Computer-assisted Tumor Surgery in Malignant Bone Tumors

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Abstract

Background Small recent case series using CT-based navigation suggest such approaches may aid in surgical planning and improve accuracy of intended resections, but the accuracy and clinical use have not been confirmed.

Questions/purposes We therefore evaluated (1) the accuracy; (2) recurrences; and (3) function in patients treated by computer-assisted tumor surgery (CATS).

Methods From 2006 to 2009, we performed CATS in 20 patients with 21 malignant tumors. The mean age was 31 years (range, 6–80 years). CT and MR images for 18 cases were fused using the navigation software. Reconstructed two-dimensional/three-dimensional images were used to plan the bone resection. The achieved bone resection was compared with the planned one by assessing margins, dimensions at the level of bone resection, or fitting of CAD custom prostheses. Function was assessed with the Musculoskeletal Tumor Society (MSTS) score. The minimum followup was 31 months (mean, 39 months; range, 5–69 months).

Results Histological examination of all resected specimens showed a clear tumor margin. The achieved bone resection matched the planned with a difference of ≤ 2 mm. The achieved positions of custom prostheses were comparable to the planned positions when merging postoperative with preoperative CT images in five cases. Three of the four patients with local recurrence had tumors at the sacral region. The mean MSTS score was 28 (range, 23–30).

Conclusion CATS with image fusion allows accurate execution of the intended bone resection. It may be beneficial to resection and reconstruction in pelvic, sacral tumors and more difficult joint-preserving intercalated tumor surgery. Comparative clinical studies with long-term followup are necessary to confirm its efficacy.

Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Although primarily developed for neurosurgical applications, computer-assisted intraoperative navigation has gained popularity and has been used effectively in orthopaedic trauma, spinal procedures, and joint arthroplasty [1, 13, 15, 21, 26]. An extended application of computer navigation-assisted resection in pelvic and sacral tumors was first described in 2004 [18, 20]. Small case series using CT-based navigation have recently been reported [5, 6] and suggest that incorporating computer navigation may aid in accurate intraoperative identification of tumor extent and facilitate bone resections with clear surgical margins in musculoskeletal tumor surgery.

Another advance has been the fusing CT and MR images with their complementary information [27]. The fusion image, when combined with surgical navigation, helps

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surgeons reproduce a preoperative plan reliably and may improve identification of margins on planned resections and avoid removing unnecessary bone in musculoskeletal tumor surgery [27].

We previously reported two case series in five and 13 patients with musculoskeletal tumors undergoing image fusion and computer-assisted tumor resection [27, 28]. Our observations suggested the use of a navigation system may enable the integration of preoperative information about local anatomy and extent of the tumor so that it may help identify resection margins accurately at surgery. It may facilitate tumor resections at complex anatomical regions that would otherwise have been difficult to achieve and also allowed accurate fitting of custom-made prostheses. However, these reports included only small numbers of patients with short followup.

We therefore investigated the results of computer-assisted tumor surgery (CATS) in malignant bone tumors by evaluating (1) the accuracy of computer-assisted bone resection by comparing the achieved resection with the planned one and by tumor margins; (2) recurrences; (3) function; and (4) complications.

Patients and Methods

We studied 20 patients with 21 malignant musculoskeletal tumors who underwent CATS from March 2006 to July 2009 (Table 1). A commercially available CT-based spine navigation system (CT spine, Version 1.6; Stryker Navigation, Freiburg, Germany) was used in all patients. Indications for the technique included anticipated difficulties in achieving an accurate tumor resection in affected bone with complex anatomy or the need for precision in making a satisfactory resection plane to accommodate a custom prosthesis. During the study period we operated on a total of 38 patients with 39 malignant musculoskeletal tumors (seven pelvis, five sacrum, 20 femur, two tibia, and five humerus). Of the 20 patients, 11 were males, nine were females, and the mean age was 31 years at the time of surgery (range, 6–80 years). Seven tumors were located in the pelvis, five sacrum, seven femur, one tibia, and one humerus. The diagnosis was primary bone sarcoma in 18 and solitary metastatic carcinoma in three. Neoadjuvant and adjuvant chemotherapy was given in seven. The minimum followup was 31 months (average, 39 months; range, 5–69 months). We did not exclude any patient and none was lost to followup in this series. No patients were recalled specifically for this study; all data were obtained from medical records and imaging.

