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Navigation-Guided Harvesting of Autologous Iliac Crest Graft for Mandibular Reconstruction

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Osseous reconstructions with free tissue transfer techniques in the facial region are well established and provide satisfactory results. Also, the introduction of new planning and transfer tools has simplified the surgical process for mandibular reconstruction. The reconstruction of the mandible remains very challenging: functional aspects like speech, swallowing, and chewing—with the help of dentures—have to be taken into account in the same way as esthetic aspects of the patient's facial appearance. Although many authors report very good results using the free fibula flaps, this technology still has some disadvantages. In dentate patients especially with hemimandibulectomy, the gracile fibula bone causes an asymmetric facial appearance and inappropriate load situations between the strong healthy hemimandible and the reconstructed part. This may subsequently lead to complications. The iliac crest bone was reported to be the first choice for these patients.[1-3]

For reconstructive surgical interventions with free-fibula flaps, several methods for virtual planning and transfer of the planning to the patient were described. The most common methods are based on the virtual reconstruction of preoperative computer tomography scans. These scans can be used to generate rapid prototyping models to show the current situation and perform the surgery as an exercise.[4] The most obvious disadvantages of this procedure are the high costs and the fact that the exercise is not repeatable.

Other authors use computed tomographic (CT) scans to perform virtual 3-dimensional (3D) reconstructions and find the best surgical procedure is by means of computer-aided surgery. Once the planning is performed, the transfer of the planning into the OR environment is provided by cutting guides and prebent plates. Several workflows have been described for the fibula graft procedures.[5-7]

For those patients who would benefit from an iliac crest graft, these 3D planning tools are not widely accessible yet. Usually, the definition of the donor site within the computer-aided planning environment is accomplished manually, ie, solely based on the surgeons' experience and skills. Therefore, this proce-

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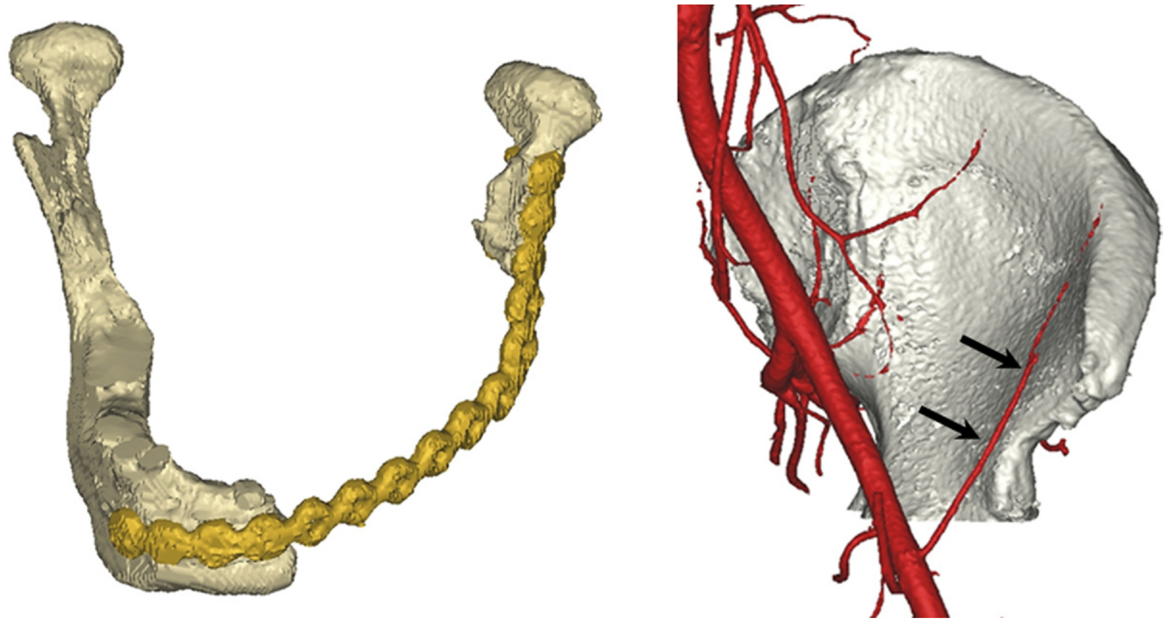

FIGURE 1. Virtual individual patient's model of the defect side—the 3D reconstruction was performed based on a CT scan (*left*). Three-dimensional view of the pelvic region also displaying the vascular situation in the donor site region (*right*). *Black arrows* indicate the Arteria circumflexa iliaca superficialis.

