Surgical inaccuracy of tumor resection and reconstruction within the pelvis

An experimental study

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Background and purpose Osseous pelvic tumors can be resected and reconstructed using massive bone allografts. Geometric accuracy of the conventional surgical procedure has not yet been documented. The aim of this experimental study was mainly to assess accuracy of tumoral resection with a 10-mm surgical margin, and also to evaluate the geometry of the host-graft reconstruction.

Methods An experimental model on plastic pelvises was designed to simulate tumor resection and reconstruction. 4 experienced surgeons were asked to resect 3 different tumors and to reconstruct pelvises. 24 resections and host-graft junctions were available for evaluation. Resection margins were measured. Several methods were created to evaluate geometric properties of the host-graft junction.

Results The probability of a surgeon obtaining a 10-mm surgical margin with a 5-mm tolerance above or below, was 52% (95% CI: 37–67). Maximal gap, gap volume, and mean gap between host and graft was 3.3 (SD 1.9) mm, 2.7 (SD 2.1) cm^3 and 3.2 (SD 2.1) mm, respectively. Correlation between these 3 reconstruction measures and the degree of contact at the host-graft junction was poor.

Interpretation 4 experienced surgeons did not manage to consistently respect a fixed surgical margin under ideal working conditions. The complex 3-dimensional architecture of the pelvis would mainly explain this inaccuracy. Solutions to this might be to increase the surgical margin or to use computer- and robotic-assisted technologies in pelvic tumor resection. Furthermore, our attempt to evaluate geometry of the pelvic reconstruction using simple parameters was not satisfactory. We believe that there is a need to define new standards of evaluation.

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Treatment of malignant tumors within the pelvis (mainly osteosarcoma, chondrosarcoma, and Ewing sarcoma) is challenging due to the complex 3-dimensional (3D) geometry of the bony pelvis and the proximity of organs and structures that are difficult to reach, such as vessels, the bladder, the rectum, and the sciatic nerve (Donati et al. 2005). Surgery with an adequate margin is necessary for a low risk of local recurrence (Kawaguchi et al. 1995, Pring et al. 2001, Weber et al. 2002). Local recurrence rates from 28% to 35% have been reported after limb-salvage procedures for pelvic tumors (Delloye et al. 2007).

Surgeons generally use anatomical landmarks on the pelvis to define cutting planes. These landmarks are based on computed tomography (CT) scanner slices, which are 2-dimensional (2D) representations of a 3D object. Errors may come from each stage of the surgical treatment: scanning and delineating the tumor, planning resection planes with an

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adequate margin, and finally performing the resection itself.

Several reconstruction methods exist. Osseous massive allografts present some technical advantages. They can be shaped to fit the pelvic defect perfectly and they allow good reinsertion of soft tissues like tendons and muscles. Hence, they provide true anatomical restoration of the complex 3D architecture of the pelvis (Delloye et al. 2007).

Nonunion and fracture are both major complications of using allografts. Many studies have dealt with these clinical outcomes (Bell et al. 1997, Ortiz-Cruz et al. 1997, Friedlaender et al. 1999, Thompson et al. 2000, Hornicek and Gebhardt 2001, Sorger et al. 2001, Dion and Sim 2002, Hillman et al. 2003, Mankin et al. 2005, Wheeler and Enneking 2005). However, the ranges of the rates reported are large. Delloye et al. (2007) wrote: "When excision of a pelvic tumor and reconstruction have been combined in one procedure, the reported complication rate has been high, ranging from 30% to 90% in series ranging in size from 9 to 96 patients". Thus, assessment of the quality of a pelvic reconstruction using clinical outcomes is still a difficult task.

