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New advances in intra-operative imaging in trauma

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- The invention of flat-panel detectors led to a revolution in medical imaging. The major benefits of this technology are a higher image quality and dose reduction. Flat-panel detectors have proved to be superior to standard C-arms (= C-arm with radiograph source and image intensifier).
- Cone-beam computed tomography (cone-beam CT) is a 3D data set, which can be acquired with a flat-panel detector. The cone-shaped beam is used for 3D data generation. For cone-beam CT acquisition, the flat-panel detector rotates around the patient lying on the operating table. Intra-operative cone-beam CT can be a very helpful tool in orthopaedic surgery. Immediate control of fracture reduction and implant positioning in high image quality can reduce the need for secondary revision surgery due to implant malposition.
- In recent years there has been a revival of standard fan beam CT technology in operating rooms. Fixed and mobile systems are available. Fixed systems are typically placed on a sliding gantry. Different mobile intra-operative CT scanners were recently introduced. Due to their mobility, they are not bound to a specific operating room. The use of standard intra-operative CT scanners results in high 3D image quality but, in comparison with a cone-beam CT scanner, fluoroscopy is not possible.
- The introduction of flat-panel detectors has led to improvements in intra-operative image quality combined with dose reduction. The possibility of high-quality 3D imaging in combination with navigation can assure optimal implant placement. Due to immediate control of the osteosynthesis, revision surgery at a later time can be prevented.

Keywords: intra-operative imaging; cone beam CT; flat-panel detector

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Introduction

A rapid evolution in technology can be observed all over the world. Whether it is electric self-driving cars, drone transportation or outer space travel, it is difficult to keep up with all the novelties we are confronted with on a daily basis. This evolution does not stop at the gates of medicine, which has also led to major advances in intra-operative imaging. Without intra-operative imaging, modern orthopaedic trauma surgery would not be possible. Most surgical procedures are highly dependent on optimal intra-operative visualization. Standard C-arms are equipped with a radiograph source and image intensifier. New implants and the trend for minimally invasive surgery and approaches made progression in intra-operative imaging inevitable. Because of a rapid evolution in intra-operative imaging, it is challenging to maintain an overview of the new technology and systems which are currently available. The aim of this publication is to present the latest advances in intra-operative imaging in trauma surgery.

But what exactly are the demands of the new and innovative intra-operative imaging devices for this special field of surgery?

The primary and main purpose of an imaging device is to assure an excellent image quality. Ideally, image quality should be increased without an accompanying increase in radiation. Further, important demands are a large field of view, the possibility of collimation and magnification, artifact reduction, 3D capability and other tools such as automatic implant detection or length measurement. Moreover, a combination with a navigation system should be possible.

Flat-panel detectors

The invention of flat-panel detectors led to a revolution in medical imaging. In the beginning, these detectors could only be installed in fixed systems. The major benefits of this technology are a high image quality and dose

Fig. 1 Mobile flat-panel detector with large source to image distance.

reduction compared with a standard C-arm.[1] Weis et al compared the radiation dose during paediatric interventions using a flat-panel and a standard C-arm. A significant reduction of radiation with the flat-panel C-arm could be seen (upper gastro-intestinal investigation 45 $\pm$ 38 µGy*m^2 *versus* 11 $\pm$ 9 µGy*m^2).[2,3] Furthermore, the use of flat-panel detectors results in zero geometrical distortion, wider dynamic range and high spatial resolution (pixel size 100 to 194 µm *versus* 2.2 to 3.5 Lp/mm).[4] A total of 60 536 grey levels can be visualized with flat-panel detectors, which is a 16-fold increase compared with standard C-arms. This leads to improved soft-tissue visualization.

Nowadays, flat-panel technology can also be incorporated into mobile C-arms (Fig. 1), which are mandatory for most orthopaedic procedures.[5] They are suitable for orthopaedic surgery as their use assures optimal dose efficiency in the operating room. Guillou et al discovered that mobile flat-panel C-arms can reduce the intra-operative dose compared with fixed systems during endovascular interventions.[6] Another major benefit of flat-panel detectors is the increased field of view of fluoroscopic images due to a larger detector diameter compared with standard C-arms. The detector size can reach up to 43 $\times$ 43 cm, in mobile C-arms 30 $\times$ 30 cm *versus* a maximum 31 cm diameter (standard C-arm). The entire pelvis can be visualized with a single fluoroscopic image.[7,8] Furthermore, because of a slimmer detector form, the 'source to image distance' is increased, leading to more workspace ($\leqslant$ 93 cm) for the surgeon and minimally invasive instruments. Another feature of modern mobile flat-panel C-arms is asymmetric collimation to motorized steering, giving the surgeon the possibility to store multiple positions, which can be reached automatically.[9]

