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Feasibility study of intraoperative cone-beam CT navigation for benign bone tumour surgery

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Abstract

Background: Intraoperative cone-beam computed tomography (CBCT) offers the advantage of navigation on the current anatomical situation and the possibility to take a control scan. We assessed the feasibility of using intraoperative CBCT for navigated intralesional curettage.

Methods: Nine benign bone tumour patients were studied. Feasibility was assessed by describing the workflow and indications for navigation, scoring CBCT image quality and registration accuracy, and measuring scan and navigation set-up times. Short-term follow-up was described.

Results: CBCT navigation was successful in all patients. Median tumour visibility, tumour delineation, and vital structure visibility scores were good. Median registration accuracy score was very good. Median scan and verification times were 5 and 3 minutes, respectively. One patient had a tumour recurrence after 6 months.

Conclusions: Intraoperative CBCT navigation is feasible and safe. Indications for use of navigation in clinical practice are closeness to vital structures, complexly shaped tumours or bone, minimally invasive surgery, and repeated surgery.

KEYWORDS

bone, computer assisted surgery, cone-beam CT, image guided surgery, intraoperative imaging, navigation, orthopaedic, tumor

1 | INTRODUCTION

Primary bone tumours are rare, ie, the proportion of malignant bone tumours is 0.2% of all cancer in the Western population.[1] The exact incidence of benign and intermediate-grade bone tumours is unclear, as often cases go undetected because of lack of symptoms.[2] The most common treatment for symptomatic nonmalignant tumours comprises intralesional curettage with or without local adjuvant treatment.[3]

The current standard intraoperative imaging technique used to support the orthopaedic surgeon is two-dimensional (2D) fluoroscopy. The major limitation of this method is that it lacks the detail for depicting challenging cases. Tumours in the proximal or distal parts of long bones, as well as in irregularly shaped bones, are not easily distinguishable on fluoroscopy. Difficult tumour localization and poor visualization may result in (microscopic) tumour residue leading to local recurrence and repeated surgery. It may also lead to damaged healthy tissue and subsequent function loss.

Surgical navigation, an application of computer-assisted surgery, provides real-time feedback of the surgical instrument position using high-resolution three-dimensional (3D) images. Navigation has been used in

malignant bone tumour resections in the pelvis since 2004,[4] and applications have expanded to other bones and limb salvage surgery.[5-9] Navigation is not yet commonly used for intralesional curettage.[10]

To enable navigation during surgery, a 3D image dataset is linked to the patient through a process called registration. Registration is almost always manual and based on computed tomography (CT) images. Magnetic resonance imaging (MRI) becomes available for navigation by image fusion with the CT images.[11]

An intraoperative cone-beam CT (CBCT) scanner enables CT-like quality 3D scans in the operating room (OR). Intraoperative CBCT offers the advantage of navigation on the current anatomical situation and the possibility to take a control scan to verify complete tumour removal. The CBCT is automatically registered to the patient, without manual user input. The combination of CBCT and navigation is commonly used for pedicle screw placement[12] but is not yet applied in bone tumour surgery.

We recently started using navigation for benign bone tumours in difficult anatomical locations. As our centre has a hybrid OR, our aim is to explore the feasibility of using intraoperative CBCT to set up navigation in patients with benign bone tumours. In this pilot study, we describe the workflow, indications for usage of navigation, image quality, registration accuracy, procedure and set-up times, and short-term follow-up.

2 | MATERIALS AND METHODS

2.1 | Study population and design

From January 2017 to November 2017, nine consecutive patients (median age, 36 years; age range 11-56 years) with different types of benign bone tumours (Table 1) were enrolled in this study. This study comprises a prospective case series. Inclusion criteria were benign bone tumour and the need to undergo navigated curettage. There were no exclusion criteria. The study was exempted from approval by the ethics committee because the CBCT scanner and navigation system are already used in clinical practice. Informed consent was obtained from all patients.

