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Intra-operative imaging in trauma surgery

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- The reconstruction of anatomical joint surfaces, limb alignment and rotational orientation are crucial in the treatment of fractures in terms of preservation of function and range of motion. To assess reduction and implant position intra-operatively, mobile C-arms are mandatory to immediately and continuously control these parameters.
- Usually, these devices are operated by OR staff or radiology technicians and assessed by the surgeon who is performing the procedure. Moreover, due to special objectives in the intra-operative setting, the situation cannot be compared with standard radiological image acquisition. Thus, surgeons need to be trained and educated to ensure correct technical conduct and interpretation of radiographs.
- It is essential to know the standard views of the joints and long bones and how to position the patient and C-arm in order to acquire these views. Additionally, the operating field must remain sterile, and the radiation exposure of the patient and staff must be kept as low as possible.
- In some situations, especially when reconstructing complex joint fractures or spinal injuries, complete evaluation of critical aspects of the surgical results is limited in two-dimensional views and fluoroscopy. Intra-operative three-dimensional imaging using special C-arms offers a valuable opportunity to improve intra-operative assessment and thus patient outcome.
- In this article, common fracture situations in trauma surgery as well as special circumstances that the surgeon may encounter are addressed.

Keywords: intra-operative imaging; trauma surgery; 3D imaging

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Introduction

Dealing with structures that are usually localized deep inside the surrounding soft tissue, trauma and orthopaedic surgery represent a challenge for intra-operative visualization and orientation to the surgeon. In addition to in-depth knowledge of the anatomy and anatomical orientation of structures, additional methods to show the position of instruments and implants and the result of reduction procedures is essential. For more than half a century, intra-operative imaging with mobile C-arms has guided the surgeon in the challenge to achieve a result as close to the original anatomy as possible.

Along with the continuing improvements of implants and surgical techniques with the subsequent diminution of surgical approaches, reduction of soft-tissue dissection and thus less exposure of the bony structures, the demand for performant and high-resolution intra-operative imaging has grown. Without the possibility of real-time visualization of the anatomy of bony structures, as well as the position of instruments and implants in relation to the bone and the ability for evaluating the reconstruction of joint surfaces and bony alignment, the rapid evolution of minimally invasive surgery would not have been possible[1,2]. Examples include percutaneous placement of pedicle screws in thoracolumbar spine surgery, closed reduction, and tunnelled placement of implants in the treatment of tibial or femoral metaphyseal fractures with specially designed plates or calcaneus osteosyntheses with slit-in plates that reduce the length of the incision to the diameter of the plate[3,4].

However, cutting-edge techniques of minimally invasive osteosynthesis are not the only procedures that pose the need for intra-operative imaging. Even in situations where complete clinical access to the surgical view is present, such as in conventional total hip arthroplasty, intra-operative images are performed to confirm correct alignment and orientation of the implant, especially the

Table 1. Doses of different diagnostics

Procedure	Dose (mSv)
Chest radiograph	0.01-0.1
Transatlantic flight	0.04-0.08
Average dose of radiation due to medical aspects, per year	2
Radiation exposure due to natural sources	2.1 (Germany) 3.1 (USA)
Skull CT	3
Spine or chest CT	1-10
Abdominal CT	10-20
Threshold for occupational exposure (per year)	20 (Germany) 50 (USA)
Threshold for elevated risk to suffer from neoplasia (per year) (Note: there is no threshold for stochastic effects such as neoplasia; this value represents the current state of literature regarding a clinically relevantly increased risk[10,11])	100

acetabular cup, and to rule out accompanying fractures of the acetabular region or the femoral shaft[5].

Technology evolves and thus new possibilities have been developed and are available for improving surgery. Intra-operative three-dimensional (3D) imaging with mobile C-arms was introduced in 2001 and has become an important adjunct for reconstruction of complex joint fractures[6]. Navigation systems that show the position of instruments in real time in a 3D volume can aid in improving precision and allow safe implant placement in the most complex situations[7,8].