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dure is characterized by the fact that the theoretical optimum from the geometrical point of view is not necessarily reached in every case. Consequently, there is always some risk of wasting donor bone, and it remains a very limited predictability of the outcome. These patients could benefit a great deal from a procedure where a segmental defect in the mandible can be virtually reconstructed with an ideally fitting osseous transplant. To identify the ideal donor site inside the iliac bone, a software tool should automatically select a region where the outline and shape are most similar to one of the missing bone parts in the mandible. At least a system has to be found to ensure a reliable transfer of the surgical plan and the determined positional data into the OR environment and consequently to successfully harvest the transplant itself.[8,9]

In our report, we present a newly developed powerful software tool for semiautomatically optimized preoperative planning of shape and geometry by means of mathematical matching algorithms, and the first clinical application of this workflow in the course of a mandible reconstruction using microvascular anastomosed bone graft from the iliac crest. For a precise intraoperative transfer of the virtual plan to the patient, we apply a 3D real-time navigation prototype system developed by the authors. Quantitative evaluation of the concept is based on preoperative validation on 3D stereolithographic model simulation and on comparison with the virtual plan with the postoperative CT scan.

Methods

A virtual model of the patient's individual anatomy was generated based on preoperative CT scans of the head and the pelvic region (Philips Brilliance 64, angio CT, head slice thickness 1.5 mm/slice distance 0.75 mm, pelvis slice thickness 1.0 mm/slice distance 0.5 mm; Philips Healthcare, Eindhoven, Netherlands).

dA commercial software package (Mimics 12.0; Materialize NV, Leuven, Belgium) served to segment the bony structures of the skull and the remaining parts of the mandible as well as metal parts such as reconstruction plates. To have the best possible information about the vascular situation at the donor site, a segmentation process was extended with an angiographic CT scan of the pelvis (Fig 1). The 3-D objects were transferred in a 3D file format (~.stl) to a self-developed software tool, by which a 2-step method was used to generate the virtual graft in a first semiautomatic step, followed by a fully automatic procedure to find the best harvesting site in the predefined donor region. The mathematical background for this procedure is an optimization of the surface-based similarity measurement between the donor region and the designed graft template. By implementing the Levenberg-Marquardt algorithm, the method could be optimized, so that once the preprocessing step has