Despite the many superior properties of flat-panel C-arms, many hospital administrations are still reserved regarding its purchase because of high acquisition costs. Patient and staff radiation safety is certainly of utmost importance, and therefore costs should not be the most relevant factor if a new C-arm is needed. It can be very confusing to decide which C-arm is most suitable for different surgical departments. The surgeon has to keep in mind that the C-arm choice is directly linked to image quality and dose efficiency. Even among flat-panel C-arms there are significant differences regarding these entities.[10]

Cone-beam computed tomography

Cone-beam CT is a 3D data set, which can be acquired with a flat-panel detector. The cone-shaped beam is used for 3D data generation. For cone-beam CT acquisition, the flat-panel detector rotates around the patient lying on the operating table. Afterwards, the data set is sent to a computer for post-processing and a 3D image is generated. This data set can be visualized in multiplanar reconstructions (MPR) or volume-rendered in 3D (volume-rendering technique (VRT)).[11] Limitations include increased artifacts due to scatter radiation compared with a regular CT.

A comparison between cone-beam and standard multi-slice fan beam CT regarding the intra-operative radiation dose remains difficult. Neither system has been proven to be superior so far.[12,13] We evaluated different 3D cone-beam protocols in comparison with a multi-slice CT using Rando-Alderon phantoms. At the thoracolumbar junction, a high- and low-dose cone-beam protocol was used. The dose of the high-dose protocol was comparable with the CT. However, it could be reduced by 75% due to the low-dose protocol. Therefore, it is mandatory to use the ideal protocol for the correct anatomical region and intervention.[14] Most of the systems on the market were initially used for vascular and cardiac interventions or procedures. Intra-operative cone-beam CT can be a helpful tool in orthopaedic surgery as well. Immediate control of fracture reduction and implant positioning in high image quality can reduce the need for secondary revision surgery due to implant malposition.[15]

Different systems are now available for orthopaedic surgery. The most prominent system is the o-arm (Medtronic, USA). It is a mobile cone-beam CT typically used for spine surgery. Only a few other indications have been published, ranging from sternoclavicular dislocation to syndesmotic reduction.[16,17] The main indication of the o-arm remains in pedicle screw placement in combination with an intra-operative navigation system. The combination of these systems can reduce the pedicle screw malposition rate.[18] The o-arm can also be a helpful tool for ilio-sacral screw placement.[19]

By comparison, the Artis zeego (Siemens, Germany) is a fixed floor-based, 3D flat-panel C-arm (Fig. 2). Operating rooms with a fixed imaging device are called hybrid

Fig. 2 Hybrid operating room - floor-based 3D flat-panel detector with cone-beam CT capability and fully integrated navigation system.

operating rooms. Initially developed for vascular and cardiac surgery, the importance of the Artis zeego for orthopaedic surgery is growing. A major benefit of the Artis zeego is the possibility of interdisciplinary use. Different departments can share the high acquisition costs leading to an optimal utilization of the system.[8] In orthopaedic trauma care, this system can also be used for a large variety of indications. Cancienne et al proved its feasibility for ankle surgery.[20] The main indications remain spinal and pelvic fractures. A complete pelvis can be visualized with a single 3D scan (Fig. 3). This can be an essential help during fracture reduction and implantation of ilio-sacral or trans-iliac trans-sacral screws. In combination with a navigation system (BrainLab Curve, BrainLab, Germany), we demonstrated that implantation accuracy was significantly increased compared with standard 3D navigation.[7]

Intra-operative fan beam computed tomography

Since the 1990s, CT has been used for orthopaedic trauma procedures. In the beginning, the operating team had to join the radiologist in a conventional CT facility, which was not designed for open surgery.[21] Only minimally invasive interventions, preferably of the pelvis, could be performed. The accuracy of the implanted screws was high and a CT scanner could also be combined with a navigation system.[22] Even though the image quality and screw accuracy were compelling, many surgeons stopped working with these systems because of the cumbersome setting and the development of mobile 3D C-arms.[23] In recent years there was a revival of CT technology in operating rooms. Fixed and mobile systems are available.

