Intraosseous ultrasonography to determine the accuracy of drill hole positioning prior to the placement of pedicle screws: an experimental study

Laboratory investigation

SVEN RAINER KANTELHARDT, M.D.,¹ JÖRG LARSEN, M.D.,² VOLKER BOCKERMANN, PH.D.,¹ WOLFGANG SCHILLINGER, M.D.,³ ALF GIESE, M.D.,¹ AND VEIT ROHDE, M.D.¹

Departments of ¹Neurosurgery, ²Neuroradiology, and ³Cardiology and Pneumology, Georg-August-University Göttingen, Germany

Object. Dorsal fixation with rods and pedicle screws (PSs) is the most frequently used surgery to correct traumatic and degenerative instabilities of the human spine. Prior to screw placement, screw holes are drilled along the vertebral pedicles. Despite the use of a variety of techniques, misplacement of screw holes, and consequently of the PSs, is a common problem. The authors investigated the usefulness of an intraspinal, intraosseous ultrasonography technique to determine the accuracy of drill hole positioning.

Methods. An endovascular ultrasound transducer was used for the intraluminal scanning of bore holes in trabecular bovine bone, 12 pedicle drill holes in cadaveric human spine, and 4 pedicle drill holes in a patient undergoing thoracic spondylodesis. Seven of the experimental bore holes in the cadaveric spine were placed optimally (that is, inside the pedicle) and 5 were placed suboptimally (breaching the medial or lateral cortical surface of the pedicle). Computed tomography scans were obtained in the patient and cadaveric specimen after the procedure.

Results. The image quality achieved in examinations of native bovine bone tissue, the formalin-fixed human spine specimen, and human vertebrae in vivo was equal. The authors endosonographically identified correct intrapedicular and intravertebral positions as well as poor (cortex breached) placement of drill holes.

Conclusions. Intraosseous ultrasonography is a promising technique for the investigation of PS holes prior to screw implantation, and may add to the safety of PS placement. (DOI: 10.3171/2009.6.SPINE08640)

KEY WORDS • pedicular screw placement • intravascular ultrasonography • bone sonography • spinal fusion technique

Spondylosis using PSs and rods is a common spinal surgical procedure. The success of the operation depends largely on the correct positioning of the transpedicle screws. Poor screw positioning increases the failure rate of the procedure and puts the spinal cord and nerve roots at risk. According to postoperative CT data, misplacements occur in as many as 10–15% of lumbar and thoracic procedures, even in experienced hands. Because of the inherently smaller pedicles, the rate of malplacements may be even higher in cervical spine procedures. Different techniques have been proposed to ensure the correct placement of PSs. Conventional intraoperative fluoroscopy was used in the aforementioned studies. More sophisticated methods have included the use of mechanical instruments and robots for drill guidance or computer-assisted image-guidance systems. Such techniques provide the spinal surgeon with information on the optimal trajectories, but fail to indicate whether the proposed trajectories indeed match the actual intraoperative positioning. In contrast, intraoperative CT scanning does allow assessment of screw position, but is a time-consuming, tedious undertaking that further exposes the patient to ionizing radiation. In the present study, we describe a novel ultrasonography-based technique for the intraoperative visualization of the luminal surface of pedicular drill holes that may facilitate the detection of pedicle breaches and thus avoid screw misplacement and consequent therapy failures.

Methods

Experimental Studies

The initial experimental evaluation of intraspinal ultrasonography was performed in native bovine bone sam-
sles. Transcortical holes, 3-mm wide and 40-mm long, were drilled into the trabecular portions of the samples. The ultrasonography studies were performed with the specimen submerged in blood (hematocrit of 35, reconstituted in physiological saline solution from red blood cell concentrates).

