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Preoperative Planning in Fracture Surgery: Current Concepts and Future Perspectives

Předoperační plánování v operační léčbě zlomenin: aktuální koncepty a budoucí perspektivy

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INTRODUCTION

Preoperative planning is an essential first step in any surgical procedure, especially in the complex fracture surgery. The quotation, credited to Benjamin Franklin: "Failing to plan is planning to fail" is true and applies to everyday life as, for example, in business, constructions and in surgery. Preoperative planning enables the surgeon to understand the fracture in all the details, to choose the right surgical approach and to outline the complete surgical tactics. Maurice Müller, the founding member of AO was a big champion of preoperative planning and AO group emphasizes its importance and puts it as an obligatory topic in many AO courses (19). Jeffrey Mast, the pioneer of indirect reduction techniques, stated that in a reconstructive bone surgery, the surgeon should have the precise plan of the procedure exactly like a builder and an architect (16). Also, Letournel and Judet's seminal work about classification of acetabular fractures with all the beautiful drawings of the fractures is in fact a sophisticated planning system (15). Thus, it is no surprise that almost all orthopedic trauma surgeons believe that preoperative planning is important, but it is difficult to understand that less than half of them use it in their daily practice (33). The aim of this current concepts article is to present classical planning methods, state-of-the-art technologies in modern planning systems and future trends.

EVOLUTION OF SURGICAL PLANNING

Pre-operative planning is essential in fracture surgery. Planning consists of three major parts: knowing the patient (fracture configuration, soft tissue status, general health, and the patient's demands), planning of the procedure, and rehabilitation. Approaches, indirect and direct reduction methods and maneuvers, a type of provisional and definitive implant choice and position are all important considerations in fracture fixation planning. The process of planning is always preformed based on known bone/fracture parameters which are normally obtained from radiological studies (plain X-rays and computer tomography (CT) images). There are two major goals of planning: tracing of the desired end result and tracing of the "surgical tactic" (20).

Classical methods of planning by using paper and pen are direct overlay, healthy side silhouette or using joint axis (17). These methods are primarily useful in treating shaft and metaphyseal fractures, where the axis, rotation and length are crucial elements for a successful and functional bony union. Even in treating metaphyseal pathology (axial or torsional malalignment corrections), some authors have noticed that the reason for mismatch between the planned and the executed procedure is in two-dimensional planning of three-dimensional pathology (7,29). In operating intraarticular fractures, the primary goal is accurate (anatomical) reduction and stable fixation. For joint fractures, the incidence of inaccurate reduction and fixation hardware misplacement is high and a revision surgery is required in 10 to 15% (23). For almost four decades the important information of intraarticular fractures has been obtained by CT images. Using classical planning based on CT images is exceedingly difficult. Although the obtained information is three-dimensional (3D), the classical method of planning can be used just in two dimensions (2D). For these reasons, many computer modules for preoperative planning have been developed in complex joint fracture treatment. In the first decade of this century, they were primarily used in acetabular fracture fixation, but recently they have been used for all intraarticular fractures (3). In the last decade, planning of the surgery has closely been connected to operation by applying modern technology to daily clinical work.

MODERN PREOPERATIVE PLANNING IN FRACTURE SURGERY

In recent years, all radiological studies have been computerized. With digitalization of the images, a possibility of additional processing and handling of the image data has arisen. Computer-assisted orthopedic surgery (CAOS) has been developed as the application of computer-based technology to assist the surgeon to improve the precision of the operative procedure (29). A surgeon's knowledge of anatomy, biomechanics, approaches, indications, and implants is inescapable, but digital modalities help provide planning, guidance, and feedback to a surgeon. Advances in imaging have enabled 3D visualization of the surgical field and patient anatomy, which is crucial for up-to-date preoperative planning and is already connected to real-time tracking of instruments and implants (7). Lately, 3D printing has enabled patients' specific implants to improve fitting of the implant to patient specific anatomy. Today we understand all the above-mentioned capabilities as the planning of surgical procedure.

