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Title:

Patient Specific Instrument Can Achieve Same Accuracy With Less Resection Time Than Navigation Assistance In Periacetabular Pelvic Tumor Surgery: A Cadaveric Study

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Abstract

Purpose Inaccurate resection in pelvic tumors can result in compromised margins with increase local recurrence. Navigation-assisted and Patient Specific Instrument (PSI) techniques have recently been reported in assisting pelvic tumor surgery with the tendency of improving surgical accuracy. We examined and compared the accuracy of transferring a virtual pelvic resection plan to actual surgery using navigation-assisted or PSI technique in a cadaver study.

Methods We performed CT scan in twelve cadaveric bodies including whole pelvic bones. Either supraacetabular or partial acetabular resection was virtually planned in a hemipelvis using engineering software. The virtual resection plan was transferred to a CT-based navigation system or was used for design and fabrication of PSI. Pelvic resections were performed using navigation assistance in six cadavers and PSI in another six. Post-resection images were co-registered with preoperative planning for comparative analysis of resection accuracy in the two techniques.

Results The mean average deviation error from the planned resection was no different (p=0.19) for the Navigation and the PSI groups: 1.9mm versus 1.4mm respectively. The mean time required for the bone resection was greater (p=0.0006) for the Navigation group than for the the PSI group: 16.2 minutes versus 1.1 minutes respectively.

Conclusions In simulated periacetabular pelvic tumor resections, PSI technique enabled surgeons to reproduce the virtual surgical plan with similar accuracy but with less bone resection time when compared with navigation assistance. Further studies are required to investigate the clinical benefits of PSI technique in pelvic tumor surgery.

Keywords

Navigation assistance, Patient specific instruments, Periacetabular pelvic tumors, Surgical accuracy

Introduction

Pelvic tumor surgery is challenging because of the complex bony anatomy and close proximity to pelvic organs and neurovascular structures. Achieving adequate resection margins is the most important prognostic factor in managing pelvic bone tumors as compromised margins may result in high local recurrence rate, ranging from 27 to 92% [1-3]. Cartiaux *et al.* [4] reported an experimental study. Under ideal working situations with complete visualization and access to the bone surfaces, four experienced tumor surgeons were asked to operate on simulated plastic pelvic models. The probability of an experienced surgeon obtaining a 10-mm surgical margin with a 5-mm tolerance above or below the resection was found to be 52 %. Therefore, there is a genuine need to improve the accuracy of resections in pelvic tumors.

In recent years, there have been many reports on the use of computer navigation in assisting resections of malignant bone tumors [2,5-11]. With real-time instant visual feedback, intraoperative navigation enables surgeon to locate anatomical and pathological structures accurately. Reports with a minimum of three years follow-up suggested that this technique is helpful in achieving safe tumor resection by improving the resection accuracy. It may also lead to better functional and oncologic results. Jeys *et al.* [2] further showed in a clinical study of 31 patients with pelvic or sacral tumors undergoing resection that the use of computer navigation reduced intralesional resection from 29% to 8.7%. Patient specific instrument (PSI) has recently been reported in pedicle screw insertion for spinal surgery [12,13], for performing difficult osteotomies in deformity correction [14,15] and in total knee arthroplasty [16,17]. The PSI is a customized tool that guides a saw and/or drill in the planned direction. PSIs were shown to achieve a better accuracy than traditional techniques in total knee arthroplasty. By replacing the traditional instrumentation they also improved operating efficiency by reducing total operating room time [16]. PSIs were also recently investigated in bone tumor surgery [18-20]. Wong *et al.* [20] showed in a cadaver study and a patient that PSI can produce similar surgical accuracy in millimeters as navigation assistance but with less operating time in the resection of an extremity bone tumor. In a study using synthetic pelvic bone tumor models, Cartiaux *et al.* [19] demonstrated that simulated periacetabular resection using PSI could provide better bone cutting accuracy than freehand manual resection. Therefore, PSI technique may have the additional advantages of using simple instruments and a minimal operative setup in contrast to navigation-assisted techniques that require bulky navigation facilities and a machine operator to manage the navigation guidance device intraoperatively.