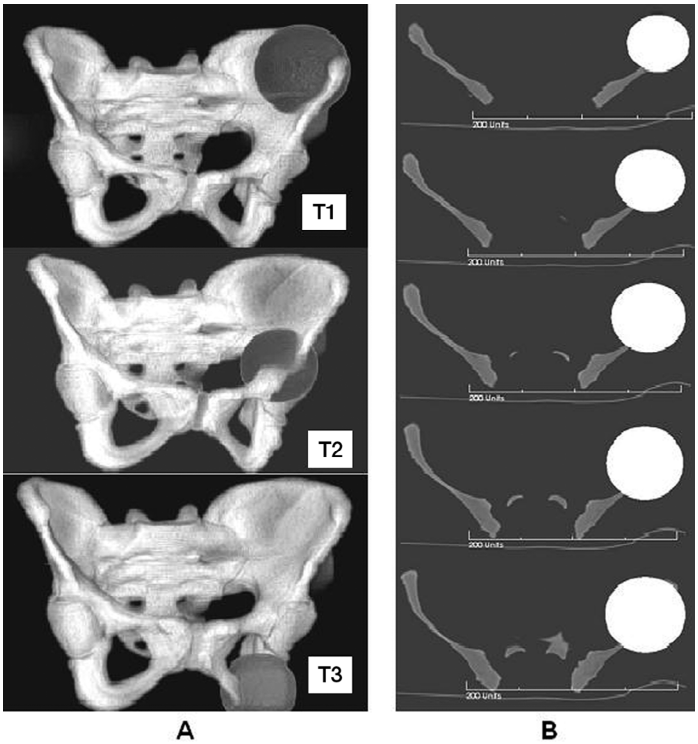

Figure 1. Virtual tumors. (A) 3D views: T1 in zone I of Enneking, T2 in zone II, and T3 in zones II–III. (B) Examples of transverse slices, given to surgeons, of the virtual tumor in zone I (T1) for resection planning. A graduated scale of 200 mm was given for each slice.

We designed an experimental model using plastic pelvises to simulate tumor resection and reconstruction using freehand (conventional) technique. We explored the following questions.

(1) Under ideal working conditions, what is the probability that a surgeon would manage to respect a fixed 10-mm surgical margin during pelvic tumor resection? (2) How can we qualify the geometry of a host-graft reconstruction?

Material and methods

4 senior surgeons, all experienced in pelvic surgery, were each asked to perform resection of 3 different pelvic tumors and their reconstruction. 12 identical plastic pelvises and 12 plastic left hemipelvises were procured (Sawbones Worldwide, Pacific Research Laboratories Inc., Vashon, WA) and considered to be host bone (host) and allograft (graft) respectively.

Experimental model of freehand technique

Creation of virtual tumors. The 12 hosts were scanned (spiral Elscint Twin CT scanner with 2.7-mm slice thickness). 3 sets of tumors were virtually created: tumor 1 in zone I (T1, iliac wing), tumor 2 in zone II (T2, acetabulum), and tumor 3 over zones II and III (T3, acetabulum and obturator foramen) according to Enneking and Dunham (1978). The tumor was represented by a sphere of fixed diameter and placed on the 3D CT scan of the pelvis (Figure 1a) using the visualization software Volview version 2.0.5 (Kitware Inc., Clifton Park, NY).

Pelvic tumor resection. Each surgeon received a print with 32 sequential coronal slices, 32 trans-

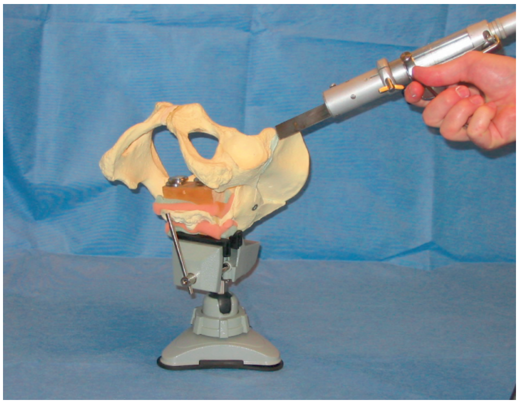

Figure 2. The sawbone is rigidly fixed by a steel clamp with a 360° rotational base. The cutting is performed using an oscillating saw.

verse slices, and 20 sagittal slices for each tumor (Figure 1b). A graduated scale of 200 mm was available on each slice.

The surgeon could plan resection planes and perform cutting of the 3 tumors (T1, T2, T3) without limitation in time. The resection should achieve a 10-mm surgical margin with a tolerance of 5 mm above or below. Based on the 2D slices of the tumor, the surgeon could put some landmarks with a skin marker on the host to guide the cutting. After planning and landmarking, he had to perform tumor resection by cutting the host using an oscillating saw. In order to simulate patient positioning on the operating table, the host was rigidly fixed by a steel clamp with a 360° rotational base (Figure 2).