Preoperative planning of fracture surgery

Contemporary planning of skeletal surgery started with computerized preparation for the prosthetic treatment of hip arthrosis. The first clinically applied system of CAOS was introduced into clinical practice in late 1980s. The idea was to help the surgeon preoperatively select the type and dimension of a cementless femoral implant. The clinical system used at that time was an active robotic system (ROBODOC) to prepare femoral cavity to the preplanned dimension of the stem (24). Although the precision of stem placement was superior to classical way, there were some serious shortcomings as steep learning curve and muscle and nerve damage. Newer systems are semi-robotic with intraoperative guidance, which is either CT or fluoroscan based or imageless navigated. Regardless of navigation system, the surgeon who performs the planning of the procedure is still the most important factor of accuracy (28). It was shown that accuracy of the preoperative planning is not significantly better when digital 3D is used in comparison with conventional analog 2D images in planning of the size of knee prosthesis (12). The accordance of the plan with the surgical execution is not 100%. In total hip replacement it varies between 30 and 100% for stem and from 40 to 100% for the cup component. More experienced surgeons are more accurate in planning, especially in complex cases (18,25).

In the field of fracture surgery, by replacing celluloid films with digitalized technology and by developing modern software programs, virtual reduction, and fixation maneuvers on computer model of real patient fracture have become possible. Digitalized software programs have enabled to import and export all picture archiving communication system (PACS) files. Numerous programs have enabled a reliable 2D preoperative planning, with a short learning curve and with good accuracy of implant size, especially in long bone shaft fractures, but it has some limitation in joint fractures planning (26). At the beginning of this century, we were involved in the development of one of the first 3D computerized planning tools which enabled a virtual operation of the fracture of the true patient. At that time, we used this tool exclusively for acetabulum fracture treatment planning (3). Data from CT in DICOM format were used. Slices of 3 mm or less were required. With smaller slices, the precision of image was better. The segmentation process was done by medical engineers. For further preoperative planning, all the data and images were transferred to the surgeon's computer where planning of the reduction and fixation of the virtual fracture was done. In further development, the EBS software (Ekliptik l.t.d.) evolved. Today we are using the updated version of this software. The complete process from data importation, 3D image rendering, to segmentation, and virtual operation is done by the surgeon himself on his personal computer. With the simplicity of the software the surgeon is independent from other people and institutions. In this way, there is no lost time by communicating with others who are not directly involved in the surgical procedure. The software is based on a watershed protocol which enables the computer to segment fracture fragments after putting marks on different fragments seen on the 3D bone object. The process is semiautomatic and already described in detail (3). In fracture surgery planning, we believe that modern computer programs should enable surgeons to complete the segmentation by themselves. On the bases of their experiences and knowledge only important fragments can be determined. The computer, however, presents the directions of fracture lines and fracture planes.

After the segmentation process, each fracture fragment becomes a separate object. In the further rendering process, each bony fragment is marked (colored). Fragments can be moved in all direction as well as rotated. The pivot point of the fracture fragment can be moved, and its axis can be rotated. In that way, the plan can mimic the movements during real time reduction. This is important in incomplete fractures and to mimic the points where ligaments or muscles attachments are. The knowledge of anatomy is obligatory to plan the reduction movements and maneuvers correctly.

After the reduction of the fracture is complete, we plan the fixation of the fracture. By positioning the implants in the desired places and finding the safe corridor for the screws, we understand the fracture sufficiently to choose the appropriate approach. If we are not able to execute the planned reduction and fixation with the approaches, we are comfortable with, we have to change the plan of fixation or learn a new approach (Fig. 1).

In multicenter study of comparing planned surgical tactics to executed surgery in acetabulum fracture operation, it was shown that the planned surgical approach was followed in more than 90% of the cases, the planned fixation (position of the plate) was completely followed in more than 50%. The number and the length of the screws were identical in more than 60% and the number and the length of the plate in more than 80% of the patients. All the planning was done by experienced pelvic and acetabular surgeons (3). The classical computerized planning (virtual operation) is done by using a computer mouse. With that the reduction movements of the fracture fragments are not even close to reality, so some so-called haptic planning modalities were designed, by which virtual operations are done by using both hands and mimics actual intraoperative maneuvers (13). Their aim is to facilitate the manipulation of 3D objects in a virtual environment with a realistic tactile sensation (22).

