacts, which in turn can negatively affect the assessability of the images. Based on this consideration, Meyer et al. (2010), for example, developed a normalized MAR (NMAR) method that can be applied almost without the introduction of new image artifacts. The authors were able to prove the advantages of this method compared to MAR and MAR-2 using both simulated and clinical images. NMAR led to a successful artifact reduction in both moderate and severe artifacts. In order to generate clinical data, patients with hip prostheses and dental prostheses, as well as patients with spinal instrumentations, were examined. The group has identified particular advantages of the NMAR method in patients with metal artifacts, particularly those resulting from metallic structures within or in the immediate vicinity of bone tissue [25].

A further result was that the native image quality was found to be best in the area of the cervical spine and worst in the area of the lumbar spine. However, it is the good quality images that benefit most from artifact reduction. Nevertheless, the image quality of a 3D scan is inferior to computed tomography, even after the use of artifact reduction programs.

The x-rayed body mass in the area of the cervical region of the body is considerably smaller than that of the thoracic or lumbar region, so that considerably less radiation is absorbed and therefore considerably more X-rays arrive at the detector. This leads to a better image quality. On the other hand, different compartments, such as lung and intestine, are also x-rayed at the level of the thorax and abdomen. These have a high range of density values (water, air, bone). These can be visualized by computer tomography and contrasted by correct windowing. A cone beam CT is limited in this regard and can only be focused on a small range of density values. As a result, 3D reconstructions in the thoraco-lumbar region are limited in contrast, whereas in the cervical region, the contrast is significantly higher.

Only a few studies focus on the image quality of 3D scans of spinal images separately. Even fewer publications deal with the quality of these images specifically on pedicle screws.

A study by Rock et al. (2001), which was carried out on a specimen model, dealt with the topic of image quality in cone-beam CT scans of the Siemens Iso-C-3D. In summary, the examination confirms that the imaging technique has sufficient quality for the assessment of peripheral joints, but limited quality for the examination of the soft tissue-covered spine, especially for the assessment of trabecular bone. This quality is questionably sufficient for the diagnosis of fractures but is suitable for the reduction control after osteosyntheses [26, 27]. Due to the absence of metal artifacts, these results can only be compared to a certain extent with our investigation. In particular, no subgroup analysis was conducted within the spine patients (with regard to spinal segment and BMI).

Kluba et al. (2009) chose a different methodological approach for the evaluation of image quality. Their study was performed to determine the reproducibility of the interpretation of lumbar pedicle screw scans with a C-arm-based imaging system compared to computed tomography. Due to the better image quality, the diagnostic reports of the CT scans showed significantly fewer deviations than in the case of the Iso-C-3D [28]. This opinion also corresponds with the results of our research.

In another study by Beck et al. (2009), the results of intraoperative 3D scans after pedicle screw placement in the thoracolumbar region were compared with the screw positions in the postoperative CT. With good scan quality, an absolute correspondence between computed tomography and intraoperative 3D imaging was accomplished. The quality achieved correlated significantly with the pedicle diameter ($P = 0.004$), the BMI of the patients ($P = 0.001$), and the spinal segment ($P = 0.001$). Wide pedicles, spinal level B11-L5, and a low BMI lead to a good scan quality [29]. In contrast to Beck, the thoracic spine in our study showed better image quality than the lumbar spine. The sample size of Beck is smaller than in the presented study (93 screws in thoracic/73 screws in lumbar spine versus 84 screws in thoracic/52 screws in lumbar spine). Whereas the eleventh and twelfth thoracic vertebrae in Beck's research are considered to belong to the lumbar spine, in our study, they are assigned to the thoracic spine according to anatomical rules. It was these vertebrae that proved to be perfectly assessable in our investigation.

Limitations

The literature review for this project was unable to identify a standardized system for evaluating the quality of images acquired with pedicle screws. A customized score system was therefore developed for this particular case. The key elements were the ability to assess the abovementioned anatomical structures, which are relevant for the surgeon with regard to possible complications.

The BMI of the patients included in the study is predominantly assigned to groups 2 and 3 and is therefore comparable to that of the average population. The heavily overweight BMI groups 4 and 5, as well as the underweight group 1, are weakly represented in the sample investigated. Also, they are unevenly distributed among the anatomical groups. The data only permit an evaluation of the difference between normal weight and underweight. The influence of severe overweight or cachexia cannot be assessed a priori using the data available.

Conclusions

In summary, the software-based artifact reduction for intraoperative 3D image datasets, for example, in the context of dorsal instrumentation of the spine, generally improves the image quality. Additional information is acquired, and so the need for an intraoperative revision may be deduced. However, an image quality comparable to computed tomography has not been achieved yet. Therefore, the potential for innovative techniques of software-based artifact reduction has yet to be realized, and approaches that already have a promising influence on image quality during the acquisition of the 3D datasets may be a possible addition or alternative to CT scans.

Additionally, a volume dataset is more than just a single image plane. The surgeon does not rely on a single image plane to evaluate screw placement. Instead, all layers are usually considered and analyzed. Nevertheless, this study has considered a concrete image plane. This is because the image quality must be assessed independently of the examiner. A single image can be evaluated far more easily using given points than several different image layers. The selected image plane with the greatest screw diameter is clearly the one with the most powerful metal artifacts and so also the sectional plane with the most restricted image quality. Therefore, the advantages provided by the software programs in clinical practice are probably higher than indicated here.

Acknowledgments Karl Barth (Siemens AG, Healthcare Sector, Erlangen, Germany) made a special contribution to this study. He provided us with the software prototypes for artifact reduction and supported us in their application.

Compliance with Ethical Standards

Conflict of Interest The authors declare the following potential conflicts of interest concerning the research, authorship, and publication of this article: The BG Trauma Center Ludwigshafen and Siemens Healthcare AG in Erlangen, Germany cooperate in the field of medical imaging and image-guided surgery. This cooperation influenced neither the outcome of the study nor the manuscript.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Since only existing anonymized image data was used, no informed consent was required for the present study.

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