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Computer-assisted surgery in orthopedic oncology
Technique, indications, and a descriptive study of 130 cases

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Abstract

Background and purpose:

In orthopaedic oncology, computer-assisted surgery (CAS) can be considered an alternative to fluoroscopy and direct measurement for orientation, planning, and margin control. However, only small case series reporting specific applications have been published. We therefore describe possible applications of CAS and report preliminary results in 130 procedures.

Patients and methods:

We conducted a retrospective cohort study of all oncological CAS procedures in a single institution from November 2006 to March 2013. Mean follow-up time was 32 months. We categorised and analysed 130 procedures for clinical parameters. The categories were image-based intralesional treatment, image-based resection, image-based resection and reconstruction, and imageless resection and reconstruction.

Results:

Application to intralesional treatment showed 1 inadequate curettage and 1 (other) recurrence in 63 cases. Image-based resections in 42 cases showed 40 R0 margins; 16 in 17 pelvic resections. Image-based reconstruction facilitated graft creation with a mean reconstruction accuracy of 0.9 mm in one case. Imageless CAS was helpful in resection planning and length- and joint line reconstruction for tumour prostheses.

Interpretation:

CAS is a promising new development. Preliminary results show a high number of R0 resections and low short-term recurrence rates for curettage.
Introduction

Oncological surgical treatment can be considered to be a trade-off between margins and function, with margins being the most important factor to consider. Accuracy is needed to achieve an efficient but oncologically safe result. To assist in this, most procedures in bone tumour surgery require intraoperative imaging with fluoroscopy and/or measurements with rulers for anatomical orientation and margin control. The best examples of this are pelvic resections. Cartiaux et al. (2008) demonstrated that 4 experienced surgeons could achieve a 10-mm resection margin, with 5-mm tolerance, on pelvic sawbones in only half of the resections. The supportive imaging and measuring modalities have, however, remained more or less unchanged for many years. In a 2-dimensional (2D) workflow such as fluoroscopy, there is still the requirement for an accurate frame of reference based on anatomical landmarks for adequate 3-dimensional (3D) margin control.

In recent years, the use of computer-assisted surgery (CAS) in orthopaedic surgery has become more common as an alternative for intraoperative imaging and measurements, providing the necessary precision in bone tumour surgery. The technique that is mostly used in orthopaedic oncology is image-based navigation. The patient’s own anatomy (MRI and/or CT) is entered into the system and used during surgery. This provides real-time, continuous, 3D imaging feedback and may lead to more precise margin control, better tissue preservation, and new approaches to reconstruction while remaining oncologically safe. Several publications have supported CAS as being a safe navigation platform for planning and performing resections (1-3). A recent publication describes lessons in the technological approach and offers comments on CAS workflow (4). However, to date the largest case series have involved only 20 and 31 cases (5-6). The reported use has mostly been limited to complex tumour resections (e.g. pelvic), and due to the novelty of the technique, applications, approaches, and set-up times differ greatly (7). Here we describe possible applications of CAS in bone tumour surgery (also outside of complex resections), consider their usefulness, and report preliminary results from 130 CAS procedures performed at a single institution.

Patients and methods

We conducted a retrospective cohort study at the University Medical Center Groningen (UMCG) between November 2006 and March 2013. We included all patients with a bone tumour for whom a CAS procedure was planned. The included group was split into a successful CAS procedure group and a CAS set-up failure group. Procedures were regarded as being successful when the CAS set-up was successfully completed and the system was used. If the set-up of the system failed or unsolvable inaccuracies were found during the set-up process, the procedure was
regarded as a CAS set-up failure and the surgery was performed by conventional means. The successful CAS procedures were analysed based on the following outcome parameters: recurrence/residue rate and margins achieved. CAS set-up failures were assessed for cause of failure. These failures were not included in the outcome analysis, as the procedures were performed using conventional methods and the purpose was to analyse the CAS application, not indications.

All CAS procedures were first classified according to the technique used: image-based or imageless. The image-based group was then subdivided into “intra-lesional procedures” (curettages), “resection procedures”, and “resection with reconstruction procedures” (figure 1). The imageless group comprised tumour prosthesis placement around the knee.

