Accuracy of 3-D Planning and Navigation in Bone Tumor Resection

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abstract

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Surgical precision in oncologic surgery is essential to achieve adequate margins in bone tumor resections. Three-dimensional preoperative planning and bone tumor resection by navigation have been introduced to orthopedic oncology in recent years. However, the accuracy of preoperative planning and navigation is unclear. The purpose of this study was to evaluate the accuracy of preoperative planning and the navigation system.

A total of 28 patients were evaluated between May 2010 and February 2011. Tumor locations were the femur (n=17), pelvis (n=6), sacrum (n=2), tibia (n=2), and humerus (n=1). All resections were planned in a virtual scenario using computed tomography and magnetic resonance imaging fusion. A total of 61 planes or osteotomies were performed to resect the tumors. Postoperatively, computed tomography scans were obtained for all surgical specimens, and the specimens were 3-dimensionally reconstructed from the scans. Differences were determined by finding the distances between the osteotomies virtually programmed and those performed. The global mean of the quantitative comparisons between the osteotomies programmed and those obtained through the resected specimen was 2.52±2.32 mm for all patients.

Differences between osteotomies virtually programmed and those achieved by navigation intraoperatively were minimal.

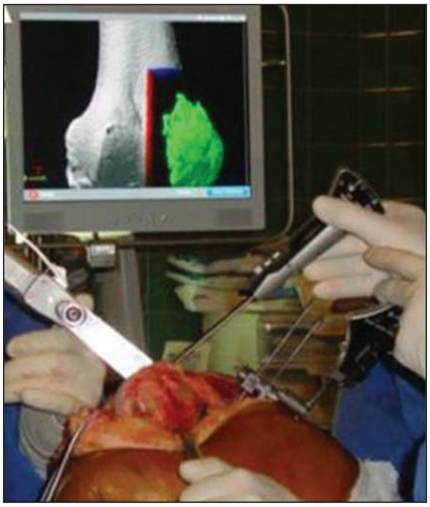

Figure: Intraoperative photograph showing a biplanar osteotomy in the medial condyle of the distal femur to perform chondrosarcoma resection guided by navigation.

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Image fusion (computed tomography [CT]/magnetic resonance imaging [MRI]) and 3-dimensional (3-D) preoperative planning for bone tumor resection by navigation were introduced in recent years as a potential aid for tumor resection.[1-11]

Although Wong et al[4] suggested that surgery aided by navigation is a precise technique for bone tumor resections, the final accuracy of the method has not been firmly established. In addition, intraoperative manual surgeon inaccuracies or saw blade bending while cutting bone could alter obtained osteotomies, creating differences between the preoperative planned osteotomy and final osteotomy performed intraoperatively.[12] Precision between preoperative planned tumor margins and performed resections are crucial in orthopedic surgical oncology.

The objective of this study was to determine the accuracy of osteotomies planned preoperatively compared with the final navigated osteotomies obtained in the resected and virtualized specimen.

Materials and Methods

Between May 2010 and February 2011, a total of 28 consecutive patients receiving treatment for a bone tumor following the same protocol for virtual planning and navigation were evaluated. Twenty-seven tumors were malignant and 1 was an aggressive giant cell tumor (Table). In all patients, the surgical specimen obtained after the tumor was resected was 3-D reconstructed and matched for accuracy with the preoperative planning performed under a 3-D virtual scenario. Twelve patients were men and 16 were women with a mean age of 32 years (range, 6-71 years). Tumors were located in the femur (n=17), pelvis (n=6), sacrum (n=2), tibia (n=2), and humerus (n=1). All tumors were preoperatively CT scanned (Multislice 64, Aquilion; Toshiba Medical Systems, Otawara, Japan). Slices with 0.5-mm thicknesses were obtained using a soft tissue algorithm (matrix 512×512 pixels). Magnetic resonance images of

Table

Demographic Data

				mm			
No. of Plane	Bone	Tumor	Osteotomy Conformation	Maximum	Minimum	Mean Absolute Error	SD
1	Humerus	Chondrosarcoma	Uniplanar	−1.59	−2.78	2.13	0.28
2	Pelvis	Chondrosarcoma	Uniplanar	1.01	−8.53	3.40	2.42
3	Femur	Osteosarcoma	Uniplanar	0.29	−1.17	0.41	0.32
4	Femur	Osteosarcoma	Uniplanar	0.26	−0.57	0.18	0.14
5	Femur	Osteosarcoma	Uniplanar	6.36	1.94	4.04	1.24
6	Femur	Osteosarcoma	Uniplanar	0.52	−4.31	1.45	1.42
7a	Femur	Osteosarcoma	Uniplanar	−5.64	−6.55	6.15	0.22
7b			Uniplanar	3.46	−5.22	1.65	1.11
8a	Femur	Ewing's sarcoma	Uniplanar	−5.33	−10.88	7.86	1.62
8b			Uniplanar	4.93	−1.72	1.84	1.40
9a	Pelvis	Chondrosarcoma	Uniplanar	2.24	−18.89	3.88	3.59
9b			Uniplanar	4.40	−5.39	2.37	1.37
10a	Femur	Chondrosarcoma	Biplanar	0.04	−3.30	1.62	1.00
10b				6.52	−1.08	1.93	1.73
11a	Femur	Chondrosarcoma	Tetraplanar	1.20	−0.95	0.39	0.24
11b				0.11	−3.76	2.43	1.06
11c				−1.04	−6.53	4.04	1.43
11d				3.58	−0.07	1.70	0.89
12a	Femur	Chondrosarcoma	Tetraplanar	3.71	2.30	2.95	0.31
12b				2.46	0.23	1.28	0.52
12c				−1.65	−4.63	2.93	0.47
12d				2.60	−0.38	1.28	0.67