The aim of the study was to compare the performance of navigation and PSI techniques in periacetabular bone tumor resections. In this study, cadaveric pelvic bones were used to simulate pelvic resections in a real clinical setting. We compared the accuracy and the resection time of transferring a preoperatively planned resection to the actual surgery using either navigation or PSI techniques.

Methods

Twelve fresh frozen cadaveric bodies including whole pelvic bones were used in this study. The mean age of the bodies was 68.8 (56 to 84). Six were males and six were females. Axial CT images of the pelvis were acquired using a 16-detector scanner (LightSpeed, GE, Milwaukee, WI). The scanning parameters were Pitch = 0.984:1, Maximum Tube Current = 300mA and Radiation Dose = ~24mSv. Slices of 0.625mm thickness were obtained using a soft tissue algorithm. The CT images in DICOM format were imported into a medical image processing software (Mimics 15.0, Materialise NV, Leuven, Belgium). The images were reformatted into sagittal and coronal views and three-dimensional (3D) bone images were generated for surgical simulation. Surgeons then developed the resection plan in the hemipelvis, using “cut’ function in MedCAD module in MIMICS software. The plan was based on MR images of two of our previously treated patients with acetabular bone sarcoma. (Fig. 1). The resection plan was a multi-planar bone resection (three planes) that was either a supra-acetabular resection (SAR) or partial acetabular resection (PAR) (Fig. 2). Twenty-four pelvic bone resections (12 SAR and 12 PAR) were virtually performed by surgeons in the 12 cadaveric bodies in MIMICS software. Twelve bone resections (6 SAR and 6 PAR) were assigned to a navigation group in which resection were performed under the guidance of computer navigation. The remaining 12 bone resections were assigned to a PSI group in which the resections were performed with the use of patient-specific instruments. In either group, six pelvic resections (3 SAR and 3 PAR) were performed in 6 right and 6 left hemipelvis. Eighteen planes from 6 SAR and another 18 planes from 6 PAR in both the Navigation and the PSI groups were subject to post-resection analysis of surgical accuracy.

Navigation planning

In the Navigation group, due to system incompatibility between MIMICS software and navigation system, the virtual resection planning in computer-aided design (CAD) format in MIMICS software cannot be directly transferred into a CT-based navigation system that can only accepts images in Digital Imaging and Communications in Medicine (DICOM) format. The transfer of the virtual surgical planning into navigation system was achieved by the method of CAD to DICOM conversion [20,21]. We first defined the virtual resection planes on the original CT images of cadaveric pelvis in MIMICS software, which were then exported in DICOM format. The modified DICOM files contained the information of the planned resection planes in addition to that of the original pelvis. The surgeons then transferred the original CT images of the cadaveric pelvis and the virtually planned, modified DICOM datasets into the CT-based navigation system (Stryker Navigation System – OrthoMap 3D module, version 2.0, Stryker, Mahwah, NJ) for resection planning (Fig. 3). The navigation system provides automatic image fusion of the original and modified DICOM data sets and also tools to define a planned bone resection. Therefore, the planned resection planes defined in MIMICS software could be identically represented in the navigation system for subsequent navigation surgery.

Design of PSI

In the PSI group, the surgeons also marked the bone surface that could be exposed within the surgical approach and the PSI could be positioned near the site of the planned resections in MIMICS software (Fig. 4). The engineers then exported the pelvic bone model, the planned resection planes and the footprints as stereolithographic (STL) files and transferred those files to a rapid prototyping (RP) software (Magics RP, version 14.0, Materialise, Leuven, Belgium). The software allowed further editing and integration of external CAD models in STL format.

The design of the PSI (Fig. 4) consisted of three components: 1) cutting blocks with a contacting surface that conform to the contour at ilium and acetabulum and the footprints predetermined by the surgeons so that the blocks could be positioned consistently on the bone surface at the planned resection sites without translation; 2) three-planar cutting slot in the blocks that were based on the unique orientation of the resection planes defined during virtual simulation in MIMICS software. The slot was 1.2mm in width to accommodate an oscillating saw blade of 1mm thickness for making the osteotomy; 3) drill sleeves for inserting Kirschner wires to fix the PSI to pelvic bone after correct positioning of the PSI. The design also took into account the surgeons' input about the surgical approach or exposure, the nearby soft tissue at the defined position of PSI and the direction of placing the PSI. Finally, the engineers combined different components of PSI in the RP software and created the unique contact interface between the PSI and the bone model at the site of intended bone resection. The surgeons then approved the final design of PSI prior to the actual fabrication of PSI.