Allograft reconstruction. Each surgeon had to reconstruct the 3 pelvises after tumor resection. An oversized graft was given to reconstruct T1 and T3, in order to increase the technical difficulties. A size-matched graft was chosen to reconstruct T2 because it simulated an articular reconstruction. As for tumor resection, the surgeon could put some landmarks on the graft with a skin marker to guide the cutting. He could also place the graft into the gap to check its size. Each surgeon was allowed additional cuttings to optimize the shape of the graft. The host-graft reconstruction was fixed temporarily with K-wires (2 mm in diameter).

Evaluation of the resection margin

Resected parts were scanned (spiral Elscint Twin CT scanner with 2.7-mm slice thickness) and registered with the 3D CT scan of the corresponding host. Margin error was calculated as the minimal distance between the 10-mm surgical margin and each resection plane, using Volview with its distance measurement tool. Negative values of margin error were given for cutting below the target and positive values for cutting above the target.

Evaluation of the reconstruction geometry

Each host-graft junction (HGJ) was evaluated by 4 different methods, each one evaluating a geometric parameter of the reconstruction. 3 observers classified each HGJ according to the degree of contact between host and graft (ordered categorical classification): degree 1 for full contact, 2 for contact > 50%, 3 for contact < 50%, or 4 for no contact.

Maximal gap between host and graft of each HGJ was measured with an electronic caliper (CD-15CP; Mitutoyo Inc., Aurora, IL) by the 3 same observers.

Gap volume between host and graft was measured for all the HGJs. An epoxy paste with scanner high-density paste (pc-7 Heavy Duty Paste Epoxy; PC-products, Allentown, PA) was used to completely fill the gap of the HGJ. All the constructs were scanned on a spiral Elscint Twin CT scanner with 2.7-mm slice thickness. As the density of the paste was high and different from the Sawbone, threshold segmentation permitted elimination of voxels corresponding to the Sawbone (Figure 3). The number of voxels corresponding to the paste was calculated, giving the HGJ gap volume.

Finally, contact surface available on the host was measured for each HGJ. Mean gap between host and graft was then calculated for each HGJ as the ratio of gap volume to the corresponding contact surface.

Statistics

Analyses were performed using the following statistical softwares: SPSS version 12.0 and SAS version 9.1. The probability that a surgeon managed to respect the determined surgical margin was calculated by a random 2-way ANOVA, considering the surgeons and the location of the resection planes as random effects. Our model was: $X_{ij} = \mu + \alpha_i + \pi_j + \alpha\pi_{ij} + e_{ij}$, where μ is the mean, α_i the effect of resection plane i, π_j the effect of surgeon j, $\alpha\pi_{ij}$ the interaction term between resection plane i and sur-

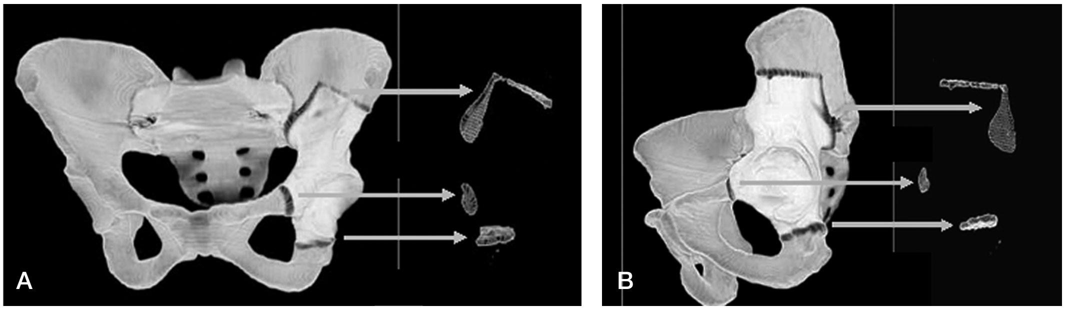

Figure 3. 3D CT scan of a host-graft reconstruction with the scanner high-density epoxy paste filling the gaps. A threshold segmentation permitted elimination of voxels corresponding to the Sawbone and to calculate the gap volume of the host-graft junction. (A) Anteroposterior view before and after segmentation of the paste. (B) Lateral view.

geon j, and e_{ij} the error term. The 95% confidence interval (CI) of the probability was calculated using the delta method (Hoffman and Kringle 2005). The variance of the probability was computed from the variance of μ and the variance of X by using partial derivatives of the probability.