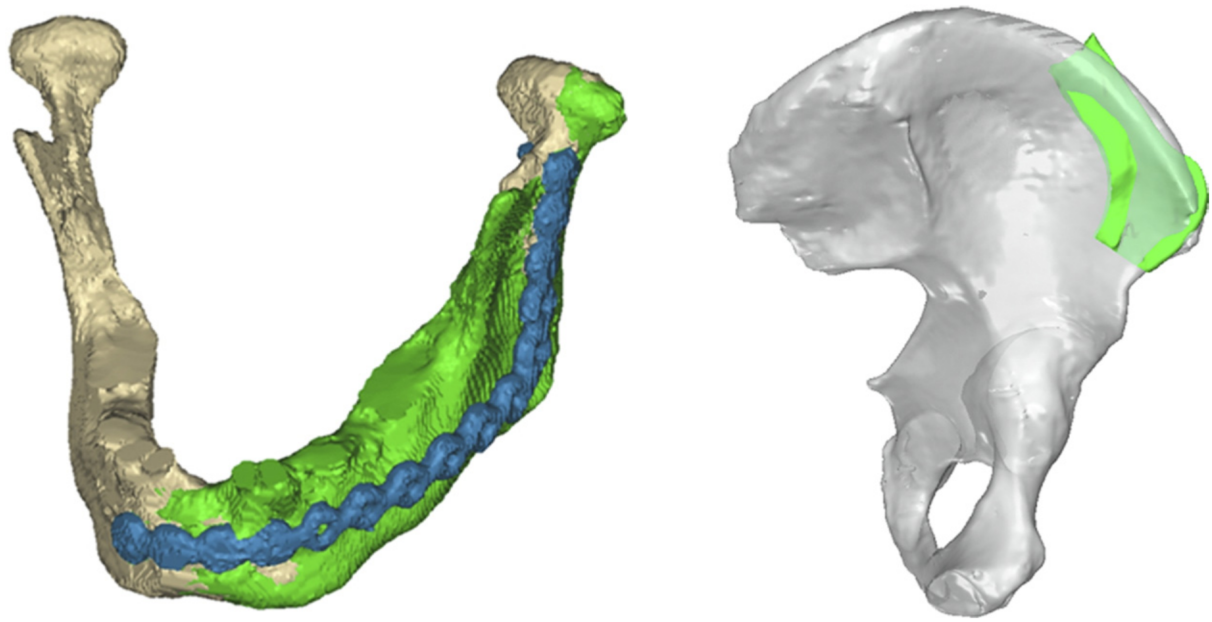

FIGURE 2. Computer-assisted planning of the surgical intervention: Step 1: Semiautomatic generation of an optimized graft to cover the defect with the means of mirroring and matching (*left*). Step 2: Fully automatic mathematical algorithm to select the ideal donor site (*right*).

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been performed, the automatic selection of the optimal donor site takes less than 1 minute (Fig 2).[10,11]

To determine the correct position for harvesting the graft from the donor site during surgery, a 3D navigational prototype system was chosen. The system consists of a software module, and a commercially available tracking system and associated modifications to conventional instruments. As tracking technology, an infrared optical system was used (Polaris; Northern Digital Inc, Waterloo, Canada). The Polaris measurement system defines position and orientation of anatomical structures and surgical instruments by measuring 3D positions of affixed marker spheres, with a spatial accuracy of 0.35 mm root-mean-squared error (RMSE). A standard Linux laptop computer equipped with accelerated 3D graphics hardware (NVIDIA Quadro FX-350-M; NVIDIA Corp, Santa Clara, CA) was used to run the application and interfaces with the Polaris connected via the serial port. To facilitate adjusting the line of sight of the 2 infrared sensors of the Polaris system, the tracking camera was mounted on a tripod. This setup allows the use in office/laboratory as well as in OR environments.

To validate the navigational system for use in the OR environment, a color-coded rapid prototyping model was generated using a powder-binder technique (ARTORG Center, University of Bern, Bern, Switzerland). The model was equipped with passive marker spheres to be detected by the Polaris tracking system. On the rapid prototyping (RP) model, 3 anatomical landmarks at the left iliac crest were defined, which could be easily exposed and identified during the surgery. To validate the registration process for our indication, 5 physicians experienced in navigational surgery performed the paired point registration process with 3 landmarks 3 times each. The 3 landmarks chosen for the validation test under laboratory circumstances were planned to be used in the real surgery as well (Fig 3).

To provide an intraoperative plausibility check as well as an additional "haptic control" for the surgeon, stereolithographic models of the complete skull (including the desired shape of the newly formed complete mandible) as well as of the separate bone of the hip transplant were manufactured and sterilized for intraoperative use. The ~.stl file required for model fabrication was transferred from the planning site to the manufacturer (Laserform Modellbau GmbH, Vienna, Austria) via the Internet (Fig 4).[12,13] In combination with the interactive online teleplanning process, this aspect can be interpreted as a telemedicine application.

Intraoperatively, one team of surgeons prepared the recipient area in the left mandible, including the preparation of cervical vessels for the anastomosis of the graft. A second team was preparing the donor site. After surgical exposure of the left iliac crest, the passive marker system of the 3D real-time navigational system and a specially developed holding and handle device were mounted using Kirschner wires (2.5 mm).