The PSI was made of a thermoplastic material (ABS) fabricated on a rapid prototyping machine (Fortus 400mc Fused Deposition Modeling (FDM) system, Stratasys Inc., Eden Prairie, MN), which has high chemical resistance and high tensile strength, and is heat stable up to 130C and can be sterilized for use in the operating theater. Ceramic pelvic bone models were also fabricated on a 3D printing machine (Zprinter 310, Z Corporation, Burlington, MA), so the surgeons could practise and familiarize the proper placement of the PSI on the bone surface before the actual procedure.

Surgical procedure of the cadaveric pelvis

The surgical procedures were carried out by the surgeons who had more than 15 years' experience in orthopaedic tumor surgery and had expertise of both Navigation and PSI-guided tumor resections. A utilitarian skin incision that consisted of an ilioinguinal and a trochanteric approach was used. Greater trochanteric osteotomy was performed and abductor muscles were reflected to expose the lateral aspect of ilium and posterior column of acetabulum. Femoral neck was osteotomized and femoral head was removed to expose the hip joint. Anterior column of acetabulum was also exposed after retracting the femoral neurovascular bundles medially.

In the Navigation group, a universal tracker was attached to ipsilateral iliac crest in which the pelvic resection was performed. Image-to-bone registration was performed using a paired-point and surface-matching algorithm [11,20]. 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. The points were easily identifiable reference locations, such as iliac tubercle, anterior superior iliac spine, anterior inferior iliac spine, greater sciatic notch or pubic tubercle. A navigation probe was then used to touch the real anatomical points that 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 bone surface. The software calculated the registration errors that represented the degree of mismatch between the intraoperatively selected points and CT images. The only direct method of verifying the accuracy of the registration was by moving the tip of the navigation probe on 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 of the navigation system to execute the planned bone resection. The navigation probe allowed real-time tracking of the spatial location of the tip of the probe in relation to the cadaveric bone anatomy on the virtual CT images. The anatomic locations and orientations of planned bone resections were identified and guided using navigated tools (Fig. 5). Because the navigation system did not support a navigated saw or an osteotome, the osteotomy was made manually with an oscillating saw or osteotome along the navigated marked resection level (Fig. 5).

In the PSI group, the PSI was placed laterally at the surgical exposure and was positioned on the predetermined bone surface at the planned bone resection site. It was then fixed to the pelvic bone with Kirschner wires (Fig. 6). The pelvic bone was osteotomized using an oscillating saw via the cutting slots of the PSI (Fig. 6).

To analyze the accuracy of the two techniques, we obtained CT images with slices of 0.625mm thickness for each of remaining hemipelvis after resection (Fig. 7). The postresection CT images were imported into MIMICS software in which 3D bone models were generated. Each postresection specimen was then co-registered with its preoperatively planned model in STL format using an engineering software (Geomagic Verify, 3D Systems, USA) that is well accepted in industry for metrology and quality control in object shapes. Then, the preoperative and postoperative hemipelvic models were perfectly aligned with identical coordinates for further analysis (Fig. 7). The achieved and the planned resection planes were compared after image co-registration of the planned model and its model from post-resection specimen. The absolute distance between all the points on the achieved plane and those on the planned plane was calculated as deviation error. For better visual representation of the absolute difference in distance between the two planes, we used another engineering software (PowerSHAPE, Delcam, UK) to provide color mapping of the deviation error (Fig. 7).

For the Navigation and the PSI groups, we compared the mean maximum deviation error from the planned resection, the mean average deviation error from the planned resection and the time required for the bone resection. The bone resection time is defined as the total time taken for placement of a patient tracker, image-to-patient registration, marking the locations of the planned resection and completion of the osteotomy under navigation guidance in the Navigation group. In the PSI group, the bone resection time is from the correct placement of PSI on predetermined bone surface to completion of the osteotomy under PSI guidance. The three measurements for SAR and PAR were compared between the Navigation and the PSI groups. We also recorded image-to-patient registration error for the

Navigation group and fitting of PSI on cadaveric bone surface by assessing whether it was identical to that on 3D printed bone models for the PSI group. The parameters were regarded as the main factors affecting the accuracy of bone resections using the techniques.