Table Continued

Demographic Data

No. of Plane	Bone	Tumor	Osteotomy Conformation	mm			
				Maximum	Minimum	Mean Absolute Error	SD
13a	Femur	Osteosarcoma	Uniplanar	0.95	−0.34	0.29	0.25
13b			Uniplanar	1.11	−2.02	0.71	0.38
14a	Pelvis	Chondrosarcoma	Uniplanar	7.85	−1.15	2.45	2.00
14b			Uniplanar	18.50	-2.86	4.16	4.74
15a	Femur	Giant cell tumor	Pentaplanar	3.68	3.06	3.41	0.12
15b				4.54	−7.58	2.44	1.74
15c				0.10	−6.36	3.38	1.40
15d				0.69	−0.39	0.20	0.13
15e				−2.96	−5.48	4.17	0.65
16a	Pelvis	Chondrosarcoma	Biplanar	3.72	−6.66	1.30	1.21
16b				4.32	−5.32	2.62	1.33
16c			Biplanar	3.91	−4.60	2.45	1.48
16d				0.42	−6.43	2.34	1.83
17a	Sacrum	Osteosarcoma	Uniplanar	3.27	−6.25	2.79	1.71
17b			Biplanar	0.18	−6.96	3.03	1.79
17c				6.16	−7.11	2.47	2.09
18	Pelvis	Malignant schwannoma	Uniplanar	4.07	−3.42	1.19	1.03
19a	Femur	Ewing's sarcoma	Uniplanar	1.79	0.28	1.02	0.37
19b			Uniplanar	0.67	−0.59	0.26	0.18
20a	Tibia	Osteosarcoma	Biplanar	−0.11	−5.46	2.85	1.51
20b				0.22	−8.88	4.07	1.79
20c			Uniplanar	−1.27	−2.60	2.02	0.30
21a	Femur	Osteosarcoma	Uniplanar	2.43	−0.21	1.16	0.70
21b			Uniplanar	7.41	−3.71	1.26	0.89
22a	Sacrum	Cordoma	Uniplanar	1.68	−13.48	4.95	3.24
22b			Uniplanar	3.36	−19.95	6.80	5.58
23a	Femur	Chondrosarcoma	Triplanar	0.87	−6.64	2.63	1.85
23b				0.85	−4.25	1.50	1.20
23c				−0.96	−3.26	2.09	0.59
24	Femur	Osteosarcoma	Uniplanar	10.51	6.01	8.21	1.35
25a	Pelvis	Ewing sarcoma	Uniplanar	2.43	−1.19	0.90	0.65
26a	Femur	Chondrosarcoma	Tetraplanar	4.23	1.13	2.65	0.90
26b				4.44	1.78	3.17	0.58
26c				1.57	−5.26	1.61	1.18
26d				−1.78	−8.65	4.37	1.15
27a	Femur	Osteosarcoma	Uniplanar	0.15	−0.70	0.23	0.17
27b			Uniplanar	2.43	−0.71	0.95	0.61
28a	Tibia	Chondrosarcoma	Uniplanar	−0.46	−1.42	0.94	0.18
28b			Uniplanar	1.05	0.29	0.70	0.14
Global statistics						2.52	2.32

