



Technical notes

Joint-preserving tumour resection around the knee with allograft reconstruction using three-dimensional preoperative planning and patient-specific instruments☆



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ABSTRACT

Background: The region around the knee joint is a common location of malignant bone tumours. Limb salvage procedures, whenever possible, are preferred to amputation. Allograft reconstruction is an accepted procedure to restore large bone defects. Preoperative three-dimensional (3D) planning and patient-specific instruments (PSI) have already been introduced. The purpose of this study was to provide a technical guideline for joint preserving tumour resection and allograft reconstruction around the knee using 3D planning and PSI.

Material and methods: 3D triangular surface models are created based on computed tomography (CT) and magnetic resonance imaging (MRI) data, whereby tumour expansion in the bone and affection of the surrounding structures are assessed. We describe the preoperative 3D analysis and planning in tumours around the knee joint. In addition, we provide a description of different PSI as well as cutting-techniques to enlarge the toolkit and facilitate a broad range of joint preserving tumour resections with allograft reconstruction around the knee. The basic guide serves for the registration of the preoperative plan for the surgery. Reference pins facilitate the application of further guides. Different additional guide designs can be applied, such as “safety guides,” “osteotomy guides,” and “allograft adjustment guides.”

Discussion: The use of 3D planning and generation of PSI offers valuable tools in tumour resection and allograft reconstruction around the knee joint. To perform complex osteotomies and to preserve vital structures PSI seems to be helpful tools. A step-by-step guideline is provided for the use of 3D preoperative planning and sequentially applied patient-specific guides.

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1. Introduction

The region around the knee joint is one of the most frequent locations of malignant bone tumours [1,2]. However, tumour surgery around the knee joint is challenging. While in the past amputation of the affected limb was the only surgical option in a high number of cases, different other procedures have been developed over time such as rotationplasty [3], massive bone allograft re-

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construction [4–7] and implantation of modular total knee arthroplasty [8–10]. Limb-preserving procedures have become an accepted alternative [11,12] and the amputation rate has decreased significantly in recent years. Preoperative three-dimensional (3D) planning and patient-specific instruments (PSI) have already been introduced for navigating tumour resections and have been shown to be useful tools in achieving these goals [13,14]. Wang et al. [14] previously described the benefit of PSI for tumour resection around the knee. The joint reconstruction was, thereby, performed with a total knee arthroplasty. However, considering joint preserving surgery, the tumour resection and the allograft preparation are probably much more challenging. To the best of our knowledge, using 3D planning and PSI for both, tumour resection and allograft reconstruction around the knee joint, has not been described thus far.

The purpose of this study was to provide a technical guideline for tumour resection and allograft reconstruction around the knee joint using 3D preoperative planning and PSI. The focus of this study was to give a detailed description of the entire spectrum of different types of PSI and their application in tumour resection near the knee joint to enlarge the toolkit of the treating surgeon. The basic principles of computer-assisted planning of joint preserving tumour resection around the knee are similar to the one previously described for the correction of posttraumatic bone deformities [15,16]. However, since the extension of the tumour is different in every case, in our opinion, it is important to have a broad tool kit for the preoperative planning and design of the PSI. Herein we provide a brief overview of the general technique and then focus on a detailed description of the steps that are specific for joint preserving tumour resection around the knee.

2. Materials and methods

2.1. Generation of 3D surface models and preoperative planning

To assess dimension and activity of the tumour, magnetic resonance imaging (MRI) and computed tomography (CT) are regularly used [17,18]. 3D triangular surface models are created with standard segmentation methods based on these CT and MRI data, as previously described in [13,15,16,19]. Thereafter, the 3D surface models are imported into the in-house-developed planning software Computer Assisted Surgery Planning Application (CASPA) (Balgrist CARD AG, Zürich, Switzerland). High-resolution CT data of the bone, required for generation of the PSI, needs to be aligned with the MRI data that show the tumour expansion. Consequently, the CT-reconstructed models and the MRI-reconstructed models (bone and tumour) have to be transferred to a common 3D space by aligning the bone model extracted from MRI with the CT-reconstructed bone model. The resulting MRI-CT coordinate transformation can then be used to transform the other soft-tissue structures contained in the MRI to the CT coordinate space. The iterative closest point (ICP) [20,21] surface registration algorithm is used for bone alignment. After union of the CT- and MRI-reconstructed models, an overview about the involvement of the structures is visualised. The exact 3D relation between the tumour and the bone can be visualised to define the resection margins and plan the surgery. In dependence on the tumour location, the surrounding structures such as the soft tissues (e.g., collateral or crucial ligaments) could be considered, and if needed, 3D models can be created from these structures. Once the margins, the resection planes, the type of reconstruction and the fixation devices are defined, different types of patient-specific guides (i.e., basic guide, safety guide, osteotomy guide, allograft adjustment guide) can be designed to transfer the preoperative plan to the surgery.