Interestingly, in very complex fractures the reduction of the fragment even in virtual environment is not perfect and the remaining fragment dislocation is around 1 mm (13). The discrepancies between the plan and its execution were predominantly caused by the facts which are not directly connected to the fracture itself but are more patient specific (anatomical variances of the important structures, shape of the patient etc.) or related to the surgeon capabilities (accuracy, skills). Some differences can also be connected to the fracture itself, which was shown in classifying proximal femur fracture in preoperative planning module compared to intra surgery classification, where accuracy was 85% (9). Another impor-

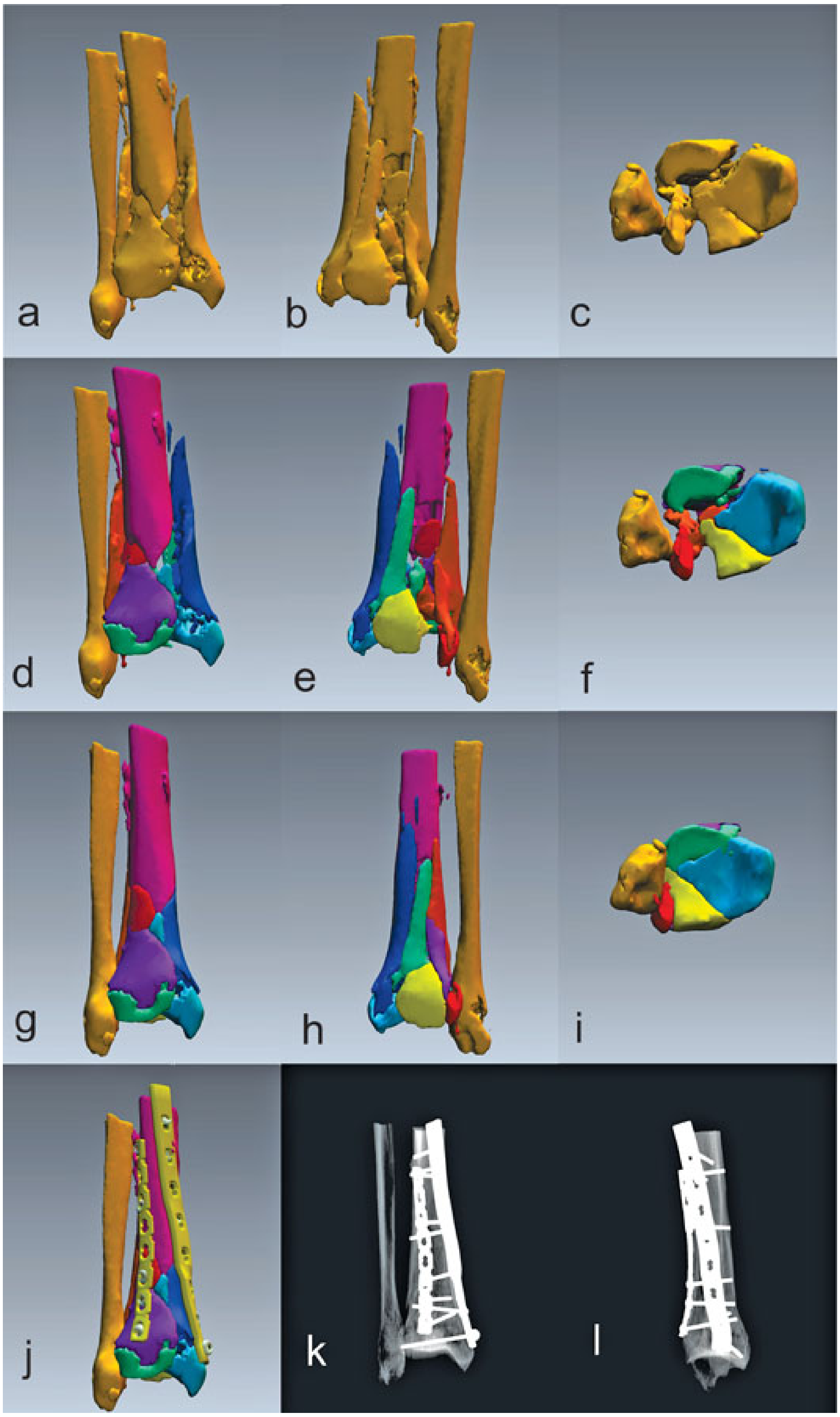

Fig. 1. Computer preoperative planning of complex distal tibia intraarticular fracture.
Images of basic 3D rendering in anteroposterior, posteroanterior and caudocranial direction (a, b, c) followed by segmentation process in anteroposterior, posteroanterior and caudocranial direction (d, e, f). In virtual surgery the reduction is done (g, h, i), followed by fixation with the plates (j), after the fixation X-ray simulation can be done (k, l).

tant reason for the mismatch of planning and surgery is also education and experiences of the surgeon performing planning and surgery (34).