Intrapedicular ultrasonography was subsequently performed in a formalin-fixed adult human lumbar spine specimen which showed no evidence of significant degenerative disc or facet joint disease. Drill holes with a 3-mm diameter and and approximate length of 40 mm were again placed through the pedicles and into the VBs from L-1 to S-1 (a total of 12 bore holes). To evaluate whether poor positioning of a drill hole may be depicted ultrasonographically, 5 holes were intentionally drilled in a suboptimal fashion, breaching the pedicular cortical surfaces, whereas 7 were correctly placed (no cortical breaches). The specimen was submerged in saline solution prior to ultrasonography.

Clinical Study

In a patient with spondylodiscitis, we examined 4 pedicles intraoperatively during dorsal thoracic bisegmental spondylodesis: 3-mm holes were drilled using a pneumatic drill under biplanar fluoroscopic guidance according to the standard technique. Following intraluminal ultrasonographic examination of the pedicle drill holes, PSs were placed, again under fluoroscopic control. Postoperative CT scanning was performed to confirm the result.

Imaging Studies

For ultrasonography, an In-Vision Gold Intravascular Ultrasound System was fitted with an Eagle Eye Gold, single-use Intravascular Ultrasound Imaging Catheter (Volcano Therapeutics, Inc.), designed for diagnostic intravascular applications in cardiology (Fig. 1). The system provides real-time, 2D 360° images at a rectangular plane relative to the long-axis of the catheter. For the experiments, the catheter was advanced into and right to the end of the drill holes and then extracted slowly, acquiring a stack of ~ 200 images for each pedicle. Image arrays were exported as DICOM image files.

Postoperatively, both the human postmortem specimen and the patient were scanned using a conventional 16-slice CT scanner (Aquilion, Toshiba Medical Systems). Images were derived from a 240-mm field of view to yield sections with 1.0-mm thickness reconstructed at 0.79-mm intervals using both the highest resolution (bone) algorithm and a soft tissue algorithm. Image postprocessing was performed using a standard medical workstation (Vitrea 2, ViTAL Images Europe). Anatomical details and surgical artifacts were specifically visualized by dedicated multiplanar image reconstruction, and image appearances further altered by adjusting window settings.

The ultrasound catheter was fitted with rings marking the distance from the piezoelement. This allowed a measurement of the catheter depth and an exact correlation with the distance from the tissue entry point on the corresponding CT scans. For the intraoperative study, the catheter depth was additionally verified by lateral 2D fluoroscopy.

Intraosseous ultrasonographic examinations of the formalin-fixed specimen, as well as intraoperative examinations in a patient were performed and interpreted online and prior to the CT scanning by a neurosurgeon. The CTs were evaluated by a neuroradiologist.

Results

Experimental Studies

The inner lumen of the drill holes in native bovine bone could easily be identified as areas of low echogenicity. Expectedly, the inner surfaces of the holes were very
Intrapedicular ultrasonography

... highly reflective and depicted as a bright white ring with a smooth margin toward the hypoechoic artificial pedicular lumen. Because of the strong reflection, no structures could be seen beyond the inner bone surface; however, ring-shaped reverberation artifacts occurred beyond the circular bone edges. The proximal and distal ends of the drill holes could be easily identified by the sudden loss of the highly echogenic ring, with soft tissue signal echoes further from the probe becoming visible (Fig. 2).

The appearance of the cadaveric human bone specimens on ultrasonography was not substantially different from those of the native bovine specimens. The inner surfaces of the intrapedicular drill holes as well as the drill holes in the trabecular bone of the VB were again visualized as ring-shaped structures of high echogenicity. Likewise, ring-shaped reverberation artifacts occurred beyond the circular bone edges. Other artifacts, such as bone dust in the drill hole, could be likewise identified (Fig. 3). Ultrasoundographic images and the corresponding position of the catheter on the CT scans could be exactly correlated by measurement of the catheter depth in the tissue and the distance from the tissue entry point on the CT scans (Fig. 4). Ultrasonography images clearly identified 5 (lateral and medial) breaches of the pedicular cortex by the loss of the low intensity signal of the drill hole lumen and loss of the high-intensity, ring-shaped reflection of the inner bone surface, which were both replaced by a soft tissue–like reflectivity (Figs. 5 and 6). In the case of far lateral deviations that miss the VB entirely, the ring-shaped echo of the bone did not reappear because the screw hole did not reenter the VB.