The interobserver agreement of the variable "degree of contact" was calculated using weighted kappa statistics. The intraclass correlation coefficient was also calculated for this variable as a measure of reliability (between observers) (Fleiss 1971, Fleiss and Cohen 1973). Non-parametric Mann-Whitney or Wilcoxon tests were performed to compare each pair of observers for the variable "maximal gap" and each pair of surgeons for the variables "maximal gap", "gap volume" and "mean gap" (Petrie 2006). Differences were considered statistically significant at p-values of < 0.05.

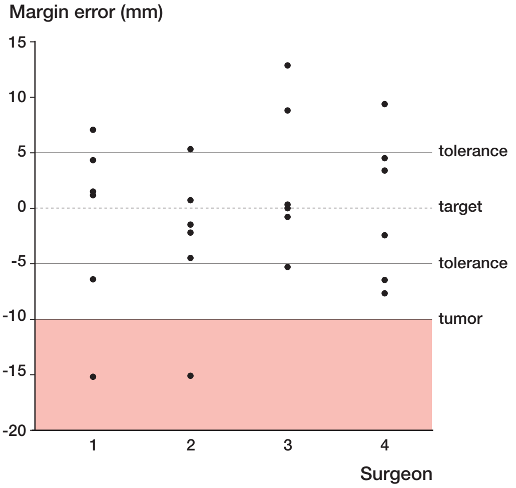

Figure 4. Margin error of the 24 resections performed by the 4 surgeons. The dashed line represents the recommended 10-mm safe margin, and the lines above and below it represent the accepted tolerance interval.

Results

24 resection planes and 24 HGJs were available for evaluation: 6 resection planes and 6 HGJs for each surgeon (1 resection plane and HGJ for each T1, 3 for each T2, and 2 for each T3).

Resection margin

The probability that a surgeon would manage to respect the 5-mm tolerance above or below the targeted 10-mm surgical margin was estimated to be 52% (95% CI: 37–67). For the 24 cutting planes, 11 did not respect the accepted 5-mm tolerance above or below the target (Figure 4). 2 cutting planes were intralesional, with error of 15 mm below the target.

Geometry of the host-graft reconstruction

Of the 24 HGJs, 22 were classified identically by the 3 observers (Obs1, Obs2 and Obs3). Most HGJs were classified as "< 50% contact" (Figure 5C). Weighted kappa correlation coefficients between observers were always very good and statistically different from zero: $\kappa_w = 0.91$ (CI: 0.77–1, $p < 0.001$) for (Obs1, Obs2) and (Obs1, Obs3) and $\kappa_w = 1$ for (Obs2, Obs3). The intraclass correlation coefficient was 0.94.

Mean maximal gap between host and graft for the 24 HGJs was 3.3 (SD 1.9) mm. Differences

Margin error and host-graft junction parameters according to the 4 surgeons. Values are mean (SD)

	Resection evaluation	Host-graft junction evaluation		
	Margin error (mm)	Maximal gap (mm)	Gap volume (cm^3)	Mean gap (mm)
Surgeon 1	5.9 (5.1)	4.2 (2.6)	2.6 (2.8)	2.4 (0.7)
Surgeon 2	4.9 (5.3)	3.0 (0.9)	3.0 (2.1)	3.9 (0.8)
Surgeon 3	4.7 (5.2)	2.4 (1.4)	2.2 (2.3)	2.5 (1.4)
Surgeon 4	5.6 (2.7)	3.6 (2.3)	2.7 (1.9)	4.1 (3.7)

between surgeons were not statistically significant (Table). Measurements performed by the 3 observers showed high correlation: Spearman correlation coefficient was 0.95 for (Obs1, Obs2), 0.96 for (Obs1, Obs3) and 0.97 for (Obs2, Obs3).

