Computer navigation-aided joint-preserving resection and custom-made endoprosthesis reconstruction for bone sarcomas: long-term outcomes

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Abstract

Background: Computed tomography (CT) and magnetic resonance imaging (MRI) data can be fused to identify the tumor boundaries. This enables surgeons to set close but tumor-free surgical margins and excise the tumor more precisely. This study aimed to report our experience in performing computer navigation-aided joint-preserving resection and custom-made endoprosthesis reconstruction to treat bone sarcoma in the diaphysis and metaphysis of the femur and tibia.

Methods: Between September 2008 and December 2015, 24 patients with bone sarcomas underwent surgical resection and joint-sparing reconstruction under image-guided computer navigation. The cohort comprised 16 males and eight females with a median age of 19.5 years (range: 12–48 years). The tumor location was the femoral diaphysis in three patients, distal femur in 19, and proximal tibia in two. The tumors were osteosarcoma ($n = 15$), chondrosarcoma ($n = 3$), Ewing sarcoma ($n = 3$), and other sarcomas ($n = 3$). We created a pre-operative plan for each patient using navigation system software and performed navigation-aided resection before reconstructing the defect with a custom-made prosthesis with extracortical plate fixation.

Results: Pathological examination verified that all resected specimens had appropriate surgical margins. The median distance from the tumor resection margin to the joint was 30 mm (range: 13–80 mm). The median follow-up duration was 62.5 months (range: 24–134 months). Of the 24 patients, 21 remain disease free, one is alive with disease, and two died of the disease. One patient developed local recurrence. Complications requiring additional surgical procedures occurred in six patients, including one with wound hematoma, one with delayed wound healing, one with superficial infection, one with deep infection, and two with mechanical failure of the prosthesis. The mean Musculoskeletal Tumor Society score at the final follow-up was 91% (range: 80%–100%). The 5- and 10-year implant survival rates were 91.3% and 79.9%, respectively.

Conclusions: Computer navigation-aided joint-preserving resection and custom-made endoprosthesis reconstruction with extracortical plate fixation is a reliable surgical treatment option for bone sarcoma in the diaphysis and metaphysis of the femur and tibia.

Keywords: Bone sarcoma; Computer-assisted navigation; Joint-preserving resection; Custom-made endoprosthesis

Introduction

Segmental resection and endoprosthesis reconstruction is commonly performed to treat sarcomas in long tubular bones.[1-3] When the sarcoma involves the metaphysis, the joint usually needs to be excised together with the tumor to achieve oncologically safe margins. Advancements in imaging technology and chemotherapy, especially the development of magnetic resonance imaging (MRI), have enabled the clear identification of tumor boundaries; this has made it possible to excise the tumor via trans-metaphysis osteotomy and spare the joint, which may result in a better functional outcome. To achieve this joint-sparing osteotomy, surgeons need to perform a precise excision. However, when the residual host bone is short, it is extremely challenging to reconstruct the defect.[4,5]

With the assistance of computer navigation, computed tomography (CT) and MRI data can be fused to identify the tumor boundaries. This enables surgeons to set close but tumor-free surgical margins and excise the tumor more precisely. This technology has been successfully used in complex sites, such as the spine, sacrum, and pelvis.[4,6-9]

In our institution, computer navigation technology is applied in joint-sparing resections for bone sarcomas located in the diaphysis and metaphysis of the femur and tibia. For each patient, we design a custom-made endoprosthesis with an extracortical plate to ensure secure fixation to the remaining host bone. This study aimed to evaluate the long-term results of these treatments in our center, including the oncologic outcomes, post-operative functions, and complications.

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Methods

Between September 2008 and December 2015, a total of 24 patients underwent computer-aided joint-sparing resection and custom-made prosthesis reconstruction in our department. We identified and retrospectively reviewed the records of these patients in our database. All patients provided written informed consent for study inclusion. The patients' clinical characteristics are summarized in Table 1. The median distance from the tumor to the knee joint was 59.5 mm (range: 31.0–89.5 mm).