All statistical analyses were conducted by a statistical software (STATA, version 13.1, StataCorp LP, USA). Non-parametric tests (Wilcoxon-Mann-Whitney tests) were used to assess statistical significance of differences in distributions in the deviations / time taken for the Navigation and the PSI groups. P values less than 0.05 were considered statistically significant.

Results

All bone resections were performed successfully, as planned, in the Navigation and the PSI groups. The mean maximum deviation error from the planned resection was no different (p=0.08) for the Navigation and the PSI groups: 3.6mm versus 2.6mm respectively. The mean average deviation error from the planned resection was also no different (p=0.1) for the Navigation and the PSI groups: 1.9mm versus 1.4mm respectively. For PAR and SAR, the mean maximum and the mean average deviation error from the planned resection were no different (p>0.05) for the Navigation and the PSI groups (Table 1).

The mean time required for the bone resection was greater (p=0.004) for the Navigation group than for the PSI group: 16.2 minutes versus 1.1 minutes respectively. For PAR and SAR, the mean time required for the bone resection was also greater (p<0.01) for the Navigation group than for the PSI group (Table 1).

The mean registration error was 0.5 mm (range, 0.4–0.8 mm) and real-time accurate matching could be achieved in all resections for the Navigation group. The placement of PSI was assessed intraoperatively to be satisfactory for all resections except in one PAR in which the cadaver was not fully thawed at the predetermined bone surface for the positioning of the PSI.

Discussion

Pelvic tumor surgery is difficult due to complex bone geometry, close proximity to vital structures and limited working space. Inaccurate resections with positive margin are associated with increased risk of local recurrence and mortality [1-3]. Excessive sacrifice of normal bone in fear of contaminated margin may result in inadequate bone for reconstruction and compromise the limb function. Accurate transfer of the virtual resection plan to the real surgery is important to achieve adequate surgical margin but yet maximally preserve the normal bone for functional reconstruction. Navigation and PSI assistance in pelvic bone tumor resections have been recently reported with the early promising results of reproducing the virtual resection plan [2,6,11,19]. We therefore compared the accuracy of the two techniques in pelvic resections by assessing the deviations of the achieved bone resections from the planned and the time required for the resections in a cadaver study.

The study has several limitations. First, the resection simulations in cadavers were based on two periacetabular bone tumors previously operated at the authors' institution. Different pelvic tumors vary in extent and locations. The results of the study may not be applicable to all pelvic tumors, in particularly those tumors with big extraosseous components that make the placement of PSI difficult. Second, there is no control group of using conventional manual technique for comparison in this study. Third, to access the accuracy of reproducing the surgical planning using the two techniques, we only calculated the absolute distance between the achieved resection plane and the corresponding planned one but did not measure the angular deviation between the two planes as used in the study by Khan *et al.* [22]. We found it was difficult and prone to manual error to determine the best-fit plane for the achieved resection. Also, as the calculation involved different software interfaces, there may have processing errors in measurements. Fourth, the results (the accuracy and the time for bone resection) of the cadaveric study may be better than that in real clinical scenarios as authors performed the bone resections in an ideal cadaveric setting. The authors have prior experience of performing virtual resection planning in engineering softwares and using both computer navigation and PSI technologies in assisting bone tumor surgery. The authors may improve in their operative skills when repeatedly performing similar resections. Fifth, the sample size was small with 12 pelvic resections for each group. However, as the mean average deviation from the planned of the two techniques was found to be less than 2mm, any difference between the two techniques may not be clinically relevant. Sixth, the cadavers were kept at a freezer while we underwent the preoperative planning and the manufacture of PSI. It takes about three days for thawing prior to the real procedure. We did not find any significant deflection of sawblades in all the bone resections after thawing of the frozen cadavers. However, one cadaver in the PSI group at the beginning of the study did not fully thaw because of large body build. Although hot water was used to irrigate the operative site, it might have errors in the correct positioning of PSI on the predetermined bone surface of a partially thawed cadaver.