We applied the technique of CATS at preoperative, intraoperative, and postoperative stages (Fig. 1). We first performed preoperative CT and MR examination of each

patient. Axial CT slices of 0.0625 mm or 1.25 mm thickness and various sequences of MR images in Digital Imaging and Communications in Medicine (DICOM) format were obtained. We then reformatted the imported image data sets into axial, coronal, and sagittal views in the navigation system. CT and MR images were fused using the navigation software in 18 cases (Table 2; Fig. 2). A navigation system (CT spine, Version 1.6; Stryker Navigation) was used for image fusion in the first eight patients, whereas a more advanced navigation system (iNtelleCt Cranial, Version 1.1; Stryker Navigation) was used for the rest. The cranial navigation software allowed automatic fusion of various image data sets regardless of imaging modalities and scan orientation. Positron emission tomographic images were also incorporated into the CT-MR-fused images for Patients 11 and 13 who had local recurrence after previous surgery and radiotherapy. Subsequent surgical planning of the fused image data sets was performed in the CT spine navigation system. We created a three-dimensional bone model by adjusting the contrast level of the CT images. Tumor extent was defined and its volume was extracted from MR images. Because different image data sets shared identical spatial coordinates after image fusion, segmented MR tumor volume was integrated into the CT-reconstructed three-dimensional bone model. We generated a three-dimensional bone tumor model. All the reconstructed two-dimensional and three-dimensional images were then used for preoperative surgical planning. We defined the plane of bone resection and marked it using multiple virtual screws sited along the margin of the planned resection. We also used the computer-aided design (CAD) data of custom-made prostheses provided by the manufacturer (Stanmore Implants, London, UK) in assisting the navigation resection planning for 10 cases (Fig. 3).

By using CAD software, MIMICS (Materialise's Interactive Medical Image Control System; Materialise, Ann Arbor, MI, USA), the CAD prosthesis in CAD data format was converted to DICOM format that was imported directly into a CT-based navigation system (CT spine, Version 1.6; Stryker Navigation) for resection planning in Patients 16 and 20 (Fig. 4). Because the CAD prosthesis could be seen in the navigation planning, virtual pedicle screws were placed along the plane of planned bone resection.

At the actual surgery, we attached a dynamic reference tracker to the bone in which the tumor was located. An image-to-patient registration to match precisely the operative anatomy and preoperative virtual CT images was performed by paired points and surface points matching. Paired points matching was begun by selecting a minimum of four points of the bony surface on the preoperative CT images in the navigation workstation. A navigation probe was then used to touch the real anatomical points that

Table 1. Demographic data of 21 cases operated with CATS

Case number	Age (years)/sex	Diagnosis	Location	Surgery	Bone reconstruction
1	47/M	Metastatic rectal carcinoma	Left acetabulum	PII resection	Custom pelvic prosthesis
2	41/F	Metastatic uterine carcinoma	Right acetabulum	P(II + III) resection	Custom pelvic prosthesis
3	48/M	Recurrent chordoma	Sacrum (S3 below)	Partial sacrectomy	No
4	46/F	Parosteal osteosarcoma	Left proximal tibia (posterior aspect)	Joint-saving resection	Vascularized fibular graft
5	42/F	Metastatic uterine carcinoma	Left ischial tuberosity	Local resection	No
6	24/F	Undifferentiated bone sarcoma	Right proximal femur	Local resection after neoadjuvant chemotherapy	Modular tumor prosthesis
7	14/M	Conventional osteosarcoma	Right femur (from subtrochanteric region to distal physis)	Joint-saving resection after neoadjuvant chemotherapy	Custom tumor prosthesis
8	80/F	Chordoma	Sacrum (below and including S2)	Resection	No
9	6/M	Conventional osteosarcoma	Right distal femur	Joint-saving resection after neoadjuvant chemotherapy	Custom extendable tumor prosthesis
10	8/M	Conventional osteosarcoma	Left distal femur	Joint-saving resection after neoadjuvant chemotherapy	Custom extendable tumor prosthesis
11	50/M	Recurrent chordoma	Left pelvic metastases	PII + III resection	Custom pelvic prosthesis
12	18/M	Conventional osteosarcoma	Sacrum (from S1 to S5)	Total sacrectomy	No
13	17/M	Recurrent malignant nerve sheath tumor	Left sciatic nerve and involving ilium and sacrum	Left hemipelvectomy (PIV resection)	No
14	21/F	Low-grade chondrosarcoma	Left proximal femur	Joint-saving resection	Custom tumor prosthesis
15	16/F	Conventional osteosarcoma	Right ischium and acetabulum	P(II + III) resection	Custom pelvic prosthesis
16	24/M	Parosteal osteosarcoma	Left distal femur	Joint-saving resection	Custom tumor prosthesis
17	41/F	Hemangio-endothelioma	Right ilium	Resection	No
18	55/M	Sacral chordoma	S1 and below	Total sacrectomy	Posterior instrumentation
19	42/M	Sacral chordoma	S3 and S4	Partial sacrectomy	No
20	6/M	Conventional osteosarcoma	Right distal femur	Joint-saving resection after neoadjuvant chemotherapy	Custom extendable tumor prosthesis
21	16/F	Low-grade chondrosarcoma	Left proximal humerus	Joint-saving resection	Bone graft