![Flow chart showing the decision-making process on CAS use, requirements per technique, and planned procedures per technique. From left to right: intralesional treatment with a navigated curette, image-based resection, image-based resection and reconstruction, and imageless resection and reconstruction.](image)

**Image-based workflow**

The standardised preoperative workflow consisted of a CT-scan of the affected bone, following a CAS protocol. Slice thickness was 1.0–1.5 mm for CT. If required, preoperative planning was performed to pre-plan resection planes and/or reconstruction options. This pre-planning was performed in advance on the planning laptop and often included CT/MRI fusion, tumour colouration, and resection planning.

During a CAS procedure, a patient tracker was rigidly attached to the involved bone of the patient (Figure 2). Image-based navigation was set up by entering
reference points, first in the navigation system and then on landmarks on the bone. The result was a fairly rough matching with moderate accuracy. This was refined using surface matching, where data points were entered with the pointer tool directly on the navigated bone. The software matched this to the bone surface on the CT. Approximate accuracies under 1.5 mm were accepted and a landmark check was performed routinely. If the landmark check failed after multiple set-up attempts, the procedure was considered to be a CAS set-up failure, the navigation was discontinued, and the surgery was performed by conventional means. Set-up time and accuracy were measured using a digital registration system. Postoperative margins were classified by the R classification (8). Clinical follow-up was routinely performed with radiographs and MRI scans. We used the Stryker Navigation System II with OrthoMap 3D software (Stryker, Mahwah, NJ).

**Intralesional treatment**

Intentional intralesional treatment (curettage) was used for benign and low-grade malignant bone tumours such as giant cell tumour (GCT), aneurysmal bone cyst, fibrous dysplasia, and grade-1 chondrosarcoma (CHS-1) (now renamed atypical cartilaginous tumour (ACT)). All CHS-1 lesions were curetted and treated with adjuvant phenol and ethanol. Some lesions were treated with radiofrequency ablation (RFA) beforehand. Most reconstructions were done with PMMA bone cement; some were done with cancellous bone chip: Vitoss (Orthovita, Malvern, PA). Most recent reconstructions were done with Engipore (Finceramica SpA, Faenza, Italy).
not use fluoroscopic control at the end of surgery. Follow-up was standardised, with radiographic controls and a baseline MRI scan 3 months postoperatively. As an indicator of the effect of CAS on surgical time, we documented reported surgical time in the operating room management software for all procedures in the largest homogenous group, CHS-1 intralesional treatment, with either CAS or fluoroscopy, within the inclusion period.

**Image-based resections**

Resection planes were planned before surgery, incorporating the margin required for the specific lesion, and checked intraoperatively. Preoperative planning consisted of CT/MRI image fusion if available, segmentation (colouring) of the tumour and critical structures, depending on tumour type and location. The pointer tool was used before and after each resection to determine and check the resection plane. Planes for the bone saw were sometimes marked with Kirschner wires, placed with navigation, as a guide for plane orientation and angulation. As proof of complete resection, screen shots of the pointer tool or navigated chisel on the planned resection plane behind the tumour were saved on the CAS machine. Every bone resection had a routine postoperative radiographic control and pathological examination.

**Image-based resections and reconstructions**

This procedure was performed for hemi-cortical resections, creating and reconstructing a partial defect and 1 full resection. Preoperative planning consisted of CT/MRI image fusion, digital linking of the host bone CT with the allograft CT, planning of the resection planes (and subsequent reconstruction planes), and entering of special interest points where resection planes intersected other planes or the cortex. Exactly the same resection planes were used for both resection of the tumour and creation of the allograft piece, to create an exact-fitting graft. The reconstructions of these defects were done with allogenic inlay bone grafts, in 1 case combined with a vascularised autograft. The allografts from the bone bank were selected based on matching of the dimensions to the host bone. The planned resection was then performed on the patient bone and subsequently repeated on the allograft bone.

