Intra-articular malunions represent an exceptional technical challenge for the treating surgeon. Multidetector CT scans (MDCT) with three-dimensional (3D) surface rendered images are increasingly used not only for the evaluation of malunions, but also to develop a road map for surgery in patients who have been selected for corrective osteotomy.\textsuperscript{1,10,12} CT-based virtual pre-operative planning, including virtual osteotomy, prediction of final positioning\textsuperscript{11} and additive manufacturing of patient-specific instruments based on the 3D bone structure are clinical reality.\textsuperscript{8,9}

**Computer-assisted Planning**

The 3D information present in the data set of a CT scan can be used for computer-assisted planning. The MDCT scans consist of a series of sequential slices with preset thickness and slice intervals. With the multidetector helicoidal CT scans, resolution of up to 0.3 mm can be achieved, though at the “cost” of a higher radiation dose.\textsuperscript{8} From the CT dataset, 3D images can be reconstructed with two distinctly different techniques. The most commonly used technique is surface rendering,\textsuperscript{11,13} which reconstructs the bone soft tissue interface presented as a 3D surface that can be viewed from all angles. On the other hand, the segmentation technique identifies the bony structure in each slice (surface x height equal to slice thickness) which is restacked in an orderly manner, resulting in mathematically described volume,\textsuperscript{8,9} with distinct mathematical sizes and shapes that can be manipulated as a geometric structure (sliced, repositioned, measured, etc.) into new configurations. Mimics software (Materialise NV, Leuven, Belgium) was used for segmentation and virtual planning.

When dealing with a distal radius malunion, the first step is to segment the radius and make a virtual 3D reconstruction. (See Exhibit 1.) Next, the different parts of the malunion are isolated as individual structures. (See Exhibit 2.) Treatment of an intra-articular malunion usually involves recreating the original fracture pattern with a series of 1mm drill holes. (See Exhibit 3.) In cases where length needs to be reconstructed, it is preferable to use the mirror image of the contralateral non-affected radius as a reference. (See Exhibit 4.) Once the virtual reduction is performed (See Exhibit 5.), a digital image of the implant (typically plate and screws) can be imported into the project. This step allows optimization of the osteotomy site and implant choice.

The implant can also be used as an assembly guide for the reconstruction. In these cases, the drill holes for the fixation of the implant have to be predrilled on the malunited radius. (See Exhibit 6.) The loca-
tion of the drill holes on the malunited bone is determined by fitting the implant to the virtual reconstruction and subsequently reverse engineering the drill hole positions in the malunited position.

Executing the Surgery Using Patient-specific Instruments

Since the goal of these procedures is to reconstruct the anatomy with (sub)millimeter precision, it’s difficult to rely on clinical judgment and fluoroscopy only. Various solutions have been suggested ranging from arthroscopy, arthroscopy with inside out osteotomy, experimental navigation and patient-specific instruments produced using additive manufacturing.

These patient-specific SurgiCase® surgical guides (Materialise NV) are produced as surface molds of the 3D bone model and have a unique fit to the bone. Additionally, these guides are designed with K-wire holes for fixation to the bone, cylinders that are fitted with drill sleeves, and slits to perform osteotomies along defined cutting planes as determined in the pre-surgical plan.

Note: when confronted with combined intra- and extra-articular malunions, the procedure requires the use of multiple consecutive guides. In these cases, the intra-articular osteotomy is performed first by drilling a series of 1.1mm drill holes along the original fracture line that structurally weakens the bone and facilitates recreating the fracture along the preset pattern. (See Exhibit 7.) Second, the drill holes for the implant fixation are made. Usually, the metaphysical osteotomy is the last step.

At this point all parts are separated. Drilling (perforating) the bone structurally weakens it to the extent that it will break along the present pattern. (See Exhibit 8.) Since the drill holes for the fixation of the implant are pre-drilled in the position of the fully reduced malunion, the implant is used as a final reduction template. (See Exhibit 9.)

The different trials are done in a virtual system at no additional cost, in contrast to trial surgery on physical models that as a rule can only be performed once.

Conclusion

This technology was first used in our department in 2005, initially for the surgical planning of a Madelung’s deformity without the use of patient-specific instruments. Patient-specific instrumentation was then introduced in 2007 with our first intra-articular malunion of the radius. Since then, five to ten cases of varying natures have been performed every year utilizing the engineering services provided by Materialise. Further, this technology has been used for treatments of malunions of the proximal radius, distal humerus, distal femur, proximal tibia, etc.

As reported previously, the pre-surgical planning alone of complex osteotomies in 3D offers multiple advantages. The surgeon not only gains more insight in the complexity of the deformity, but he can also fine-tune the surgery and evaluate different, sometimes conflicting, treatment strategies suggested in literature. The different trials are done in a virtual system at no additional cost, in contrast to trial surgery on physical models that as a rule can only be performed once.
Soon after the possibilities of virtual surgery planning were reported, surgeons tried to bring planning into the operating theater. One possibility is to upload the project into navigation software. The problem in the upper extremity, however, is the use of tracking markers on the upper extremity and instruments due to size limiting factors. The first attempts to bring the surgery into the operating theater produced spacing blocks to exactly match the void space after opening wedge osteotomies. Of course, this was of no use in closing wedge or intra-articular osteotomies.

With the introduction of patient-specific instruments to the orthopaedic field, it became possible to perform intra- and extra-articular osteotomies with a high degree of precision as pre-surgically planned for the individual patient.

Along came the next technological advancement for surgery planning via the development of patient-specific instruments, such as surgical guides. This technology has been used for many years in dental implantology and more recently, was introduced to knee arthroplasty. These patient-specific instruments serve as an intra-operative navigation tool to perform surgical functions with high precision; the green color indicates <1mm accuracy. (See Figures 9.1, 9.2 and 9.3 in Exhibit 9.) The accuracy facilitates a unique fitting of the patient-specific instrument onto the surface of the affected bone. The more irregularities can be included in the molded surface, the more reliable the fit.

With the introduction of patient-specific instruments to the orthopaedic field, it became possible to perform intra- and extra-articular osteotomies with a high degree of precision as pre-surgically planned for the individual patient. Further introducing the fixation device into the planning process allows assembling the different fragments using the fixation implant as a distraction template. Although conventional surgical skills and pre-operative fluoroscopy are sufficient in many cases, the more complex cases like combined intra- and extra-articular osteotomies with length reconstruction or rotational malunion, most certainly are facilitated with the use of the fixation device as an assembly template.

REFERENCES


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