A

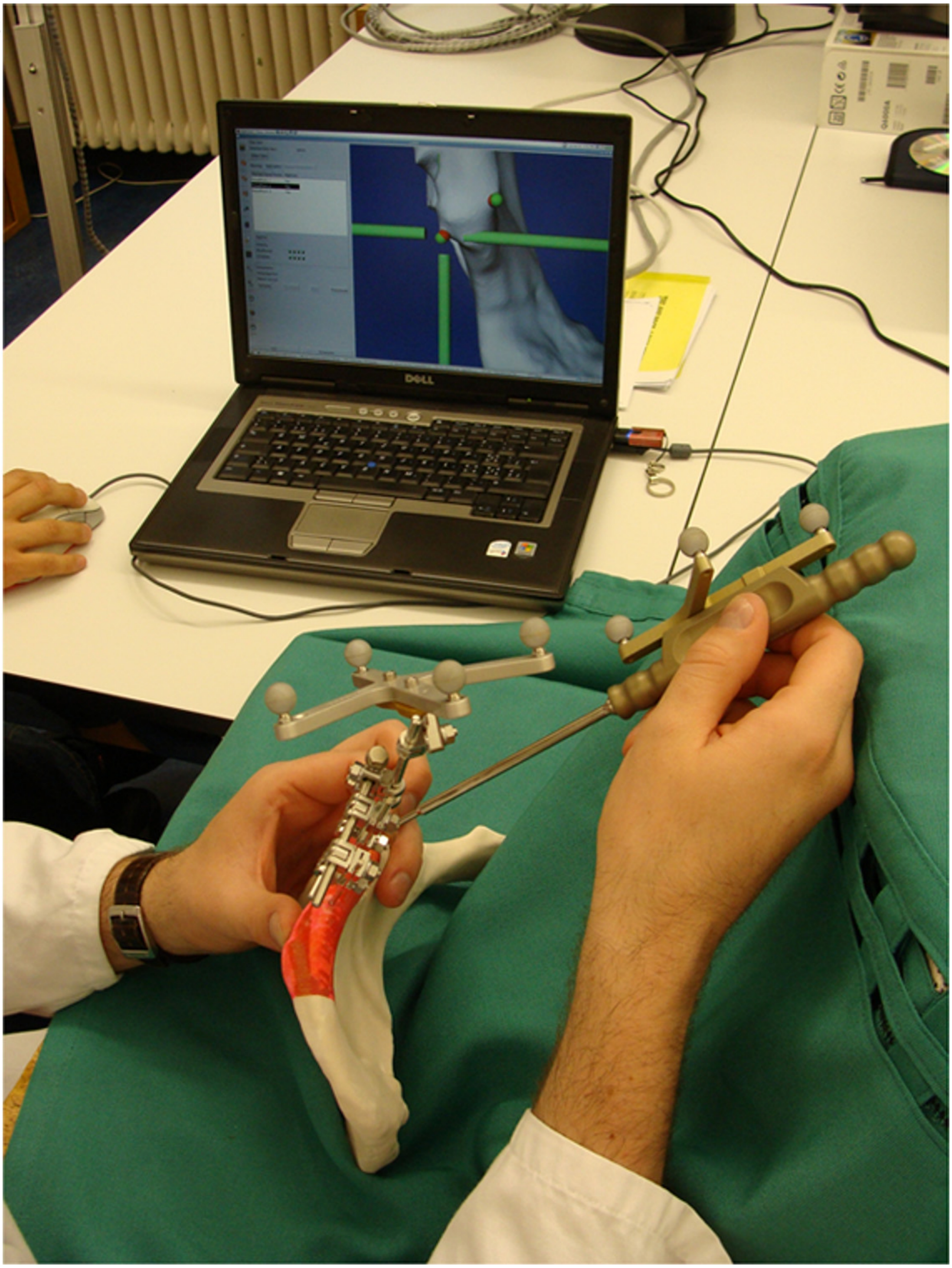

FIGURE 3. *A*, Experimental setup for preoperative in vitro simulation on a stereolithographic hip model with attached rigid body markers for navigation-controlled definition of the graft's geometry. **(Figure 3 continued on next page.)**