2.2. Design of patient-specific guides

2.2.1. Basic guide

The basic guide serves as a reference guide, applied first on the bone and serving as a registration tool between the 3D planning and the intraoperative situation (Figure 1). In other words, for an accurate matching of the preoperative plan to the

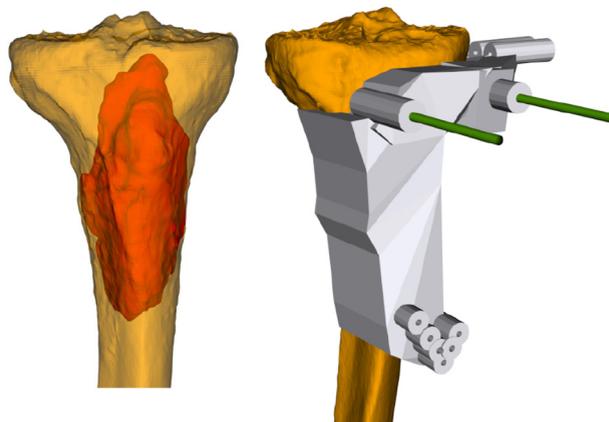


Figure 1. Basic guide: The Basic guide is marked in grey with the inserted reference surgical pins in green. The tumour mass is marked in red.

intraoperative situation, the guide needs to be placed exactly on the position that has been pre-planned. Shaping the undersurface of the guide as a negative of the bone surface in regions with distinct bone features ensures that the guide can be placed precisely on the planned position on the bone. To control the fitting accuracy, a 3D printout of the native bone is regularly used. Due to soft-tissue interruption, it is important to remove the whole periosteum. It has to be kept in mind that this step is only allowed in regions where the tumour does not reach the surface of the bone. In other words, in every case it is necessary to plan the part of the basic guide that matches the bone surface in safe distance to the affected bone area. Thereby, the reference pins can be placed safely in the unaffected bone. On one hand this is necessary to prevent dissemination of tumour cells through the pins. On the other hand the pins need to stay in place and shall not be removed with the resected tumour since they might be needed for additional guides. Thus, the basic guide probably needs to be planned several centimetres outside of the affected bone area, especially in cases where the tumour reaches the surface of the bone or even disrupts its continuity. To improve precise positioning of the guide, additional hooks can be incorporated in the design of the guide shape that fits on unique levels of the bone. Hooks that clasp the bone give additional rotational and translational stability for correct positioning of the guide and it could be shown that guides with such stabilising hooks enable more precise osteotomies [22]. The basic guide should be carefully designed since the entire procedure builds on it. As soon as the surgeon finds the right position for the basic guide, placement of reference surgical pins is performed (Figure 1, reference surgical pins in green). For this purpose the design of the basic guide needs predefined drill sleeves attached on it. Every further step relies on these pins, including every further placement of other guides (Figures 2, 3, and 5, green surgical pins).

2.2.2. Safety guides

One of the most important differences between corrective osteotomies and tumour resection is that in tumour resection planning of the osteotomy planes needs to respect tumour location and expansion as well as required resection margins. In such cases, it may be possible that the osteotomy weakens the bone relevantly and a fracture can occur during further procedures or during the osteotomy itself. To prevent such a scenario, safeguarding surgical pins could be planned and used. The surgical pins provide temporary stabilisation and minimise the risk of a fracture. Furthermore, they can be used for a temporary external fixator, to secure the position of the fragments during the surgery (i.e., during the osteotomy or the tumour resection). In cases where the resection of the tumour might destabilise the bone, such an external fixator needs to be attached before the tumour resection and, therefore, it is crucial to plan the positioning of the surgical pins accordingly. To prevent dissemination of tumour cells, the pins need to be placed a safe distance outside the tumour tissue (Figure 2, gold surgical pins). In an ideal case, these surgical pins should be placed in a way that their boreholes can be used later as screw holes for fixation of the plate. For this reason, we use 4.0 mm Schanz pins, which are smaller than the 4.3 mm drill, used for the screws of 4.5/5 mm plates. The surgical pins are also screwed in through guides that likewise are equipped with drill sleeves.