It is up to the surgeon to carefully use the possibilities technology offers to improve treatment outcomes and the lives of our patients.

Radiation protection

Depending on the place of residence, there is a natural radiation exposure that causes a dose of 2 to 200 mSv per year (in most areas in Europe and the Americas, it is around 2 to 3 mSv). In industrialized countries, the average additional dose due to exposure to ionizing radiation from medical devices causes an equal dose of about 2 mSv[9]. The doses caused by different diagnostics are shown in Table 1.

C-arms are x-ray machines and thus pose a potential threat to the patient as well as to the staff in the operating room as they emit ionizing radiation[12,13]. As with all x-ray-based diagnostic devices used in medicine, the referring and responsible physicians have to weigh the potential hazard due to the radiation against the benefit that can be drawn by the result of the examination. Usually, doses applied in stationary radiology are higher than in intra-operative settings due to higher energy levels used. Depending on the local situation, the responsible usage of an x-ray device is restricted to specially trained staff. In Germany, medical staff must apply for a special qualification to be allowed to operate devices that emit ionizing radiation or even to supervise the operation of such a device. The curriculum for this qualification includes the assessment of the technical aspect of images but not the medical conclusion that can be drawn from these. Nonetheless, local regulations regarding qualifications and restrictions should be known and followed.

To monitor the individual dose, the use of personal dosimetry is compulsory in many countries when dealing with ionizing radiation within the so-called radiation control zone. Regarding intra-operative imaging, this includes the operation room (technically, the control area is a circular area around the x-ray source with a radius of 4 metres, depending on the device). In Germany, these films are evaluated on a monthly term; in cases where the threshold for monthly or annual dose is exceeded, the staff member is not allowed to continue working in radiation control areas for the rest of the year.

Indeed, there are many factors that can be controlled by the surgeon regarding radiation protection. This starts with knowledge of the settings of the device and how they should be applied. In trauma and orthopaedic surgery, it is usually sufficient to take single shots instead of constant fluoroscopy. This automatically causes a considerably lower radiation, so dynamic fluoroscopy should only be used when needed, for example in osteosyntheses of the humeral head, where rotation of the upper arm under fluoroscopy is used to assure the correct screw length and extra-articular position of the screw tips. If used, length of fluoroscopy time should be as low as possible.

Most of the emitted radiation does not reach the detector and is either scattered or absorbed in the patient. Following this, the amount of scattered radiation is up to two times higher on the side of the source, so, whenever possible, the detector should be positioned above the table in anteroposterior (AP) views and the surgeon should position himself on the side of the detector in lateral views.

Most currently available C-arms offer methods for limiting the exposed field. These are slit diaphragms for making the viewable field smaller, for example when assessing long bones, and iris diaphragms for concentrically

Fig. 1 Example of iris diaphragms to reduce the dose to the patient.

diminishing the viewable field (Fig. 1 shows a situation with iris diaphragms). Depending on the actual device, this might keep the local dose for the patient equal, but lowers scattered radiation and the risk of exposure to the surgeon's hand. Additionally, the contrast of the image might be increased.

Lead gowns including thyroid protection need to be worn by all staff in the operating room as long as the procedure is running and radiation may be applied. These gowns need to be checked regularly (and replaced, if necessary) to ensure that the structure of the material is intact. Of course, the patient should be protected with lead mats as well, as long as these mats do not hinder the acquisition of the correct views.

The most effective method to reduce exposure is to keep a distance. All staff that do not need to be close to the C-arm should try to position themselves as far away from the C-arm as possible; the exposure is reduced by square with increasing distance. Outside the radiological control zone (4 metres for most C-arms), there is no significant exposure. For the surgeon it is important to keep his or her own body – especially the hands! – out of the beam.

Maintenance of radiation protection is a team task and is mandatory to reduce risk for all of the staff and the patient.