CATS = computer-assisted tumor surgery; M = male; F = female.

corresponded to those selected in the workstation. The registration was further refined through surface points matching, a process in which multiple points (a minimum of 35) were chosen on the exposed surface of normal bone. The navigation software then matched these clouds of points to the three-dimensional bone model generated from the preoperative CT data. The software calculated the

registration errors that represented the degree of mismatch between the intraoperatively selected points and CT images. The only direct means of verifying the accuracy of the registration was by moving the tip of the navigation probe along the exposed bone surface. Only if there was real-time accurate matching within 1 mm between the operative anatomy and virtual images could we rely on the accuracy

Fig. 1 The workflow of CATS in the study is shown.

of the navigation system to execute the planned bone resection (Fig. 5). The mean registration error was 0.46 mm (range, 0.31–0.8 mm) and real-time accurate matching could be achieved in all cases. We next calibrated the operative instruments (drill, bone burr, or diathermy) mounted with navigation trackers to the navigation system. This allowed real-time tracking of the spatial location of the tip of these instruments in relation to the patient's anatomy on the virtual preoperative images. The anatomic locations of virtual pedicle screws were identified and the intended bone resection level and plane were marked using navigated tools. Because the navigation system did not support a navigated saw or osteotome, the osteotomy was made manually with an oscillating saw or osteotome along the navigated marked resection level. The tumor was removed en bloc. The achieved bone resection was considered accurate if the bone dimensions at the resection plane matched that in navigation planning (Fig. 6) or custom prostheses were fit to the resected bone ends with a difference of ≤ 2 mm on ruler measurement by the authors. Skeletal defects were reconstructed using custom-made pelvic prostheses in four cases, custom-made joint-saving intercalated prostheses in six, a modular proximal femur prosthesis in one, bone graft in two, and no reconstruction in eight cases. Because not all patients agreed with an additional early postoperative CT scan, we obtained postoperative CT images only for Patients 1, 2, 11, 14, and 15 and the achieved positions of custom prostheses were merged with their preoperative navigation plans. We determined the accuracy of CATS in malignant bone tumors by evaluating the accuracy of achieved bone resection by comparing the dimensions at the level of bone resection with their preoperative navigation planning, assessing the fit of the custom prostheses to the remaining bone at the surgery and assessing the histology of resection margins in all resected specimens. We validated only the

dimensions of the proximal-most or distal-most levels of the resections in Patients 3, 4, 8, 12, 13, 18, 19, and 21 because their resection planes were irregular or curved. All tumor resections could be carried out as planned under navigation guidance. The mean time for intraoperative navigation procedures was 30.4 minutes (range, 13–60 minutes).

The resected specimens were sectioned longitudinally with an electric band saw. Serial 5-mm-thick, parallel slabs of the specimens showing the maximal extent of the tumor were obtained. The two largest slabs containing the tumor were further divided and paraffin-embedded into tissue blocks with 2 cm $\times$ 2.5-cm dimensions. Representative blocks were also extensively sampled from the remaining slabs. During such maneuver, the blocks containing the margins of resection (medial, lateral, anterior, posterior, proximal, and distal) were secured. In addition, specific margins of particular concern by the surgeons were carefully taken. All the tissue blocks were examined histologically for the surgical margin. Histologically, surgical margins of the resected specimens were defined according to Enneking [9] as (1) wide in 16 tumors (76%); (2) marginal in five (24%); (3) intralesional (0%); (4) and wide-contaminated (0%) if intraoperatively the tumor was exposed or its pseudocapsule was seen, but further tissue was removed finally achieving a wide margin.