**Imageless workflow and imageless resection and reconstruction**

Imageless workflow comprised a normal imageless knee set-up, with trackers on the femur and tibia. The imageless system provided accurate measurements of length and rotation. The software used in these cases was Precision Knee Navigation on
the same navigation system. All imageless cases were performed on or around the knee joint. The resection length was identified by CAS using the pointer tool. Joint line reconstruction, length-checking, and rotation were done with the normal imageless prosthesis-placement checking tools. We used a modular GSMS/MRH tumour prosthesis (Stryker) in all cases.

**Results**

The most performed procedure was grade-1 chondrosarcoma curettage (Table). The "reactive lesions" group contained cases where the surgery was performed by oncological principles but the pathological diagnosis was not a tumour. Most CAS procedures were done for a lesion in the femur (68 of 130). Figure 3 demonstrated the anatomical distribution. Mean follow-up time was 32 (4–80) months.

**Intralesional treatment**

CAS was used as an alternative to fluoroscopy in 60 procedures (Figure 4). The mean follow-up time was 25 (4–68) months. Most procedures were done for CHS-1. In 1 case of CHS-1 of the humerus, the postoperative radiographic control showed residual tumour. This was confirmed by biopsy and was treated with radiofrequency ablation (RFA). There was 1 recurrence of a CHS-1, 15 months after primary treatment. A biopsy showed vital tumour tissue and no dedifferentiation, and the lesion was treated with RFA. 43 CHS-1 patients were treated using CAS. This resulted in a recurrence rate of 1 in 43 for this group, at a mean follow-up time of 24 (7–61) months. There were 4 pathological fractures, all of which were treated and healed with internal fixation. Median surgical time was similar in the 2 groups: it was 1 hour and 24 min (0:54–3:10) in 88 non-CAS CHS-1 intralesional treatment procedures and it was 1 hour and 26 min (0:37–2:25) in the 43 CAS procedures (p = 0.7).

**Image-based resection**

There were 43 CAS procedures with a mean follow-up time of 39 (5–80) months. 40 of 43 procedures were classified as R0 resections; 1 CHS grade-2 periacetabular resection had R1 margins due to a compromised soft-tissue margin, 1 CHS grade-1B proximal tibia had R1 margins due to a compromised bone margin, and 1 pelvic CHS grade-2A had an R2 resection—also due to compromised bone margins. The patient with peripheral CHS-1 of the fibula with inadequate bone margins (R1) had a re-resection, but it did not show residual tumour, and the patient is disease-free 6 years after surgery.
6 of 17 pelvic resections were performed for high-grade tumours. 2 of 4 Enneking type-2/3 resections (9), 1 of 1 type-1/2/3 hemipelvectomy, and 1 of 1 type-2 resection had R0 margins. 1 of 2 type-2/3 resections had a soft-tissue R1 resection as described above. All others, except 1 type-3 resection for a large osteochondroma, were partial resections. All had R0 margins.

There were 4 local recurrences: pelvic chondrosarcoma grade-2 (2 resections, R2 and R0), pelvic CHS grade-3 (1 resection, R0) and osteosarcoma of the femur (1 resection, R0). 3 patients—all of whom had local recurrence and dedifferentiation—died of disease, pelvic CHS grade 2 (2 patients), and pelvic CHS grade 3 (1 patient). In these 3 patients, dedifferentiation of the tumour was found in the biopsy of the local recurrence.

Joint-sparing procedures were performed using CAS, for example using a modified Enneking 2/3 acetabulum-sparing resection in a case of grade-2 chondrosarcoma of the pelvis (Figure 5).
Fig 3 (left): Illustration of the bone localisations of the CAS cases. Based on Patrick J. Lynch, medical illustrator; C. Carl Jaffe, MD, cardiologist; “Human skeleton diagrams, lateral and anterior views” via Wikimedia Commons, Creative Commons Attribution 2.5.

Fig 4 (right): A screenshot acquired on the CAS system during curettage. Patient information is digitally edited out. The case is a 31-year-old patient with fibrous dysplasia of the femoral head. The location was such that there was a risk of damaging the cartilage on the femoral head during curettage, potentially invalidating the patient. The cavity was filled with PMMA. Weight bearing was 50% in the first 6 weeks, gradually increasing to full in the subsequent 6 weeks.