2.2 | Preoperative planning

As bone tumours can occur in every bone of the body, a preoperative position planning of patient, optical camera (Curve, Brainlab, Munich, Germany), and reference base was made for every patient (Figure 1 A). This planning was then executed during surgery (Figure 1B). The

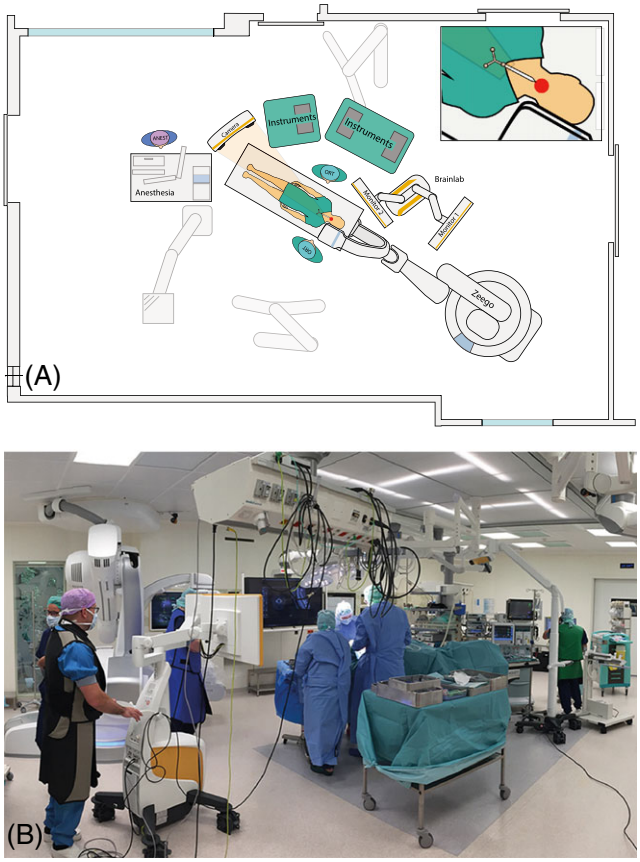

FIGURE 1 A-B, The preoperative position planning for patient 9 (A), depicting how to position the patient, where to place the navigation system and camera, and where to place the reference base. The red circle indicates the lesion in the C7 vertebra; (B) shows the actual situation during surgery

TABLE 1 Patient and procedure characteristics

Patient No. /sex/age	Tumour Type	Tumour Size, mm	Tumour Location	Surgery Performed
1/M/14	Atypical cartilaginous tumour	16 × 20 × 18	Proximal humerus (right)	Curettage + cryo + bone graft
2/F/11	Subchondral cysts	1: 12 2: 8	Proximal tibia (left)	Curettage + bone graft
3/M/21	Chronic osteomyelitis	43 × 12 × 9	Distal femur (right)	Curettage + flush
4/M/17	Osteochondroma	14	Distal radius (left) + ulna (left)	Resection
5/M/38	Reactive cyst	71 × 61 × 61	Acetabulum (right)	Curettage + cryo + bone graft
6/M/56	Atypical cartilaginous tumour	58 × 34 × 32	Proximal humerus (right)	Curettage + cryo + cement
7/F/51	Giant cell tumour	41 × 41 × 32	Proximal tibia (left)	Curettage + cryo + bone graft
8/F/48	Osteoid osteoma	13	Spinous process C7	Curettage
9/M/36	Intraosseous ganglion	34 × 43 × 35	Proximal tibia (right)	Curettage + bone graft

CBCT scanner (Artis Zeego, Siemens Healthineers, Erlangen, Germany) is a floor-mounted multi-axis robotic C-arm system. A CBCT is made by isocentric rotation of the C-arm. The acquired projection images are reconstructed to a 3D volume. The patient was positioned according to preoperative planning on an operating table with a radiolucent carbon fibre table top (MAQUET MAGNUS, MAQUET, Rastatt, Germany). Its static floor mount limits the C-arm range of motion to the proximal half of the operating table. Patients were positioned head first towards the scanner for tumours located in the spine and upper extremity, and feet first for tumours located in the pelvis and lower extremity. The tumour was positioned in the isocenter of the 3D scan. For example, a patient with a tumour in the humerus was positioned laterally on the laterally extended table. A thin gel mattress was used to prevent collision between patient and C-arm during the 3D run. A collision check was performed before draping. If a 3D run was not possible, the patient was repositioned.

