SUBSPECIALTY PROCEDURES

VIRTUAL PLANNING AND ALLOGRAFT PREPARATION GUIDED BY NAVIGATION FOR RECONSTRUCTIVE ONCOLOGIC SURGERY

A TECHNICAL REPORT

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Introduction

Advanced virtual simulators can be used to accurately detect the best allograft according to size and shape. Tumor margins are measured, a planar configuration is determined in a virtual scenario for the patient and the allograft, and then a 3-dimensional (3D) plan is produced for the patient and the allograft.

Allograft preparation is usually done intraoperatively, with the graft modeled manually. We previously shaped the allograft manually by a trial-and-error process once the defect had been created, leading to potential anatomic inaccuracies between the sculpted allograft and the recipient site. In recent years, bone tumor resections guided by computer navigation have been reported¹⁻²⁰. Navigation can be a useful tool to improve allograft shaping to match with the recipient site and the alignment. Navigation of both the tumor resection and the intraoperative manipulations of the allograft as well as the preoperative allograft selection with a virtual bone bank may increase the accuracy of the entire procedure. The aims are to reduce inaccuracies between the planned and actual osteotomies, reduce allograft complications resulting from technical errors during implantation, minimize limb-length discrepancies, improve restoration of the joint line, and optimize rotational alignment. An alternative tool for 3D preoperative planning is the patient-specific instrument (PSI). Recently, results using personalized jigs, which showed similar accuracy between PSI and navigation, have been reported^{1,2,16}.

In 2015, we analyzed the cases of 69 consecutive patients with bone tumors of the extremities that were reconstructed with massive bone allograft using intraoperative computer-navigation assistance³. We achieved accurate osteotomy placement for the bone tumor resection, allowing adequate margin, when using the navigation system. In addition, we reported on 5 patients with low-grade chondrosarcoma of the knee in whom multiplanar osteotomies were performed for resection¹⁷. In all cases, after the tumor was resected, a second

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navigation-assisted surgery was performed on the selected allograft. This technique diminished inaccuracies of the osteotomies in the allograft and improved matching to the host bone. Furthermore, in a previous study, we described a series of 28 patients in whom 61 planes, or osteotomies, had been created. Postoperatively, computed tomography (CT) scans of the specimens were used to create 3D reconstructions that were compared with the virtual preoperative planning and the osteotomies performed with navigation, obtaining an average error of 2.5 mm in 61 osteotomies⁹.

In 2017, we reported on our learning curve for computer-assisted navigation in bone resection and allograft preparation after 8 years of experience²⁰. We concluded that technical difficulties related to navigation precluded the use of navigation in 5% of the cases in this series. Navigation time decreased with more experience in the procedure, but we did not improve the registration error over time (Video 1).

Video 1 The resection of a bone tumor and the use of a suitable allograft using computer-assisted navigation.

Indications & Contraindications

Indications

- Tumor resection and intercalary allograft reconstruction.
- Tumor resection and osteoarticular allograft reconstruction.
- Tumor resection and multiplanar allograft reconstruction.
- Tumor resection and prosthesis reconstruction.

Contraindications

- Patients without digital images available.
- Patients without digital images acquired in the correct protocol.

Step 1: Acquisition of Medical Images

Obtain a multislice CT scan and a magnetic resonance imaging (MRI) scan preoperatively for each patient; however, if the time between the scans and the surgery is > 1 month, consider repeating the MRI because the size of the tumor may have changed during that time.

- Obtain a CT scan (Toshiba Aquilion) using a DICOM (Digital Imaging and Communications in Medicine) image matrix of 512×512 pixels and 1-mm thickness without gap.
- Use the same imaging protocol for scanning the allograft.
- Obtain an MRI scan on a 1.5-T unit (Magnetom Avanto; Siemens Medical Solutions) using a DICOM image matrix of 256×256 pixels, with slices of 1-mm thickness obtained using T1-weighted or fat-suppressed sequences to optimize bone tumor visualization^{9,12}.

Step 2: Select an Allograft Using Virtual Imaging to Optimize Size Matching

Load DICOM images into a virtual simulation station (Windows 7 Service Pack 1, 64 bit, Intel Core i5/i7 or equivalent) and use mediCAS planning software (medicas3d.com) or equivalent (Materialise Mimics or Amira software [FEI]) for image segmentation and virtual simulation with STL (stereolithography) files.

- Process manual segmentation of the bone in the CT images. This is done when the intensities (in Hounsfield units) in the image corresponding to bone are virtually separated from the rest of the tissues (metals and soft tissue) in the image. An operator (a physician or radiology technician with expertise in imaging software), supervised by an orthopaedic oncology surgeon, performs this work with the use of manual and semiautomatic tools provided by the software. At the end of the process, a 3D reconstruction of the bone is created in a virtual scenario. This information is saved in an STL file format.
- When the 3D reconstruction of the patient's bone is complete, it is compared in a virtual scenario with bones available in the virtual library of banked allografts (Virtual Bone Bank System)⁸.
- Choose the most suitable structural allograft according to size and shape.
- Use mediCAS planning software or an equivalent (ParaView software) to perform virtual calculation between both STL surfaces (point to point calculation).
- Thereby, a quantitative (distances between surfaces in millimeters) and qualitative assessment (differences in a colorimetric map to localize which areas are the best match) is established between host and donor bone geometry.

