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Image-guided bone resection as a prospective alternative to cutting templates—A preliminary study

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A B S T R A C T

Objective: To evaluate the accuracy of craniomaxillofacial resections performed with an image-guided surgical sagittal saw.

Material and methods: Twenty-four craniomaxillofacial resections were performed using an image-guided sagittal saw. Surgical outcomes were compared with a preoperative virtual plan in terms of the resected bone volume, control point position and osteotomy trajectory angle. Each measurement was performed twice by two independent observers.

Results: The best convergence between the planned and actual bone resection was observed for the orbital region (6.33 ± 4.04%). The smallest mean difference between the preoperative and postoperative control point positions (2.00 ± 0.66 mm) and the lowest mean angular deviation between the virtual and actual osteotomy (5.49 ± 3.17 degrees) were documented for the maxillary region. When all the performed procedures were analyzed together, mean difference between the planned and actual bone resection volumes was 9.48 ± 4.91%, mean difference between the preoperative and postoperative control point positions amounted to 2.59 ± 1.41 mm, and mean angular deviation between the planned and actual osteotomy trajectory equaled 8.21 ± 5.69 degrees.

Conclusion: The results of this study are encouraging but not fully satisfactory. If further improved, the hereby presented navigation technique may become a valuable supporting method for craniomaxillofacial resections.

1. Introduction

Due to recent progress in computer-aided design and computer-aided manufacturing (CAD/CAM), this technology could be implemented as a valuable adjunct tool used in craniomaxillofacial surgery. The range of its applications varies from planning virtual surgeries, simulation of their results (Markiewicz and Bell, 2011; Adolphs et al., 2014), development of stereolithographic models (Chopra et al., 2014), preparation of custom-made implants (Subburaj et al., 2007; Singare et al., 2008; Zhao et al., 2012), dental splints (Xia et al., 2009), and reconstructive plates (Mazzoni et al., 2013), to the production of cutting template guides. The latter application, referred to as Prosthetically Guided Maxillofacial Surgery, has been gaining increasing interest recently. The guide enables precise execution of preplanned virtual osteotomy and shifting bone fragments into a fixed position, thereby contributing to the improvement of surgical outcomes and shortened operation time (Hirsch et al., 2009; Roser et al., 2010; Foley et al., 2013; Li et al., 2013; Mazzoni et al., 2013; Mardini et al., 2014). Surgical guides have been successfully applied in orthognathic surgery and reconstructive surgery for the treatment of traumatic and post-oncologic defects as well as for the management of congenital malformations (Burge et al., 2011; Mardini et al., 2014). However, this method is not free of drawbacks, such as high cost, need for cooperation with specialist companies, and the long time required to produce and deliver a guide to the medical center.

In our opinion, intraoperative navigation, also referred to as computer-assisted navigation or image-guided surgery, may

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constitute an alternative to surgical guides, especially during surgical treatment of primary posttraumatic and postoncologic deformations. In this article, we present the results of the osteotomy aided by a novel intraoperative navigation system, performed in the craniomaxillofacial region. To the best of our knowledge, this is the first published attempt to assess the accuracy of a navigated surgical instrument other than a tip-pointer. Moreover, we discussed and compared the surgeries assisted with surgical guides and intraoperative navigation technology.

2. Material and methods

2.1. Computed tomographic imaging and virtual surgical planning

Fifty-three titanium microscrews (diameter 1.0 mm, length 4.0 mm) were inserted into a plastic skull model (type: A20, 3B Scientific GmbH, Hamburg, Germany) as fiducial markers, which enabled us to register the skull, measure the navigation accuracy, and subjectively evaluate the accuracy of the surgical saw calibration. The skull model was scanned with a 32-slice computed tomography (CT) scanner (GE LightSpeed Pro 32 CT, GE Healthcare, Waukesha, WI, USA) with 512 × 512 pixel dataset acquired at 0.625-mm slice thickness. The images were saved as Digital Imaging and Communication in Medicine (DICOM) format and transferred to a Windows-based computer workstation with Maxillo-Facial Surgery System (MFSS) created by the bioengineers and software engineers from the Wroclaw University of Technology in cooperation with Maria Skłodowska-Curie Memorial Cancer Center and Institute of Oncology in Warsaw (Swiatek-Najwer et al., 2013; Majak et al., 2013).