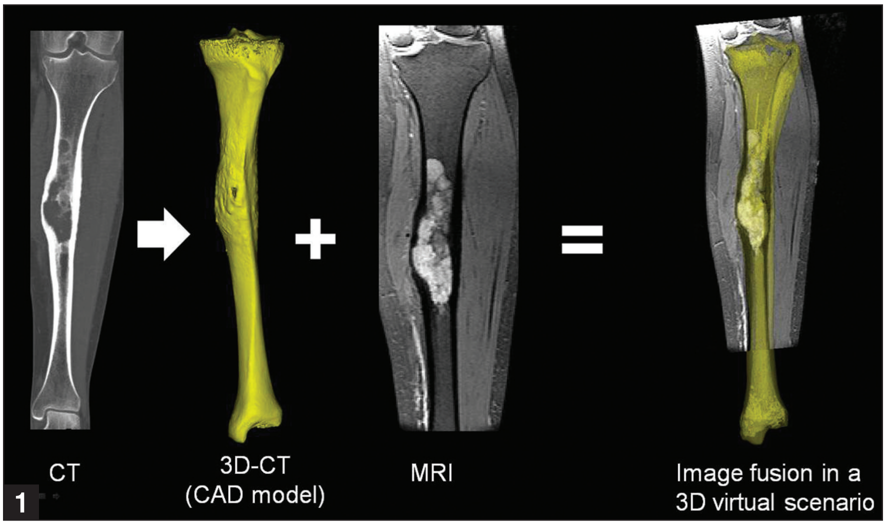

Figure 1: Image fusion of patient 28. Computed tomography (CT) scans were obtained of a tibia diaphyseal chondrosarcoma to create a computer-aided design (CAD) model and were then merged with magnetic resonance images (MRIs). Abbreviation: 3-D, 3-dimensional.

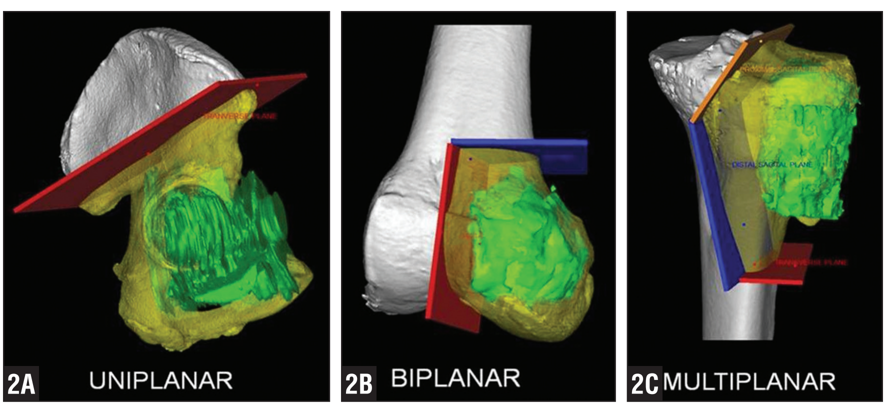

Figure 2: Three-dimensional images of patients 2, 10, and 20, respectively, showing the types of osteotomies that were planned virtually. Based on image fusion (Figure 1), osteotomies conformation in a 3-dimensional virtual scenario were determined as uniplanar (A), biplanar (B), or multiplanar (more than 2 planes) (C) according to resection planning.

the corresponding regions were acquired using a 1.5-T unit (Magnetom Avanto; Siemens Medical Solutions, Erlangen, Germany). Slices with 1-mm thicknesses were obtained using T1-weighted or fat-suppressed sequences to optimize visualization of the signal intensity from the bone tumor (matrix, 256×256 pixels).

3-D Preoperative Planning

Computed tomography scans and MRIs were fused (image fusion) to determine bone cortex and intra-extraosseous soft tissues tumor extension (Figure 1). These studies were merged to visualize the tumor and to program and perform a virtual osteotomy for tumor resection taking into account a 3-D situation. Image fusion CT/MRI and preoperative planning were performed by using the computer-aided design Mimics version 14.1 software (Materialise, Leuven, Belgium) (Figure 1). Once fusion was obtained, osteotomies were planned according to the tumor extension. Uni-, bi-, or multiplanar (more than 2 planes) osteotomies (Figure 2) were determined in a 3-D virtual scenario. The type of osteotomy performed was defined according to tumor nature, location, and definition of clear tumor margins (Figure 3).

Operative Procedure and Navigation

Once the 3-D preoperative planning was obtained in computer-aided design format, 3-D models were converted to CT data sets in Digital Imaging and Communications in Medicine format and imported to the navigator (3D OrthoMap navigation software version 1.0; Stryker Navigator, Freiburg, Germany).[4] Through appropriate navigation devices (navigated pointer, camera, and infrared tracker devices applied to the patient), the surgeons (G.L.F., L.A.A.-T.) established a correspondence between the 3-D images and the real bone with direct visualization of the monitor (Figure 4).[3,4] Surgeons were guided by navigation in the operating room using a navigated pointer to mark the osteotomy, which had been previously planned, on the superficial bone with a surgical marking pen. Next, the surgeons performed the osteotomy following this mark with a freehand saw (Figure 4).

Surgical Specimen Virtualized and Measurements

Once osteotomies were performed, the tumor surgical specimen obtained was CT scanned and 3-D reconstructed (Figure 5[B]) with the same protocol used for the preoperative acquisition of CT scans (Figure 5[A]).