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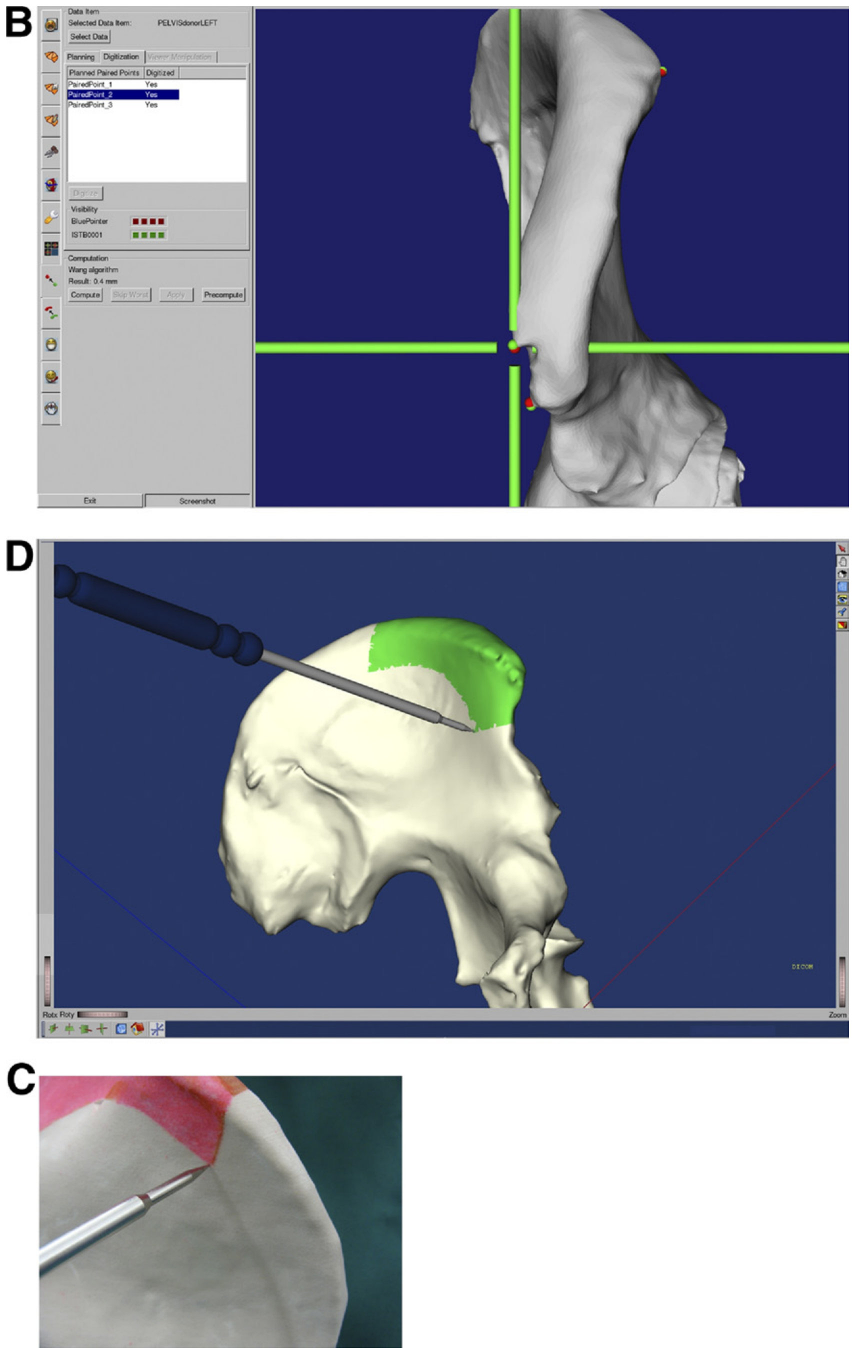

FIG. 3 (Cont'd). *B,* Validation of the paired-point matching registration process with the 3 anatomical landmarks (screenshot). *C,* Qualitative testing of accuracy during navigation process: position of the pointer tip on the rapid prototyping model. *D,* Corresponding screenshot.

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EVALUATION AND STATISTICS

Registration accuracy of the navigation system was documented in terms of RMSE (during stereolithography simulation as well as intraoperatively). Surgical outcome was judged by means of image matching between preoperative virtual planning and corresponding postoperative CT scans. Data presentation is accomplished using descriptive statistics. Furthermore, the time required for the steps of the workflow is registered.

