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Does Intraoperative Navigation Assistance Improve Bone Tumor Resection and Allograft Reconstruction Results?

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Abstract

Background Bone tumor resections for limb salvage have become standard treatment. Recently, computer-assisted navigation has been introduced to improve the accuracy of joint arthroplasty and possible tumor resection surgery; however, like with any new technology, its benefits and limitations need to be characterized for surgeons to make informed decisions about whether to use it.

Questions/purposes We wanted to (1) assess the technical problems associated with computer-assisted navigation; (2) assess the accuracy of the registration technique; (3) define the time required to perform a navigated resection in orthopedic oncology; and (4) the frequency of complications such as local recurrence, infection, nonunion, fracture, and articular collapse after tumor resection and

bone reconstruction with allografts using intraoperative navigation assistance.

Methods We analyzed 69 consecutive patients with bone tumors of the extremities that were reconstructed with massive bone allografts using intraoperative navigation assistance with a minimum followup of 12 months (mean, 29 months; range, 12–43 months). All patients had their tumors reconstructed in three-dimensional format in a virtual platform and planning was performed to determine the osteotomy position according to oncology margins in a CT-MRI image fusion. Tumor resections and allograft reconstructions were performed using a computer navigation system according to the previously planned cuts. We analyzed intraoperative data such as technical problems related to the navigation procedure, registration technique error, length of time for the navigation procedure, and postoperative complications such as local recurrence, infection, nonunion, fracture, and articular collapse.

Results In three patients (4%), the navigation was not carried out as a result of technical problems. Of the 66 cases in which navigation was performed, the mean registration error was 0.65 mm (range, 0.3–1.2 mm). The mean required time for navigation procedures, including bone resection and allograft reconstruction during surgery, was 35 minutes (range, 18–65 minutes). Complications that required a second surgical procedure were recorded for nine patients including one local recurrence, one infection, two fractures, one articular collapse, and four nonunions. In two of these nine patients, the allograft needed to be removed. At latest followup, three patients died of their original disease.

Conclusions The navigation procedure could not be performed for technical reasons in 4% of the series. The mean registration error was 0.65 mm in this series and the navigation procedure itself adds a mean of 35 minutes during

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All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research* editors and board members are on file with the publication and can be viewed on request. Each author certifies that his or her institution approved the reporting of this case report, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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surgery. The complications rate for this series was 14%. We found a nonunion rate of 6% in allograft reconstructions when we used a navigation system for the cuts.

Level of Evidence Level IV, case series. See the Guidelines for Authors for a complete description of levels of evidence.

Introduction

Advances in the last three decades regarding bone tumor treatment are related to adjuvant therapies, advances in imaging, and surgical techniques. However, successful transfer of information from advanced imaging techniques such as MRI and CT to the surgical field can be difficult [4, 16]. The use of image fusion from CT and MRI scans with the subsequent transfer of this information to a navigation system could help to achieve this objective [4, 16, 20].

This technology allows the surgeon to program preoperatively the bone tumor resection in a three-dimensional (3-D) virtual scenario and to analyze different alternatives in real time [4, 16, 17, 20]. Intraoperatively, it is possible to reproduce the preoperative plan accurately and to also perform bone reconstructions with prostheses [21], allografts [2], or a combination of both [5]. Adequate limb reconstruction is performed minimizing limb length discrepancies, improving restoration of the joint line, and addressing rotational concerns [4, 5, 16, 17, 21].

Although there are potential advantages of computer-assisted surgery, in conventional orthopaedic surgery (such as trauma and arthroplasty), the use of this technology is at times associated with technical problems [3, 11], increased surgical time of the procedures [7, 19], and no clear improvement in clinical outcome regarding conventional surgeries [3, 11]. In orthopaedic oncology, this technology is reported to aid in achieving adequate margins [8, 20] and improve the accuracy of bone cuts [10, 14, 21]. However, it will likely become more extensively used if it decreases the time of the procedures and shows that clinical outcomes are improved [4, 16]; to date, these remain open questions. Navigation of both the tumor resection and the intraoperative manipulations of the allograft [15] as well as the preoperative allograft selection with a virtual bone bank may increase accuracy of the whole procedure [13]. This is aimed to reduce local tumor recurrences as a result of inaccuracies between the planned osteotomies and the osteotomies finally performed [14] and allograft complications resulting from technical errors during implantation; however, again, these purported advantages have been the subject of relatively little research to date [2, 6].