The 3-D virtual surgical specimen obtained after tumor resection was superposed on the 3-D preoperative planning (Figure 5[C]) (3-D registration). Distances between the osteotomy planned and the plane created by the saw blade in the 3-D virtual surgical specimen (aligned on the preoperative planning model) were measured.[13] The 3-D virtual surgical specimen and preoperative osteotomy planes were converted to point cloud models (Figure 5[D]).[14] A point cloud model is a virtual tool capable of considering only the points of a surface. This method helps determine a region of interest to calculate point-to-point distances between the preoperative planned osteotomies and final osteotomies obtained in the 3-D virtual surgical specimen (Figure 5[E]).

Statistical Analysis

A total of 61 osteotomies were obtained and analyzed in 3 groups according to the type of plane conformation: uni- (n=31), bi- (n=10), and multiplanar (n=20).

Quantitative determinations were performed by measuring the distances between the planned and performed osteotomies at the resected specimen (Figure 5[E]). The correlation between the 61 osteotomies preoperatively planned and the osteotomies achieved by navigation were expressed in mean absolute error (Table). This value represents the mean (in absolute values) of differences between the points of the osteotomy planned and virtual specimen point cloud model in each patient (Figure 5[E]). To calculate the global mean in all patients, each mean absolute error was divided for the same quantity of points (sum of points taken into account in all patients). The global mean was calculated, and values were determined in millimeters.

According to the distances between the tumor location and osteotomy performed, maximum and minimum values were considered. If the plane of the 3-D virtual surgical specimen was closer to the tumor than planned, values were considered negatives. If the plane of 3-D virtual surgical specimen was farther to the tumor than planned, values were considered positives. If the plane of the 3-D virtual surgical specimen corresponded exactly with the osteotomy planned, the values were considered 0 (Table). These values were also illustrated using colorimetric accuracy mapping, which was reflected on the preoperative plane (Figure 5[F]). Green points established distances close to 0 in mm. The plane of the 3-D virtual surgical specimen was expressed as orange or red points if it was near the tumor and as blue

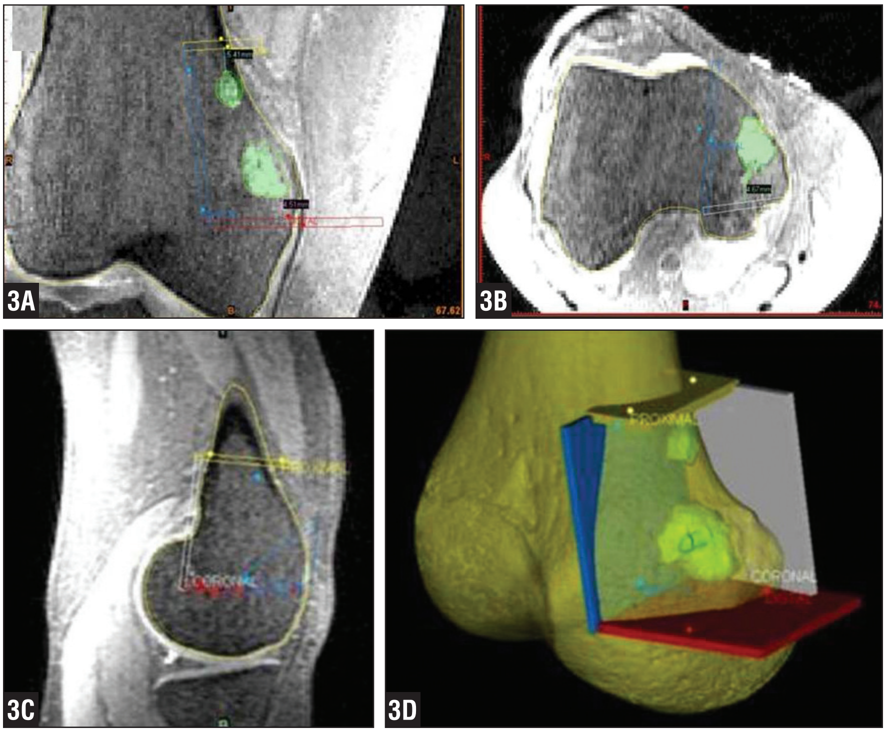

Figure 3: Coronal (A), axial (B), sagittal (C), and 3-dimensional (D) preoperative planning for patient 11. A multiplanar osteotomy was programmed. Oncologic margins of this chondrosarcoma were determined measuring the minimal distance between each plane planned projected on the image fusion and tumor (green).