Results

PREOPERATIVE IN VITRO SYSTEM VALIDATION

With the stereolithography-based simulation procedure, an average accuracy of the point-to-point registration process of 0.45 mm (min 0.1 mm, max 0.6 mm) RMSE was achieved (Table 1). In a second stage, a verification of the accuracy could be reached by pointing out target landmarks on the

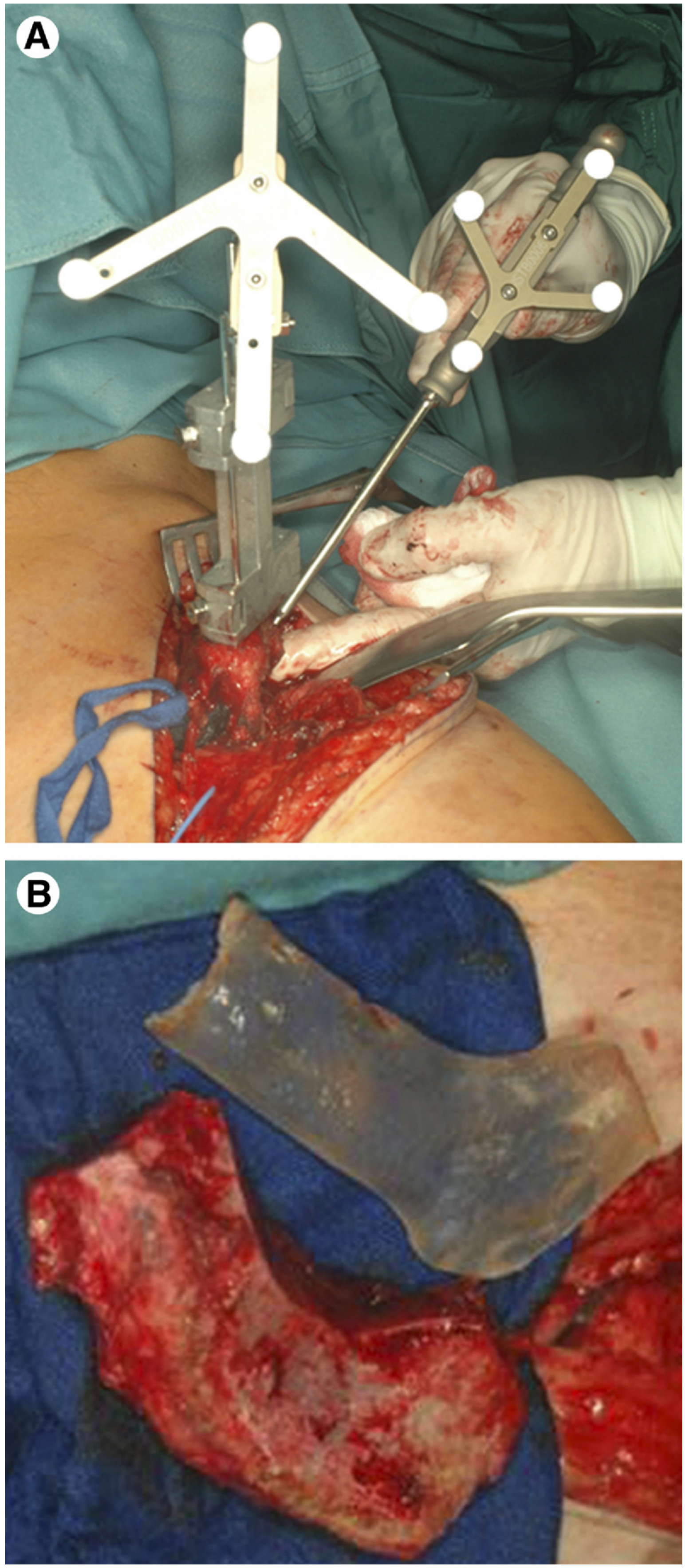

FIGURE 4. Intraoperative situation: *A*, Passive marker spheres attached on the exposed left iliac crest; the pointer tool is used to identify the margins of the graft. *B*, Comparison of the harvested bone graft with a stereolithographic model representing the mathematically optimized geometry.

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Table 1. CHECK OF THE REGISTRATION PROCESS

	Physician				
[mm]	A	B	C	D	E
RMSE 1	0.5	0.6	0.6	0.6	0.4
RMSE 2	0.6	0.4	0.4	0.4	0.5
RMSE 3	0.1	0.5	0.4	0.2	0.5
MinRMSE	0.5	0.4	0.4	0.4	0.4
MaxRMSE	0.6	0.6	0.6	0.6	0.5
MeanRMSE	0.6	0.5	0.5	0.5	0.5

RMSE, root-mean-squared error as automatically calculated by the navigation system in the 3 measurements performed by 5 physicians.

