Fully Digitally Guided Implant Surgery Based on Magnetic Resonance Imaging

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Purpose: The purpose of this study was to evaluate whether fully digitally guided implant surgery may be performed with sufficient accuracy based on printing virtually designed templates after matching a surface scan with the magnetic resonance imaging (MRI) dataset mimicking edentulous cases based on cadaver maxillae of pigs. Materials and Methods: The palatal mucosa of five young pig cadavers was scanned with an intraoral scanner. High-resolution MRI of the jaws was performed, and the images were exported as DICOM files and uploaded into software for implant planning. Six implant osteotomies were virtually planned in each jaw. The intraoral surface scans were fused with the volumetric MRI data based on the palatal soft tissue, and virtual templates for guided implant surgery were created and exported as STL files. These were printed and the templates were used to perform flapless guided osteotomy, with the templates fitting on the soft tissue of the jaws alone. Cone beam computed tomography (CBCT) of the jaws was performed after osteotomy. These data were fused with the virtually planned osteotomies, and the 3D crestal, apical, and axial deviations between the virtually planned and physically performed osteotomies were determined.

Results: Matching the surface scans with the mucosa was possible in three cases automatically; additional manual corrections were necessary in two cases. Thirty osteotomies were performed by applying the printed mucosa-supported templates. The mean angular deviation between the planned and realized cavities was 3.29 degrees (0.3 to 11.1 degrees; SD = 2.5 degrees), the mean 3D apical deviation was 1.3 mm (0.22 to 3.98 mm; SD = 0.94 mm), and the mean crestal deviation was 1.76 mm (0.39 to 3.79 mm; SD = 0.88 mm).

Conclusion: MRI in combination with the presented workflow may be used in edentulous cases for guided implant surgery. Further studies are needed to prove the promising accuracy of this alternative approach in clinical trials. Int J Oral Maxillofac Implants 2019;34:529–534. doi: 10.11607/jomi.7076

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Guided implant surgery is based on transforming prosthetically driven virtual planning into reality through the use of templates. Two main workflows and many different systems are available for guided implant surgery. In the past it was mandatory to use radiographic templates, which were transformed into templates for guidance in a laboratory. Therefore, it was necessary to include system-specific reference elements in the radiographic templates. These allow the virtual planning to be transformed into reality by means of specially designed drilling devices. Recently an alternative workflow became available,¹² making a radiographic template unnecessary and representing fully digitally guided implant surgery. In this workflow, the three-dimensional (3D) radiographs are directly fused with an intraoral surface scan of the patient’s teeth. After implant planning, virtual templates may be designed based on the fused surface scan. If exported as a surface tessellation language (STL) file, the virtually designed templates may be printed by 3D printing devices.

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Several advantages are associated with fully digitally guided implant surgery: no need for radiographic templates, leading to cost reduction; more time efficiency, since 3D imaging may be performed in the first session; and finally, fewer sources of inaccuracies related to transforming the radiographic template into a surgical template in a dental laboratory.\footnote{1,2} However, matching a surface scan with cone beam computed tomography (CBCT) or computed tomography (CT) requires structures that are visible in both radiography (CBCT or CT) and the surface scan. These visible structures are most likely teeth. In edentulous patients, the surface scan has to be matched with the mucosa, which consequently must be visible in CBCT or CT. With insufficient visualization of the mucosa in both CBCT and CT, matching with a surface scan is almost impossible without additional effort. Various attempts were made by the authors to optimize the visualization of soft tissue in CBCT or CT. Applying iodoform paste or different radiopaque powders was considered, but the resulting visualization of the soft tissue still seemed unsatisfactory for a high-accuracy matching procedure. Magnetic resonance imaging (MRI) is the gold standard in visualization of soft tissue and organs in medicine.\footnote{3} Using dedicated MRI methods, such as ultrashort echo time (UTE) or zero echo time (ZTE), however, even bone or teeth may be visualized.\footnote{4} As a result, it should be possible to visualize the mucosa for matching—as well as the bone—for implant planning purposes.\footnote{5} Thus, MRI might represent a valuable alternative to CBCT or CT, especially in edentulous patients for whom guided implant surgery is required.

The aim of the present study was to (1) test whether it is possible to fabricate templates based on matching surface scans of the mucosa with MRI and (2) estimate the achievable accuracy of these templates if used for guided implant surgery. The hypothesis was that it is feasible to perform guided implant surgery based on matching a surface scan with an MRI and printing a virtually designed template with acceptable accuracy.