The C-arm also limited the initial optical camera position, as its reflective tracking stickers should be visible to the camera when starting the 3D run (Figure 2). During surgery, the camera could be moved freely. The reference base was placed on the affected bone between the operating field and the optical camera. If this was not possible, camera and reference positions were planned so that the line of sight between the camera and reference base was not obstructed by the surgeon during surgery.

2.3 | Cone-beam CT navigation

All patients underwent treatment under general or epidural anaesthesia. All procedures were performed by one orthopaedic surgeon (I.v.d.G., 9 years of experience in orthopaedic oncology). Two pins 4 mm in diameter were drilled percutaneously in the affected bone, on which the reference base was clamped. For patient 8 (see also Table 1), the reference base was clamped to the spinal process of the T1 vertebra. The CBCT imaging protocol was based on patient size and tumour location. The low-dose protocol (5 s DynaCT Body Care) takes 133 projection images, whereas the high-dose protocol (6 s DynaCT Body) takes 397 projection images. More projections resulted in higher image quality, required for body parts with more mass, at the cost of a higher radiation dose. The resulting images were automatically registered to the patient, because the C-arm was previously calibrated and is tracked using reflective stickers (Figure 2). The registration accuracy was validated visually by the surgeon using a navigated pointer (Figure 3A). Either the curette or high-speed burr (Midas Rex, Medtronic, Minneapolis, USA) was calibrated and navigated throughout the treatment (Figure 3B). Navigation was used both as a confirmation of position and to assess direction. In case of uncertainty about entire tumour removal, a control CBCT scan was acquired with the possibility of directly continuing navigation based on the current anatomical situation.

2.4 | Analyses

As this is a feasibility study, we mainly used descriptive statistics, ie, mean/median imaging and navigation parameters, procedural durations, and image quality.

FIGURE 2 This is the starting position of the C-arm before acquiring a 3D scan. The black circles indicate the reflective calibration stickers that allow the navigation system to "see" the C-arm. The camera needs to have a clear line of sight to these stickers when starting the 3D run, otherwise the system cannot perform an automatic image registration

Technical success was defined as properly setting up CBCT navigation and having this available for the surgeon throughout the procedure.

In order to define indications for the use of CBCT navigation that can be applied to all variations in benign bone tumours, the surgeon was asked to list the reasons for the use of navigation per patient and if navigation was of added value.

Imaging protocols and dose area products (DAP) were collected from the database. DAP is defined as the absorbed dose over the irradiated area and includes all scans and fluoroscopy images made during surgery.

CBCT image quality for each of the patients was scored by a radiologist (J.J.F., 9 years of experience in interventional radiology) and the orthopaedic surgeon on a five-point scale ranging from 1 to 5, corresponding to very poor, poor, acceptable, good, and very good image quality. This scale was used to score tumour visibility, tumour delineation, and the visibility of vital structures. The Cohen's kappa coefficient (κ) was calculated using IBM SPSS Statistics version 25.0 (IBM, Armonk, NY) to measure interrater agreement.

The registration accuracy was scored by the orthopaedic surgeon using the same five-point scale as was used to score the image quality. The scores were retrospectively obtained based on validation images that were recorded during the registration validation step (see also Figure 3A).