In this cadaver study, we showed that both navigation and PSI assisted technique for the simulated pelvic resection could achieve clinically acceptable accuracy of reproducing the planned bone resection with a mean deviation error of < 2mm from the planned. The result concurred with the accuracy of the two techniques reported in other clinical, sawbone or cadaveric studies [5,11,19,22-24]. When we compared the accuracy between the two techniques in simulated pelvic bone resections, no statistical difference was noted. Based on our results, after surgeons plan and perform virtual bone resections and precisely define bone resection planes in pelvis using appropriate engineering softwares, the virtual resection planning may be transferred to the real surgical procedure with high degree of accuracy using either navigation or PSI techniques.

The mean time required for the bone resection in the Navigation group was significantly greater than that in the PSI group. Although the planes of pelvic resection were different from those in this study, the pelvic sawbone study by Cartiaux O *et al.*[19,22] showed a similar trend of mean time required for the bone resection, 49 minutes for navigation assistance versus 6.9 minutes in PSI assistance. The greater operative time in the Navigation group was due to the fact that time was required for the placement of patient tracker, system calibration and image-to-patient registration prior to the navigated bone resections. Also, as the existing navigation system does not support a navigated saw, the surgeons had to manually control the direction of the sawblade for the resection under the visual guidance on the navigation display. The intraoperative use of PSI is simpler. Once the PSI is correctly placed on the predetermined bone surface, a physical image-to-patient registration is completed. Surgeons can focus on the operative field while performing the bone resection as the cutting slots of the PSI confine the sawblade to the specific planes of the planned resection [20].

The mean registration error was < 1mm and the real-time accurate matching could be achieved in all resections for the Navigation group. This was comparable to that reported by other clinical studies [2,5,6,10,11]. However, for the PSI group, it was difficult to intraoperatively measure the amount of deviation in the placement of PSI from its predetermined bone surface. We could only assess subjectively whether the PSI had an identical fit on the cadaveric bone surface similar to the one on the 3D printed bone model surface. Although this is a subjective feeling, the mean deviation error of < 2mm from the planned resection for PSI group suggested that the PSI technique was clinically practical and the subjective comparison on the model was quite helpful. Further studies are needed to investigate how much bone contact surface is necessary for the consistently accurate placement of the PSI and how the placement of PSI will be affected by tumors at various other locations in the pelvis.

The differences of the workflow between navigation-assisted and PSI techniques have been described [20]. Given that the two techniques adopted the same workflow at the preoperative planning stage, both techniques have the same planning errors. Therefore, the registration error for navigation-assisted technique and the error in the placement of PSI for PSI technique are the most important factors contributing to the overall accuracy of these new techniques [20,25]. Surgeons may then choose which technique is more suitable for their patients, based on how well they can minimize the error within each technique.

The currently available navigation systems can only support a navigation-assisted bone resection. Even if a navigated saw or an osteotome is made available in the future, confining the sawblade to follow a pre-determined path may require cutting guides as in PSI. Therefore, current PSI techniques may be superior to navigation-assisted techniques, in particular, when the resection involves multiple resection planes. On the other hand, intraoperative computer navigation provides real-time instant visual feedback to locate anatomical and pathological structures, a feature that is not available with PSI techniques. The exact indications for selecting each of these techniques in pelvic bone tumor surgery need to be further defined.

The extra cost of spending on navigation facilities and 3D printed PSIs is a valid concern. Navigation facilities are one-off expenses with maintenance costs but the facilities can be used in various procedures by different sub-specialities in the same hospital. The total cost of the PSI and bone model for one resection used in this study is USD 520. Studies are required to examine the cost-effectiveness of these two techniques in the context of improved surgical accuracy in pelvic tumor resection.

In this cadaveric study of simulated resection of periacetabular pelvic tumors, we showed that PSI technique enabled surgeons to reproduce the virtual surgical plan with a clinically acceptable accuracy that was similar to that using Navigation-assisted technique but with reduction of the time required for resection. Further studies are warranted to evaluate the error in the placement of PSI on the predetermined bone surface and the efficacy of using PSI technique in the real clinical setting.