Technical aspects

Intra-operative imaging with a C-arm, as is used today, was introduced for the first time in 1955 by Diethelm et al[14]. The current status of surgical procedures and advanced techniques such as minimally invasive surgery in trauma and orthopaedic surgery cannot be imagined without the continuous improvement of imaging technologies. Following this, it is mandatory for the surgeon to consider carefully the technical handling of these machines as well as the possibilities and limitations for intra-operative imaging. Depending on the actual on-site situation, the surgeon may be the only person who has knowledge about the specific abilities of the C-arm used, or the surgeon may even have to operate the C-arm. In many cases, there will be specially trained staff to take care of technical issues, but evaluation of the images – including potentially incorrect settings of image acquisition – must be handled by the surgeon. Usually there is no structured curriculum for medical staff regarding either the technical handling or evaluation of the images. The appropriate training regarding when and how images are acquired, and what consequences can be drawn from these, is disposed to the particular disciplines. Hence, the quality of this training depends very much on the emphasis of the importance of these procedures in the institution concerned.

Two-dimensional imaging and fluoroscopy

Technically, a C-arm consists of an x-ray source and a corresponding detector at the opposite end of the 'C'. The emitted radiation passes through the object in between both ends of the C-arm and is diluted depending on the degree of radio-opacity of the object. Most of the C-arms currently in use are based upon a so-called image intensifier. The x-ray radiation that passes the object hits a fluorescent surface and causes the production of light photons. These photons are accelerated in a tube, electronically intensified and registered with a video camera. This camera is either directly linked to a TV screen or – as used in current techniques – digitalized and sent to a computer for post-processing and storage. The technical evolution in detector technology led to the construction of flat panel detectors in which the x-ray radiation is directly converted into a digital signal that can be used as raw data for image reconstruction. As there is no longer any need for a tube or video chain, these detectors can be constructed in a much more compact fashion than detectors based on image intensifiers. The image quality is improved in terms of contrast and resolution, while the dosage is equal or might even be reduced[15].

Stationary radiography systems as used in radiological departments have a stronger power supply, so the dosage that is used for one image is higher than in the intra-operative setting. Due to this, the image quality in terms of contrast and resolution is lower in intra-operative imaging. Also, the size of the objects 'fitting' into one view is much lower and limited by the distance between both ends of the C-arm. This is a restriction that particularly applies in the management of shaft fractures of long

Fig. 2 Lateral view of the sacrum showing the low contrast between bone and soft tissue.

bones, as the axis of the total bone can barely be visualized. Additionally, depending on the anatomical region, the soft tissues can absorb significant amounts of radiation. In the obese, this causes reduction of contrast, so the assessment of the bony structures is hindered. Figure 2 shows an intra-operative lateral view of the sacrum with two screws fixating the sacroiliac (SI) joints on both sides. Due to low contrast, the delimitation of the bone towards the surrounding soft tissue is very restricted.

While there are established standards for axis alignments and patient positioning in radiological departments, the intra-operative settings vary a lot due to positioning requirements, actual surgical procedure and patient-related factors such as obesity or limitations in joint movement. The surgeon is responsible for ensuring the correct positioning of the operational field and the possibility of acquiring the standard views of the actual region with the C-arm.

Standard views

The most essential knowledge for the surgeon is how to position the C-arm depending on the operation in order to acquire the views required in this situation. Although there are many situations in trauma surgery that are far from standard, these views should be mastered. In this section, standard procedures for four common fracture types are described.

Distal radius

The joint surface of the distal radius is tilted to the palmar side by 5° to 10° in the AP view. The most common technique in osteosynthesis of the distal radius is fixation with a palmar locking plate. When controlling the implant position and reduction, the arm must not be positioned straight on the table. Instead, the elbow has to be elevated to the extent of 5° to 10°, to balance out this anatomical tilt. Only using this technique is it possible to assess reduction, implant positioning and screw placement. The same applies to the lateral view, where the joint line is tilted 23° to 30°. To obtain a correct view, the hand has to be elevated to this level. Figure 3 shows a correct orientation with distinct presentation of the radiocarpal joint space in both views.