Transmission of preoperative planning to operating procedure

Intraoperative navigation systems were developed after connecting of contemporary intraoperative 3D visualization systems and technology allowing real-time tracing of objects. This technology enables us to follow and control the planned maneuvers of reduction and fixation of the fractures during real surgery. At the beginning navigation systems were solely used for the placement of the implants in the regions where they could jeopardize other structures (spinal cord in placement of pedicle screws, articular surface in minimally invasive acetabulum fracture treatment) (7). With further technology development, intraoperative tracing of major fracture fragments is possible and is especially useful in fractures where fragments are easily marked at the beginning of the surgery before reduction maneuvers start, so we can trace them during the reduction. In these cases, we have a good control of reduction and fixation (32). Some studies regarding accuracy by using navigation were done in the field of maxillofacial surgery. The measured difference between the planned and executed surgery using computer-assisted surgery can exceed 2 mm in length and 4^0 in angulation (6). The precision of the fracture reduction is still problematic especially if we do not have clearly defined anatomical landmarks on the fragments. This is common in comminuted fractures or if the fragments cannot be marked before the start of manipulation. To avoid these shortcomings of intraoperative navigation systems, some surgeons proposed using 3D printed navigation templates for minimally invasive plate osteosynthesis in periarticular regions. These templates are used for the proper plate positioning and fixation of the screws (27).