**Image-based resection and image-based reconstruction**

4 adamantinoma cases were treated with hemicortical resections and 1 Ewing sarcoma was treated with a segmental resection and solid allograft bone reconstruction. Mean follow-up time was 20 (10–33) months. The mean length of reconstruction for the hemicortical cases was 8 (6–9) cm, for the segmental reconstruction case it was 19 cm. In 3 of 4 hemicortical cases, half or more of the bone circumference was affected by the tumour. A CT-scan of 1 case showed a mean gap between host and allograft of 0.9 (0–5.4) mm along the 6-cm resection (Figure 6) (10). All margins were classified as R0. There was 1 local recurrence in an adamantinoma, after an R0 resection with adequate margin, located in the soft-tissue resection plane. There were no complications.

**Imageless resection and reconstruction**

There were 14 procedures with a mean follow-up of 41 (8–60) months. The CAS group comprised 10 osteosarcomas, 2 metastases, and 2 tumour prosthetic placements in non-union or allograft failure after earlier tumour surgery. All tumour resections were reported as R0 resections. The 10 osteosarcomas could be subdivided using MSTS classification into: IA (1), IB (1), IIB (6), and III (2). There were 2 local recurrences—R0 resections—both of osteosarcomas of the femur with MSTS classifications IIB and III. 1 patient with local recurrence had a re-resection
and is disease-free. The other patient was treated with hip ex-articulation but died of metastatic disease. 1 osteosarcoma patient had proven lung metastasis at the time of surgery and had a local recurrence 1 year later. Figure 7 demonstrates a rotation and joint line check.

**CAS failures**

There were 8 failures, including 3 set-up failures for intralesional treatment CAS procedures; these were due to matching error, software failure, and loss of match after set-up. 3 failures in image-based resections were due to to software failure, matching error, or loss of match after set-up on the before-first-use accuracy check. These last 2 failures were both in the ulna and were considered to be due to unstable fixation in this small bone, which was detected during the set-up phase. There were 2 failures in imageless CAS mode for tumour prosthesis placement due to tracker issues: 1 due to loss of accuracy on check because of instability caused by a preoperative pathological fracture and 1 where it proved impossible to place the trackers inside the software-defined work field.

**System use**

There were no direct complications and no morbidity related to use of the CAS system. There were no fractures or infections due to the pin placement. All software-reported accuracies were between 0.3 mm and 1.2 mm. Set-up time was measured in the last 47 cases. Mean set-up time was 6.5 (2.3–14) min.

**Discussion**

Intralesional treatment is currently the standard surgical treatment for CHS-1/ACT lesions and an accepted alternative to resection (11, 12). There is a risk of local recurrence with intralesional treatment. Intraoperative image assistance is normally performed with fluoroscopy. The advantages of CAS over fluoroscopy are mainly real-time 3D feedback and high-resolution images. Both the patient and the surgical team are exposed to ionising radiation during a CAS procedure, and although the exposure is usually low, the effects of long-term multiple low-dosage exposure are unknown (13).

Of 60 successful CAS cases, there was only 1 with an inadequate curettage identified on the baseline MRI and another case with recurrence of grade-1 CHS. The follow-up is short, and longer follow-up is needed for a conclusion on CAS curettage. There were 4 fractures in this treatment group, all in the diaphysis of the femur. We then started routine plating and no more fractures occurred. The main indication where CAS offers additional value with better feedback is large lesions, especially situated
Figure 5: A. (left panel). Surgical planning of the resection planes in the Orthomap oncology module with colouration of the tumour on the fused MRI/CT image. Patient information has been digitally edited out in the bottom-left panel. The bottom-right panel shows a 3D rendering of the pelvic bone and the resection planes. Two-thirds of the acetabulum could be saved. The patient was disease-free at the 5-year follow-up, functions well, and has resumed work. B. (right panel). 3D AP volume rendering of the 3.5-year follow-up CT.