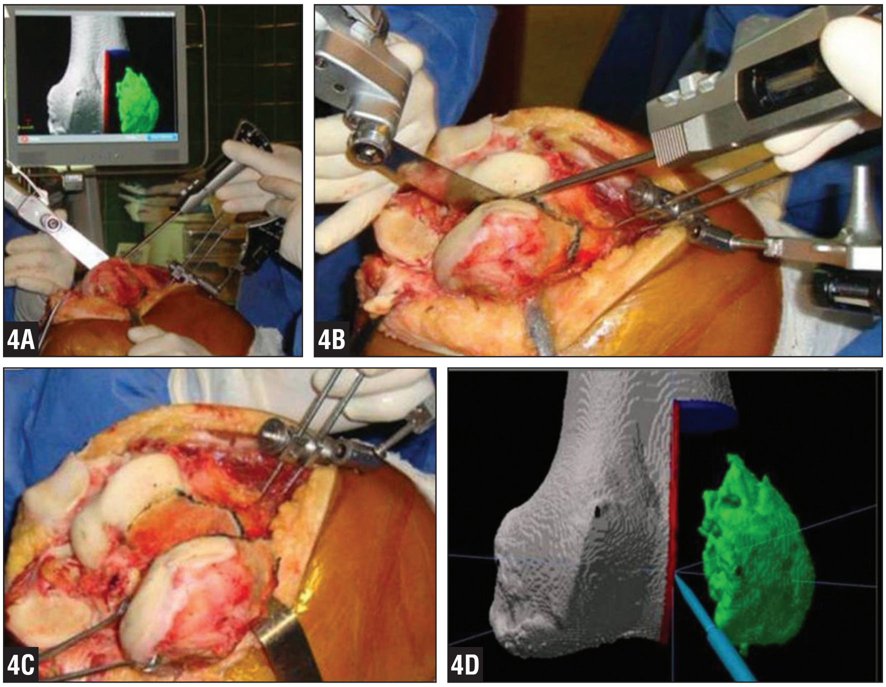

Figure 4: Images showing the intraoperative navigation of patient 10. Intraoperative photographs showing a biplanar osteotomy in the medial condyle of the distal femur to perform chondrosarcoma resection guided by navigation (A) and the surgeon evaluating the correct orientation of the resection osteotomy according to virtual preplanning with a navigated pointer (B). The medial condyle is removed from the distal femur (C). Three-dimensional model showing that the medial condyle is resected (D).

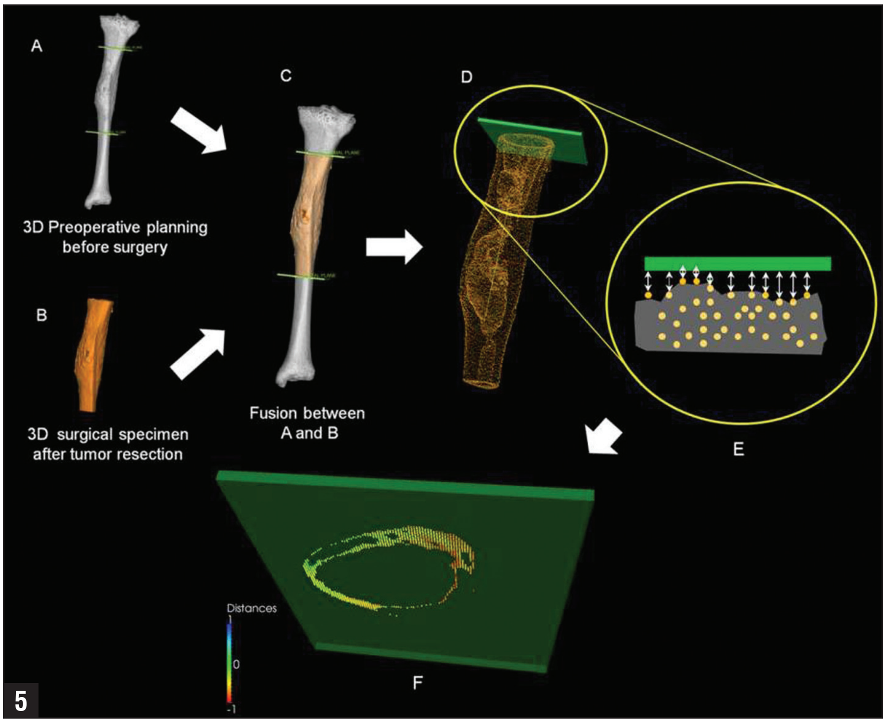

Figure 5: Experimental design and virtual specimen preprocessing pipeline of patient 28. Three-dimensional (3D) preoperative planning of a diaphyseal chondrosarcoma of the tibia with 2 osteotomies (A). Three-dimensional virtual tumor surgical specimen (orange) (B). Three-dimensional virtual tumor surgical specimen overlapped with the 3-D preoperative planning (C). Virtual specimen converted to a point of clouds (D). Accuracy was measured by determining the distances from point to point (white arrows) between the osteotomy programmed (green) and the osteotomy performed (nearest orange points) (E). Distances in mm between the osteotomy programmed and the osteotomy performed are shown in a colorimetric accuracy map printed in the preoperative proximal osteotomy planned (F).