We therefore sought to assess (1) the technical problems associated with computer-assisted navigation; (2) the accuracy of the registration technique; (3) define the time

required to perform a navigated resection in orthopedic oncology; and (4) the rate of complications such as local recurrence, infection, nonunion, fracture, and articular collapse after tumor resection and bone reconstruction with allografts using intraoperative navigation assistance.

Patients and Methods

Between May 2010 and November 2012, we performed 93 resections of long-bone tumors; of these, 69 (74%) were reconstructed with massive bone allografts using intraoperative navigation assistance and were available for followup at a minimum of 12 months (mean, 29 months; range, 12–43 months). During this period, our general indications for use of navigation included pelvic and sacral tumors and those tumors that will be reconstructed with massive bone allografts to obtain precise matching of the host and allograft osteotomies. For this study we excluded pelvic and sacral tumors and those reconstructed with endoprostheses so that we could focus on allograft reconstructions of the extremity. There were no patients who were lost to followup. After approval by our institution's institutional review board, preoperative data (demographic information, including patient age, sex, affected bone, and diagnosis), intraoperative data (technical problems related to the navigation procedure, registration error, length of time for the navigation procedure, histological margins), and postoperative data (complications) were recorded.

Mean patient age at the time of diagnosis was 28.9 years (range, 3–85 years). There were 37 females and 32 males. Forty-three tumors were localized in the femur, 21 in the tibia, three in the humerus, one in the elbow, and one in the medial cuneiform. Diagnoses included osteosarcoma in 26 patients, chondrosarcoma in 18, pleomorphic sarcoma in six, Ewing's sarcoma in three, adamantinoma in two, renal clear cell bone metastasis in two, and benign tumors in 12.

All patients were studied with CT scans and MRIs of the affected bone. CT scans and MRIs were fused to determine bone cortex and intra-/extraosseous tumor extension [14, 15]. The fused images were reconstructed in a 3-D virtual platform and, according to the tumor, a virtual osteotomy was planned (Video 1) [14, 15]. Allografts were selected from our digital bone bank to match the resected bone [13]. The selected allograft was fused in the tumor preoperative planning, and the osteotomies were also planned for the allograft in a 3-D virtual scenario (Video 2). Once the 3-D preoperative planning was obtained in a computer-aided design format for both tumor resection and allograft reconstruction, 3-D models were converted to CT data sets in Digital Imaging and Communications in Medicine (DICOM) format and imported to the navigator (3D

Fig. 1 This figure shows the point-to-point registration to match the operative anatomy of the patient with the preoperative virtual plan. Although five landmark points were selected preoperatively based on the surgical exposure and anatomic visible points, three points were enough to obtain an adequate registration (registration error of 1.9 mm).

Fig. 2 After surface refinement mapping of anatomic landmarks of the bone, the registration error is reduced to 0.7 mm. Note that the points are selected in nonaffected bone to avoid touching the affected bone with the pointer.

OrthoMap navigation software Version 1.0; Stryker Navigator, Freiburg, Germany) [14].

Intraoperatively, the navigation procedure consisted of two parts: (1) bone tumor resection; and (2) allograft reconstruction. After surgical exposure of the affected bone, an infrared tracker device is applied in noncompromised bone. The surgeon established correspondence between the 3-D images and the real bone with visible anatomic points (Fig. 1). After that, surface mapping of the bone was performed to reduce any mismatch between the 3-D image and the patient bone (Fig. 2). When the surgeons were confident with the accuracy of the registration (less than 2 mm), the osteotomies were marked using a navigated pointer (Fig. 3). The surgeon used the navigation pointer in the surgical field (Video 3) guided by the navigation system (Video 4). We recorded the time required for navigation from the fixation of the tracker to the bone until we marked the osteotomies with the navigated pointer. The osteotomies were performed with a freehand saw following the previous mark (Fig. 4). This procedure was also performed in the allograft. The surgeon established correspondence between the 3-D images and the allograft bone with visible anatomic points (Fig. 5). After that, surface mapping of the bone was performed to reduce any mismatch between the 3-D image and the allograft bone (Fig. 6). When the surgeons were

