Computer-assisted orthopaedic tumour surgery (CAOTS)

With the advancement of bone sarcoma surgery, limb-sparing resection has almost replaced limb amputation. The surgical difficulty lies with the mental integration of the two-dimensional (2D) film data into a three-dimensional (3D) anatomy of the tumour extent for planning the precise tumour removal. This may have implications for the adequacy of the margin and functional outcomes. Intraoperatively, the technique of executing the mental plan into reality requires years of experience. In most situations, direct visual assessment of anatomy with surgical experience and fluoroscan assistance is sufficient to achieve adequate results. In other situations, minor errors in precision resectioning has minimal or no implications for the outcome. However, some cases such as patients with tumours involving the acetabulum require the procedure to be as accurate as possible. Cutting too much will certainly have good margin but leaves a difficult case for reconstruction, but cutting too little may compromise the tumour margin.

Computer-assisted orthopaedic surgery has only recently been developed, but it is now widely used in spine surgery, trauma surgery and joint replacement. The computer software that is currently used was not designated for use with orthopaedic tumours. After the original development of computer-assisted orthopaedic surgery, the technique has now advanced into a new computer-assisted orthopaedic tumour surgery (CAOTS) technique in which a CT scan is fused with an MRI image using the existing spine software. The importance is that the use of both the fusion of the MRI image for a better assessment of the extent of the tumour combined with the CT image which provides the basis of the intraoperative navigation, results in a more accurate plan for the pre-operative surgical procedure. In addition, it provides the detail for post-resection reconstruction, and it allows for the fabrication of a custom-made implant, if required, to the exact shape by providing a 3D digital image to the implant company for the implant design. This pre-operative planning, intraoperative resection and post-resection reconstruction makes the process much more effective than previously.

**Procedure for CAOTS**

- **1. CT and MRI image fusion.**
- **2. Tumour object creation by extraction of the tumour data from the MRI image.**
- **3. Virtual tumour image expansion to mark the expected resection margin.**
- **4. Planning of the resection plane by creation of trajectories outside the resection margin.**
- **5. CT data with the tumour image, expanded tumour image and resection plan transferred to the execution platform before surgery.**
- **6. Intraoperative tracker placement and spatial relationship of patient registration.**
- **7. Execution of the resection with navigated tools such as drill, osteotome and saw.**

**Areas of application**

CAOTS has been applied to many aspects of tumour surgery:

1. **3D image and appreciation of the surrounding structural relationship.** Experienced orthopaedic surgeons can mentally work out the anatomical image of the tumour by looking at the 2D MRI image. However, it takes quite a long learning curve to acquire this technique especially for tumours of soft tissue or the soft part of bone. The computer software will create an easily understandable 3D image of the tumour, so that even trainees can readily visualise the 3D relationship of the tumour to its surrounding structure and are able to mark the vessels and muscles.

   **Case illustration:** A patient with metastatic high grade sarcoma over the groin (Fig. 1) was scheduled to have surgical resection. The tumour and the surrounding structures including the pelvis, sacrum, femur, vessels, bladder and rectum are individually labeled by using the computer software. Therefore, the 3D relationship is clear for subsequent planning of the surgical procedure.

2. **Fluoroscopically invisible lesion.** Bone lesions that are invisible on radiographs are difficult to manage with standard surgical techniques. The current treatment method is with CT-guided localisation and removal. However, the CT-guided procedure is not real time, whereas with CAOTS, a real time view of the lesion and curettage is accomplished.

   **Case illustration:** A young patient had chondroblastoma of the proximal tibia, which was completely invisible to the x-ray (Fig. 2). Preoperatively, the CAOTS planning was performed for intraoperative real time navigated procedure, followed by tumour curettage.

3. **Precise tumour resection with margin.** Pelvic tumours are best planned with CAOTS software and resected with computer guidance. Removal of the exact amount of bone may help preserve the vital acetabulum structure. Moreover, the resection plane may be obliquely positioned or may require a v-shaped cut. Without CAOTS, the resection is sometimes difficult to perform as planned. Patellar osteotomy in the extra-articular knee resection is another procedure in which CAOTS is particularly beneficial. Without opening the knee joint, CAOTS can guide the Chevron osteotomy of the patella parallel to the two facets of the patella bone so that a larger piece of bone remains.