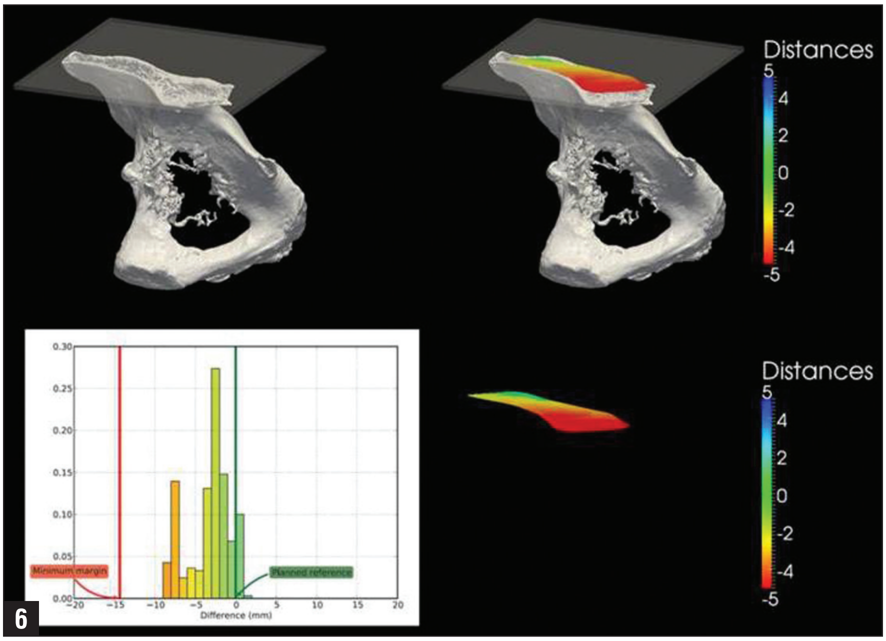

Figure 6: Colorimetric accuracy mapping of patient 2. Uniplanar pelvic osteotomy of a chondrosarcoma in zones II and III. The topographic area compromised was evaluated comparing the osteotomy performed over the virtual tumor specimen postoperatively. The colorimetric illustration and histogram show the distances between the osteotomy planned and the osteotomy obtained in the virtual resected specimen.

points if it was far from the tumor (Figures 5[F], 6). These results were analyzed with Open Source ParaView software package (ParaView, Clifton Park, New York). A colorimetric histogram was made to illustrate accuracy behavior.

Three experimental groups were analyzed considering different parameters. The types of osteotomies planned virtually were uni- (n=31), bi- (n=5), and multiplanar (n=5). Bones that were compromised by tumors were the long bones (n=20) and the sacrum-pelvis (n=8). Pathologies were osteosarcoma (n=11), chondrosarcoma (n=11), Ewing's sarcoma (n=3), and other tumors (n=3) (Table). Differences between the groups were determined with a test of equivalence.[15] The test of equivalence builds the 95% confidence interval (CI) of each group and calculates the total range of these CIs (Rg). To calculate whether 2 or more sets of measures were equivalent, a range of indifference (δ) was established (Figure 7). This range was determined assuming that discrepancies less than 1 mm between measures were not significant. When this CI (Rg) was less than the proposed range of indifference (δ=1 mm), the compared groups were equivalent.

Results

The authors performed the study in all 28 patients. Mean difference between osteotomies preoperatively planned and those achieved by navigation was 2.52±2.32 mm in a total of 61 planes (Table).

The compromised topographic areas were evaluated using colorimetric accuracy mapping and colorimetric histogram. The authors determined the accuracy map location in each patient (Figure 6). The colorimetric histogram illustrates accuracy behavior between the planned osteotomies and those obtained in the virtual specimen (Figure 6). The colorimetric histogram in Figure 8 shows the distribution of the differences between the osteotomies preoperatively planned and those achieved by navigation in the 61 osteoto-