confident with the accuracy of the registration, the osteotomies in the allograft were marked using a navigated pointer (Fig. 7). Afterward, the allograft was implanted in the defect and secured in all cases with plates and screws (Fig. 8). In the first 20 procedures in this series, allograft cuts were navigated after tumor resection navigated cuts were performed. Once we were confident with the accuracy of the procedure, the allograft cuts were performed while the surgical approach was performed. Reconstructions in this series included 47 intercalary allografts (22 hemicylindrical and 25 segmental), 18 osteoarticular allografts

Fig. 4 The osteotomies are performed with a freehand saw following the previous mark as it is shown in this intraoperative photograph.

Fig. 3 This figure shows how the proximal osteotomy and rotation are marked in the patient using a navigated pointer after adequate registration in an intercalary resection.

Fig. 5 Point-to-point registration is used to match the operative anatomy of the allograft with the preoperative virtual reconstructive plan.

Fig. 6 After surface refinement mapping of anatomic landmarks of the allograft bone, the registration error is reduced to 0.9 mm.

Fig. 7 This figure shows how the proximal osteotomy and rotation are marked using a navigated pointer after adequate registration to perform the allograft cuts.

Fig. 8 Intraoperative photograph after fixation of the allograft to the host with two short anterior plates and one long lateral plate is shown.

(five unicondylar and 13 bicondylar), and four allograft-prosthetic composites (APCs).

Antibiotics were administered postoperatively for a minimum of 24 hours or until the deep drains were discontinued. Patients were restricted from weightbearing for 3 to 6 months after reconstruction based on radiographic evidence of allograft healing (Fig. 9).

To test the first research purpose, we defined technical problems associated with navigation as those intraoperative problems that made it impossible for the surgeon to perform the navigation. So in these cases, the surgeon must continue the surgery without the assistance of navigation. To evaluate this, we registered consecutively in all cases those that we were not able to perform the navigation and

Fig. 9 Postoperative AP radiograph showing both femurs performed 30 months after reconstruction with adequate alignment and limb length.

afterward we analyzed the problem and divided them into hardware (malfunction of the system, tracker rupture, disruption of the infrared signal between the camera and the

surgical tools) or software problems (incompatibility between the images and the navigation system, exceeding the capacity of the programs). When these problems were identified, we performed procedures to avoid them.

We defined accuracy of the registration technique as the correspondence between the fused images reconstructed in a 3-D virtual platform in the preoperative planning and the real anatomic region in the surgical field. Intraoperative registration of the patient to the patient images is the key step in the navigation process [17] and is calculated by the navigation system software. These data were obtained intraoperatively in the navigation system after point and surface registration and were registered in all the cases in which navigation was performed. To determine the time required for navigation procedures in bone tumor resection and allograft reconstruction using this technology, we registered in all the procedures in this series the time required for fixation of the device in the bone, registration, and marking the osteotomies in both the receptor and the bone allograft with the navigated pointer. The time required for navigation procedures was in consequence the sum of this two times (the mark of the osteotomies in the affected bone and the allograft). Although we performed the allograft navigation procedure after tumor resection in the 20 first cases and afterward the allograft navigation procedure was done while the surgical approach was performed, we determined the amount of time as the summatory of this two times as if it was performed sequentially.

Finally, the rate of complications such as local recurrence, infection, nonunion, fracture, and articular collapse after tumor resection and bone reconstruction with allografts using intraoperative navigation assistance was evaluated at last followup control. We considered a reconstruction a failure when it was removed during a revision procedure or amputation. Followups were performed 2 weeks, 6 weeks, and 3 months after surgery, then every 3 months until 2 years after surgery, and then every 6 months. No patient was lost to followup. Plain radiographs and physical examination were performed at each followup. Chest CT was performed every 3 months until 2 years after surgery and then every 6 months to evaluate for metastatic disease. Outcomes including allograft healing, nonunion, tumor recurrence, fracture, hardware failure, and infection were recorded.