Surgical time was defined as the time between the first incision and last suture. These times were extracted from the anaesthesiology logs. Setting up navigation was split into acquiring the CBCT and validating the registration. These times were extracted from the navigation system logs. The scan time started when the C-arm was moved to the operating table and ended after acquiring the 3D volume. The validation time started directly after acquiring the CBCT and ended after the registration was accepted. Validation thus also included moving all instrument tables and monitors back into place, as well as properly visualizing the CBCT. The duration of a possible control scan was not included in the scan time.

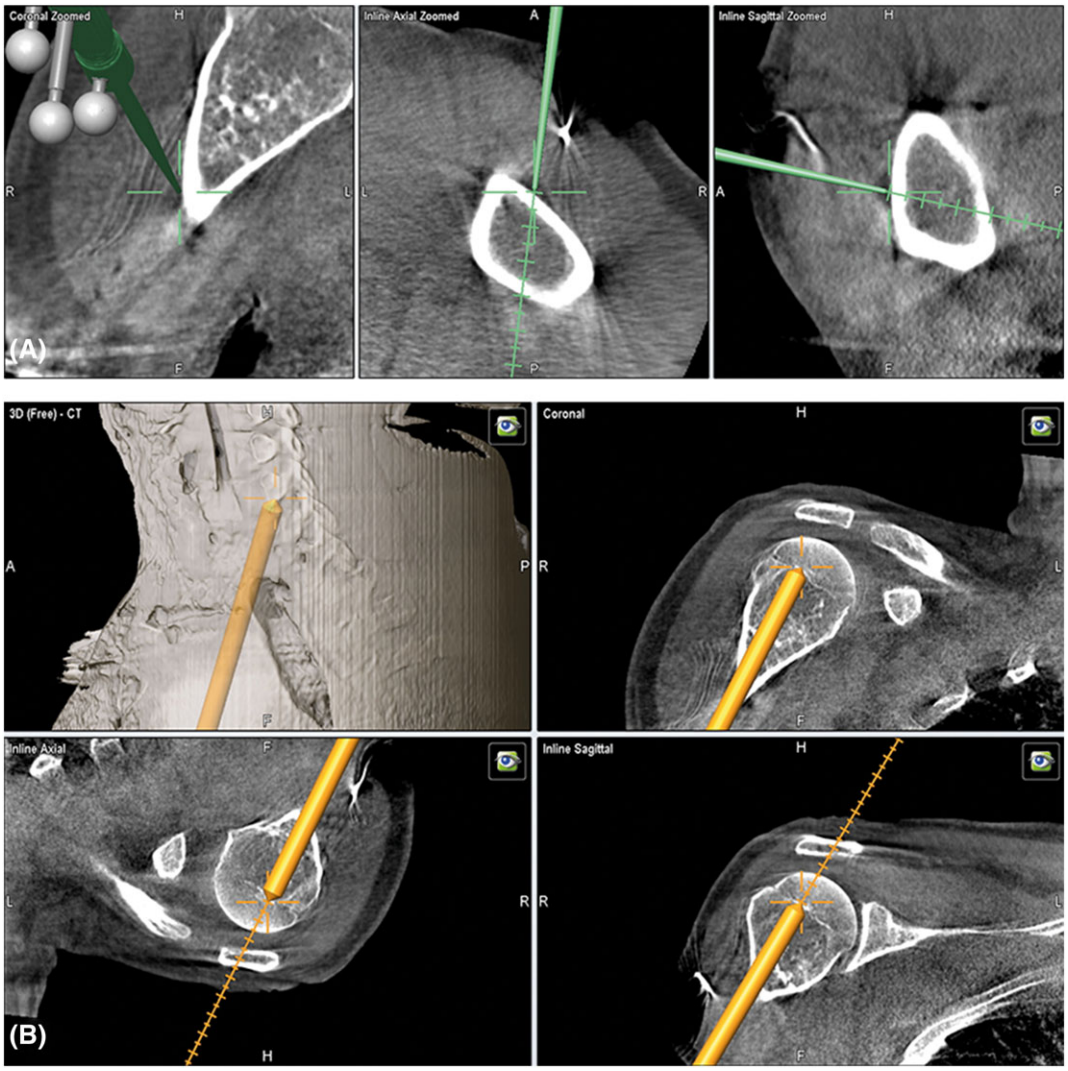

FIGURE 3 A-B, The validation and navigation view for patient 6, who had an atypical cartilaginous tumour in the proximal right humerus. A, The surgeon has to validate the automatic registration using the navigated pointer by following the bony surface and visually verifying the navigation view. B, After removing the tumour with the navigated curette, the surgeon checks the cavity for potential tumour residue