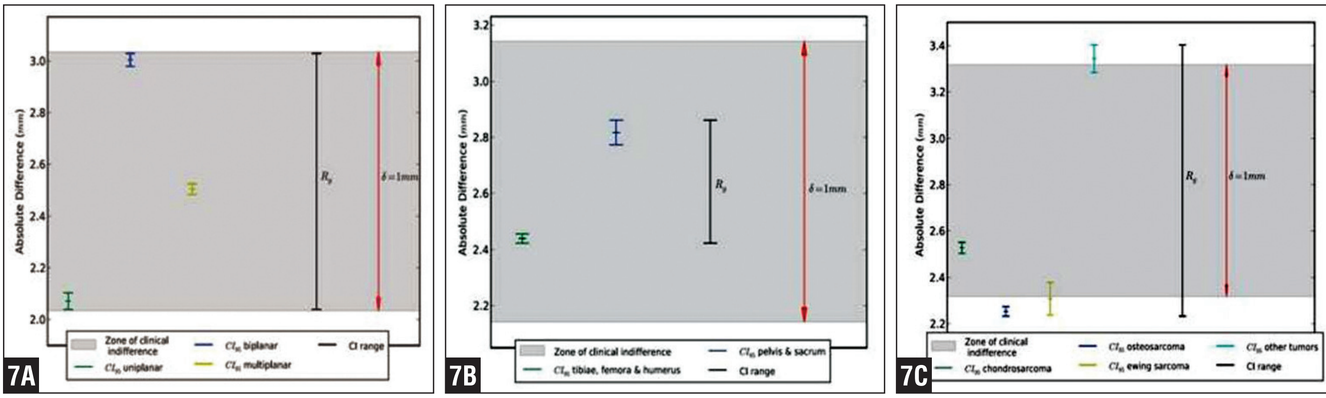

Figure 7: Results of the test of equivalence showing the 95% confidence intervals (CI), for uniplanar (A), biplanar (B), and multiplanar (C) resections. The total range of the CI is reflected in the Rg interval (black), δ: clinical indifference area (red) (A). Two 95% CIs are shown for the long bones and for the pelvis-sacrum (B). Four 95% CIs are shown for chondrosarcomas, osteosarcomas, Ewing's sarcomas, and other tumors (giant cell tumor, cordoma, and malignant schwannoma). Chondrosarcomas, osteosarcomas, and Ewing's sarcomas are equivalent (C).

mies evaluated. The main amount of differences (51%) ranged from −2 to 2 mm (the sign of the values reflected the side of the plane where the error was committed, being the negative values on the tumor side), and the 80% of the differences ranged from −4 to 4 mm.

Three experimental groups were analyzed with the absolute mean error. Considering the type of osteotomy, the absolute mean errors were 2.07±2.8 mm for uniplanar, 3±2.15 mm for biplanar, and 2.5±1.6 mm for multiplanar osteotomies. Considering the locations of the bone affected by the tumor, the absolute mean error was 2.43±2.08 mm for the long bones and 2.82±2.01 mm for the sacrum-pelvis. When different pathologies were analyzed, the absolute mean errors were 2.53±2.23 mm for osteosarcoma, 2.25±1.78 mm for chondrosarcoma, 2.3±2.83 mm for Ewing's sarcoma, and 3.34±3.17 mm for other tumors.

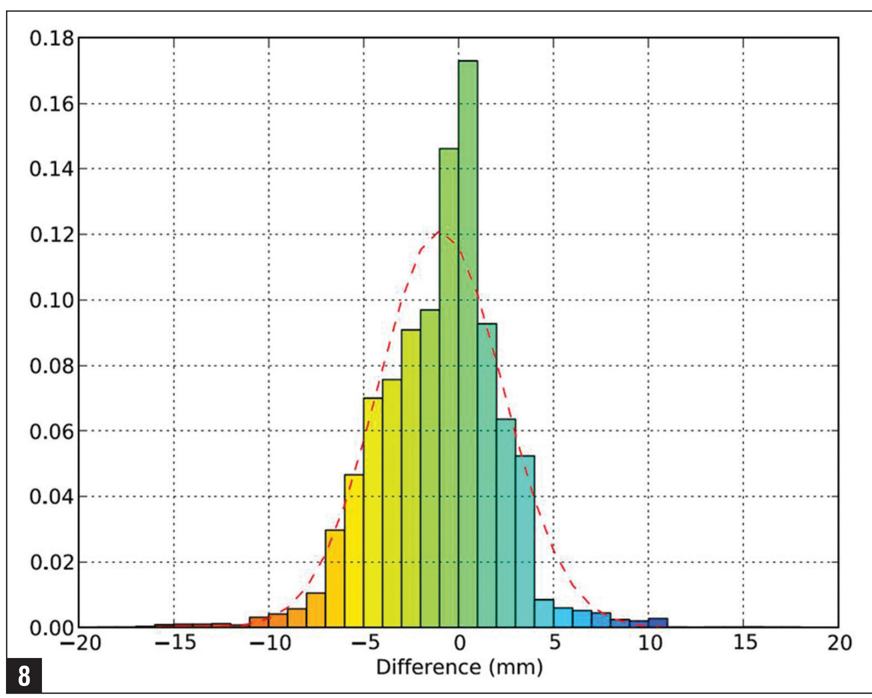

Figure 8: General histogram of 61 osteotomies performed showing a Gaussian distribution (dotted red line). The height of each bar represents the percentage of difference between the osteotomy programmed and the osteotomy performed in all patients.

The 3 experimental groups were also analyzed using the test of equivalence. Differences in type of osteotomy in 95% CI were 2.04 to 2.10 mm for uniplanar, 2.98 to 3.03 mm for biplanar, and 2.48 to 2.53 mm for multiplanar (Rg=0.99 mm). Differences in bone type compromised by the tumor in 95% CI were 2.43 to 2.46 mm for the long bone and 2.78 to 2.87 mm for the pelvis-sacrum (Rg=0.44 mm). Differences in variable pathologies in 95% CI were 2.50 to 2.55 mm for osteosarcoma, 2.23 to 2.27 mm for chondrosarcoma, 2.24 to 2.38 mm for Ewing's sarcoma, and 3.28 to 3.40 mm for other tumors (Rg=1.17 mm).