Conflict of Interest

The institutions of one or more authors (SMK and CMW) have received funding from the Research Grants Council of the Hong Kong Special Administration Region (RGC Grant: CUHK 465412) for the work in the manuscript. Other authors (WKC, SKY and WIOL) declare no conflict of interest.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors. No informed consent is needed as the study does not contain human participants.

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Reference

1. Jeys L, Matharu GS, Nandra RS, Grimer RJ. Can computer navigation-assisted surgery reduce the risk of an intralesional margin and reduce the rate of local recurrence in patients with a tumour of the pelvis or sacrum? Bone Joint J. 2013;95- B(10):1417–24.

2. Fuchs B, Hoekzema N, Larson DR, Inwards CY, Sim FH. Osteosarcoma of the pelvis: outcome analysis of surgical treatment. Clin Orthop Relat Res 2009;467:510–518.

3. Ozaki T, Flege S, Kevric M, Lindner N, Maas R, Delling G, Schwarz R, von Hochstetter AR, Salzer-Kuntschik M, Berdel WE, Jürgens H, Exner GU, Reichardt P, Mayer-Steinacker R, Ewerbeck V, Kotz R, Winkelmann W, Bielack SS. Osteosarcoma of the pelvis: experience of the Cooperative Osteosarcoma Study Group. J Clin Oncol 2003;21:334–341.

4. Cartiaux O, Docquier PL, Paul L, Francq BG, Cornu OH, Delloye C, Raucent B, Dehez B, Banse X. Surgical inaccuracy of tumor resection and reconstruction within the pelvis: an experimental study. Acta Orthop 2008; 79:695–702.

5. Aponte-Tinao LA, Ritacco LE, Ayerza MA, Muscolo DL, Farfalli GL. Multiplanar osteotomies guided by navigation in chondrosarcoma of the knee. Orthopedics. 2013; 36(3):e325–30.

6. Cho HS, Oh JH, Han I, Kim HS. The outcomes of navigation-assisted bone tumour surgery: minimum three-year follow-up. J Bone Joint Surg [Br] 2012;94-B:1414–1420.

7. Ieguchi M, Hoshi M, Takada J, Hidaka N, Nakamura H. Navigation-assisted surgery for bone and soft tissue tumors with bony extension. Clin Orthop Relat Res 2012;470:275–283.

8. Li J, Wang Z, Guo Z, Chen GJ, Yang M, Pei GX. Irregular osteotomy in limb salvage for juxta-articular osteosarcoma under computer-assisted navigation. J Surg Oncol. 2012; 106(4):411–6.

9. So TY, Lam YL, Mak KL. Computer-assisted navigation in bone tumor surgery: seamless workflow model and evolution of technique. Clin Orthop Relat Res 2010; 468:2985–2991.

10. Wong KC, Kumta SM, Chiu KH, Antonio GE, Unwin P, Leung KS. Precision tumour resection and reconstruction using image-guided computer navigation. J Bone Joint Surg [Br] 2007;89-B:943– 947.

11. Wong KC, Kumta SM. Computer-assisted tumor surgery in malignant bone tumors. Clin Orthop Relat Res 2013;471:750–761.

12. Lu S, Xu YQ, Lu WW, Ni GX, Li YB, Shi JH, Li DP, Chen GP, Chen YB, Zhang YZ. A novel patient-specific navigational template for cervical pedicle screw placement. Spine (Phila Pa 1976) 2009;34(26):E959–E966.

13. Mac-Thiong JM, Labelle H, Rooze M, Feipel V, Aubin CE. Evaluation of a transpedicular drill guide for pedicle screw placement in the thoracic spine. Eur Spine J 2003;12:542–547.

14. Miyake J, Murase T, Moritomo H, Sugamoto K, Yoshikawa H. Distal radius osteotomy with volar locking plates based on computer simulation. Clin Orthop Relat Res 2011; 469(6):1766–1773.