Clinical follow-up data was extracted from the patient management system.

3 | RESULTS

3.1 | Indications

CBCT navigation was a technical success in all nine cases. The surgeon reported added value of CBCT navigation in all cases with the exception of patient 4. This patient had an ulnar deformation due to multiple osteochondroma, and an osteochondroma had to be removed. The deformation made it difficult to see the osteochondroma in all planes, and thus navigation had no added value in resection of the lesion. Reasons to use navigation are listed in Table 2.

Patients 1 and 2 underwent an intraoperative control scan to check if complete tissue removal was achieved. For patient 1, the scan showed no complications. Patient 2 had subchondral cysts (Figure 4A). After initial curettage, the control scan revealed a small cyst was still partially intact, so curettage was extended to this part of the lesion (Figure 4B).

3.2 | Image quality and registration accuracy

Patients 5 and 6 were imaged using the high-dose protocol, because the pelvis and thorax have a relatively high mass. The proximal humerus of patient 1 could be imaged with the low-dose protocol because of his age and smaller body size. The DAP data for patient 2 were missing from our registration system.

The image quality scores are reported in Table 3. Both the radiologist and orthopaedic surgeon gave the tumour visibility and tumour delineation a median score of "good." The orthopaedic surgeon gave the vital structure visibility and registration accuracy a median score of "very good." The κ was 0.37, 0.40, and 0.12 for tumour visibility, tumour delineation, and vital structure visibility, respectively, without

TABLE 2 Imaging and navigation characteristics

Patient No.	Scan Protocol	Total Dose Area Product (DAP), Gy.cm^2	Registration Accuracy	Reason for Navigation	Added Value
1	Low dose	16.17[a]	5	Close to open growth plate Close to joint Bone shape poorly visible on fluoroscopy Repeated surgery (tumour residue)	Yes
2	Low dose	N/A[b]	N/A[c]	Close to open growth plate Close to joint Bone shape poorly visible on fluoroscopy	Yes
3	Low dose	8.22	N/A[c]	Bone shape poorly visible on fluoroscopy Repeated surgery (tumour residue)	Yes
4	Low dose	9.26	2	Tumour shape poorly visible on fluoroscopy	No
5	High dose	42.15	4	Bone shape poorly visible on fluoroscopy Close to joint	Yes
6	High dose	43.49	5	Bone shape poorly visible on fluoroscopy Close to joint	Yes
7	Low dose	4.16	5	Bone shape poorly visible on fluoroscopy Close to joint	Yes
8	Low dose	3.44	5	Minimally invasive surgery Close to spinal cord	Yes
9	Low dose	0.49	5	Bone shape poorly visible on fluoroscopy Close to joint	Yes

[a]This total DAP includes both an initial CBCT and a control scan of the same dose protocol.

[b]Not available (N/A). The DAP data for this patient was missing from our registration system.

[c]No validation images were recorded during registration accuracy assessment for these patients.

statistical significance. Only for patient 4 were some characteristics rated "poor." Because of the severity of the deformations, the arm had to be placed on the abdomen instead of above the head. The low-dose image protocol proved not to be suitable for this amount of tissue. The large difference in tumour visibility scores for patient 4 might be because navigation was of no benefit to the orthopaedic surgeon. Furthermore, the helpfulness of navigation in preserving the spinal cord for patient 8 can explain the difference in vital structure visibility score between the orthopaedic surgeon and radiologist.