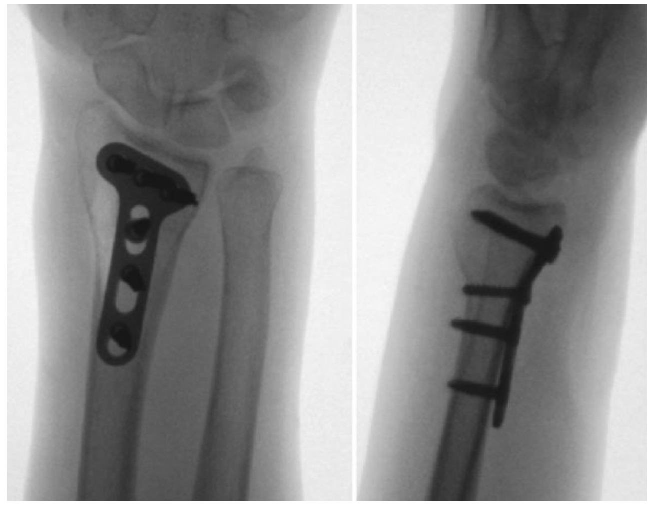

Fig. 3 Correct aspect of the radio-carpal and radio-ulnar joint in antero-posterior and lateral views.

This differs from standard views in radiology. Here, usually the arm and wrist are positioned parallel to the detector, so the resulting images are different from those that need to be acquired in an intra-operative setting.

Proximal humerus

In osteosyntheses of the proximal humerus, there are special circumstances that make acquisition of the correct standard views challenging. Usually, the patient is positioned in the so-called beach-chair position. Following this, the upper arm is already tilted towards the floor. This has to be evened out by tilting the C-arm, so the level of the central beam is perpendicular to the axis of the humeral shaft. The standard views are defined by an AP view with maximal extension of the greater tubercle and a lateral view with 90° outward rotation of the humerus. When assessing screw length, the spherical shape of the humeral head must be considered. As mentioned above, it might be helpful in these cases to assess the implant length with constant fluoroscopy while rotating the arm. Figure 4 shows AP and lateral views of the proximal humerus.

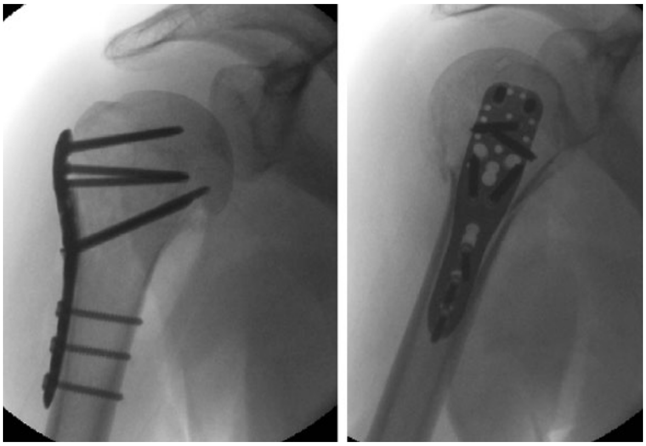

Fig. 4 Correct aspect of the proximal humerus in antero-posterior and lateral views.

Proximal femur

For osteosynthesis of the proximal femur, there are similar issues as with the proximal humerus. For successful minimally invasive procedures, it is crucial to be able to obtain standard AP and lateral views. Independent of using an extension table or similar device, the contralateral leg is elevated in a leg holder. The C-arm is placed oblique between the legs to make an axial view possible. The AP position is perpendicular to the floor. When adjusting the axial view, it needs to be kept in mind that the anteversion of the femoral neck of 10° to 15° must be compensated by tilting the C-arm to this extent. The correct view is determined by a straight connection from the femoral neck to the femoral shaft axis. Figure 5 shows AP and axial views with an implant in place. Note the straight line of the femoral neck continuing to the femoral shaft in the axial view.