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rapid prototyping model and documentation of the corresponding virtual tip position on the display of the navigation system (Fig 3).

INTRAOPERATIVE USE OF THE 3D REAL-TIME NAVIGATION SYSTEM

After exploration of the donor site and mounting of the marker spheres, the point-to-point registration process was performed and an accuracy of 0.8 mm RMSE could be achieved. An additional surface registration process improved the accuracy to a value of 0.5 mm RMSE. After the registration process, navigation was used to transfer the margins of the osseous graft onto the site. Although the shape of the ideal graft was displayed on the computer screen, its margins could be marked onto the real pelvic bone with marking drills under guidance of the navigational instrument. After resection of the bone graft with an oscillating saw along the marked borders, its outer shape was compared with the RP model of the virtually generated graft and minor adjustments of its form were performed. The placement of the graft into the defect region could then be accomplished without any further shaping. The procedure of trimming the transplant to make it fit to the defect during the time of ischemia could be reduced to less than 10 minutes (Fig 5).

Postoperatively, the patient presented excellent healing without any complications. We achieved very satisfactory results in terms of function and symmetry. Eight months after the reconstructive surgery, the patient was supplied with dental implants also in the area of the bone graft, that were later on loaded with a fixed prosthetic teeth substitute. The orthopantomogram acquired in June 2009 shows excellent osseointegration of the dental implant in the reconstructed area of the mandible. Neither signs of osteosynthesis material loosening nor pseudarthrosis could be detected (Fig 6). The patient is still under regular control, now 26 months after surgery, and still no complications related to the surgery have occurred.

Discussion

In this report, we present a workflow from data acquisition to virtual planning for the reconstruction of a mandibular defect. The identification of the ideal donor site in the iliac crest is performed with a newly developed semiautomatized planning algorithm and finally the transfer of the surgical plan to the patient is realized with an in-house-developed 3D real-time navigation prototype system. This process chain was set up, evaluated, validated, and finally successfully transferred to the clinic. We were able to precisely detect the macrostructure of the defect and could virtually generate a graft to cover this missing part of bone. The use of a commercial software solution in combination with self-developed algorithms allowed us to identify the ideal donor site in the pelvic bone in terms of shape as well as blood supply. The implementation of the algorithms for mathematical optimization of the donor site is an additional option that facilitates the planning and does not complicate from the technical point of view, because the programming endeavor is already successfully finalized.

Because of its complexity in form and function, reconstructive orofacial surgery with osseous free

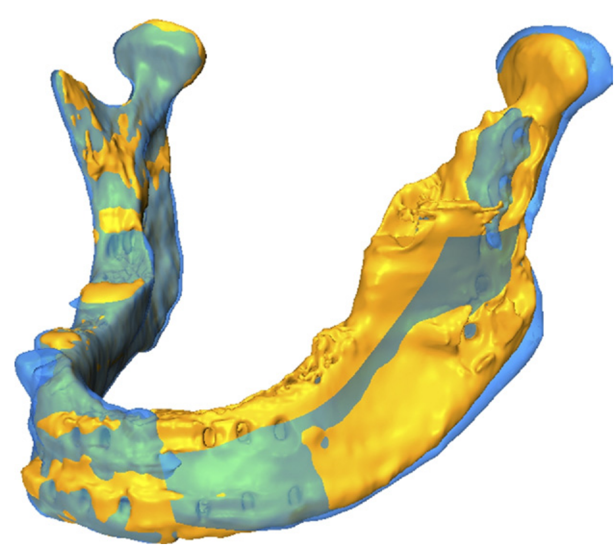

FIGURE 5. Three-dimensional reconstruction of the postoperative CT scan superimposed with the virtual planning shows excellent matching between corresponding data sets. Color coding: *blue* = planning; *orange/gold* = postoperative CT scan.