Fixed systems are typically placed on a sliding gantry. Thereby the CT scanner can be parked away from the operating table if not needed. A navigation system can be linked to the CT scanner assuring optimal placement accuracy.[24]

Different mobile intra-operative CT scanners were recently introduced.[25,26] Due to their mobility, they are not bound to a specific operating room. However, some of the CT scanners are fixed to the operating table and cannot be used in operating rooms with permanently fixed table columns. Furthermore, there has to be enough room in the operating room for the CT scanner. The Airo (BrainLab, Germany) is automatically combined with a navigation system. The first clinical trials in spine surgery showed promising results.[26,27] The use of intra-operative CT scanners results in high 3D image quality, but in comparison with a cone-beam CT scanner, fluoroscopy is not possible. If fluoroscopy images have to be performed during surgery, an additional C-arm must be provided.

Radiation safety

For some of the mentioned imaging devices, a radiology technician and/or a radiologist are required, mainly depending on the laws of the country in which the system is operated.

With new advances in intra-operative imaging, radiation safety becomes more important. It is mandatory to stand behind a radiation protection wall or to leave the operating room during cone-beam or CT scans; thereby, the exposure of the surgical staff can be eliminated during the scan. Furthermore, a lead apron and thyroid collar should always be worn. Lead goggles can offer additional protection to the eyes.[28] Another option to raise radiation awareness is the use of real-time dosimeters allowing direct visualization of the radiation (Fig. 4).

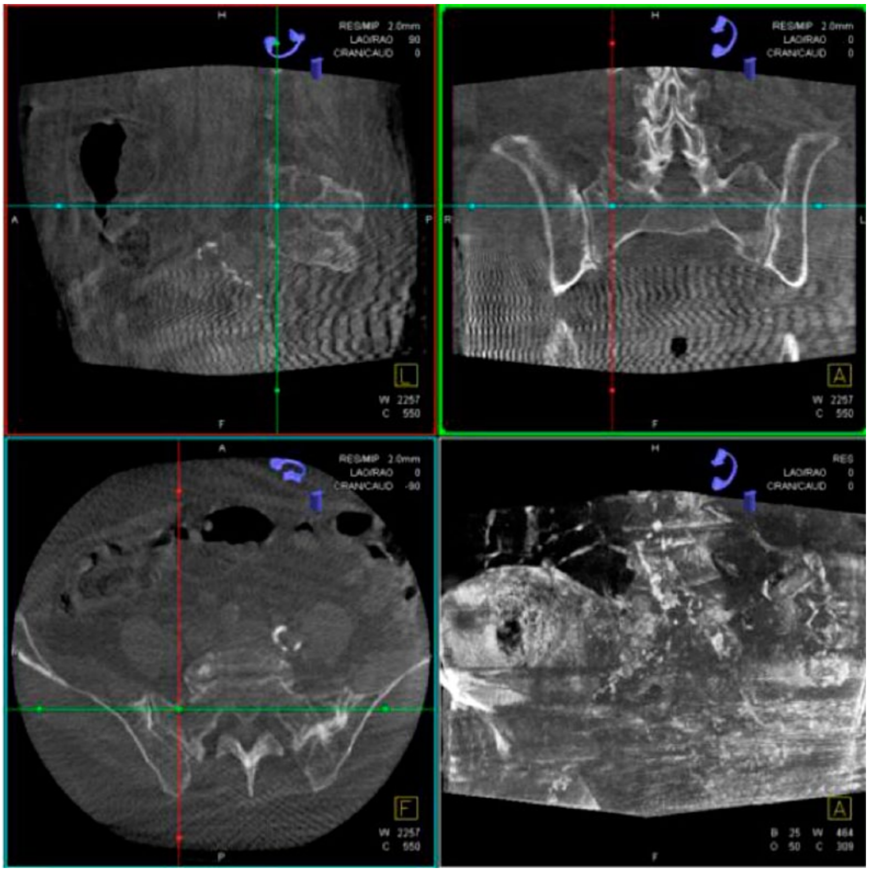

Fig. 3 Large 3D-volume - an entire pelvis can be visualized with a single scan.

Fig. 4 Real-time dosimetry with Raysafe (Unfors Raysafe; Sweden).

Conclusions

The introduction of flat-panel detectors has led to improvements in intra-operative image quality combined with dose reduction. The possibility of high-quality 3D imaging in combination with navigation can assure optimal implant placement. Due to immediate control of the osteosynthesis, revision surgery at a later time can be prevented. The rapid evolution of intra-operative imaging has just begun. It is important to continuously develop imaging in trauma surgery to ensure that patient and staff safety can be further optimized.

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