All patients were followed at 1 month, 2 months, every 3 months for 2 years, every 6 months until 5 years, and then annually. At each visit we obtained a Musculoskeletal Tumor Society (MSTS) score [10] in patients with limb salvage surgery. We monitored patients for recurrences by clinical examination and plain radiographs of the operated sites and distant metastases by CT thorax and bone scan annually or whenever patients presented with symptoms suggestive of metastases. We recorded complications and stratified by major and minor [2]. Surgical complications were considered minor if they did not require any surgical treatment and major when they required surgery.

Results

One hundred percent (12) of pelvic and sacral tumors and 33% (nine of 27) of all long bone tumors that required resection were indicated with the CATS technique during the study period. The achieved bone resection matched to the planned with a difference of ≤ 2 mm in those patients who were validated either by comparing the dimensions at the level of bone resection with that in the surgical navigation planning or fitting of custom prostheses to the resected bone ends. Histological examination of all resected specimens showed a clear tumor margin. The achieved positions of

Table 2. Navigation data and clinical outcome of 21 cases operated with CATS

Case number	Preoperative fusion image data sets	Registration error (mm)	Navigation time (minutes)	Function (MSTS score*)	Followup (months)	Complications and outcome
1	CT	0.36	50	25	18	Died of distant metastases 1.5 years postsurgery
2	CT	0.40	35	28	69	CDF, prosthesis infection on long-term antibiotic
3	CT	0.37	13	–	67	Regional and distant metastases
4	CT angiogram and MRI	0.44	40	28	65	CDF
5	CT and MRI	0.37	13	–	65	CDF
6	CT and MRI	0.36	18	29	64	Lung metastasis 5 years postsurgery treated with metastectomy, CDF
7	CT and MRI	0.50	30	30	59	CDF
8	CT and MRI	0.61	35	–	58	Superficial wound infection, CDF
9	CT and MRI	0.41	20	26	5	Died of distant metastases 5 months postsurgery
10	CT and MRI	0.35	15	30	52	CDF
11	CT angiogram, MRI, and PET	0.46	15	23	51	Soft tissue local recurrence 1 year postsurgery
12	CT and MRI	0.59	15		6	Wound infection; died of metastasis postoperative 6 months
13	CT angiogram, MRI, and PET	0.44	30	–	7	Local recurrence 5 months postsurgery and died of distant metastases 7 months postsurgery
14	CT and MRI	0.42	50	28	48	CDF
15	CT and MRI	0.31	30	30	46	CDF
16	CT and MRI	0.34	60	28	42	CDF, loosened femur stem with revision 2.5 years postsurgery
17	CT and MRI	0.59	45	–	40	CDF
18	CT and MRI	0.50	30	–	12	Local recurrence and distal metastases 12 months postsurgery
19	CT and MRI	0.49	45	–	33	CDF
20	CT and MRI	0.80	25	30	32	CDF
21	CT and MRI	0.54	25	30	31	CDF

* Total score is 30; CATS = computer-assisted tumor surgery; MSTS = Musculoskeletal Tumor Society score; CDF = continuous disease-free; PET = positron emission tomography.

custom prostheses were comparable to the planned positions when merging postoperative with preoperative CT images in Patients 1, 2, 11, 14, and 15 (Fig. 7). For Patients 16 and 20, direct data import of CAD custom prostheses into the navigation resection planning enabled accurate osteotomies and precise fit of CAD custom prostheses.

Wide resection margins could be achieved in 16 cases and marginal in the remaining five cases. Local recurrence was noted in four cases and they all had marginal resection.

Three of the four patients with local recurrence had tumors at the sacral region. Three of the four were recurrences of soft tissue tumors. Five patients died of distant metastases and disease progression. One patient had lung metastases at 5 years postsurgery and she was in disease remission after metastectomy.