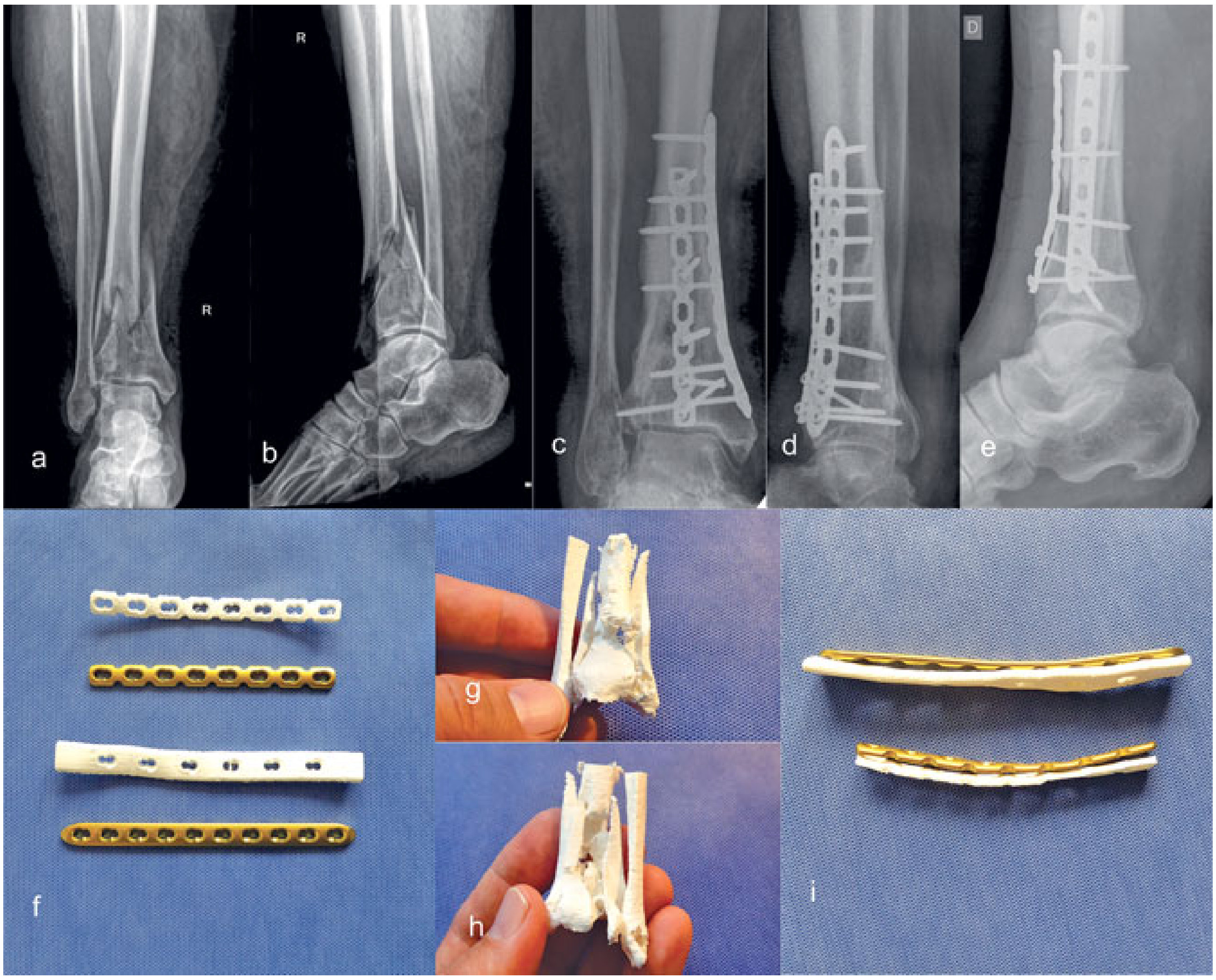

Fig. 2. Planning of the patient and fracture specific implants for distal intraarticular fracture of tibia.
X-ray image of the fracture (a, b). Based on preoperative planning presented in Figure 1 the implants were designed and printed. The appropriate plates from osteosynthesis set were chosen (f). 3D printed fracture in reduced size were used to get better 3D perception of the fracture (g, h). Chosen plates were curved according to 3D printed model (i). End result of the surgery according to plan with sterilized patient specific precurved plates (c, d, e).

With the development of three-dimensional printing of the objects, new era of patient's specific implants has arisen. In pelvic and acetabular fracture surgery, it was shown that the plate can be shaped according to the contralateral healthy side on the 3D printed pelvis of the patient (1). The mirroring of the implant can cause some minor discrepancies, which can influence accuracy of implant placement during the surgery. In some special situation of severe bone defects (tumors), specially planned and designed implants are printed and applied during surgery (8). The need of the newly designed implants can justify costs and time needed to produce the implant. Nowadays, we have a rich armamentarium of the fracture specific plates in fracture surgery. Not surprisingly, there are more and more reports of unfitting of the designed implants to the specific anatomical site (2). Fortunately, we rarely need the design of the plate which cannot be modeled from the existing plates in our osteosynthesis sets. During the computerized preoperative planning we can design the shape of the plate which would fit best to specific reduced fracture of the patient and can also be specific to surgeon preferences. We can print 3D plastic model of the desired plate in real size. This model serves as a template for shaping the reconstruction plate to fit best to a specific patient. The accuracy of this fixation is acceptable (30). In our institution patient and surgeon specific implants are routinely used for complex intra- and periarticular fractures and are modeled according to a preplanned plastic model (Fig. 2). Another useful benefit of easily accessible 3D printing is making a model of the fractured bone. It can be printed in actual size to test the fitting of the implants to the bone, or in smaller dimensions, whatever is useful to get the three-dimensional impression of the fracture and its relation to the neighboring intact bone (31). (Fig. 2).

Treatment of malunited fractures can be exceedingly difficult in the presence of complex deformities. Planning itself requires particularly good knowledge of anatomy, biomechanics, and geometry. The methods of classical deformity correction planning using paper have been described and used for decades. With the advancement of mechanics and software applications, the gradual correction of the deformity is possible under the guidance of the computer program to correct deformities in all dimensions using the hexapod technology and circular frame fixator (11). The gradual deformity correction using circular frame is sometimes impossible because of the body region (pelvis), badly tolerated by