Step 3: Plan and Outline the Tumor Margins on the Preoperative Imaging

Determine and outline the tumor margin on manually fused CT and MRI studies using the registration tool of the mediCAS planning software or equivalent (Materialise Mimics software.)

- In the virtual platform, define the cutting planes (osteotomies) with 2-mm thickness (Fig. 1).
- The distance between the planned osteotomy plane and the tumor determines the tumor margin and then the planar configuration.
- The planar configuration is defined according to the number of planes necessary to resect the tumor. One plane is uniplanar, 2 planes are biplanar, and ≥ 3 planes are multiplanar.
- The final osteotomy position determines the geometric shape of the cut.

Fig. 1

Fig. 1 The CT and MRI scans of a 35-year-old patient with a grade-2 chondrosarcoma were fused in a virtual scenario. The oncologic margin was determined to be 5 mm in the proximal and distal planes.

Step 4: Plan and Outline the Same Osteotomies on the Allograft

Determine and outline the osteotomies between host and donor using the registration tool of the mediCAS planning software or equivalent (Materialise Mimics software.)

- Apply this geometric shape on both the host and donor bone to obtain an appropriate match (Fig. 2). This task consists of manually placing the STL image of the donor bone over the STL image of the host bone using a registration tool.
- Specific osseous landmarks are never used, but matching the diaphyseal cortical bones where the fixation plate will be placed is important. For example, in the femur, we match the lateral and anterior diaphyseal cortical bone and the condylar base between host and donor.
- As soon as the images of the host and donor bone are overlapped in the position described, a new virtual osteotomy (allograft osteotomy) with an offset of 2 mm is created to assess the bone loss in the patient and donor when sawing the bone.

Fig. 2

Figs. 2-A and 2-B Images from the same patient as in Figure 1. **Fig. 2-A** First, the proximal and distal planes were determined according to the oncologic margin. Then, the planar situation in the allograft was defined with respect to the host bone. The allograft is 4 mm longer than the host bone because of the thickness of the saw blade (2 mm in the proximal plane and 2 mm in the distal plane). **Fig. 2-B** A virtual trial of the host and donor bone is possible, to determine the best match.

Step 5: Assess the Patient and Allograft in a Virtual Scenario

Be sure to consider the disintegration of bone tissue that occurs during the osteotomy and corresponds to the thickness of the blade (approximately 1.5 mm).

- Be aware of the bone loss (approximately 1.5 mm) that occurs in the patient and allograft during the sawing of the bone.
- Adjust the osteotomy plane on the allograft to enlarge the allograft by 2 mm to account for the thickness of the saw blade.
- An optimal match between the prepared donor bone and the host bone is achieved when the lateral and anterior diaphyseal cortical bone and the condylar base are aligned.

- The tumor is resected within the virtual scenario simulation.
- The tumor resection in the patient (dashed yellow arrows) and the sizing and preparation of the allograft (solid yellow arrows) are both virtually planned (as shown in Figure 3).

Fig. 3

Fig. 3 Diagram showing the workflow that allows the operators to use 2 simultaneous surgical teams in the operating room.

Step 6: Navigation Settings

A tool of the mediCAS planning software allows the virtual preoperative planning (STL files) to be transferred to the surgical navigation format, DICOM files.

- Load both plans into the navigator platform (OrthoMap 2.0; Stryker) as 2 independent navigation projects.
- Locate the navigator device 4.8 ft (1.5 m) from the patient.
- Establish a system of corresponding points between the 3D image and the patient through the registration process.
- The registration process consists of attaching 2 pins that are 3 mm in diameter and 150 mm long in the diaphysis. According to the location, we prefer to place the pins far the tumor and within 5 cm of the planned osteotomy. We control these parameters using a ruler intraoperatively.
- A clamp (OrthoLock; Stryker) joins the 2 pins to a tracker. Most navigation systems use optical balls, whereas the Stryker system uses an infrared active emitter. According to the tracker location, the 2 pins should be attached no more than 10 cm from the osteotomy (we never place the pins near the tumor). We believe that the best place is in the normal bone segments away from the resection sites.
- In order to establish a registration between the 3D image and the patient, it is necessary to determine at least 3 landmarks. This step is the point registration.
- Next, to improve the registration, apply the surface registration, which consists of the addition of at least 32 more points.
- The last and most important part of this step is to check the coronal, axial, and sagittal views for 3 different landmarks where the points should be marked in the image at the limit between cortical bone and the air in the image (air-bone interface).