The mean functional MSTS score in patients with limb salvage surgery was 28 (range, 23–30). All patients (except Patient 11 who had bilateral pelvic prostheses) with

Fig. 2A–D CT/MR/PET images are shown of fusion in the navigation display in Patient 19 with sacral chordoma involving S3 and S4. (A) Reformatted coronal view of CT images was fused with coronal view of T2-weighted MR images. (B) Reformatted sagittal view of CT images was fused with sagittal view of T1-weighted MR images. (C) Axial view of CT images was fused with axial view of PET images. The blue color in the PET image at the sacrum bone represented the tumor with hypermetabolic activities. (D) Anterior view of three-dimensional (3D) reconstruction of sacrum bone. The red structure represented the tumor extent that was determined and

outlined from MR images. After multimodal image fusion, the segmented tumor volume was imported into the sacrum bone to form a 3D bone-tumor model. The two-dimensional reformatted images and the 3D model could be studied in detail and it greatly facilitated the surgical planning of the tumor resection. We resected the sacrum through a posterior approach under navigation guidance. We osteotomized the sacrum through right S2 and left S3 anterior foramina without sacrificing sacroiliac joint and could preserve both S2 and left S3 nerve roots. PET = positron emission tomography.

limb-sparing surgery and prosthetic reconstruction could walk without aids.

We noted two major and two minor complications. A postoperative superficial wound infection developed in Patient 8 with sacral chordoma that resolved with antibiotics, whereas a wound infection in Patient 12 with sacral osteosarcoma required surgical debridement and antibiotics. Patient 3 developed a delayed low-grade

infection of a right custom pelvic prosthesis. The prosthesis was retained with long-term antibiotics. Aseptic loosening of the proximal component of a custom joint-saving prosthesis developed in Patient 16 with distal femur parosteal osteosarcoma. He was subsequently revised at 2.5 years postsurgery with another new component while the joint-saving component was still retained.

Fig. 3A–D CAD custom prostheses are shown. Patient 20, a 6-year-old boy with distal femur osteosarcoma, (A) shows a joint-preserving extendable prosthesis and distal femur remaining epiphysis and (B) depicts the cross-section at the bone-implant junction. The gap between the edge of the prosthesis and the bone epiphysis represents the thickness of the femoral cartilage that could be outlined from the CT-MR fused image. For Patient 15, a 16-year-old girl with pelvic osteosarcoma, (C–D) the surgical planning of PII and PIII resection and fitting of a custom pelvic prosthesis are shown.

Discussion

Conventionally, tumor surgeons analyze two-dimensional imaging information and mentally integrate and formulate a three-dimensional surgical plan. Tumor resection will be difficult with an increase in case complexity and distorted surgical anatomy. Although computer-assisted surgery has been widely used in cranial biopsies and brain tumor resection, only small case series with early experience have been recently reported in the field of orthopaedic oncology [5, 6]. By including more patients with longer followup in the study, we investigated the accuracy and clinical results of CATS in malignant bone tumors with the help of a CT-based navigation system.

This study has a few limitations. First, we had a relatively small group of patients with a heterogeneous group of diagnoses and grades of tumor, so they are not all comparable. However, our intent was to provide information to support the concept of CATS rather than to identify specific indications. Second, we had no control subjects for comparing the likelihood of recurrences or function. Given the relative rarity of these cases and their heterogeneity, it

would be difficult to establish concurrent or well-matched historical controls. Nonetheless, without well-conducted clinical trials with a larger sample size, the benefits of the CATS technique may not be realized. Third, the potential benefits of the CATS technique in improving surgical accuracy may help reduce the risk of local recurrence but may not translate into better patient survival owing to metastatic disease. Fourth, the dimensions of the achieved resection were visually assessed and measured by authors and may be prone to errors. Fifth, a judgment of clear surgical margins is based on sampling of the entire margin in resected specimen and may underestimate the actual incidence of involved margins.