The registration accuracy could not be scored for patients 2 and 3. No validation images were recorded during registration accuracy assessment for these patients. For the other seven patients, the registration accuracy had a median score of 5 (range 2-5). Patient 4 was scored a 2, indicating a poor registration (Table 2).

3.3 | Procedure and set-up times

All procedure and set-up times are listed in Table 4. The median procedure time was 85 minutes (range 54-104 minutes). The median scan time was 5 minutes (range 2.5-15.5 minutes), and the median verification time was 3 minutes (range 2-5.5 minutes).

3.4 | Follow-up

The follow-up data after 2 months, consisting of an X-ray and a visit to the surgeon, are summarized for all patients in Table 5. Only patient 7 showed potential tumour residue on X-ray imaging. An MRI after 6 months revealed tumour recurrence. Patient 8 had a small avulsion fracture. Patient 4 did not return for follow-up, as this is not required for osteochondroma.

4 | DISCUSSION

It was feasible to use CBCT to set up navigation for benign bone tumour surgery. Navigation allowed control on tumour removal and tissue preservation. Indications for the use of CBCT navigation were (1) closeness to vital structures; (2) complexly shaped tumours or bone; (3) minimally invasive surgery; and (4) repeated surgery. The main indication for 60 navigated curettages by Gerbers et al[10] was large lesions located in difficult anatomical locations. Our study extends these indications in order to help other centres that want to selectively employ surgical navigation for benign bone tumours.

The majority of our patients either had a good or very good CBCT image quality. The κ was low, but both observers agreed image quality was at least acceptable in all but one patient. High-dose protocols can be used for body parts with a high mass, such as the pelvis or shoulders. The use of a low-dose protocol for a high-mass body part may result in image quality that is unfit for surgical navigation. However, a low dose should be considered whenever possible as this can reduce patient radiation exposure by a factor three while maintaining image quality.[12] Literature suggests that drawbacks of intraoperative 3D

