Intraoperative and dynamic 3D rotational X-ray imaging

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Summary
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Three dimensional imaging techniques like computed tomography are frequently used in the pre- and postoperative evaluation of surgical procedures. However, the progress during the operation is currently evaluated using visual and physical inspection or 2D fluoroscopy. Consequently, suboptimal positioning of implants, insufficient reconstructions and joint incongruities frequently remain unrevealed intraoperatively.

Three dimensional rotational X-ray (3D-RX), also called cone beam CT, is a technique to obtain images of cross sections of a 3D object with a C-arm. To this end, a series of X-ray projection images acquired on a near semi-circular trajectory is reconstructed to 3D volume. The mobile 3D-RX system was designed to be utilized in the operating room. The propeller movement limits application to the distal extremities and head/neck. Application of intraoperative 3D-RX is appreciated in orthopedic, hand and trauma surgery where 2D fluoroscopy is standard. In fields such as sinus, ear and orbital surgery involving bony structures, where 2D fluoroscopy is hardly ever used because over projection of the anatomical structures yields low definition images, 3D-RX is appreciated.

In this thesis a number of investigations on 3D-RX imaging are described. The first aim was to investigate the image quality of high contrast imaging mobile, intraoperative 3D-RX system (Chapter 2). The second aim was to investigate application of intraoperative 3D-RX in Cochlear implantation (ENT surgery), Orbital surgery, Hand surgery, and Trauma surgery (Chapters 3-6). Additionally, the 3D-RX system was utilized for a third aim: the development of dynamic 3D-RX (4D-RX) imaging for detection of motion patterns in the wrist joint (Chapters 7&8).

3D-RX

In Chapter 2 we objectively determined the image quality of a mobile 3D-RX device by measurement of contrast-to-noise ratio (CNR) and spatial resolution, and we estimated the effective dose. The detectability of small bone details was predicted using the measured parameters. For comparison we made measurements with a multi slice CT (MSCT) scanner with standard ear, orbit and skeleton protocols. The maximum spatial resolution of mobile 3D-RX can be better than that of MSCT, while the tissue-air CNR with MSCT is better. However, the effective dose is much higher for MSCT. Small bone details can be detected both with MSCT and 3D-RX. This prediction was confirmed by the fact that clinically relevant details of sub millimeter size, like the incus and malleus in the middle ear, can be visualized equally well with both systems.

In Chapter 3 we described intraoperative 3D-RX scanning during cochlear implantation surgery. Scanning the multielectrode array is performed once before removal of the stylet carrying the implant and once after full insertion. When dissatisfied with the position of the multielectrode a repositioning is performed which happened occasionally. Twenty-three cochlear implantations were performed with aid of 3D-RX imaging, eventually resulting all in full insertions. The major advantage of using 3D-RX in this procedure is the extra certainty of the multielectrode array position in the cochlea at the prize of only low-dose and little extra time. All cochlear implantations are now routinely scanned during surgery.
We investigated the application of intraoperative 3D-RX for surgery of the bony parts in the orbit in Chapter 4. Our primary research objective was to compare surgical performance and certainty interpreted from direct visual and physical inspection with surgical performance and certainty interpreted from intraoperative 3D-RX. Sixty-four intraoperative findings and 3D-RX scans (30 patients, 56 orbits) were compared by means of a questionnaire. Prior to a 3D-RX scan, the surgeon was allowed to check the state of the current operation by means of direct visual and physical examination. After the scan was made, but before seeing the 3D image, the surgeon completed the questionnaire. The 3D-RX images were reviewed 6 months later by the surgeon. We showed that intraoperative 3D-RX provides the surgeon with additional information, especially for assessing the orbital floor. For most other bony parts, the performance was often less satisfactory interpreted from 3D-RX imaging than assessed intraoperatively by the surgeon. The certainty about treatment of the medial wall, deep sphenoid lateral wall, and orbital floor was assessed clearly higher with 3D-RX than with direct visual and physical inspection. The assessment of proptosis (bulging of the eye) from 3D-RX images was considered inadequate.