One study investigated the surgical accuracy of an experienced surgeon in performing a pelvic tumor resection with planned 1-cm surgical margins [4]. The authors reported the surgeon could achieve 1-cm surgical margins (± 5 mm) with a probability of only 52%. The difficult pelvic anatomy and its complex geometry might contribute to the inaccuracy. In our study, the achieved bone resection comparable to the planned resection suggested that surgeons might execute their surgical planning with less error under computer navigation and it might improve the accuracy of bone tumor surgery. Our result concurs with the previous studies [5, 6] with regard to the potential benefits of improving accuracy in bone tumor resection with the help of a CT-based navigation system. The studies assess the accuracy of the computer-assisted resection by comparing the proximal and distal resection margin with the navigation planning in only one dimension. The orientation of planned resection was not assessed. It may not be so critical if allograft was used for the bone reconstruction because allograft can still be trimmed to fit the achieved bone defect at surgery. In our study, custom CAD prostheses were used for reconstruction in 10 patients. The planned resections not only required clear surgical margins, but also correct orientation to fit the custom prostheses. We found that the measurement of dimensions at the resection level and fitting of custom prostheses helped assess the accuracy of planned resection with the CATS technique. Also, for five adult patients with custom CAD prostheses (Fig. 7A–E), the accuracy of computer-assisted resections could be further assessed by postoperative CT scans, as similarly described by Ieguchi et al. [19]. In contrast to CT comparison of margin in only one dimension [19], we fused the postoperative CT images with the preoperative ones. The achieved positions of prostheses comparable to the planned positions suggested that CATS may facilitate not only planned resection with clear surgical margins, but also planned reconstruction of custom CAD prostheses.

Four patients developed local recurrence and three were located at the sacral region in our study. The local recurrence rates of 42% to 78% have been reported for sacral

Fig. 4A–D (A) A coronal section of the CT images with incorporation of a CAD prosthesis for Patient 16, a 24-year-old man with right distal femur parosteal osteosarcoma, is shown. By using the CAD software, CAD data of custom prosthesis could be directly imported into the navigation system for planning of bone resection. The central cross represented the virtual marker (pedicle screw in the CT spine navigation software) that marked one of the locations of intended bone resection. (B) A sagittal section of the MR images showed the extent of the tumor. (C) A axial section of CT/MR image fusion at the intended resection of distal femur is shown.

(D) A three-dimensional bone tumor model reconstructed from CT and MR image data sets is shown. The tumor volume was red. A joint-preserving resection with multiplanar osteotomies was planned at the distal femur and intended bone resections were marked with virtual screws. Reprinted with courtesy of Wong KC, Kumta SM, Tse LF, Ng EW, Lee KS. Image fusion for computer assisted tumor surgery (CATS). In: Ukimura O, ed. *Image Fusion*. 2011:373–390. Available at: <http://www.intechopen.com/books/image-fusion/image-fusion-for-computer-assisted-tumor-surgery-cats->. Accessed January 12, 2011.

chordomas [11, 22, 24, 31]. A surgical resection with wide margins has been associated with a 5% to 17% local recurrence rate compared with 71% to 81% when margins were intralesional or marginal [3, 11]. These findings were similar to the four patients with sacral chordoma operated on with the CATS technique in this series. Two patients with wide margins had no local recurrence, whereas the two with marginal margins developed local recurrence. The

higher chance of recurrence in our patients with marginal margins for sacral tumors might also be explained by the nature of the tumor itself; they all had large soft tissue extraosseous tumor extension and two of them were operated on as recurrent cases. These factors have been reported as the additional risk factors for local recurrence [31]. Although CATS could help visualize the preoperative images and plan the surgery, navigation by itself could

Fig. 5A–D For Patient 14, a 21-year-old woman with left proximal femur low-grade chondrosarcoma, navigation images show intraoperative reformatted (A) coronal view (CT-MR fused image), (B) sagittal view (CT image), (C) axial view (CT-MR image), and (D) three-dimensional bone-tumor model. After registration with paired point and surface matching of the proximal femur bone, we

verified the accuracy of the registration by running the tip of the navigation probe on the bone surface. The tip of the navigation probe was exactly at the bone surface on the virtual images. We could then proceed to execute the planned bone resection under navigation because the operative anatomy was real-time matching well with the virtual images.

only assist and guide the bone resection at the surgery. Surgeons still adopted a conventional technique in soft tissue resection. However, two case reports [5, 16] have demonstrated the CATS technique may help in partial sacral resection through a posterior approach by preserving unaffected sacral nerve roots as a result of improved accuracy of bone resection. We also found the CATS technique useful in Patients 3 and 19 in whom we could preserve both S2 nerve roots and Patient 8 with both S1 nerve roots.

