Techniques in surgical navigation of extremity tumors: state of the art

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Abstract Image-guided surgical navigation allows the orthopedic oncologist to perform adequate tumor resection based on fused images (CT, MRI, PET). Although surgical navigation was first performed in spine and pelvis, recent reports have described the use of this technique in bone tumors located in the extremities. In long bones, this technique has moved from localization or percutaneous resection of benign tumors to complex bone tumor resections and guided reconstructions (allograft or endoprostheses). In recent years, the reported series have increased from small numbers (5 to 16 patients) to larger ones (up to 130 patients). The purpose of this paper is to review recent reports regarding surgical navigation in the extremities, describing the results obtained with different kind of reconstructions when navigation is used and how the previously described problems were solved.

Keywords Navigation · Orthopedic oncology · Extremities · Bone tumors · Limb salvage

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Introduction

Surgical navigation in orthopedic oncology has evolved since the first report in 2004 [1]. The potential benefits shown in the first series that were mainly in spine and pelvic tumors had encouraged us to use this technique in extremity bone tumors [2–5]. Although, long follow-up is not available yet, due to the continued development and improvement of this technique, larger series were described in recent years that allow one to compare results in specific locations and different type of reconstructions [6•, 7, 8, 9•, 10•]. The aim of the review was to analyze the current state of navigation assistance in orthopedic oncology extremity surgeries and assess how the most common limitations that occur with this technology were solved.

Current surgical procedures performed with navigation

Intralesional resection

Surgical navigation to performed intralesional resection has been reported in numerous papers [2–5, 6•, 11]. It is often beneficial to start using navigation in cases that do not require en bloc resection to allow the surgeon to gain more experience before attempting a more challenging case. It is useful for minimally invasive approaches or to localize small lesions [11]. Gerbers et al. [6•] reported the largest series of computer-assisted surgery in orthopedic oncology that includes 130 cases. In this series, intralesional resection for benign and low-grade malignant tumors was used in 63 patients and low-grade chondrosarcoma was the most common diagnosis (43 patients). There were three navigation failures in this series,

so 60 procedures were completed. Regarding the 43 patients with diagnosis of chondrosarcoma, they had one local recurrence and one patient showed residual tumor. The median surgical time in the 43 patients with intralesional resection for low-grade chondrosarcoma with surgical navigation was 1 h and 26 min that was similar with the median surgical time (1 h and 24 min) in intralesional resection in 88 patients with the same diagnosis without surgical navigation.

Treatment of locally aggressive bone tumors is a challenge between achieving ideal local tumor control and satisfactory recurrence rates, with acceptable surgical morbidity and durable function. Intralesional curettage, with or without adjuvant therapy, implies higher risk of local recurrence. Wide resection showed lower local recurrence, but at the cost of reconstruction problems and complications that the benign nature of these lesions would not justify. This dilemma is seen especially in cases where lesions are either meta or epiphyseal, and surgery may compromise the joint integrity and stability representing a surgical challenge as no joint replacement can function identically to the original joint. Computer-assisted tumor surgery is expected to minimize unnecessary resection of bone, preserve maximum function, and achieve good oncological and functional results. Further clarification is needed to identify the ideal candidate for en bloc resection using surgical navigation vs intralesional resection with surgical navigation.

Extraskeletal resection

Articular resections and endoprostheses reconstruction

Cheong et al. [4] reported 20 patients undergoing orthopedic oncology surgery using surgical navigation that included resection and reconstruction with endoprostheses in the majority of the cases. Regarding the reconstructive procedure, they were able to minimize leg length discrepancies, improve restoration of the joint line, and address rotational concerns of implant alignment. Young et al. [10•] used computer navigation to reconstruct the bony defect in eight of the 18 patients analyzed. The reconstruction was radiologically accurate in terms of rotation and limb length. There have been reports of the use of surgical navigation in tumor resection and reconstruction with custom prostheses, but those cases were in joint sparing procedures [12•].