The diagnosis in each case was made following a multidisciplinary discussion. All patients underwent clinical examination and pre-operative imaging for staging, including plain radiography, contrast CT and MRI, and technetium (TC) -99 bone scans. Core needle biopsies were performed, and the diagnosis was confirmed by senior pathologists. Patients with osteosarcoma and Ewing sarcoma received neoadjuvant chemotherapy in accordance with current international protocols. The response to neoadjuvant chemotherapy was evaluated by oncologists. The chemotherapeutic strategies achieved a good response in all cases.

All tumors were excised with the aim of achieving wide margins. Patients were selected for joint-preserving resection and custom-made endoprosthesis reconstruction if they had a residual host bone of at least 10 mm for a tibial tumor and 30 mm for a femoral tumor, as these were the minimum residual bone lengths enabling adequate fixation [Figure 1].

Radiographic data in the digital imaging and communications in medicine format of the pre-operative axial CT and MRI were imported into a CT-based navigation system workstation (CT Spine, version 1.2; Stryker Navigation, Freiburg, Germany). The tumor and its boundaries were identified on each axial CT and MR image. The CT and MR images were fused using navigation software to generate a three-dimensional model of the tumor. The software was used to set the osteotomy line using a virtual lane or screws at a distance of at least 10 mm from the tumor edge [Figure 2].

CT data were used to build a three-dimensional bone model using specific software (Mimics®; Materialise,

Table 1: Clinical characteristics of patients who underwent computer-aided joint-sparing resection and custom-made prosthesis reconstruction ($n = 24$).

Characteristics	Values
Median age, years	19.5 (12–48)
Gender	
Male	16
Female	8
Pathological diagnosis	
Conventional osteosarcoma	15
Parosteal osteosarcoma	1
Ewing sarcoma	3
Spindle cell sarcoma	1
Chondrosarcoma	3
Epithelioid haemangioendothelioma	1
Tumor site	
Diaphyseal femur	3
Distal femur	19
Proximal tibia	2
Chemo	18
Surgical margin	
Wide	24
Follow-up	
Continuously disease free	21
Metastasis	3
Alive with disease	1
Dead of disease	2
Median follow-up time, months	62.5 (24–134)

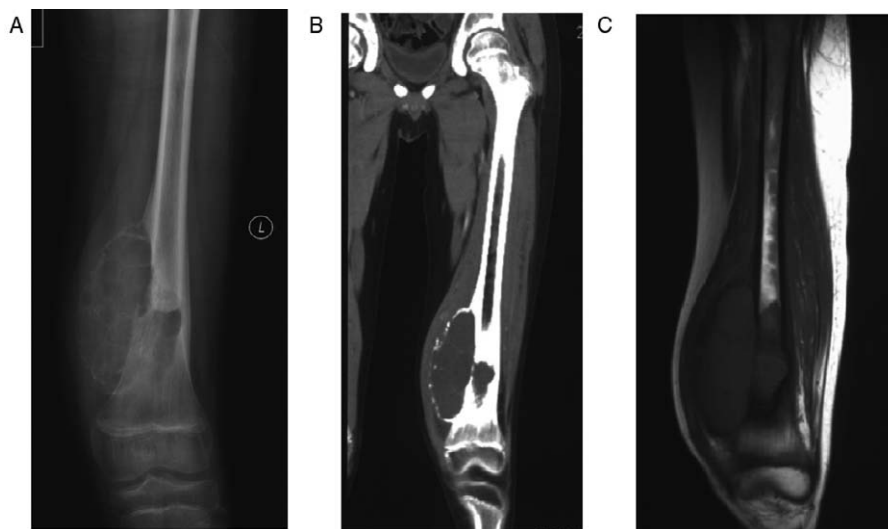Data are presented as n or media (range).