Considering the different experimental groups analyzed, the type of osteotomy (uni-, bi-, and multiplanar) and type of bone compromised by the tumor (long bones and sacrum-pelvis), Rg was less than the proposed indifference range (1 mm) in these experimental groups, suggesting that the measures of the different groups under testing were equivalent. However, considering different pathologies (osteosarcoma, chondrosarcoma, Ewing's sarcoma, and other tumors) in the experimental group, results were not equivalent, with a Rg greater than 1 mm. If the other tumors group was excluded, the results among osteosarcoma, chondrosarcoma, and Ewing's sarcoma were equivalent.

Discussion

When a surgeon treats an extremity sarcoma, he or she must determine where the bone and soft tissues should be cut with the highest precision to preserve as much unaffected tissue as possible without invading tumor margins. If the tumor margins obtained are too wide, this may jeopardize the durability of the reconstruction. If inaccurate planning or tumor resection shows violation of the oncologic margins, the patient's prognosis may be worse. The surgeon must resect as minimal an amount of tissue as possible and preserve safe tumor margins.

Intraoperatively, the surgeon must rely on 2-dimensional images (CT or MRI studies available in the operating room), mentally integrate them into a 3-D intraoperative surgical situation, and perform the tumor resection. This is a potentially dangerous source of inaccuracies for even the most experienced oncologic surgeons. Recent advances in computerized techniques applied to orthopedic oncologic surgery may significantly influence the accuracy and predictability of tumor resections.[12]

Wong et al[3] reported 13 bone tumor resections, 3 of which were aided by navigation, and reported that navigation facilitates performing planned tumor resection and may offer clinical benefits. In another study, Wong et al[16] reported advantages provided by 21 patients with 22 musculoskeletal tumors. All tumor resections were performed as planned under navigation. Cho et al[1] and Krettek et al[6] reported that the advantages of computer-aided surgery can be applied in the resection of malignant pelvic and sacral tumors.

However, few studies have specifically addressed how to determine the accuracy of the procedure. So et al[2] reported that the meaning of accuracy in most published literature only represented the accuracy of the intraoperative registration process as recorded by the navigation machine. However, bone tumor resection by navigation includes virtual planning, intraoperative registration, tumor location guided by navigation, and freehand sawing. They suggested that the best way to measure the accuracy of the navigation outcome is by the pathologist through the resected specimen.[2] Wong et al[4] reported that examination of the resected specimens showed clear margins in all tumor lesions studied, suggesting that the resections were executed as planned, but the method used to measure accuracy was not explained. Ieguchi et al[17] and Cho et al[5] evaluated the efficacy of navigation-assisted excision of bone tumors, determining the differences between the planned margins and final tumor margins obtained only by histological analyses. Although safe oncologic margins are the main objective of the surgeon, the current method cannot be compared with postoperative pathological findings. With a histological evaluation, the authors were unable to determine the differences between the osteotomies virtually programmed and those performed. The authors evaluated the accuracy of bone tumor resection guided by navigation compared with a target previously planned. In addition, this study provides a tool for establishing differences between osteotomies virtually programmed and those performed.

Considering previous reports, the accuracy of bone tumor resection by navigation is unclear.[3,4,11] Abraham[18] suggested that postoperative processing of the resected specimen by imaging and matching with preoperative planning would give a valid measure of accuracy. The purpose of the current study was to determine the accuracy of 3-D preoperative planning and surgical navigation in the treatment of patients with sarcomas and aggressive musculoskeletal tumors. The 3-D virtual surgical specimen obtained after the tumor resection was virtually superimposed on the 3-D preoperative planning. Distances between both osteotomy surfaces were measured.

Virtual planning and navigation surgery applied to orthopedic oncology is a novel and evolving technique. The use of computer-aided surgery will not eliminate the need for an orthopedic oncologic surgeon to treat these patients. Three-dimensional preoperative virtual planning and navigated surgery should be performed by a surgeon who is experienced in treating this disease. The rationale for introducing computerized assistance in orthopedic oncology to increase intraoperative accuracy and precision. This is necessary for a patient who requires a tumor resection and may help the surgeon to perform a confident and reliable operation. This may be particularly valuable for complex bi- or multiplanar tumor resection osteotomies in demanding anatomic areas, such as the pelvis, spine, groin, or popliteal fossae.

Results of this study analyzing the surgical tumor resected specimen in a virtual scenario showed that differences between osteotomies planned and the resection performed were 2.52×2.32-mm standard error for the whole series of 61 osteotomies. The accuracy of the procedure may be measured by matching the preoperative virtual planning with the 3-D virtual surgical specimen obtained after tumor resection.

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