**MATERIALS AND METHODS**

The palatal mucosa of the maxillae of five young pig cadavers was scanned with an intraoral scanner (Trios, 3Shape). The complete area from the incisor region to the tuberosity was scanned until all rugae were clearly visible on the monitor of the intraoral scanner (Fig 1). The data were extracted as STL files and stored on a desktop personal computer.

After the surface scans had been performed, all maxillae underwent MRI. The MRI scanning was performed on a 3T whole-body MRI system (Magnetom Prisma, Siemens Healthineers) using a 20-channel head and neck coil (Fig 2). The built-in body coil was used for radio frequency (RF) transmission.

Imaging was performed with a nonselective 3D fast spin-echo (SE) sequence\footnote{6} with \(0.9 \times 0.9 \times 0.9\) mm\(^3\) isotropic spatial resolution; interpolated on the MRI system to \(0.45 \times 0.45 \times 0.45\) mm\(^3\). Other sequence parameters were: FOV = 288 × 259.2 × 86.4 mm\(^3\) (imaging matrix = 320 × 288 × 96), GRAPPA acceleration factor 2, repetition time = 700 ms, echo time = 3.8 ms, bandwidth = 625 Hz/Px, echo spacing = 3.84 ms, echo train duration = 150 ms, turbo factor = 38, total acquisition time = 4:56 minutes.

The MRI data were stored in the digital imaging and communications in medicine (DICOM) format and uploaded into software for implant planning (coDiagnostiX, Version 9.7.6.11426, Dental Wings) and subsequently segmented (Fig 1). Six osteotomies with a diameter of 3.5 mm and an intrabony length of 10 mm were planned in each jaw where bone was visible (Fig 1). Due to developing teeth, these regions were scarce and the position of osteotomies could not be planned equally in each respective jaw. After planning of the osteotomies, the surface scans were uploaded as an STL file into the coDiagnostiX software and matched with the volumetric MRI data (Figs 1 and 3). The software has an algorithm allowing three identical points in each dataset (MRI and surface scan) to be determined for automatic matching. The corresponding or identical points were limited to the mucosa in order to mimic an edentulous situation. After fusion, the correct fit was checked manually by scrolling through the matched datasets. Finally, virtual templates were created, including spaces for tubes for guidance corresponding to the Straumann Guided Surgery system (Institut Straumann AG) (Fig 1). The distance between mucosa and virtual template was chosen to be 0.1 mm, and the thickness of the template was set at 3.0 mm. Since teeth were not extracted, the template design was chosen in such a way that no contact to teeth was obtained and, as a result, the template only fitted on the mucosa (Fig 4). The mucosa was left untouched as it was. The templates were then stored as STL files and sent to a high-end 3D printing device (Objet Eden 260 Connex 2, Stratasys). A biocompatible composite material was used for the printing process (MED610, Stratasys). T-tubes with a length and diameter of 5 mm (Institut Straumann AG) were incorporated into the templates manually.

The templates were positioned on the palatal mucosa of the corresponding jaws. The fit was checked visually (Fig 5). For osteotomy preparation, the Straumann Guided Surgery set was used according to the protocol given by coDiagnostiX software for osteotomy for a 4.1-mm-diameter and 10-mm-long implant (Straumann Tissue level SP, Institut Straumann AG), resulting in a diameter of 3.5 mm. The protocol is...
adapted to the respective system and includes depth control by choosing the correct combination of drill length, sleeve position, and drill handle length. The depths of the cavities were not additionally controlled.