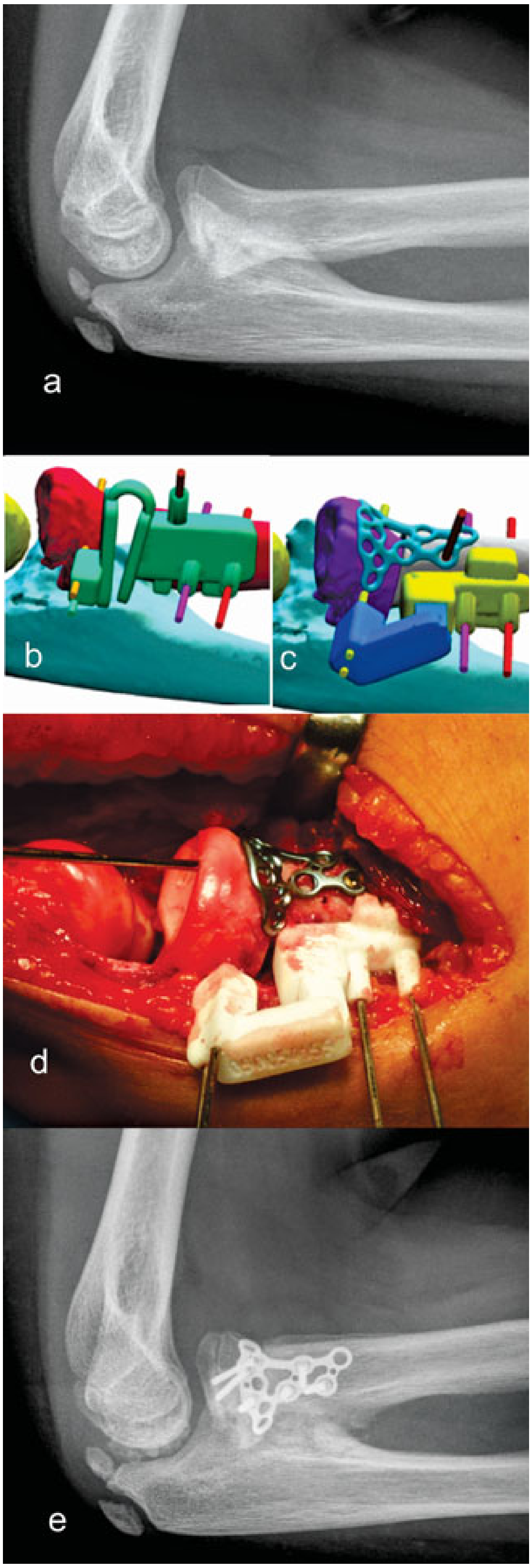

Fig. 3. Case of preoperative planning and operation using patient specific jig for correction osteotomy of proximal radius deformation in a child.
Lateral X-ray view of deformity of proximal radius causing anterior radius head dislocation (a). Computer preoperative planning in more steps to design patient's specific jigs (b, c). During the surgery jig was applied and osteotomy and fixation done (d). Postoperative lateral X-ray with corrected deformation (image e).

patients because of the region (thigh) or because of the patient's personality or age. In these cases, even in complex malunions, a single-cut osteotomy is possible and preferred in cases of angular deformity in three dimensions. Planning and performing this type of osteotomy is relatively complex. 3D computer-assisted planning is done and the optimal location of the osteotomy and cutting plane defined. The jigs which fit the exact spot on the bone are designed according to the planned direction of the bone cut and are created in the computer planning model. This patient specific jigs are 3D printed and used for osteotomy (4). (Fig. 3).

FUTURE PERSPECTIVES

In the future, fracture planning will be further connected to other emerging sciences. By incorporation of new features in existing planning software, the fracture surgery will get some new perspectives.

Weight bearing after articular surface fracture is usually postponed until the bone heals, on the other hand, passive and active physiotherapy is started promptly after the surgery. The knowledge in biomechanics of the normal joints and influence of pathology on joint stress distribution has grown exponentially in last decades. It is known that forces during joints movements are not distributed evenly on the articular surface and are related to the direction and velocity of the move. They can even exceed the forces during weightbearing (14). In the future, the biomechanical knowledge will be incorporated in the preoperative planning. By doing that the surgeon will know in advance which part of the fracture has to be fixed more stably to avoid micromovements which can lead to a secondary displacement of the fragment and mal- or non-union of the fracture.

The treatment of bone defects remains a significant clinical challenge. Still today, it usually requires autogenous bone grafts or bone graft substitutes. Bone grafts can fail to provide enough structural support, beside that problems with donor site morbidity are sometimes also challenging. Existing bone substitutes showed unreliability of bone ingrowth and degradability. Development of computer software, possibility of 3D printing and tissue engineering promise an extremely exciting future. We can expect that 3D porous scaffolds will be printed based on preoperative computerized planning. With further development in tissue engineering scaffolds will be cultivated with active substances including cells and growth factors. Some promising results have already been published (5).

Classical surgical training with excessive practicing of approaches and even fixation of bones in the cadaver labs are becoming more and more difficult and in some parts of the world even illegal. Future we see in expanding the preoperative planning from the bone also to the surrounding soft tissue of the real patients. With the introduction of surgical simulators which will enable performing surgery in virtual environment, the learning curve will be shorter and the quality and safety of the education of surgical trainees will be improved.

CONCLUSIONS

Surgical procedure planning is an important first step in a successful and eventless surgery with satisfying clinical result. Computer technology enables the preoperative planning to be user- (surgeon) friendly. By doing that, we can expect its usage will become (even) more popular, especially with a younger generation of the surgeons. The interdisciplinary cooperation and new technologies have brought us new intraoperative possibilities, such as patient specific implants, intraoperative navigation, and more. All this would never be possible without the advanced planning. In the future, we can look forward to new important features in preoperative planning tools and applying newer technologies to intraoperative usage, which will be assisted by planning.

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