Likewise all 7 correctly placed drill holes were identified by intraosseous ultrasonography. The results from CT scanning matched the intraosseous ultrasonography interpretation in all 12 cases. The diameter of the smallest breach identified by intraosseous ultrasonography in this study was ~ 4 mm on axial CT scans.
Fig. 3. Transpedicular drill hole (3-mm drill) and puncture hole (1 mm) in the cadaveric human spine are shown. On the left, ultrasonographic artifacts are highlighted and explained.

Fig. 4. Quantitative correlation of CT and ultrasonographic images. A tape line marks the distance from the piezoelement on the catheter. By correlation of the catheter depth below the tissue entry point and the distance on the CT scan the exact position of the catheter can be determined. Each ultrasonographic image can be selected after completion of the study by the recording time, or more exactly by its individual number (right upper corner of each ultrasonographic image).
Intraoperative Assessment

Given the satisfactory findings from the pilot experiments, the technique was used in a single patient to consider the intraoperative practicalities of the method: 4 thoracic PSs were placed in the dorsal spine to stabilize an intervertebral disc space affected by spondylodiscitis. There was no substantial difference in the imaging appearances of drill holes in vivo compared with in cadaveric bone. The lumen of intrapedicular and intravertebral drill holes could be clearly identified, and the inner surface of the bone channel appeared again as a highly reflective ring (Fig. 7). The correct implantation technique of the drill holes and PSs, as suggested by intraosseous sonography, was proven on postoperative CT scans. In the clinical part of this study, the catheter depth in the drill hole was additionally validated using lateral 2D fluoroscopy intraoperatively. Performance of ultrasonography studies required ~1 minute for each drill hole. Handling of the sterile, single-use ultrasound catheter was straight-

Fig. 5. Transpedicular drill hole in formalin-fixed cadaveric L-1 vertebra. Oblique-axial reformatted images of the spiral CT data set on the left demonstrate the drill holes (A–E). The position of the ultrasonography catheter is schematically superimposed. The corresponding intraluminal 360° ultrasonography images are shown on the right (1–20).
forward. Remaining bone dust in the PS hole could be removed by simply flushing with normal saline solution. Ultrasonography images were displayed in real time, and examinations could be repeated as needed. Simultaneously, a stack of 200 images per pedicle was recorded for later review.

Discussion

Incorrect positioning of PSs is recognized to be the source of neurological deficits and reduced stability after dorsal spondylodesis. To reduce the number of poorly placed screws, some spinal surgeons perform interlaminar fenestration for direct visualization of the inner aspect of the pedicle, spinal cord, and adjacent nerve roots. This strategy allows avoidance of neural damage, but carries the disadvantages of extended surgical exposure and increased instability because of the required extended bone resection, which often includes arthrectomy and ligament resection. Furthermore, lateral deviation of the trajectory is not controlled. In recent years, drill guides, robots, and computer-assisted image-guidance systems have been used to aid correct screw positioning in dorsal transpedicle fixation. These tools have in common that they propose optimal trajectories for drilling and screw placement on the basis of preoperative imaging. However, they do not allow direct intraoperative confirmation of whether preoperative registration of the image guidance system is still correct, and whether the proposed trajectory indeed matches the actual operative site, unless the images are updated by intraoperative CT or MR imaging. Because fatty connective tissue can be found both intra- and extraspinaly, Kosay and coworkers5 proposed that finding fatty material in the drill hole may indicate that a cortical breach occurred during drilling. Other authors have proposed controlling screw position by diathermy or intraoperative electromyography. Both of these techniques can identify a direct contact between the screw and nerve root.5,18 Intraosseous ultrasonography follows a similar principal, but allows direct visualization of the PS hole.