Our research objective in Chapter 5 was to compare performance as interpreted from conventional methods with intraoperative 3D Rotational X-ray (3D-RX) for hand surgery. Therefore we prospectively compared the performance of the surgeon interpreted from conventional methods (2D fluoroscopy and direct visual and physical inspection) versus 3D-RX imaging as well as the occurrence of revision surgeries based on post-op radiological findings. Twenty-four intraoperative findings based on 2D fluoroscopy and direct visual and physical inspections were compared with intraoperative acquired 3D-RX scans by means of a questionnaire. During the operation, just before a 3D-RX scan, the surgeon had to give an opinion on his surgical results, based on conventional examination methods. Six months later the 3D-RX scans were reviewed by two experienced surgeons to compare with the intraoperative findings. Record was kept of revision surgery (3 months follow up) for all patients treated with the aid of 3D-RX. A difference was observed between the performance based on conventional methods and that based on intraoperative 3D-RX for hand surgery. Post-operative radiological examinations revealed that none of the 56 patients treated with aid of 3D-RX needed revision surgery while the reported revision rate can be as high as 23%.

In Chapter 6 we compared the effectiveness of different aspects of fracture reduction for 50 judgments interpreted from conventional (2D) methods versus intraoperative 3D-RX by means of a questionnaire. In addition, we investigated the need for revision surgery based on postoperative radiological findings in 81 patients. After fracture reduction, just before a 3D-RX scan, the surgeon intraoperatively assessed the result of surgery. Three months after surgery, the 3D-RX scan was judged by three experienced surgeons independently. Intraoperative 3D-RX clearly showed more information as to screw positioning and rotation of the fracture reduction than the conventional methods. None of the 81 patients who were operated with aid of 3D-RX needed surgical revision based on post-operative radiological examinations while the reported revision rate can be as high as 26%.
Summary

For the applications described above, intraoperative 3D-RX imaging has the potential to decrease the number of revision surgeries. For cochlear implantation and complex orbital, wrist and fracture surgery the use of 3D-RX has become a standard procedure. Future research is recommended on functional outcome of patients treated with aid of 3D-RX. Sophisticated visualization and additional image processing will improve the utilization of intraoperative 3D-RX. The image quality of mobile 3D-RX, especially concerning soft tissue contrast, has potential to improve by enhanced mechanics, software and hardware. This will broaden its application both in numbers as in complexity.

4D-RX

Current methods for imaging wrist joint motion are limited to either two-dimensional 2D video fluoroscopy or to animated motion patterns from a series of static three-dimensional 3D images. We present a method for the acquisition of dynamic 3D images of a moving joint in Chapter 7. In our method a 3D-RX system is used to image a cyclically moving joint. The cyclic motion is synchronized to the X-ray acquisition to yield multiple sets of projection images, which are reconstructed to a series of time resolved 3D images, i.e., four dimensional rotational X-ray (4D-RX). We compared the achieved image quality of 4D-RX with that of stationary 3D-RX images. The main deterioration of 4D-RX images compared to 3D-RX images is due to the low number of projection images used and not to the motion of the object. Experiments on a postmortem wrist show the feasibility of the method for imaging 3D dynamic joint motion.

In Chapter 8 we present a method for in vivo measurement of dynamic carpal motion patterns. The method consists of a 4D-RX with improved image quality and image processing for accurate detection of in vivo wrist motion. A static and a dynamic 3D image is made of the same wrist. Next, static acquired and segmented carpal reconstructions are registered to their dynamically acquired counterparts in all phases of the motion. The registration procedure yields the translation and rotation of the carpal bones relative to the static image (motion parameters). With this information the relation between the applied motion and carpal kinematic behavior is acquired, i.e., the motion patterns. We investigated the precision and reproducibility of the image acquisition and processing. The current setup of mechanical enforced movement of the hand and 4D-RX imaging does not give in on 3D-RX imaging spatial resolution. The precision of the image acquisition, image processing, and retrospective synchronization is sub millimeter and sub degree which is better than existing systems and is expected to be sufficient for clinical investigations. Repeated measurements to determine the reproducibility show some more deviation (<1 mm and <2 degrees). This method for obtaining motion patterns was tested in 4 human volunteers, illustrating hysteresis and change of motion patterns with and without axial load on the wrist joint. The motion patterns potentially reveal dynamic disorders which could not have detected and quantified in either video fluoroscopy, CT or MRI imaging. However, more research with more subjects on the interpretation of these motion patterns is necessary to fully exploit the benefits of this method. The clinical value is currently being investigated.