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Case Illustration: A patient suffered from grade II chondrosarcoma of the ischial tuberosity. The tumour resection was planned with CAOST. The planning indicated that only the lower portion of the acetabulum required removal and the remaining hip joint was stable. Hence, no reconstruction was needed and post-operatively, the patient could walk unaided. The histology results showed that the margin was free from the tumour (Fig. 3).

4. Radiofrequency (RF) in osteoid osteoma. The current management of osteoid osteoma is to have RF ablation of tumour nidus. The success rate is approximately 95%, but incomplete ablation of an elongated nidus may result in persistent symptoms. Pre-operative planning of how to place the RF probe may ensure the complete coverage of the nidus without ablating the uninvolved tissue.

5. Custom-made prosthetic replacement or custom-made allograft reconstruction. After planning the resection plane, the removed portion in digital form is sent to the implant company for fabrication of a custom-made prosthesis. With the intra-operative guided excision, the exact amount is removed and the custom-made prosthesis replacement is carried out in the subsequent reconstruction. Alternatively by using CAOTS, a piece of allograft can be cut to the exact size as the tumour bone and then replace the defect. This method is particularly useful with pelvic tumour resection and for reconstructing the remaining pelvis using custom-made implant and intra-epiphyseal resection of distal femur with segmental implant replacement.

Case Illustration: A female with chondrosarcoma underwent partial pelvectomy. The hip joint was removed and the resection plane was pre-planned. The defect was sent to the implant company in STL file and an exact implant was designed as planned (Fig. 4).

6. Additional uses for CAOTS. When computer navigation systems combine with endoscopy, curettage procedures can be performed under minimal invasive approach. Theoretically, all instruments such as the curet, osteotome and endoscope can all be real-time navigated.

Discussion
CAOTS is still in its early stages of development with few published research reports to date. No designated software for use with orthopaedic tumours is available at present. In addition, it is not known whether the potential benefits of the accuracy of CAOTS will improve the overall survival and functional outcomes for the patient, although we believe this to be the case.

Concerning the surgical margin, CAOTS can guide the surgeon to cut precisely as pre-planned. However, this is not a technique for reducing the surgical margin since the decision on the margin width depends on the clinical experience of the safety margin in the individual tumour. Concerning the functional outcomes, the pre-operative planning will show the exact amount of the remaining bone and will therefore, help both with the reconstruction design and prepare the patient for the subsequent outcome.

The studies by Wong et al reported that the mean pre-operative time for computer assisted surgery was between 1.4 and 3.0 h, and the intraoperative execution time was 24.3
to 28.0 min. We found that by using CAOTS, the mean pre-operative planning time (in 13 procedures) was 51 min and the intraoperative execution time was 74 min. However, the planning and execution time are related to the complexity of the individual cases, but with more experience, the overall duration time is expected to be reduced.\textsuperscript{13}

CAOTS is designed for improving the accuracy of the pre-operative surgical plan. The intraoperative registration is very important for ensuring its success. By using the registered pointer to touch the identifiable bony landmarks, the accuracy can be verified intraoperatively. Moreover, the software can calculate the registration accuracy. Less than 1.9 mm is considered acceptable, but an even smaller figure is better. In a report by So et al.,\textsuperscript{5} the tumour resection margin was confirmed to be very close to the plan, and initially, there was no tumour margin contamination. Also, the post-operative resection margin was measured against the pre-operative planned margin. Using the paired points and surface marking registration technique, the correlation coefficient in their study was 0.631, but with the CT-fluoroscopy matching registration technique, it was much improved at 0.985.

In addition to improved surgical outcomes, CAOTS also benefits with a lower occupational hazard. The radiation exposure to the operation room staff and to the patient is much lower than with the conventional intraoperative X-ray guided procedure.

For the future, it is hoped that new software will be designed for the CAOTS to make it more user-friendly. Intraoperative registration may use intraoperative 3D fluoroscopic scanning image fusion with pre-operative CT imaging. This may prove to be more important than the surface landmark registration or the 2D CT-fluoroscopy matching. In addition, a newer MRI scan guided CAOTS\textsuperscript{14} is being developed along with further investigations into newer areas of application. These developments may also prove to be a further step towards eventually having a robotic execution. Considering all the present information, the CAOTS could potentially
become the gold standard in orthopaedic tumour surgery. Therefore, despite the extra time required for pre-operative planning and intraoperative execution, it may prove to be well worthwhile.

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References