Although in this experimental study the neurosurgeon
Intrapedicular ultrasonography

(S.R.K.) did interpret the ultrasonographic examinations of all 12 cadaveric pedicles correctly without knowledge of the CT findings, these data are too subjective to yield values for sensitivity and specificity of the new technique. We could show, however, that intrapedicular ultrasonography carries the potential to identify misplaced PS holes, and therefore might be developed into a promising tool for PS placement in future. After ultrasonographic identification of a deviated PS holes, the trajectory may be corrected intraoperatively. In patients with narrow pedicles, the intrapedicular portion of a second screw hole in the same pedicle might be difficult to assess. Two or more screw holes can cross each other and result in distorted ultrasonographic images. Clearly separated bur channels in larger pedicles, especially when a small drill is used, may still be separately analyzed by introduction of the probe, however. In cases in which the first screw hole leaves the bone entirely (far lateral deviations) the reappearance of a highly echogenic ring-like structure in the redirected screw hole can confirm the proper placement of the corrected trajectory and exclude lateral deviations.

In cardiology, special ultrasonographic transducers have been developed for intravascular imaging; these have proven to be a valuable adjunct in coronary angiography, for example. Although angiography provides no more than a luminal cast of a vascular lumen, intravascular ultrasonography allows a tomographic assessment of the lumen area as well as of plaque size, distribution, and composition. This modality’s high resolution allows imaging of intravascular disease, such as plaques, of < 1 mm diameter. We used a cardiological intravascular ultrasonography probe for intrapedicular and intravertebral imaging.

Other authors have already experimented with ultrasonography in the evaluation of bone structure. Padilla et al. focused on the mathematical modeling of ultrasonic backscatter for the assessment of trabecular bone thickness, and Moilanen and colleagues analyzed the velocity of guided ultrasound waves to estimate the cortical thickness of bone specimens. The results of these studies indicate that ultrasonographic imaging of bone has the potential to provide key information on bone structure and density. The focus of the present study was different, however. Our aim was to evaluate whether intrasosseous ultrasonography during dorsal spondylodesis could be used to identify the actual position of drill holes, specifically to identify potentially harmful lateral, medial, or caudal deviations from the ideal trajectory prior to PS placement. We have shown that ultrasonography indeed allows differentiation between correctly and poorly placed pedicelar screw holes. In cadaveric human specimens, pedicle breaches in the cervical spine as small as 2 mm in diameter could be identified (Kantelhardt et al., unpublished data). In selected cases, ultrasonography could even visualize fissure-like fractures in cadaveric bone. However, the potential limitations of the currently used hardware were identified. The design of the flexible catheter as it is required for coronary endosonography does not allow alignment of the 360° ultrasonogram with the anatomy. Although it is a straightforward matter to identify pedicle perforation, it is not as easy to identify its exact site. In future, a modified 360° rigid probe may overcome this limitation; this device is currently under investigation at our institution.

**Conclusions**

Identification of improperly placed drill holes that
have breached the pedicle wall prior to PS placement is technically possible using intraosseous ultrasonography. This method has the potential to reduce the rate of screw malpositioning in open and especially percutaneous interventions for spinal instability. Further investigations ex vivo as well as intraoperatively are necessary to further establish these preliminary findings.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Acknowledgement

The lumbar spine specimens were kindly provided by Dr. Karlhans Endlich of the Anatomical Institute of the University of Greifswald, Germany.

References

15. S. R. Kantelhardt et al.


Portions of this work have been presented in talks given at the meeting of the Section of Intraoperative Imaging of the German Society of Neurosurgery, May 17, 2008, Göttingen; the 59th Annual Meeting of the German Society of Neurosurgery, June 1–4, 2008, Würzburg; and the Meeting of the Section of Spine Surgery of the German Society of Neurosurgery, September 20, 2008, Oldenburg, Germany.

Address correspondence to: Sven Rainer Kantelhardt, M.D., Department of Neurosurgery, Georg-August-University of Göttingen, Robert-Koch-Strasse 40, 37075 Göttingen, Germany. email: sven.kantelhardt@web.de.