Figure 1: Images of a 13-year-old boy with osteosarcoma. (A) Anteroposterior radiograph, (B) coronal CT image, and (C) coronal T1-weighted MR image. CT: Computed tomography; MR: Magnetic resonance.
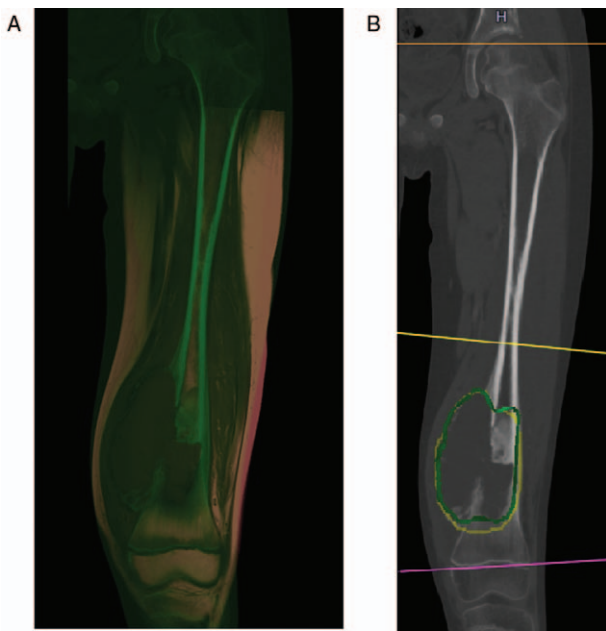
Figure 2: (A) Image created by fusing CT and MRI data. (B) Preoperative plan showing the virtual lane based on fused CT and MRI data in the navigation software. CT: Computed tomography; MRI: Magnetic resonance imaging.
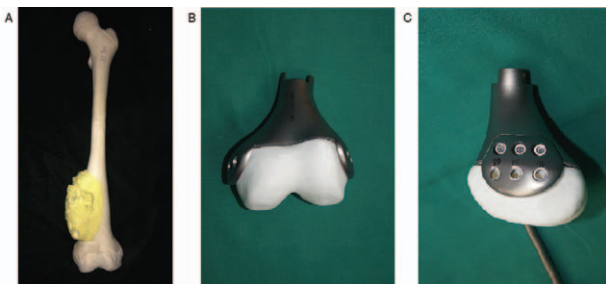

Figure 3: (A) Three-dimensional bone model. (B) Custom-made prosthesis with an extracortical plate (front view). (C) Custom-made prosthesis with an extracortical plate (lateral view).

Leuven, Belgium). The bone model was resected in accordance with the pre-operative plan with the assistance of computer navigation. Based on the model data and the surgical plan, the manufacturer (LDK Co., Ltd., Beijing, China) designed and manufactured a custom-made endoprosthesis with an extracortical plate fixation system [Figure 3].

After routine exposure, we placed the navigation tracker on the normal zone of the bone outside of the segment to be excised. Image-to-patient registration was done via point-to-point registration for one patient. For the other 23 patients, we used an intra-operative ISO-C C-arm (Siremobil Iso-C 3D, Siemens Medical Solutions, Erlangen, Germany) to obtain the data of the surgical field and exported the data to the navigation workstation where we fused the image and the pre-operative CT data with the navigation software to finish the image-to-patient registration; this method removes the need to adequately expose bony landmarks for registration by excising large amounts of soft tissue, which might result in inadequate surgical margins. Computer navigation was used to confirm the correct resection plane in the pre-operative plan before the bone was resected [Figure 4]. For the 21 patients in whom the tumor was confined to the distal femur or proximal tibia, we reconstructed the defect with a custom-made endoprosthesis and used an extracortical plate for fixation to the residual bone; the other end of the prosthesis was fixed with an intramedullary stem and bone cement. For the remaining three patients with a tumor in the proximal or distal femur, we resected most of the femur and reconstructed the hip via bipolar arthroplasty in addition to the insertion of the distal custom-made prosthesis and extracortical plate fixation. For tibial tumors, we used a gastrocnemius muscle flap to cover the anterior side of the prosthesis after the patellar tendon was fixed to the prosthesis.