15. Murase T, Oka K, Moritomo H, Goto A, Yoshikawa H, Sugamoto K. Three-dimensional corrective osteotomy of malunited fractures of the upper extremity with use of a computer simulation system. J Bone Joint Surg Am 2008;90(11):2375–2389.

16. Lionberger DR, Crocker CL, Chen V. Patient Specific Instrumentation. J Arthroplasty. 2014 Sep;29(9):1699-704

17. Ng VY, DeClaire JH, Berend KR, Gulick BC, Lombardi AV Jr. Improved accuracy of alignment with patient-specific positioning guides compared with manual instrumentation in TKA. Clin Orthop Relat Res. 2012 Jan;470(1):99-107.

18. Bellanova L, Paul L, Docquier PL. Surgical guides (patient specific instruments) for pediatric tibial bone sarcoma resection and allograft reconstruction. Sarcoma. 2013;2013:787653.

19. Cartiaux O, Paul L, Francq BG, Banse X, Docquier PL. Improved accuracy with 3D planning and patient-specific instruments during simulated pelvic bone tumor surgery. Ann Biomed Eng. 2014 Jan;42(1):205-13.

20. Wong KC, Kumta SM, Sze KY, Wong CM. Use of a patient specific CAD/CAM surgical jig in extremity bone tumor resection and custom prosthetic reconstruction. Comput Aided Surg. 2012;17(6):284–93.

21. Wong KC, Kumta SM, Leung KS, Ng KW, Ng EW, Lee KS. Integration of CAD/CAM planning into computer assisted orthopaedic surgery. Comput Aided Surg. 2010;15:65–74.

22. Khan FA, Lipman JD, Pearle AD, Boland PJ, Healey JH. Surgical technique: computer-generated custom jigs improve accuracy of wide resection of bone tumors. Clin Orthop Relat Res. 2013;471(6):2007–16.

23. Cartiaux O, Banse X, Paul L, Francq BG, Aubin CE´, Docquier PL. Computer-assisted planning and navigation improves cutting accuracy during simulated bone tumor surgery of the pelvis. Comput Aided Surg. 2013;18(1–2):19–26.

24. Ritacco LE, Milano FE, Farfalli GL, Ayerza MA, Muscolo DL, Aponte-Tinao LA. Accuracy of 3-D planning and navigation in bone tumor resection. Orthopedics. 2013;36(7):e942–50.

25. Wong KC, Kumta SM. Use of Computer Navigation in Orthopedic Oncology. Curr Surg Rep. 2014 Feb 22;2:47. eCollection 2014. Review.

Legends

Figure 1A-B. (A) A coronal T1-weighted MR image in a patient with a high-grade chondrosarcoma involving left acetabular and pubic rami (red arrows). A PII and III resection at the supra-acetabular region (SAR) was planned. (B) A coronal T1-weighted MR image in a patient with a low-grade chondrosarcoma involving the anterior column of left acetabulum (red arrows). A partial acetabular resection including the anterior column (PAR) was planned.

Figure 2A-C. (A) CT images of a cadaveric pelvis were imported into an engineering software that generated a 3D pelvic bone model. Surgeons virtually defined and simulated the multi-planar pelvic resections, SAR on right hemipelvis and PAR on left hemipelvis, in the pelvic model. (B) shows the lateral view of right hemipelvis with a three-planar osteotomy (pink) of SAR. The postresection bone (blue) represents the tumor specimen after simulated PII and III resection. (C) shows the lateral view of left hemipelvis with a three-planar osteotomy (orange) of PAR. The postresection bone (brown) represents the tumor specimen after simulated resection of anterior column pelvic tumor. The bone surface footprints (red line and dots) were marked on the pelvic model near the sites of planned resections and at the region that could be surgically exposed. The engineer then used the information of the footprints and the planned resection planes to design a PSI for the pelvic resection.

Figure 3A-D. Preoperative images of surgical navigation planning on the navigation monitor for the cadaveric study. The original CT image datasets (CT01) were fused with a modified CT dataset (CT02) (whiter images pointed by red arrows) containing the virtually planned resection planes and the remaining pelvic bones after simulated tumor resections. The planned resection planes could then be marked with tools in the navigation system same as planned in the engineering software. Axial (A), reformatted sagittal (B) and coronal (C) images and the reconstructed 3D planning bone model with resection planes (D) illustrate the transfer of the virtual planning to the navigation system by the method of CAD to DICOM conversion and image fusion.