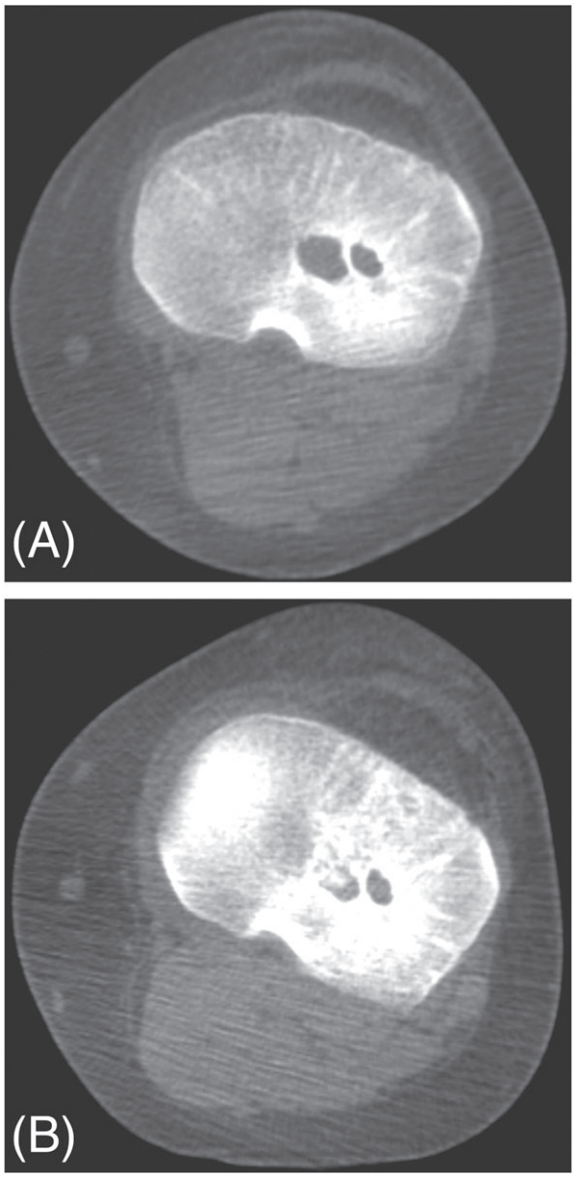

FIGURE 4 A-B, Axial slides of the CBCT of patient 2, showing subchondral cysts in the proximal left tibia. (A) The CBCT before curettage shows two cysts, while the control scan (B) reveals incomplete removal of one of the cysts. Surgery was continued, and the remaining cyst was removed

images are poor quality and a partial volumetric view.[13] The CBCT image volume with an 18.5-cm height and 24-cm diameter is limited, but every tumour in this study was small enough to be visualized completely together with surrounding vital structures. Gerbers et al[10] argued that navigation can be used for curettage when a CT dataset is available. Most of our bone tumour patients, however, did not have a CT scan available, so one had to be acquired either preoperatively or intraoperatively in order to use navigation. Our results suggested that intraoperative CBCT provides sufficient quality to be an alternative to preoperative CT.

The intraoperative CBCT was automatically registered to the patient with a median accuracy score of very good. In literature, three manual registration methods are commonly used: (1) pairing of anatomical landmarks or fiducial markers[14]; (2) matching of a point cloud with the bony surface[5-10]; and (3) matching two intraoperative fluoroscopic images with the 3D volume.[15,16] The most frequently used registration method is surface matching. Its registration accuracy is commonly reported as the root mean square (RMS) error between the points and the matched surface[13] and should be less than 1 mm.[17] As automatic registration does not require user input, an RMS error value cannot be calculated. The true registration error is, however, not uniform over the navigated volume, but differs per location.[18] Visual verification using a pointer forces the surgeon to assess the registration accuracy across the entire region of interest, which may be more representative than a numerical value. Surface matching requires a relatively large and irregularly shaped surface for accurate registration. This might be possible for large resections, but small tumours with barely exposed bone limit the registration accuracy.[19] Surface matching also works poorly for long bones because of the similar anatomy along its length.[13] For these cases, automatic registration with an intraoperative 3D scan, which does not require exposed bone for matching, can be a more appealing alternative.

Various studies have reported an increased surgery time because of the use of surgical navigation.[9,11] Steps potentially costing additional time as compared to non-navigated surgery were patient positioning, placing the reference base, acquiring a 3D scan, and validating the automatic registration. Patient positioning was planned beforehand and performed during the anaesthesiologic routine and therefore did not cost extra time. Another study on CBCT navigation did not report on patient positioning because of little variation in operating field for pedicle screw placement.[12] The duration of reference base placement was not measured. The median navigation set-up time was about 8 minutes. According to the literature, the duration of setting up navigation using a preoperative CT scan in an experienced centre was on average 4:25 minutes (range 2:03-5:40 minutes).[20] This measurement consisted of reference base attachment, manual image registration, and validation. Navigation did not significantly increase procedure time as compared with non-navigated surgery according to Gerbers et al.[10] Another group reported on navigation time including the osteotomy,[17] which makes it difficult to compare with our set-up times; however, a learning curve was evident, so that navigation times decreased. CBCT navigation set-up time appears to be longer than preoperative CT navigation set-up time, but we found this acceptable given the benefits of navigation. Our set-up times may still decrease because of the learning curve.

One of the nine patients had potential residual tumour at the follow-up X-ray, which resulted in a tumour recurrence after 6 months. Another study by Gerbers et al,[20] where two of 17 navigation patients had potential tumour residue, showed similar results. Here, the outcome of navigated curettage was compared with fluoroscopy-guided curettage of atypical cartilaginous tumours. No significant difference in tumour residue rates between these two groups was reported. It was suggested that navigated curettage can be improved by implementing a feedback mechanism on treatment progress.