The protection of structures, which are in danger due to a break out, is another benefit that can be achieved with safety guides. As an example, the use of a surgical pin for protection of the bony insertion of the posterior cruciate ligament (PCL) is shown in Figure 2. The inserted pin holds the bony insertion of the PCL in position during the resection osteotomy and subsequent removal of the bone block to prevent a break out. Obviously, such securing pins can be placed in other regions as well, such as the insertion of the anterior cruciate ligament or femoral insertion site.

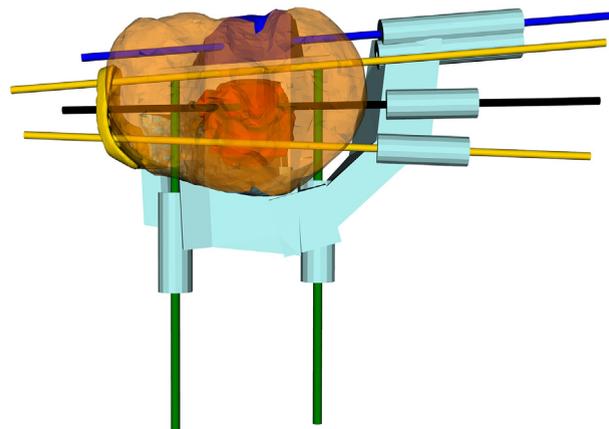


Figure 2. Safety guide: In green, the reference surgical pins that serve for orientation of the safety guide that is marked in turquoise. The black pin is a pin that is wrongly placed, and it risks dissemination of tumour cells due to its placement through the tumour. The most posterior pin in blue (respectively the one on top in this graphic) is a safety surgical pin that holds the bony insertion of the posterior cruciate ligament (also marked in blue) in position during osteotomy and subsequent tumour removal. In gold, surgical pins that serve for temporary external fixation. These boreholes of the pins also serve for later plate fixation (plate is marked in gold).

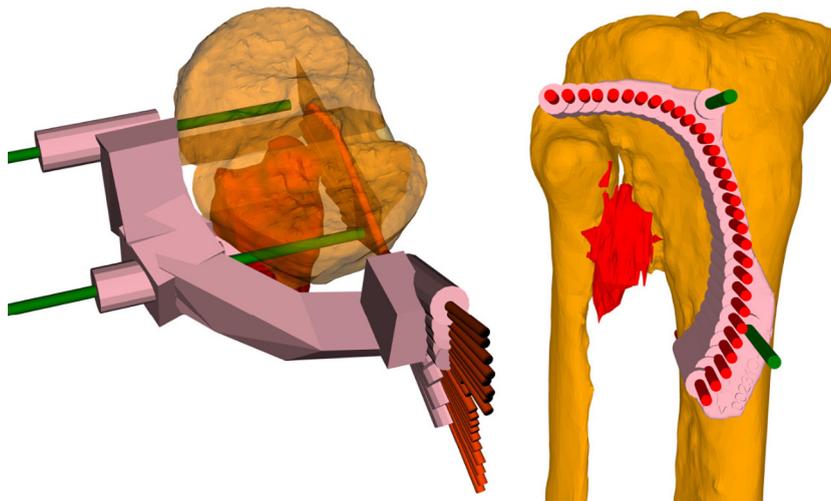


Figure 3. Osteotomy guide: Osteotomy guides marked in pink. The reference surgical pins in green. The red-marked masses illustrate the tumours. On the left side, the fan-technique is shown to perform an osteotomy behind a tumour in an area difficult to reach without such guides. The drill sleeves of the guide define the drill depth to prevent drilling too deep into surrounding vital tissue.