Mean gap volume between host and graft was 2.7 (SD 2.1) cm^3. There was no statistically significant difference between surgeons (Table).

There was a strong correlation between gap volume and contact surface (Figure 5A). Mean gap between host and graft was 3.2 (SD 2.1) mm. There was no statistically significant difference between surgeons.

Correlation between the 4 HGJ variables was relatively poor (Figure 5).

Discussion

Resection margin

This study was performed on plastic pelvises by 4 experienced surgeons working under ideal conditions: complete visualization and accessibility of the bone surface, absence of muscles and nerves, and absence of bleeding. Under these experimental conditions, the probability of managing a good surgical margin was 52% (CI: 37–67). The relatively large CI is explained by the great variation among the results of each surgeon (Figure 4), demonstrating a lack of accuracy. This estimation also means that, in the best case, around 33% of tumor resections did not respect a 5-mm tolerance above or below a fixed surgical margin.

Delloye et al. (2007), in a series of 24 patients, reported that surgical resection was wide in 19 cases, marginal in 6, and intralesional in 1. According to Enneking et al. (1980), our data, obtained under ideal working conditions, are consistent with those findings.

Inaccuracy during tumor resection can be explained by the anatomy of the pelvis. Due to its complex 3D geometry, delineating tumor extension, planning resection planes on 2D CT scan slices, manually transferring this planning to the pelvic bone, and finally performing the resection are difficult tasks even for experienced surgeons. Our study is the first to quantify the overall inaccuracy of these different sources of error experimentally.

To deal with this surgical inaccuracy, we can propose 2 solutions. Firstly, we can increase the resection margin from 10 mm to a safety margin of at least 20 mm. Surgical resection would not be more accurate. However, the safety would be increased but at the expense of surgical difficulties.

Secondly, we believe that the accuracy of tumor resection could be improved by using computer-assisted (CA) technologies. Commercially available navigation systems using preoperative CT scan data already exist for tumor resection in the pelvis (Hüfner et al. 2004, Krettek et al. 2004) and also for sacroiliac screw insertion (Gautier et al. 2001), pelvic osteotomies (Langlotz et al. 1998, Van Hellemondt et al. 2002), and pelvic ring fracture reduction (Hüfner et al. 2001, 2002). However, to our knowledge, no comparisons of the accuracy of osseous pelvic tumor resection between conventional and CA procedures have yet been performed. The data presented here could be useful for further evaluation of computer- and robotic-assisted technologies.