Figure 6 (left): A. An image-based resection and reconstruction procedure; intraoperative screen shot of the navigation system. The pointer tool is being used to align 1 of the 2 resection planes of the proximal “dome”-type resection. An intraoperative view is shown in Figure 2. B. Anteroposterior radiograph of the patient 11 months after surgery. Progressive incorporation of the allograft and vascularised autograft.

Figure 7 (right): Imageless resection and reconstruction. The CAS tibial guide is used to check the cut angulation and placement of the tibial component. Reconstruction was done with a GMRS/MRH prosthesis, with the CAS system being used for rotation control, joint angulation control, and length reconstruction.
in difficult anatomical locations such as the femoral head and pelvis. However, with datasets available CAS can be used as a technologically superior alternative without increased surgical time.

Regarding image-based resection, margin control was good with 40 of 43 R0 resections in the CAS cases. 1 was a soft-tissue R1 margin. The R1 and R2 resections in bone occurred in the first 10 cases. Most procedures were osteochondroma resections, where the system was used to support anatomical orientation. There was 1 local recurrence in an osteosarcoma of the tibia after resection with adequate margins. This recurrence may have been caused by multiple core needle biopsy attempts before referral, as 1 attempt punctured the tumour. R0 margin in pelvic resection was reached in 15 of 17 cases. 1 R1 resection was a soft-tissue margin; CAS was not used for this resection plane. The cause of the R2 resection is unknown. Sometimes it was possible, with careful planning and CAS precision support, to spare structures that would otherwise have had to be sacrificed due to lack of resection plane control using conventional means (14). This—together with the pelvic resections and procedures for malignant lesions—is the main indication for CAS. Osteochondroma resections have little additional value, except better orientation and instrument position feedback.

In image-based resection and image-based reconstruction, the CAS system served as an objective measurement and guidance tool for the allograft-creation process. The ease with which the allograft could be created made the operation less demanding and more precise. A study of hemicortical resections showed complications, early and late fractures, in 6 of 21 patients, and called for better means of reconstruction (15). Use of CAS for reconstruction enables highly accurate bony reconstruction with massive hybrid (allogenic and autogenic) bone grafts. This may reduce the risk of complications and enable earlier mobilization. More complex resection and reconstruction shapes were possible, for minimal bone loss. We feel that the most inaccurate step at present in this type of procedure is the inaccuracy of the oscillating saw blade.

There have been reports of the use of CAS with good functional results in imageless resection and imageless reconstructions with custom tumour prostheses (16). As far as we know, there have been no reports of using imageless CAS in the placement of modular tumour prostheses. CAS can be helpful in accurate planning and measurement of resection length. It can also helpful in joint line reconstruction, as direct feedback on angulation, reconstruction length, and rotation is available in the software. However, no specific implant placement data are yet available to clinically support this improved feedback.

Margin control was excellent, with R0 resections in all 12 oncological procedures. The local recurrence rate for osteosarcoma was 20% (2 out of 10)—which is higher than
the recurrence rates of around 10% reported in the literature (17-19). The cause of this is unknown. However, in both cases where local recurrence occurred there was a poor response to chemotherapy, a well-known predictor of local recurrence. Use of CAS most likely does not influence recurrence rate, as this is mostly dependent on soft-tissue margins and response to chemotherapy.

Overall margin control using CAS was excellent. The pathologist reported R0 resections in 59 of 62 resections. 1 of the 3 resections that were not R0 was a soft-tissue R1 margin. Of the 18 high-grade tumour resections, there were 16 adequate bone margins.

Most set-up failures occurred early in the learning curve. Set-up time was measured for the last 47 cases and the mean value was 6.55 min. There were no complications related to CAS.

Due to the large heterogeneity and small number of patients per diagnosis and procedure, limited conclusions can be drawn from these data on clinical outcomes and functional results. Furthermore, there was insufficient follow-up and there were insufficient patient numbers for us to be able to draw conclusions about the recurrence rate.

In summary, CAS appears to be a promising new development in orthopaedic oncology. With limb salvage and function-saving surgery, there is a need for accurate navigation. It is also our opinion that CAS can be used in less complex procedures such as image-based resections and curetages too, where it is an accurate, technologically superior, and radiation-free alternative to fluoroscopy.
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