2.2.3. Osteotomy guides

There are already different techniques introduced to perform an osteotomy with PSI. The first option is to design a guide that constrains the saw blade (i.e., cutting slit guide, cutting saw guide or metallic inlet guide), as previously described [16]. These guides are useful if long and straight osteotomies have to be performed. In cases in which more complex osteotomies have to be performed, another option is to set surgical pins in cornerstones and use an additional cannulated chisel to complete the osteotomy. The third option is to perform the whole osteotomy with concatenated drill holes [16] (Figure 3). A relevant advantage of this third technique is that complex curved osteotomies can be performed more easily. This technique has become the preferred technique in complex osteotomies and tumour resection in our clinic. Further to the direction of the cut, the guide also navigates the surgeon in the depth. Therefore, the lengths of the drill sleeves are matched to the required drilling depth, preventing the surgeon from drilling too deep. For example, with an anterior approach to the knee (i.e., to the tibia or the femur), osteotomies in the sagittal plane are feasible and the individual lengths of the drill sleeves prevent the surgeon from cutting too deep into the surrounding tissue (Figure 3). Performing an osteotomy in the coronal plane (i.e., posterior to the tumour), is more challenging without an additional approach and without harming the surrounding tissue (Figure 4). Considerations about

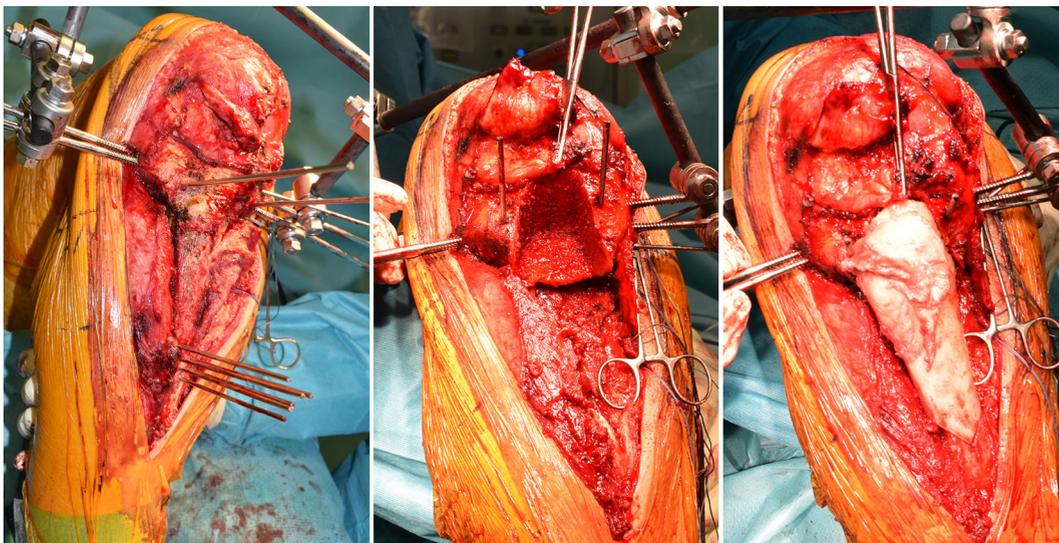


Figure 4. Patient with a tumour in the proximal tibia. On the left side, the exposed proximal tibia with the already applied external fixator. Performing an osteotomy in the sagittal plane is feasible with the anterior approach, but the second osteotomy in the coronal plane (i.e., behind the tumour) is much more challenging. Therefore, application of the fan-technique as shown in Figure 3 is helpful. In the middle, the site after resection of the tumour. On the right side, the site after insertion of the adjusted allograft.

this issue led us to the development of a further technique, the so-called fan-technique, using only a single borehole to perform the osteotomy (Figure 3). Using a guide, it is possible to perform, for example, in the coronal plane, a deep osteotomy through one borehole. Fanning through the hole allows cutting in the entire plane; likewise, the individual length of the drill sleeves pre-define the fanning depth. In some cases, this technique requires more than one guide to complete the osteotomy, because the differently orientated drill bushes can get in the way of each other. This approach enables the surgeon to cut behind the tumour while protecting the surrounding tissue (i.e., the crucial ligaments). Such a technique also could be used for other regions that are difficult to reach through the initial approach. The main advantage of this technique is the need of just a minimal exposition of the bone with a minimum of weakening of the cortical bone.