Ankle joint

The positioning of the C-arm for osteosyntheses of the ankle joint is easier, as there is no collision hazard of the device with the patient. When adjusting the views, it is important to consider that an AP view perpendicular to the floor will not allow assessment of the joint lines. The lower leg has to be rotated 15° to 20° inwards to obtain the so-called Mortise view. In this view, the medial and lateral joint space should be equal in size and the margins of the talus should show no double-contour. For adjusting the lateral view, the condyles of the talus must be positioned stacked exactly above each other and the tibiotalar joint space must be visible completely. An important issue when treating ankle fractures is to determine syndesmotic injuries. After completion of the osteosynthesis of the distal fibula, the stability of the syndesmosis is tested with constant fluoroscopic view in the Mortise position. With a suitable instrument, lateral traction is applied to the fibula while the lower leg is fixed. A positive finding is considered when there is significant movement of the fibula in the distal tibiofibular joint (see Fig. 6 – in this case, no movement of the fibula was observed). If this occurs, reduction of the fibula and fixation of the distal tibiofibular joint is necessary. When it comes to assessing the position of the fibula in the tibial incision, it is difficult to determine definitely the reduction in two-dimensional (2D) imaging as it is not possible to acquire an axial view of this joint. If available, it is helpful to perform an intra-operative 3D scan.

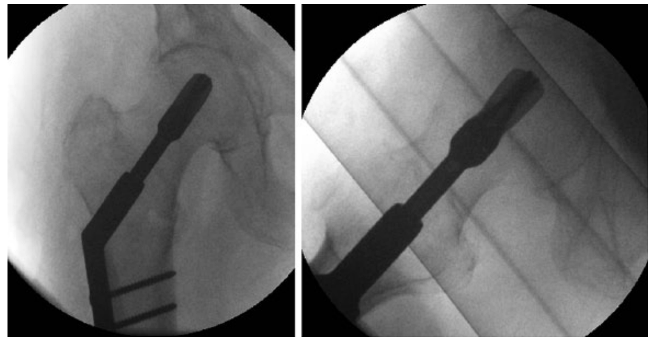

Fig. 5 Correct aspect of the proximal femur in in antero-posterior and axial views.

Intra-operative 3D imaging

The anatomical reconstruction of joint surfaces and the extra-articular position of implants are crucial for surgical success in the osteosynthesis of complex joint fractures. As described above, these parameters are intra-operatively controlled by 2D imaging in standard views as well as dynamic fluoroscopy to assess, for example, the course of single screws. However, there are situations where the assessment of the joint surface or the course of implants is not completely visible in 2D imaging. This is especially the case when the joint surface has a concave configuration, such as in the acetabulum or the tibial head, or in irregularly shaped bones like the calcaneus[16-18]. Another aspect is the impossibility of acquiring axial views in many cases, as in the spine or the ankle joint[19-21]. Under these circumstances, intra-operative 3D imaging might be a helpful adjunct to immediately ensure the reduction quality and extra-articular position of implants.

Usually, intra-operative 3D imaging is achieved by special C-arms that can be used in 2D mode as any other C-arm. For 3D acquisition, these devices perform a motorized movement around the region of interest and automatically acquire a large number of images (typically 50 to 100). With computational methods, coming from CT, a CT-like dataset is generated. These volumes are cubic with

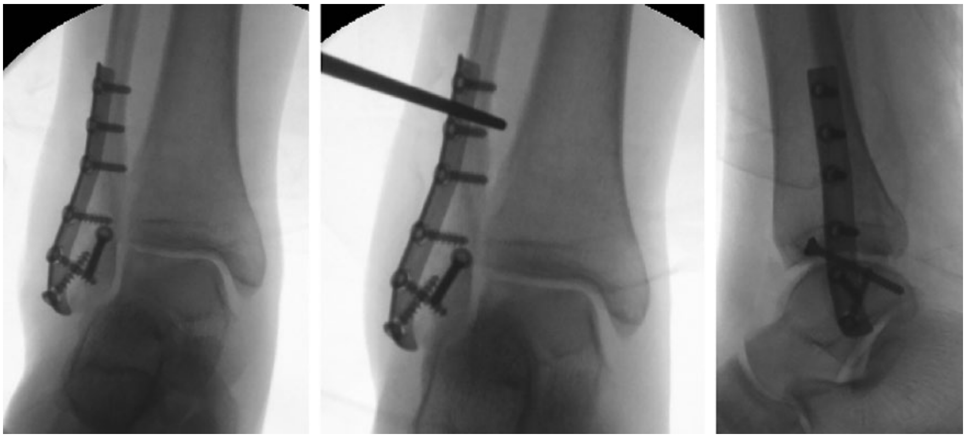

Fig. 6 Mortise view of the ankle joint (left) with testing of the stability of the syndesmosis with the hook test (middle). Lateral view of the ankle joint (right).