Results

In three patients (4%) the navigation was not carried out as a result of technical problems (two osteoarticular and one hemicylindrical). In one, the technical issue was secondary to software problems, and in the remaining two cases, the cause was the result of hardware problems. The software technical problem originated when we tried to navigate the position of the plate in the reconstruction and the

information to perform this exceeded the capacity of the computer of the navigation system. The hardware failures were related to broken trackers undetected during the procedure. To avoid this problem, we performed subsequent procedures with two sets of trackers.

Of the 66 cases in which the navigation was performed, the mean registration error obtained in the navigation system software was 0.65 mm (range, 0.3–1.2 mm) after point and surface registration. Histological examinations of all specimens showed a clear tumor margin in all patients.

The mean time for navigation procedures including bone resection and allograft reconstruction during surgery was 35 minutes (range, 18–65 minutes). However, in most cases, the allograft navigation procedure was performed during the surgical approach simultaneously by a second surgeon, so it did not extend the overall time of the procedure.

Complications that required a second surgical procedure were recorded in nine patients including one local recurrence, one infection, two fractures, one articular collapse, and four nonunions. In two of these nine patients, the allograft needed to be removed, and those patients were considered to have failed results. The patient with a local recurrence was treated with amputation. The patient who had an infection was treated with surgical débridement without removing the allograft. Of the two patients who had a fracture, both were intercalary segmental allografts (one femur and one tibia). The femur fracture was treated with removal of the allograft and reconstructed with a new intercalary allograft. The tibia fracture was treated with autologous bone graft and a new plate without removing the original allograft. The patient with an articular collapse was converted to an APC maintaining the allograft. The four patients who underwent nonunion were treated with autologous bone grafts and a new plate without removing the original allograft. If we consider the 66 patients who were navigated (we excluded two osteoarticular and one hemicylindrical in which the navigation was not able to be performed), the rate of patients with nonunion was 6%; however, we must consider that there were more osteotomies than patients. If we excluded hemicylindrical allograft that had no nonunion in this series, we have 50 osteotomies in 25 segmental intercalary allografts and 20 osteotomies in 16 osteoarticular allografts and four APCs, which gives us a final nonunion rate of 6% in 70 osteotomies. At final followup, three patients died of their original disease without allograft failure.

Discussion

The use of image fusion from advanced CT and MRI scans with the subsequent transfer of this information to a navigation system could help the oncology surgeon to

reproduce the preoperative plan in the surgical field [4, 16]. However, the use of this technology could cause new difficulties related to their use and may increase operative time. Furthermore, it is not clear that this additional time and expense will reduce oncological (local recurrence) or nononcological complications (infection, nonunion, fracture, malposition) [4, 16, 20]. With these considerations, we sought to report technical problems that caused us to abort the navigation procedure, the accuracy of the registration technique and time required to perform navigation, and complications after tumor resection and bone reconstruction with allografts using intraoperative navigation assistance such as local recurrence, infection, nonunion, fracture, and articular collapse.

Our study has several limitations that must be taken into consideration. We analyzed only the time that was required in the operating room with the use of the navigation system. However, we must acknowledge that the virtual preoperative plan required considerable time before surgery. The time required for the preoperative planning depends on the complexity of the resection. Moreover, all preoperative planning was performed by the same person (LER) who assists the navigation procedure in the operating room; although the computer software used is available to others, he developed expertise and facility with navigation that over time reduced the overall time of the navigation procedure. In addition, to include all patients treated with extremity sarcomas with this technology, different types of diagnosis, resection types, and reconstructions were included. Another major limitation is that we have no comparison group to document if we have improved outcomes. Finally, this report had a short mean followup so we cannot determine the advantages of this approach over the longer run. Although a longer period of time is necessary, infection and host-donor nonunion rates are usually early complications so we believe we have identified most of the significant complications in this series of patients. However, it is too early to determine if these results will hold up with longer followup. At short-term followup, the nonunion and infection rates appear lower than previously reported [1, 7, 12].