2.2.4. Allograft adjustment guides

Using allograft for interposition after tumour resection around the knee is an established technique in limb salvage procedures [4–7]. Due to the fact that tumour resection potentially produces an essential bone defect, allograft size needs to be considered. In very extensive cases, we prefer to use an equivalent bone (i.e., same bone in the same dimensions) as the affected bone, if possible. Using an equivalent allograft bone offers the advantage that the allograft needed for insertion could be used in one single piece, and, therefore, complex constructs can be avoided. Otherwise, an allograft construct has to be assembled that exactly fits in the bone defect. For this purpose, 3D surface models are created from CT scans of the allograft, similar to what was previously described. For preparation of the allograft, cutting guides are necessary as well, to customise the allograft to the proper shape needed for implantation.

Therefore, the cutting guides need to be applied on the allograft, as shown in Figure 5. Another method is to create a guide in which the allograft could be inserted, like a casket (Figure 5). In the latter option, the “casket guide” needs to be designed to find the proper fit of the allograft in its planned position. We prefer this type of guide when using an allograft from a diaphysis. Due to the absence of irregular bony landmarks on the diaphysis of the bone, it is more difficult to find a unique position for the guide. Therefore, it seems to be more feasible to use a casket guide whereby the allograft is placed and fixed in one position, and subsequent modelling of the allograft is easier. Avoiding repetitive placement of the guide on the allograft with the casket guide reduces the risk of malpositioning of the guide due to the absence of irregular bony landmarks. Additional drill sleeves and cutting slits need to be added onto this guide in such a manner that the allograft could be prepared as needed. With the cutting slits and the drill sleeves, the drill bit or saw blade is constrained to the planned osteotomy planes, and proper customising of the allograft to a suitable strut will be achieved. It is important also to consider the offset in preparation of the allograft. The offset is the thickness of the saw blade or the drill that is used for preparation of the allograft.

The local ethical committee approved this study (Zurich Cantonal Ethics Commission, KEK-ZH 2017-01810), and all patients gave their informed consent for their participation in and the publication of this study.

3. Discussion

Tumour surgery around the knee joint is challenging, but in the course of time, different procedures have been developed for limb salvage. Limb salvage procedures show higher patients satisfaction than does amputation [23]. Improvements in surgical techniques allow limb salvage procedures in most cases nowadays. The most frequently performed techniques for the reconstruction after tumour resections are modular megaprosthesis or massive bone allografts. A disadvantage of an arthroplasty is the limited lifetime of a prosthesis as well as poorer function of the knee [24]. Furthermore, the attachment of important soft-tissue

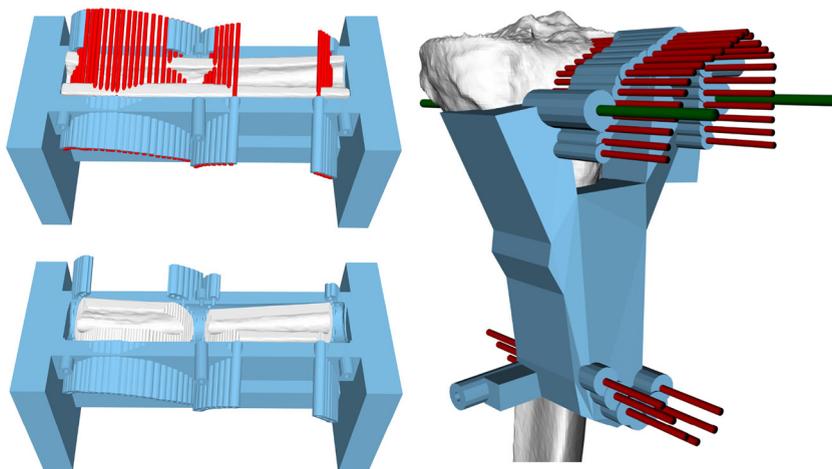


Figure 5. Allograft adjustment guide: The allograft adjustment guides are marked in light blue. The reference surgical pins are green. On the left side, a casket guide for adjustment of the allograft is marked in white. On the right side, adjustment of an allograft of the proximal tibia is shown.