Articular resections and osteoarticular allograft reconstruction

Preoperative navigation and surgical navigation is of great utility during osteoarticular allograft reconstruction. Osteoarticular allograft can be chosen in the preoperative

setting to increase the anatomic match. Surgical navigation can be used to assist both tumor resection and also limb reconstruction by optimizing the osteotomies in the remaining native bone and allograft bone. This has the potential advantage of decreasing nonunions at the osteotomy sites [13•]. Wu et al. [14] report 14 patients of whom 12 had tumors in the extremities. In these patients, they choose the allograft in a three-dimensional virtual bone bank system for selecting the allograft, and they use surgical navigation to cut the patient and the allograft osteotomies. They reported that selection time was reduced and matching accuracy was increased. After 27.5 months of follow-up, the mean musculoskeletal tumor society (MSTS) score was 25.7 points. The same technique was described in other report [9•] that from a total number of 69 patients, 18 were osteoarticular allografts (5 unicondylar and 13 bicondylar); however, they did not analyze the results in the osteoarticular allograft independently. Although, these results are promising, longer follow-up is necessary.

Articular resections and allograft prosthetic composite reconstruction

Fan et al. [15] report a series of 12 patients who underwent unicondylar allograft prosthesis composite after unicondylar resection for tumors with surgical navigation. Although they used surgical navigation to remove the tumor, they did not use this method to cut the allograft. The average MSTS score at last follow-up was 27 points; however, they had three failures in their series. Aponte-Tinco et al. [9•] reported only four APC reconstruction failure from a total of 69 reconstructions performed with surgical navigation assistance, but they were not analyzed independently.

Transepiphyseal osteotomies and intercalary reconstructions

Transepiphyseal osteotomies with joint preservation help to maintain normal joint kinematics and reduce complications associated with osteoarticular allografts or endoprostheses; however, they are technically demanding and difficult to reproduce the planned osteotomy without the assistance of navigation. Intercalary reconstructions with custom endoprostheses [12•] or allografts [6•, 10•, 16•, 17] have been described with the use of this technology; custom prostheses could be designed preoperatively and allograft could be selected and cut with the assistance of navigation.

Wong et al. [12•] described their experience in eight patients who underwent joint-preserving tumor resection and reconstruction using computer navigation. In six cases, based on preoperative studies, a custom-made joint-preserving prosthesis was designed and manufactured; and in all these cases, the bone resections matched the prosthetic template leading to less than 2 mm of error in

any dimension. There were no local recurrences with a mean MSTS score of 29.1 points (range 28–30).

Li et al. [16•] reported six cases of transepiphyseal osteotomy out of a series of nine cases of surgical navigation. These patients were reconstructed with a combined intercalary allograft with vascularized fibular graft; however, reconstruction was not performed with surgical navigation. The mean MSTS score for the nine patients was 26.7 points, while for the six patients with preservation of the articular surface was 28.3 points.

The same authors [17] performed surgical navigation on six patients with proximal humeral sarcomas in order to achieve a clear surgical margin while preserving the humeral head and rotator cuff. All tumors were removed en bloc and intercalary defects were reconstructed by a combination of allograft and vascularized fibula graft. No patient experienced local recurrence. With a MSTS score was 27.6 points. They concluded that with careful patient selection, image-guided surgical navigation made it possible to excise the bone exactly as seen in orientation in magnetic resonance imaging (MRI) image, yielding a clear margin and preserving all or part of the humeral head.

Multiplanar or irregular osteotomies

Multiplanar or irregular osteotomies for bone tumor resections are technically demanding to plan and perform intraoperatively [18]. Intraoperative navigation allows a view of the tumor in the bone that allows the surgeon to perform these complex osteotomies with accuracy. Li et al. [19] reported six patients with juxtaarticular osteosarcomas of the long bones in which planed irregular osteotomies under image-guided navigation was employed. They reported clear margins in all case with no evidence of local recurrence at a minimum of 2 years of follow-up. The authors used irregular osteotomies to preserve host bone and important soft tissue attachments which would be sacrificed if a standard transverse osteotomy was used. However, they remarked that they had an unsolved problem for reconstruction which is how to shape the allograft to match the defect. One year later, another report [20] described five patients with low-grade chondrosarcoma of the knee in which multiplanar osteotomies were performed for resection. In all cases, after the tumor was resected, a second navigation was performed in the allograft selected previously. The authors chose similar bone allograft from the bone bank based on three-dimensional models of the allograft bone created using MIMICS. This technique solved the problem of creating osteotomies in the allograft to match the host bone. Gerbers et al. [21] reported a similar technique at the same time in four patients with hemicortical resections. They used intraoperative navigation for these

complex osteotomies for bone tumor resection and the same technique to cut the allograft.