Fig. 7 Intra-operative 3D imaging of the ankle joint in the standard reconstruction planes (left: coronal, middle: sagittal, right: axial).

a length of the edges of typically 12 to 14 cm. A typical example is shown in Figure 7. In these views, implant position and reduction of the fracture as well as the reduction of the distal fibula in the tibial incision can be assessed completely. With the help of intra-operative 3D imaging, in the majority of cases it is possible to completely assess the reduction quality and implant position; therefore, in our institution it is used commonly after certain procedures. This applies to osteosyntheses of the acetabulum, the tibial head and plafond, the calcaneus, syndesmotic injuries and difficult spinal instrumentation. In a prospective clinical register, each case with intra-operative 3D imaging is documented with regard to the anatomic region and the findings of the imaging. With the help of that register, the incidence of intra-operative revisions can be determined. In an analysis of cases over eight years and 1841 scans, an intra-operative revision rate of up to 40.3% was observed[22]. This underlines the essential benefit of this technique, as a 3D scan is performed only when the reduction and implant placement is considered correct in fluoroscopic views.

This method does have some disadvantages compared with CT data, especially regarding artefacts caused by implants. Depending on the material and length of the implants, image assessment is severely limited or even impossible[23]. When assessing longer spinal segments or larger regions of the pelvis the volume might be too small, so several scans might be necessary.

In terms of high-end solutions to avoid the above-mentioned limitations, there are special CT scanners available that are constructed to meet intra-operative needs. This includes a large gantry opening and a mobile design which can change between several settings (Fig. 8). These devices improve the intra-operative 3D image capabilities with very large fields of view (including complete spine or complete pelvis)[24]. As an example, an intra-operative total pelvis scan is shown in Figure 9. However, these devices have special requirements for radiation protection and training of the operating staff. Regarding the cost for the devices as well as the necessary building modifications, intra-operative CT scanners are reserved for special centres with large numbers of eligible cases.

Fig. 8 Mobile intra-operative CT Brainlab Airo®.

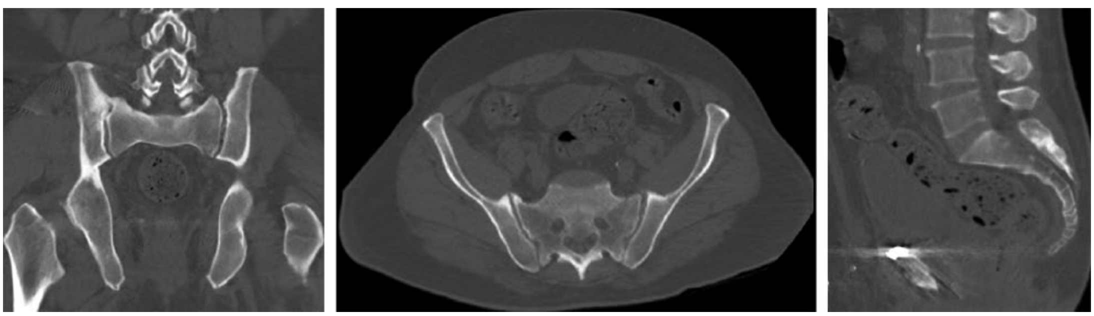

Fig. 9 Intra-operative CT scan of the pelvis showing the large field of view and good contrast of bone and soft tissue.