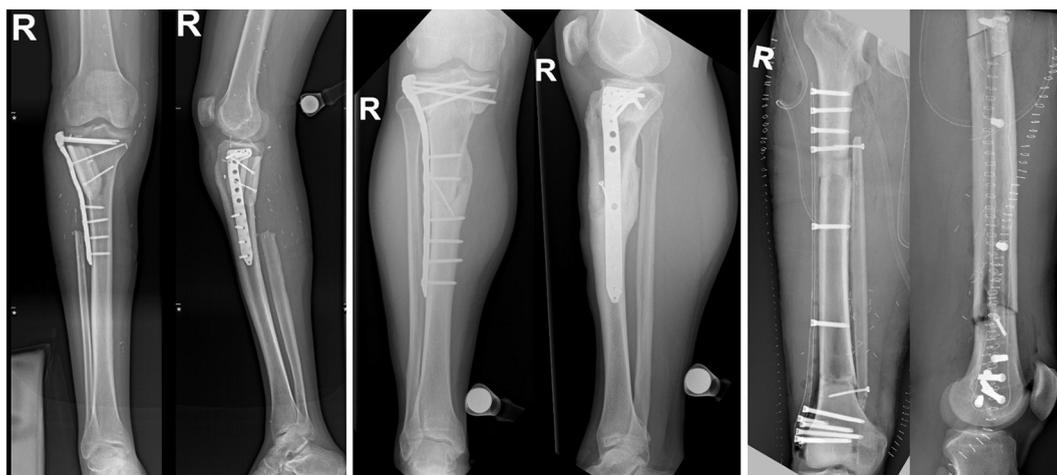


Figure 6. Postoperative radiographs after tumour resection and allograft reconstruction around the knee joint using preoperative three-dimensional planning and patient specific guides.

structures such as the patellar tendon to the metallic surface of the prosthesis remains difficult. However, in massive bone allografts, the spared host tendons can be sutured directly to the allograft tendon insertions. Especially in young patients, whenever possible arthroplasty should be avoided in our opinion. Hence, using allograft offers a valuable alternative. Particularly, using an allograft for the reconstruction after tumour resection around the knee is a well-established technique [4–7]. In addition, 3D preoperative planning is becoming more popular and shows high potential together with PSI. To the best of our knowledge, allograft reconstruction using 3D planning and PSI in joint-preserving tumour resection around the knee has not been described thus far.

The hereby-introduced technique for the treatment of tumours around the knee joint cannot be standardised for every tumour resection. Every case needs to be analysed individually and has to be planned carefully. For this purpose, the techniques presented here are a tool set and guideline for the treating surgeon to allow thorough planning of the surgery and precise execution of the preoperative plan. The application of the different types of guides (i.e., basic, safety, osteotomy, and allograft adjustment guides) facilitates surgical execution. Thereby, the whole procedure becomes more accurate or even feasible by applying the guides not only for resection of the tumour but also for preparation of the allograft. Through the aid of the different cutting techniques (i.e., cutting with drills), it is possible to perform complex curved osteotomies and to spare vital tissue. For example, the presented fan-technique allows cutting in regions difficult to reach with a minimum of exposure of bone and thereby with the least harm to the surrounding tissue. Examples of patients that have undergone tumor resection with the use of the here presented techniques are illustrated in Figure 6.

One of the leading principles in tumour surgery is to adhere to the desired resection margins to prevent local recurrence of the tumour. Marginal or intralesional resections cause higher recurrence rates than wide resection margins. Guo Z. et al. [25] showed in a case series about malignant tumour resection at the pelvis, a 33% local recurrence in patients with marginal or intralesional resection in comparison to 11% local recurrence in patients with wide resection margins. It has been shown that application of PSI can be useful and allows good cutting accuracy [13,14,26]. Cartiaux O. et al. [26] showed in simulated pelvic bone tumour surgery no intralesional tumour cutting with the use of PSI.

Notwithstanding, we must mention that application of such complex PSI should be in the hands of a surgeon who already has vast experience with these systems. Inappropriate application of a guide could cause serious consequences.

As a limitation of the technique has to be noted, that it is solely applicable in solid bone tumours. Precise resection of soft-tissue tumours is not possible due to the circumstance of missing rigidity of the structures and, thus, absent rigid landmarks for the orientation of the application of PSI.

In our opinion, the herein described procedure offers valuable tools in tumour surgery around the knee joint and should be considered for patients for whom limb salvage procedure is reasonable and aimed.

Ethical statement

The local ethical committee approved this study (Zurich Cantonal Ethics Commission, KEK-ZH 2017-01810) and all patients gave their informed consent for their participation in and the publication of this study.

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