TABLE 3 Image quality scores on a five-point scale (1 = *very poor*, 2 = *poor*, 3 = *acceptable*, 4 = *good*, 5 = *very good*)

	Tumour Visibility		Tumour Delineation		Vital Structure Visibility	
Patient No.	Radiologist	Orthopaedic Surgeon	Radiologist	Orthopaedic Surgeon	Radiologist	Orthopaedic Surgeon
1	4	4	4	4	4	5
2	5	5	5	5	5	5
3	5	4	4	4	4	5
4	4	2[a]	3	3	3	2
5	4	4	4	4	4	4
6	4	4	4	5	3	4
7	5	4	4	4	4	4
8	4	4	3	4	3	5
9	5	5	5	4	4	5

[a]Image quality scores below acceptable were underscored.

TABLE 4 Procedure times and set up duration

Patient No.	Procedure Time, minutes	Scan Time, minutes	Validation Time, minutes
1	96	15.5[a]	2.0
2	91	5.0	2.0
3	59	5.5	3.0
4	85	7.5[b]	4.5
5	94	5.5	2.5
6	68	3.0	5.5
7	104	3.0	4.0
8	54	2.5	2.5
9	59	5.0	5.0

[a]The 15.5-minute scan time for patient 1 occurred because of connection problems between the CBCT scanner and the navigation system. After the procedure, this problem was solved and never occurred again.

[b]The 7.5-minute scan time for patient 4 was caused by improper initial patient positioning, which led to the C-arm hitting the table during the collision check.

TABLE 5 Follow-up data after 2 months

Patient No.	Complications on X-ray
1	No
2	No
3	No
4	N/A[a]
5	No
6	No
7	Recurrence
8	Avulsion fracture
9	No

[a]For the patient with an osteochondroma (no. 4) follow-up was not required (N/A).

Some potential limitations of this pilot study should also be discussed. First, the number of patients is low and follow-up is limited, which is inherent to a feasibility study. However, it is a quick way of assessing feasibility and indicating points of improvement, and it can be a starting point for further studies. Second, because of the heterogeneity in benign bone tumour patients, it was not possible to compare procedure times with a historical cohort to provide a realistic estimation of the extra time needed to set-up CBCT navigation.

Hybrid operating theatres are becoming more widespread, while clinicians and researchers are investigating new indications for intraoperative 3D imaging. Challenging cases of benign bone tumours, where fluoroscopy does not sufficiently visualize the area of interest, may benefit from this technique. When preoperative CT navigation is not possible, either because there is no CT scan available or too little bone is exposed to perform an accurate registration, intraoperative CBCT navigation could be an alternative. Intraoperative CBCT navigation was only used in selected cases with an expected health benefit, so as to use the system efficiently because of its limited availability and costs of usage.

Navigation was used during benign bone tumour curettage to achieve better tumour control as compared with fluoroscopic guidance. This is, however, not yet demonstrated. Not every patient in this study had a control CBCT to show that the resection was accurate. Instead, we will investigate how well a surgeon can resect planned lesions in a cadaver study and verify this with control CBCT scans. Moreover, current navigation software only shows where an instrument is at any given time, but not where it has previously been. Because treatment progress is not monitored, (microscopic) tumour residue might remain. The residue rate after navigated bone tumour surgery may be improved by software that updates which parts of the delineated tumour were treated.[20] To go from instrument tracking to progress tracking requires dedicated software, as well as preoperative treatment planning on MRI and intraoperative image fusion. Once planning and execution of navigation is optimized, we can set up an IDEAL stage 2b exploration study to

investigate the clinical effects of navigated curettage by comparing it with a control group.[21]

In conclusion, it is feasible and safe to use intraoperative CBCT to set up navigation for benign bone tumour surgery. Indications for navigation in daily clinical practice are closeness to vital structures, complexly shaped tumours or bone, minimally invasive surgery, and repeated surgery.

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CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

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