The mean MSTS functional score in our patients with limb salvage surgery and extremity tumor endoprosthesis was 93% (28 of 30), which was superior to that described in other long-term studies [12, 23, 25], in which the mean functional score in patients with conventional limb salvage surgery and tumor endoprosthesis was 74% to 79%. We believe that the better functional scores may be related to the joint-saving intercalated tumor resections in six patients that were facilitated with the CATS technique. The preservation of native epiphysis and knee ligaments and

Fig. 6A–B For Patient 11, a 50-year-old man with recurrent chordoma and left pelvic metastases, PII and PIII resection and custom pelvic prosthesis were performed. The dimensions (length *ab* and *cd*) of the achieved bone resection at ilium were measured (**A**).

They were then compared with the corresponding cross-section at the navigation planning (**B**). The difference of the dimension was ≤ 2 mm and the achieved bone resection was considered to be accurate as that planned.

Fig. 7A–E Postoperative CT scans were performed in some patients with CAD custom prostheses. The postoperative CT images were fused with the preoperative CT images to validate the accuracy of

CATS. The achieved positions of prostheses (yellow) were comparable to the planned ones (gray) in Patients 1 (**A**), 2 (**B**), 11 (**C**), 14 (**E**), and 15 (**D**).

accurate fitting of these custom prostheses may allow better early limb functions. Also, the extendable prostheses in the two skeletally immature children (Patients 10 and 20) were serially lengthened to compensate for leg shortening. It remains to be seen whether the CATS technique can achieve better function in long-term followup.

Only four complications were noted in the present study. Two of them were wound infections in sacral resections. The rate of wound complications was 40% (two of five sacral tumors), which was comparable to that of 33% to 45% in previous studies [11, 17, 24] without the CATS technique. The delayed infection of the pelvic

prosthesis in Patient 2 was caused by dental caries. The early aseptic loosening of the proximal femoral stem in Patient 16 was the result of the absence of adequate bone ingrowth on the hydroxyapatite collar at the bone-implant junction. These complications were not related to the CATS technique itself. This finding was consistent with the experience reported by other authors [5, 6, 19] that CATS seems to be a safe technique and we can further evaluate its clinical efficacy in musculoskeletal oncology surgery.

Image-to-patient registration is a critical step in CT-based, image-guided navigation surgery. The registration procedure is responsible for accurate linking of the virtual imaging and planning to the surgical site and is the most important factor influencing the accuracy of image-guided surgery [7, 8, 14]. Paired point-based registration using fiducial markers that are fixed invasively to the surface of the involved bone before surgery and multiple noninvasive skin-point markers have been described as an accurate registration method in computer-assisted tumor surgery [6, 19]. However, the markers must be placed before another dedicated imaging for registration purposes in addition to the diagnostic CT imaging that has been performed during the initial workup of the disease. Also, the markers must be kept in their positions until the registration is completed in the operating room. We adopted a markerless registration method with paired point and surface matching on the diagnostic image data sets with a mean registration error of 0.46 mm. The low registration error only suggested that the subsequent image-based navigation procedure would be reliable and it only contributed little to the final accuracy of intended bone resection in this study. The registration method that is the best and most reliable for CATS in orthopaedic oncology is still controversial and may depend on surgeon preference. Separate studies are needed to better define the accuracy of various registration methods at different anatomical regions in the future.

At the beginning of the study, because the electronic data sets of CAD custom prostheses could not be directly imported into the navigation system for resection planning, we had to transfer electronic measurements from the CAD data sets to the navigation system manually. It is time-consuming and tedious. This may be prone to errors in measurement. Later, by using the commercially available CAD software, we developed the technique of incorporating CAD data sets into navigation system [29, 30]. It was successfully applied to Patients 16 and 20. Their CAD custom prostheses could be seen in the navigation system and it greatly helped the resection planning and reconstruction. We believe that with the new technique, more complex surgical planning simulated in CAD software could be executed under computer navigation in the field of orthopaedic oncology.

Our study suggests CATS with image fusion offers advanced preoperative three-dimensional surgical planning and supports surgeons to accurately execute the intended bone resection in bone tumors. It may be beneficial to resection and reconstruction in pelvic, sacral tumors and more difficult joint-preserving intercalated tumor surgery. Comparative clinical studies with long-term followup are necessary to confirm its efficacy in orthopaedic oncology.

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