The specimens were sliced after surgical removal. The specimen length and the distance from the resection margin to the tumor were measured and recorded [Figure 5].
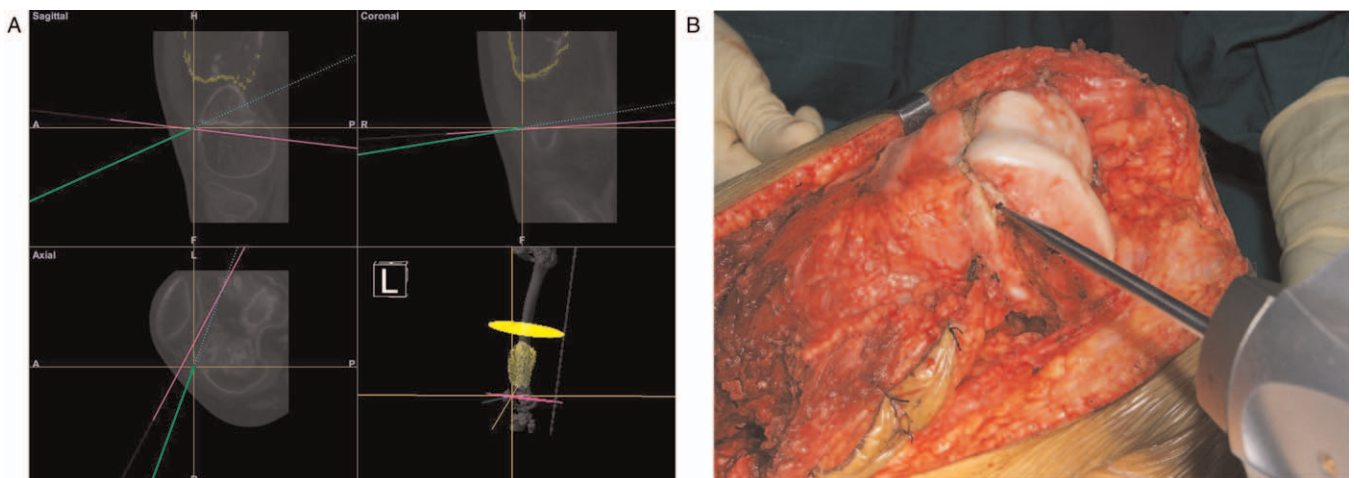

Figure 4: Confirmation of the resection plane with the intraoperative navigation. (A). Photo taken during the operation (B).

Post-operatively, active physiotherapy was started after the drainage was removed. Patients were permitted to begin partial weight-bearing at 3 to 6 weeks post-operatively with the help of crutches for about 3 months and were then encouraged to commence fully weight-bearing. For patients with patellar tendon attachment refixation, a long leg brace was used to keep the knee joint in an extension position for 8 weeks post-operatively; these patients were then allowed to begin to flex the knee joint and commence weight-bearing. Patients with osteosarcoma and Ewing sarcoma continued to receive adjuvant chemotherapy after their wounds healed.

The patients were followed up every 3 months for the first 2 years post-operatively, every 4 to 6 months until 5 years post-operatively, and annually thereafter. Besides clinical examinations and radiographs [Figure 6], we performed ultrasonographic examinations of the surgical site to exclude tumor recurrence in the soft tissue. Chest CT was performed every 3 to 6 months, and bone scanning was performed every 6 months. Patients who could not come to the hospital in person were followed up via telephone

Figure 5: Sliced specimen of the patient with osteosarcoma.

interviews. The Musculoskeletal Tumor Society (MSTS) scores[10] were recorded.

Statistical analysis

Non-parametric tests were used to compare quantitative variables between two groups, with P values of <0.050 considered statistically significant. The Kaplan-Meier survival curve was used to calculate the prosthesis survival rate. The time of prosthesis failure was defined as the time from the primary operation to the date at which revision surgery was suggested for any reason during follow-up. Statistical analyses were performed using SPSS for Windows (version 20.0; SPSS, Chicago, IL, USA).