Limitations

In 2012, Saidi [5] described six limitations for the use of surgical navigation—cost, time, education, pediatric specific research, lack of evidence of oncologic benefit, and lack of tracker system validation and standardization of error reporting as it pertains to orthopedic oncology. What has changed in the last several years?

The cost is still a major concern, not only for navigation devices but also for the software used for preoperative planning that differs from the software of the navigation system. However, some groups [9••] share platforms that are used for neurosurgery and maxillofacial surgeons; this reduces the overall cost for the Hospital.

Recent papers described the time used in intraoperative navigation [6••, 9••, 10••]. A recent report [9••] that used navigation for tumor resection and for bone reconstruction in 69 patients with tumors of the extremities described that the mean additional required time was 35 min (range, 18–65 min). This time was defined as that required for fixation of the device in the bone, registration, and marking the osteotomies in both the receptor and the bone allograft with the navigation pointer. Young et al. [10••] in 18 patients with bone tumors in which surgical navigation was used showed a similar mean intraoperative navigation time (30 min) and found that from the fifth patient onward, the mean time was 20 min. The same report described the preoperative planning time that took a mean of 45 min; however, after the fifth patient onwards was 25 min. Gerbers et al. [6••] found that the median surgical time was similar in low-grade chondrosarcomas in which intralesional treatment was performed with the use of surgical navigation in 43 patients (1 h and 26 min) compared with 88 patients that navigation was not performed (1 h and 24 min).

Education is still a major limitation for the use of this technique. Although the software used in most centers is available to others, there is a lack of training courses in navigation to allow surgeons to gain experience. There is a need of this kind of training and to have support in specific cases to avoid failures of the system.

Recent papers have focused on pediatric populations, and they found similar results to that in the adult population. Li et al. [16•] report nine patients with a mean age of 12.6 years in which navigation resection was used with an average MSTS score of 26.7. They did not find any complications regarding smaller patient size or immature anatomical characteristic such as an open physis.

Regarding oncologic benefit, there is still a short period of follow-up in extremity navigation to analyze this

data. However, Jeys et al. [22] reported in pelvic tumors resected with surgical navigation, a lower incidence of local recurrence in patients operated with this technology. Moreover, when assessing reconstructive surgery in limb salvage, recent papers described the benefits of surgical navigation. Lall et al. [13•] quantified average surface contact areas across simulated intraoperative osteotomies using both free-hand and computer-assisted navigation techniques. They found that the mean contact area using free-hand osteotomy technique was equal to 0.21 in.². Compared with a control of 0.69 in.², 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 in.². Compared with a control of 0.76 in.², average contact area was found to be 43.7 % of optimal surface contact. They considered that using computer-assisted navigation may improve rates of bone healing. In a recent report [9••] of 69 patients in which this technique was used, the nonunion rate was low (6 %) corroborating the previous authors conclusion.

Regarding the last limitation, Milano et al. [23••] analyzed the accuracy and precision of the transfer of a planar osteotomy described in a virtual scenario to the anatomy of the patient during an operation. The error never exceeded 0.73 mm, which is in the order of magnitude of the CT scan resolution.

Conclusions

Preoperative planning and its application in the operative room through surgical navigation has spread around different orthopedic oncology centers. However, these developments were based on individual enthusiastic physicians and engineers, trying to adapt or modify hardware and software utilized for other purposes. Although some orthopedic companies, based on the work of these physicians and engineers, improved the navigation systems, they did not give support in the operating room or for the preoperative planning. Based on this, future developments should focus to facilitate and simplify the software to make it more user friendly and to improve the technical support offered to the surgeon both preoperatively and intraoperatively. Surgical navigation continues to evolve and, with improved software and support, will likely become more commonly used in orthopedic oncology.

Compliance with Ethics Guidelines

Conflict of Interest Dr. Aponte-Tinao has received consultant fees from Stryker Orthopedics. Dr. Ritacco, Dr. Milano, Dr. Ayerza, and Dr. Farfalli have nothing to disclose.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors

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