The use of new technologies to a surgical procedure adds the risk of failures at every stage of navigation [16, 21]. In our series, 4% of the navigation procedures were not carried out as a result of technical problems. These complications occurred in the first year of the analyzed series and we were able to solve these problems so that they did not recur.

Of the 66 cases in which the navigation was performed, the mean registration error obtained in the navigation system software was 0.65 mm (range, 0.3–1.2 mm) after point and surface registration. Although histological examinations of all specimens showed a clear tumor margin in all patients like in previous reports [8, 10, 14, 17, 20, 21] with this technique, it is important to note that the navigation

assistance only reproduces accurately the preoperative plan performed by the surgeon based on fusion images (CT and MRI). However, the surgeon could misinterpret those preoperative images and plan inadequate cuts that could lead to inadequate margins. The oncologic surgeon faces two initial challenges when treating a bone tumor, how to determine the osteotomy site according to the exact limit of tumor growth and how to perform what was preoperatively planned during the surgical resection. The accuracy of the first is limited by what surgeons have available to determine the tumor extent at the time of presentation: CT and MRI techniques [4, 16]. We believe that surgeons may potentially improve their accuracy by recently incorporated computer navigation assistance techniques to increase precision at the time of performing the surgery [14]. In addition, if the surgeon chooses an allograft to reconstruct the bone loss, these computerized techniques may help to decrease relevant complications two different ways. First, virtually selecting the appropriate donor bone with the use of a virtual bone bank will provide the surgeon with the most suitable graft to obtain the best anatomical fitting [13]. Second, the allograft can be precisely cut using intraoperative navigation techniques to perform osteotomies with extreme accuracy with what was previously virtually planned [9].

Clinical studies that have compared the surgical duration of conventional and navigation-assisted orthopaedic procedures show increased operating time [3, 7, 11, 18]. The mean time for navigation procedures including bone resection and allograft reconstruction during surgery was 35 minutes in our series. Surgical time is clearly extended in conventional operations such as trauma [19] and joint arthroplasty [7] with the use of navigation assistance. However, in tumor surgeries, the use of navigation assistance, although it adds time, helps the surgeon to provide anatomic details related to intraoperative findings about the surgical bed, adding a level of accuracy and precision to the surgical resection and reconstruction. It is reported that with an appropriate learning curve, the results and the mean navigation time can be reduced [3, 18].

The complications reported in this series did not differ from the expected in this kind of surgery [1, 6, 12]. However, we found a lower nonunion rate (6%) if we compare our series with previous reports that show nonunion rates of more than 10% [1, 6, 12]. Nonunions are frequently related to the accuracy of the osteotomies performed at the host-allograft junctions. Virtual planning of the cuts and intraoperative navigation during the procedure may increase accuracy of the fitting of the host-donor junctions and application of the preplanned fixation. Lall et al. [9] analyzed 32 samples to quantify average surface contact areas across simulated intraoperative osteotomies using both freehand and computer-assisted navigation techniques. Mean contact area using the freehand osteotomy technique

was equal to 0.21 square inches. Compared with a control of 0.69 square inches, average contact area was found to be 30.5% of optimal surface contact. Mean contact area using computer-assisted navigation was equal to 0.33 square inches. Compared with a control of 0.76 square inches, average contact area was found to be 43.7% of optimal surface contact. They concluded that an increase in contact area using computer-assisted navigation may improve rates of bone healing, as we found in our study.

Although navigation procedures demand time during surgery, they allow the surgeon to transfer information from preoperative CT and MRI scans to the operating room. We were able to use navigation in all but three of our cases and found that navigation system achieved accurate osteotomy placement for bone tumor resection allowing adequate margins. Our findings need to be confirmed in other studies because we have no comparison group and our methods in the operating room and planning likely differ from other centers, but if confirmed by others, this technology might be beneficial in selected tumor resection such as multiplanar and transepiphyseal osteotomies and reconstruction situations.

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