Results

The operation was completed in accordance with the pre-operative plan in all 24 patients, and all resections achieved adequate margins. The median distance from the bone resection site (near the joint) to the joint was 30 mm (range: 13–80 mm). The median length of the planned resection segment (180 mm; range: 100–390 mm) did not significantly differ from the median specimen length (183 mm; range: 97–403 mm) ($P = 0.626$), and the mean error was 3.12 mm (range: 0–13 mm). The median planned distance from the tumor to the plane of bone resection (30 mm; range: 10–30 mm) did not differ from that of the actual specimens (27.75 mm; range: 9.50–35.00 mm) ($P = 0.794$), and the mean error was 2.09 mm (range: 0–6 mm).

The median follow-up duration for all patients was 62.5 months (range: 24–134 months). Twenty-one patients were continuously disease free during follow-up, while three patients developed lung metastases. One patient with Ewing sarcoma who developed lung metastasis at 50 months post-operatively was still alive at the latest follow-up. The other two patients with lung metastases died after the metastases occurred; in one of these patients with chondrosarcoma, local soft tissue recurrence was detected before the lung metastasis occurred.

Figure 6: Plain radiographs taken 43 months post-operatively.

Table 2: Prosthesis failure classification.

Mechanism of failure	N	Note
Mechanical		
Type 1 (soft tissue failure)	0	
Type 2 (aseptic loosening)	0	
Type 3 (structure failure)	2	Prosthesis stem fracture, screws loosening
Non-mechanical		
Type 4 (infection)	0	
Type 5 (tumor progression)	0	
Total failures	2	

Six complications requiring additional surgery occurred in six patients (25%). The complications included a wound hematoma in one patient, delayed wound healing in one, and superficial wound infection in one; all of these complications healed after debridement. One patient developed a deep wound infection that was successfully treated with the debridement and a local flap. There were two femoral endoprosthesis failures, both of which were structural failures. In one case, the locking screw of the extracortical plate developed loosening at 7 months post-operatively and was revised with a total femoral endoprosthesis. In the other case, the prosthesis failure was associated with the loosening of the implant locking screws at 87 months post-operatively and was revised with a new spacer clamp. The 5- and 10-year implant survival rates were 91.3% and 79.9%, respectively [Table 2].

Twenty-one patients were evaluated for function using the MSTS scoring system at the latest follow-up. The median follow-up duration was 67 months (range: 24–134 months). The mean MSTS score at the final follow-up was 91% (range: 80–100%).

Discussion

Endoprosthesis reconstruction after bone sarcoma resection is commonly performed by orthopedic surgeons. The articular surface is a good natural barrier, and it is easy to determine the cutting edge intra-operatively when excising the tumor and joint together. In contrast, transmetaphysis osteotomy preserves the joint but increases the risk of inappropriate margins. In our study, we measured the resection accuracy by examining the cross section of the removed specimen. Compared with the pre-operative plan, the mean resection length error was 3.12 mm, and the mean error of the distance from the tumor to the resection margin was 2.09 mm. With the assistance of the navigation system, we were able to precisely reproduce the bone resection plan, enabling us to achieve a close but safe bone margin and preserve the maximum amount of normal tissue. The rate of tumor recurrence in our study (4%) was comparable to the rate reported in the literature (0%–4%).[4,5,11,12] It should be noted that the computer navigation itself does not reduce the recurrence rate, as the current navigation technology cannot aid in the resection of soft tissue masses, and the margins of malignant soft tissue tumors still depend on the experience of the surgeon.[13]

The advantages of endoprosthesis reconstruction after bone tumor resection include earlier post-operative weight-bearing and a quick and accurate match of the bone defect, especially with the modular endoprosthesis system. However, these mega-endoprostheses are associated with a high failure rate that may necessitate revision surgery. Henderson et al[1] classified five types of endoprosthesis failure in oncological patients: soft tissue failure (type 1), aseptic loosening (type 2), structure failure (type 3), infection (type 4), and tumor progression (type 5). A retrospective meta-analysis performed in 2019 reported that the aseptic loosening rate of mega-endoprostheses is about 12%, while the structural failure rate is 16%.[3]