Step 7: Patient and Allograft Intraoperative Navigation

The tumor and allograft are resected using the navigated guidelines, which were previously planned with the virtual platform.

- Use the camera and an infrared active emitter, called a tracker.
- Attach the tracker to the bone of the patient.
- Using an infrared pointer, the surgeon knows exactly where he or she should make the cut in the bone because it is possible to see in a monitor and in real time the 3D image of the bone with the osteotomy planned according to the preoperative virtual planning. Although this system does not use an intraoperative CT scan, the preoperative virtual plan, which is based on the preoperative CT and MRI scans, is used.
- Have 2 simultaneous surgical teams in the operating room.
- One surgical team navigates the virtually planned osteotomy in the allograft. In uniplanar cases, it is possible to do the planned osteotomies on the allograft before the tumor is resected. However, in biplanar and multiplanar osteotomies, because of unexpected factors (saw blade deflections), it is better to wait and do the allograft osteotomies after the tumor has been resected.
- In biplanar and multiplanar osteotomies, because it is technically difficult to fit the allograft, it could be necessary to recut the allograft.
- A second surgical team begins with the approach (Fig. 4).
- Resect the tumor under navigated guidance. One surgeon uses a pointer, and a second surgeon marks the osteotomy with methylene blue according to the 3D plan. Next, with a regular saw blade, cut the bone. In real time, it is possible to control the pathway according to the planned osteotomy by watching the navigation system's screen.
- The structural allograft will be ready to be placed with the corresponding geometry.

Fig. 4

Fig. 4 A photograph showing 2 simultaneous surgical teams in the operating room. One surgical team navigates the virtually planned osteotomy, while a second surgical team simultaneously begins with the approach.

Results

The 3D virtual preoperative planning and surgical navigation software are tools designed to increase the accuracy of bone tumor resection and allograft reconstruction³. The accuracy of the method was described in a report on 61 patients for whom the differences between the planned osteotomies and the resection that was performed had a standard error of <2.5 mm⁹. Navigation could be repeated, with 5% of the procedures cancelled because of technical error³. However, the navigation procedure increased the operative time, by a mean of 35 minutes, and the cost. For allograft reconstructions and bone resections guided by navigation, the nonunion rate was approximately 6%. In pelvic and sacral resections, navigation-assisted surgery reduced the intralesional resection rate for primary tumors

3D Preoperative Planning in Virtual Scenarios

Advantages

- The tumor, or oncologic, margin is measured in 3D in a virtual scenario with MRI and CT scans, which achieves an exhaustive analysis of the tumor area.

- The type of osteotomy (uniplanar, biplanar, or multiplanar) is determined according to the oncologic margin.
- The tumor resection is visualized and the oncologic margin is measured virtually, which allows the surgeon to more precisely visualize the bone defect preoperatively.
- Reconstructive alternatives can be considered according to the estimated size and shape of the bone defect⁹.
- Virtual planning allows allograft selection and preparation to be done according to the estimated size and shape of the bone defect.

Disadvantages

- An operator with expertise in medical imaging software is necessary.
- Extra cost is involved.
- The virtual scenario preparation, which involves importing and processing images (fusion, segmentation, measurement of the minimal margin, etc.), is a time-consuming process that requires an average of 4 hours per case.

Navigation-Assisted Surgery**Advantages**

- The use of the preoperatively planned osteotomy optimizes the bone tumor resection, providing safety and control during the surgical procedure.
- The use of the previously planned osteotomy optimizes bone allograft preparation, avoiding multiple bone recuts that lead to extra time consumed during surgery.
- The preoperative planning of the bone tumor resection and the allograft preparation are done in the operating room with 2 teams of surgeons working simultaneously, which optimizes the operative time.

Disadvantages

- An operator with expertise in navigation is required.
- Extra cost is involved.
- There is a long learning curve for the operator and the surgical team.
- The technique adds a mean of 35 minutes to the operative time.

Pitfalls & Challenges

- When selecting a femoral allograft in a patient with open physes, the surgeon must overestimate the length of the allograft, taking into account the future growth of healthy bone.
- The allograft needs to be 4 mm longer than the host bone because of the thickness of the saw blade (2 mm in the proximal plane and 2 mm in the distal plane).
- To rotate the donor allograft in the patient, we print a mark in the 3D planning image perpendicular to the planned cuts. The mark is printed in the donor bone and in the patient bone under navigation-assisted guidance. In the reconstructive step, we match both marks to maintain the planned rotation.
- Note that the deeper the cut, the less the control of the navigation system device and the more inaccurate the result. This parameter must be taken into account in epiphyseal cuts in the knee.
- To avoid or minimize possible errors during the entire workflow, we use other cutting tools, such as diathermy or a bone burr, which could add more precision to the final execution.

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