Using the MFSS, a three-dimensional (3D) model of the skull was generated in the form of an STL file that was sent to a facility specializing in CAD/CAM, which manufactured four plaster-made stereolithographic models. Using the MFSS virtual planning module, separate virtual surgery plans were developed for six various resection procedures as described in Table 1. Subsequently, all of the microscrew heads were manually identified and labeled as registration fiducials or target fiducials. Each virtual surgical plan was saved and exported to the intraoperative navigation module of the MFSS system (Fig. 1).

2.2. Image-guided surgery

All of the procedures were performed in a real operating room with the support of the MFFS system compatible with an infrared tracking camera of the commercial intraoperative navigation system (StealthStation S7, Medtronic, Minneapolis, MN, USA). Image-supported bone resections were always performed by the same operator according to the same operating protocol. First, the dynamic reference frame (StealthStation Spine Referencing Set, Medtronic, Minneapolis, MN, USA) was attached to the skull. Then, an optical tracking adapter (SureTrak II Universal Tracker, Medtronic, Minneapolis, MN, USA) was installed on the handle of the surgical sagittal saw (GB129R, Aesculap, Center Valley, PA, USA). The registration process for the skull model in the navigation system was performed with a tip-pointer (Passive Planar Blunt Probe, Medtronic, Minneapolis, MN, USA), using six characteristic points marked as registration fiducials. The accuracy of the registration process was measured as the Fiducial Registration Error (FRE). After registration, the accuracy of the navigation was verified by applying a pointer to the points marked as target fiducials around the fragment of bone planned for resection, and expressed as a Target Registration Error (TRE) (Fitzpatrick and West, 2001). The average of FRE <1 mm and the average of TRE <1.5 mm were considered as the indices of a successfully completed registration process.

The next step included calibration of the sagittal saw blade in the navigation system, conducted with a navigated pointer (Popek et al., 2013). Calibration of the sagittal saw blade is necessary for appropriate orientation and location of the cutting plane tracked by the navigation system. The accuracy of the saw blade navigation was assessed subjectively during the surgery, by applying it to the fiducial landmarks of the skull and comparing its position and angle in physical and virtual spaces. After completing calibration of the surgical saw, it was used for the resection of bone structures in accordance with the virtual surgery plan. During the procedure, the position and the tilt of the saw blade were displayed on the screen in real time in various two-dimensional (2D) cross-sections (axial, sagittal, and frontal planes) and on the 3D image of the surgical field, which enabled the operator to perform the bone resection in line with the planned position and osteotomy trajectory.

2.3. Evaluation of postoperative results

All of the operated models of the skull and resected fragments were subjected to postoperative CT imaging. The images were stored in DICOM format. Using the MFSS evaluation module, a fusion of the postoperative imaging data with the virtual preoperative CT-based plan was performed. For an appropriate fusion of the virtual plan and the postoperative datasets, the positions of the 10 corresponding microscrew heads were labeled manually in such way that an automatic landmark registration algorithm could be used. The accuracy of the fusion was measured in each case. The image fusion with an average error of <1 mm was considered acceptable. We analyzed angular deviation from the planned osteotomy trajectory, difference between the planned and actual volume of the resected bone fragment, and differences in the locations of points labeled on the edges of the trajectory of planned and actually performed osteotomy (Fig. 2). The deviation in the location of these control points was calculated using the same formula as for the TRE parameter. Each measurement was taken twice by two independent observers.

2.4. Statistical analysis

The Student *t* test was used for statistical analysis of the results ($p < 0.05$). The intraobserver variability between the first and the

Table 1
Overview of the resection procedures.

Procedure	Control points	Osteotomy planes	Description
Resection A	8	3	Partial resection of the alveolar process of the right maxilla (Fig. 1A).
Resection B	6	2	Partial resection of the alveolar process of the left maxilla (Fig. 1B).
Resection C	6	3	Resection of the lateral wall of the right orbit (Fig. 1C).
Resection D	9	4	Partial resection of the inferior and lateral wall of the left orbit (Fig. 1D).
Resection E	8	4	Partial resection of the right frontal bone (Fig. 1E).
Resection F	8	4	Partial resection of the left frontal bone (Fig. 1F).

Control points, number of control points; Osteotomy planes, number of osteotomy planes.