Figure 4A-D. With the information of the footprints and the surgeons' defined resection planes, the engineer designed a PSI with a cutting block and slot that not only could be positioned on the predetermined bone surface but also could correspond to the desired resection planes. Drill sleeves were also incorporated in the PSI for insertion of

Kirschner wires, so to stabilize the PSI after its placement on the bone surface. (A) shows the CAD model of the PSI for SAR in left hemipelvis and (B) shows the real PSI on the bone model.(C) shows the CAD model of the PSI for PAR in right hemipelvis and (D) shows the real PSI on the bone model.

Figure 5A-B. (A) After surgical exposure of inner and outer tables of left ilium for SAR, a patient tracker was placed at iliac crest and an image-to-patient registration was performed. Two Kirschner wires were inserted at the intersection of each planar osteotomy under navigation guidance. The sites of the planned resections were further identified and marked with a navigation probe. The final bone resection was performed manually with an oscillating saw along the orientation guided by the navigation system. (B) shows the postresection bone ends in SAR. CT scan of the postresection bone was taken for the analysis of the resection accuracy with navigation technique.

Figure 6A-B. (A) After surgical exposure of the right acetabulum for PAR, the PSI was placed and fixed to the pelvic bone with two Kirschner wires. The bone resection was performed with an oscillating saw along the desired orientation of the cutting slots of the PSI. (B) shows the postresection bone ends in PAR. CT scan of the postresection bone was also taken for the analysis of the resection accuracy with PSI technique.

Figure 7A-D. (A) and (B) show the assessment of postresection accuracy in the cadaveric pelvis with SAR in the Navigation group and PAR in the PSI group respectively. The remaining right hemipelvis after resection (green in (A) and pink in (B)) was coregistered with its 3D preoperative planning by an engineering software. The achieved resection plane was converted and represented by point clouds. The absolute distance from point to point between the achieved plane and the corresponding planned plane was calculated as the deviation error. (C) and (D) show the difference of the distance in the form of a color mapping of resection deviation. Each pelvic resection consisted of three planar osteotomies and was labeled as plane “1”, “2” and “3”. For the color bar at right lower corner, “MAX” (blue) represents overcut from the planned resection while “- MAX” represents undercut from the planned resection.

Table 1 Absolute deviation of the achieved resection from the planned

Pelvic resection*	Parameters**	The Navigation group			The PSI group		P value***
		Mean	95% CI		Mean	95% CI	
Supraacetabular resection (SAR)	Mean maximum deviation	3.24	(1.06, 5.43)		2.26	(1.54, 2.97)	0.522
	Mean average deviation	1.81	(1.31, 2.32)		1.19	(0.64, 1.75)	0.078
	Time	15.55	(8.42, 22.69)		1.34	(0.44, 2.23)	*0.004*
Partial acetabular resection (PAR)	Mean maximum deviation	3.96	(2.37, 5.55)		2.98	(0.75, 5.21)	0.200
	Mean average deviation	1.90	(1.37, 2.43)		1.54	(0.28, 2.80)	0.078
	Time	16.78	(12.72, 20.83)		0.86	(0.54, 1.18)	*0.004*
SAR + PAR	Mean maximum deviation	3.60	(2.33, 4.88)		2.62	(1.72, 3.52)	0.078
	Mean average deviation	1.86	(1.49, 2.22)		1.37	(0.57, 2.16)	0.109
	Time	16.16	(11.01, 21.32)		1.10	(0.50, 1.69)	*0.004*

All analyses were conducted by the statistical software, STATA version 13.1.

CI = confidence interval

* regardless of the side of hemipelvis (left / right)

** “deviation” (in mm) represents the absolute distance of the achieved resection from the planned; “time” (in minute) represents the time taken from the start of navigation or PSI technique to the completion of pelvic bone resection.

*** Wilcoxon-Mann-Whitney test to assess statistical significance of differences in distributions in the deviations / time taken for the Navigation and the PSI groups; p-value < 0.05 indicates statistically significant.