The reconstruction with a joint-preserving prosthesis performed in the present study preserves the main structure of the knee joint, as it is essentially an intercalary prosthesis. Although the intercalary prosthesis avoids the need for joint reconstruction, which may avoid some complications such as bushing wear and hinge failure, several studies have showed that intercalary reconstruction carries a high risk of complications. Benevenia et al[11] reported that 57% of femoral reconstructions with an intercalary prosthesis develop implant-related complications (failure types 2–4). Aldlyami et al[14] reported a 10-year prosthesis failure rate of 63% for 35 joint-preserving prosthetic replacements of diaphyseal bone defects after bone tumor resections; the reason for these failures was considered to be the short segment fixation that was necessary to preserve the adjacent joint. Hanna et al[12] reported a 22% failure rate for 16 femoral intercalary prostheses; with the help of an extracortical plate to fix the prosthesis and residual bone, the survival rate of the custom-made prosthesis was 68% at 10 years. More recently, Stevenson et al[15] reported an aseptic loosening rate of 8% and a structural failure rate of 5% at 7 years after joint-preserving endoprosthetic replacement with a short-stemmed prosthesis and an extracortical plate in 37 patients; the authors concluded that the hydroxyapatite-coated extracortical plate increased the stability of the short-stemmed prosthesis.

Our study evaluated a total of 22 femoral implants during a median follow-up of 62.5 months. Of the 24 patients, 2 (9%) had structural failure, while no patient had aseptic loosening. The median length of the residual bone in our series was 30 mm, while the definition of the short stem in the literature is 50 mm.[5] Therefore, for most of our patients, a short-stemmed prosthesis design was not suitable. Although the extracortical plate we used did not have a hydroxyapatite coating, the implant survival rate was 91.3% at 5 years and 79.9% at 10 years. The main reason for these high implant survival rates was the stable fixation of the extracortical plate and residual bone. The key to stable fixation is the precise execution of the pre-operative plan. In each case, the custom-made prosthesis was manufactured based on the surgical plan; the same plan was used to perform the computer-aided resection. This enabled the attainment of the best prosthesis-bone interface match, resulting in a mean error of only 2.09 mm. The screws were also fixed perfectly in accordance with the pre-operative design, which can achieve the fixation of a maximum of six screws in the

residual epiphysis. The long-term follow-up results proved that this immediate fixation was reliable.

The patients in the present series had a mean MSTS score of 91%, which was higher than the reported MSTS score of 77% to 88% in previous studies of joint-sparing resection and intercalary prosthesis reconstruction without computer navigation.[5,12] Wong and Kumta[4] performed computer-aided joint-sparing surgery with a custom-made prosthesis and extracortical plate reconstruction in eight patients. The mean length of the remaining epiphysis was 16.6 mm, and some planned osteotomy lines were irregular to enable the preservation of the maximum amount of normal tissue. The mean MSTS score in this previous study was 97%. The authors suggested that the computer-assisted approach helped achieve this excellent MSTS functional score in patients with a small remaining epiphysis.

Despite its advantages, computer navigation-assisted surgery may increase the operation time and may sometimes result in some complications.[6,9,16] In our study, none of the complications were associated with the use of the navigation system. The incidence of complications in our study was 25%, which is comparable to the complication rates reported in the literature, ranging from 22% to 31%.[12,14]

The present study had some limitations. First, this was a retrospective study with a small sample size and no randomization; there was inevitable selection bias because the computer navigation-aided joint-preserving surgery can only be performed in certain patients. Second, the single-group study design did not allow comparative assessment with other traditional surgery methods; there was no control group of patients who underwent joint-sparing resection and reconstruction without computer navigation.

In conclusion, computer navigation made it possible to achieve precise and safe surgical margins during joint-sparing resection. The custom-made prosthesis and extracortical plate fixation based on the same surgical plan enabled the patients to obtain good function post-operatively. Future research is required to evaluate whether the extracortical plate can achieve reliable fixation when the remaining epiphysis of the femur is <30 mm after joint-sparing resection.

Conflicts of interest

None.

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