Navigation

Since the late 1980s, different approaches to allow intra-operative navigation in 3D datasets were developed, and as of today there are several products available. Most of them are based on infrared tracking of specially equipped instruments and a fixed reference that should be placed close to the surgical field. Usually, an intra-operative 3D scan is performed and registered with the navigation system. It is also possible to use a pre-operative CT or MRI scan for intra-operative navigation, which is very common in neurosurgery.

During surgery, these data can be used to visualize the position of the instruments in the 3D views, so the placement and handling of instruments and implants is facilitated. Figure 10 shows the planning process for a screw in the SI joint on the right side. Especially in anatomical regions with difficult visibility in 2D views, particularly the spine and posterior pelvic ring, this improves the placement of implants and security of the operation[25–28]. Several studies have shown that the placement of SI screws is improved when 3D navigation is used[29,30]. A situation that illustrates the benefit of navigation is the dysmorphic sacrum. Dysmorphic means a variation in the configuration of the sacral ala leading to a narrowing of the safe zone for SI screw placement. Additionally, fluoroscopic techniques become unreliable in these patients, so 3D navigation significantly improves the precision of screw placement and thus patient safety[31]. In combination with an intra-operative CT scanner, navigation is a very powerful tool for improving the accuracy and precision of the surgical procedure[32].

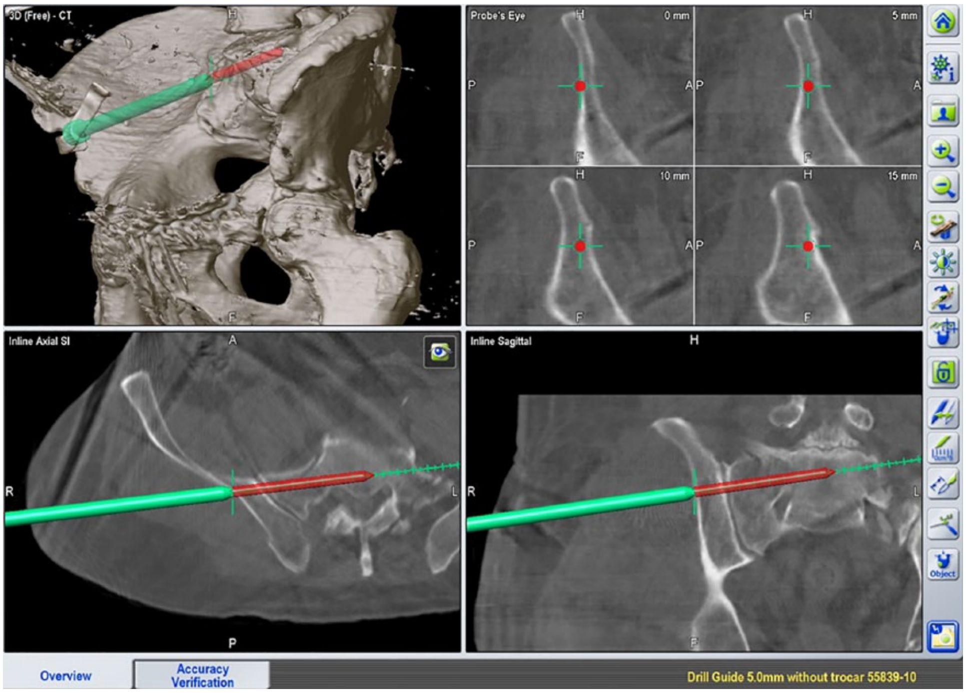

Fig. 10 Screenshot of the planning procedure with the intra-operative, CT-based navigation.

Conclusions

Intra-operative imaging in trauma and orthopaedic surgery is a demanding skill to be mastered by the surgeon. Even if the operation itself is carried out by staff in many cases, the technical settings and their application must be known. Radiation protection measures are important (and the responsibility of the surgeon), as uncontrolled application of ionizing radiation can be harmful to the patient and staff. The standard views for the most common fractures and the characteristics of the specific settings are mandatory to assure the success of the osteosynthesis. If available, intra-operative 3D imaging and navigation are valuable adjuncts to assure extra-articular implant positioning and anatomical reduction.

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