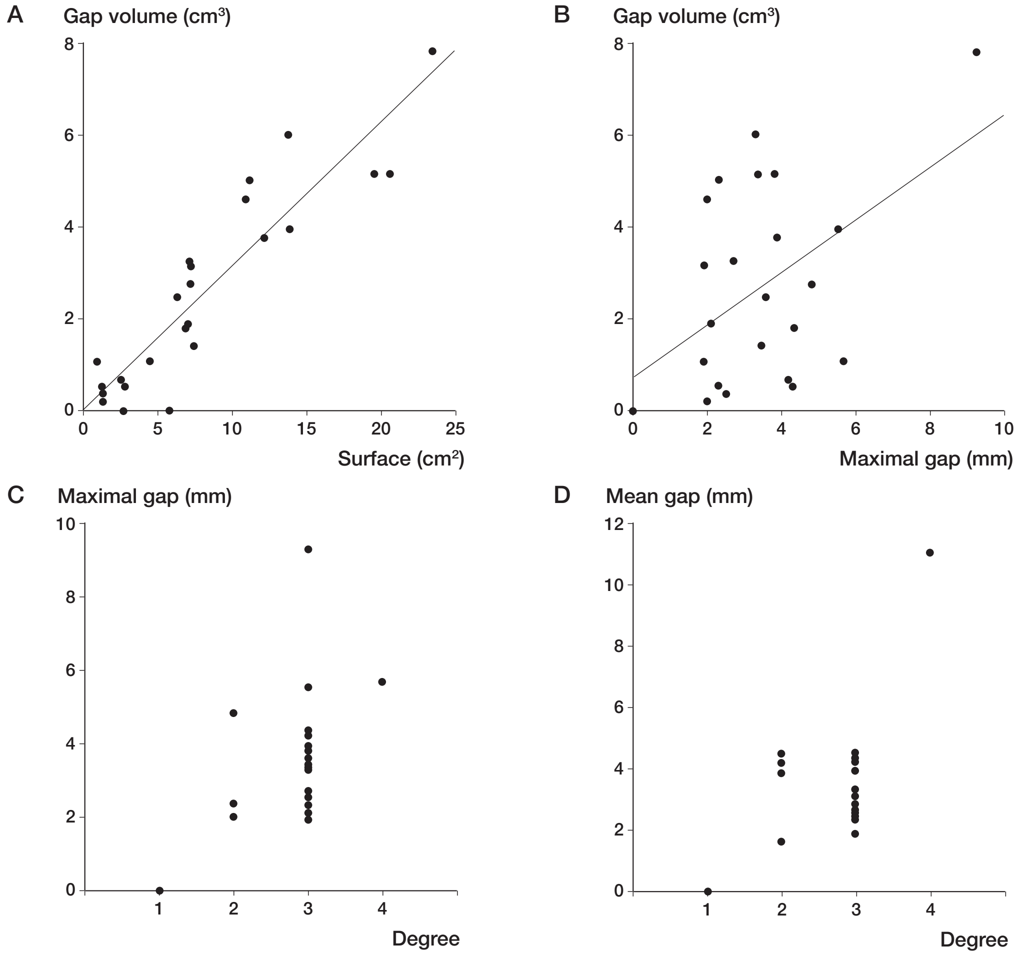

Figure 5. Correlation between host-graft junction parameters: maximal gap, gap volume, contact surface, mean gap, and degree of contact.

Reconstruction geometry

The second aim of this study was to evaluate the geometry of a host-graft reconstruction. We thus explored several methods to quantify simple geometrical properties of a host-graft junction. However, union of a host-graft junction is a multifactorial process: adequacy of the allograft, type and accuracy of the osteosynthesis, type and location of contact at the osteotomy site, modality of the rehabilitation, etc.

Enneking and Campanacci (2001) emphasized the need for an accurate and intimate contact at the osteotomy site in order to promote and accelerate union. Delloye et al. (2007) stated gaps and narrow surfaces posed concerns of nonunion at the junctions. Consequently, we assumed that good reconstruction geometry has a good degree of contact, a small maximal gap, a small gap volume, and a small mean gap. However, correlation between our host-graft junction measures was relatively poor. For degree of contact between host and graft, weak contact did not necessarily imply large maximal gap (Figure 5C).

Gap volume has some clinical meaning. It quantifies osteogenesis required to completely fill the gap between host and graft. There was a poor correlation between gap volume and maximal gap (Figure 5B), and also between gap volume and degree of contact. Junctions with smallest gap volumes did not necessarily have the smallest maximal gaps, nor the highest degrees of contact.

This lack of correlation and the great variation between each result show that assessment of the quality of the reconstruction geometry with only 1 of our 4 host-graft junction measures is not efficient. It is also impossible to point out all the different sources of error that can occur during reconstruction: manual transfer of resection planes on the allograft, positioning and orientation of the cutting tool on the bone, and cutting of the allograft. As for tumor resection, we believe that using computer- and robotic-assisted technologies could improve the accuracy of allograft cutting.

As our attempt to define what good host-graft geometry is was not satisfactory, we believe that there is a need to define new standards of evaluation that are independent of the reconstructed osseous structure. We believe that mechanical engineering tools, like geometrical tolerances and mechanical fittings, are well adapted to this problem.

Contributions of authors

OC designed and conducted the experiments, collected data, and wrote the manuscript. XB supervised the experiments and the writing of the manuscript, and performed the simulated surgeries. BR and BD supervised the engineering aspects of the experiments. LP performed data collection and processing of the medical images. BGF performed statistical analyses. PLD supervised the medical aspects of the experiments, and performed data collection and the simulated surgeries. OHC and CD performed the simulated surgeries.

No competing interests declared.

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