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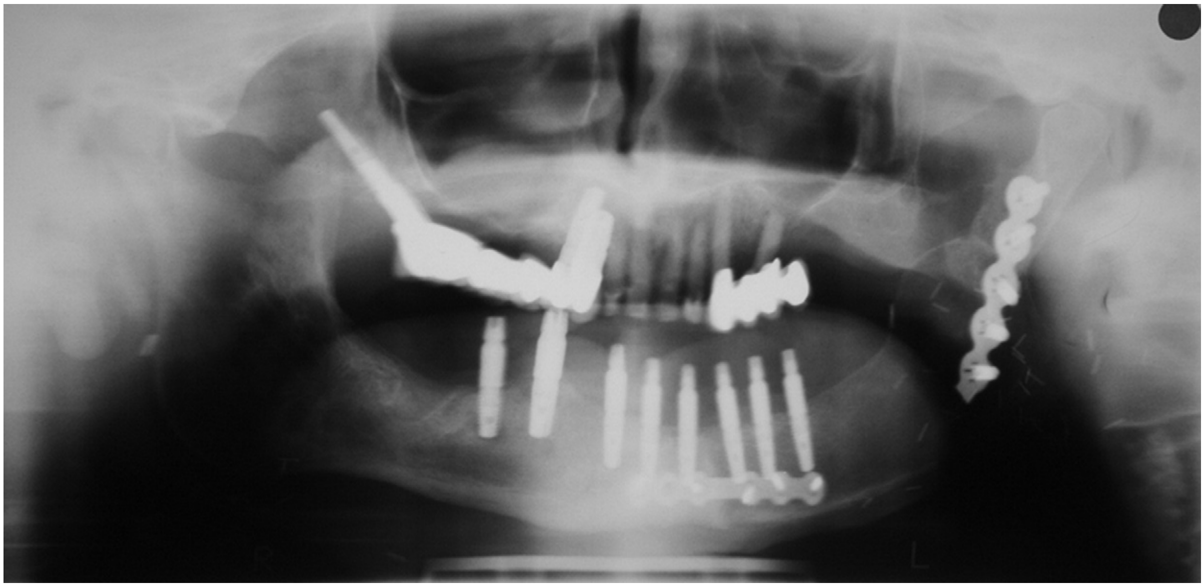

FIGURE 6. The orthopantomogram acquired in June 2009 shows excellent osseointegration of the dental implant in the reconstructed area of the mandible. No signs of loosening of the osteosynthesis material nor signs of pseudarthrosis could be detected.

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flaps is still challenging, even if all technical possibilities to facilitate the surgery are used and work properly. Besides the reconstruction of the bony defect, the surgeon has to take into account the functional aspects of speech, swallowing, upper airway, and masticatory apparatus. In this context, the surgeon also has to consider the rehabilitation of the chewing function with implant-supported dentures already at the time of reconstructive surgery. This can be achieved by implant-positioning into the fibula already in advance of the reconstructive surgery or, as in our case, by ensuring that the bone graft has a form as close to the natural form of the mandible as possible.[14,15]

From the patient's point of view, the esthetic outcome is almost as important as the functional result.[16] In cases of dentate patients with hemimandibulectomy, the iliac crest graft is reported to provide the most satisfying results.

With this method we could provide an optimum of preoperative planning to our patient.

To transfer our planning to the patient, the use of the 3D real-time navigational prototype system was the right decision. We could show that our system provided accuracy comparable to the accuracy of the CT dataset. In the OR environment, the 3-D display of the patient's anatomy was 1 of the most evident advantages of this prototype in comparison with other commercial systems. Keeping the stereolithographic model of the bone graft—a clinically tested and approved method—"in standby" at the OR site so that it could serve as a cutting guide provides an excellent backup in the case of unexpected malfunction of the navigational prototype system[12,13] and—probably much more important—supply the surgeon with a haptic feeling that cannot be fully substituted even by sophisticated computer graphics.

Obviously, this workflow could easily be applied at every craniomaxillofacial surgery department as soon as the premarket phase of the system itself is overcome and a more widespread access to planning and navigation system is available. To the best of our knowledge, it is the first time that harvesting an osseous graft from the pelvic bone was performed under the guidance of a real-time navigation system.

In conclusion, in our experience with the presented case, the surgeons could clearly benefit from the technology. The use of this new technological support was helpful to reduce the time of the surgery and provide optimal accuracy. In the future, the system will help to make the surgical approaches less invasive, and a more frequent use of the system could help to make these interventions even more cost-effective through reduced time in the OR. Apart from this, patients will benefit in improved function and esthetics.

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