Drilling in a central position was tried, avoiding the application of eccentric forces. As the templates were fitted only onto soft tissue, every cavity preparation was performed flapless.
After the drilling procedure, CBCT of all maxillae was performed (3D Accuitomo 170, Morita) with a field of view of 140 × 100 mm² diameter. The data were extracted as DICOM files and uploaded into the coDiagnostiX software. CBCT was matched with MRI and the included virtually planned implant cavities. The software has a specific tool, which, after matching MRI with CBCT, allows direct evaluation of the deviations between the virtual osteotomies and real position. For this purpose, both datasets (planned osteotomies based on the MRI and the postoperative CBCT) were aligned based on anatomic landmarks, eg, tooth buds. The software offers a specific window tool for this purpose, and the position of the alignment is stored automatically. For evaluation of the deviations, the postoperative CBCT was manually aligned according to the osteotomies performed and the virtually planned osteotomies using a "drag and drop" procedure in all three dimensions; this was carried out by an experienced coworker (A.S., see acknowledgment). The software has a specific tool for this purpose. The postoperative CBCT was uploaded into the coDiagnostiX software and aligned with the MRI in which the virtual osteotomies were planned. The alignment was stored. In a second step, the CBCT (in which the osteotomies were perfectly visible) was manually aligned by “drag and drop” based on matching each single and corresponding osteotomy of both datasets: virtually planned osteotomy in the MRI and realized osteotomy in the CBCT. Once both osteotomies are perfectly aligned, the software automatically calculates the respective 3D deviations. The alignment is based on a region-based surface matching algorithm.

For each implant, the 3D crestal and apical, as well as axial deviations were determined in mm and degrees, respectively.

Descriptive statistical analysis was performed with maximum, minimum, mean and standard deviations (SD) based on an Excel sheet (Microsoft Excel 2010).

RESULTS

The matching of surface scans with the MRI dataset could be performed in the automated mode in three cases. In two cases the automatic matching feature needed slight manual corrections in order to optimize the alignment. The quality of the alignment was evaluated visually based on scrolling through the axial and sagittal sections of the MRI and surface scan. The soft tissue was clearly visible in the MRI, generally facilitating the matching procedure. Bone, developing teeth, and nerve could be estimated through fat, giving a signal for MRI.

In total, 30 implant osteotomies were drilled. The templates showed a visually perfect fit on the mucosa. However, in some regions where the bone had a strong cortical structure, the templates showed some movement due to the movable palatal mucosa, as drilling forces had to be increased for cavity preparation.

The mean angular deviation was 3.29 degrees (0.3 to 11.1 degrees; SD = 2.5 degrees). The mean 3D apical deviation was 1.3 mm (0.22 to 3.98 mm; SD = 0.94 mm) and the mean crestal deviation was 1.76 mm (0.39 to 3.79 mm; SD = 0.88 mm).

DISCUSSION

This study showed that MRI may be used to perform the workflow for guided implant surgery based on matching a surface scan of the mucosa with the 3D imaging dataset in pigs. With regard to the hypothesis, it can be stated that it is feasible to perform guided implant surgery based on matching a surface scan with an MRI and printing a virtually designed template with an accuracy that is comparable to the conventional workflow for guided implant surgery in edentulous cases. The overall accuracy was comparable to other accuracy studies in which conventional workflows for guided implant surgery were used, based on evaluating the deviation between planned and realized cavity preparation in vitro, applying stereolithographic templates in resin-like jaws, or using a navigation system in stone-like casts. Jung et al reported mean deviations of 0.74 mm at the implant shoulder and 0.85 mm at the implant axis. Tahmaseb et al reported mean deviations of 1.12 mm at the implant shoulder and 1.39 mm at the implant axis. They also determined the mean axial deviation, which was reported to be 3.89 degrees. Both studies reported maximum deviations of 4.5 mm at the implant shoulder and 7.1 mm at the implant tip. These high inaccuracies were related to a study in which the templates were bone-supported. Jung et al and Tahmaseb et al showed that accuracy is dependent on the way in which templates are supported (tooth versus bone- or mucosa-supported). In a recent review on the accuracy of bone- or mucosa-supported templates, Marlière et al reported inaccuracies ranging from 1.8 to 8.4 degrees, and 0.17- to 2.17-mm and 0.77- to 2.86-mm deviations at the implant shoulder and apex, respectively. However, they concluded that the highest inaccuracies occurred in situations with mucosa-supported templates.

In the present study it was decided not to insert implants, which would have been another additional source of inaccuracy, in order to simplify the evaluation of accuracy measurements of the basic workflow. However, it can be assumed that, under clinical conditions...
involving insertion of implants, the inaccuracy might be much higher, as implant placement represents another source of inaccuracy. Since the study was conducted as a feasibility study, this aspect needs to be addressed in future studies. The workflow for guided implant surgery based on fusing a surface scan with CBCT or CT data has become more and more popular. For matching purposes, anatomic structures must be visible in both CBCT/CT and intraoral scans. This aspect is crucial in edentulous patients, as the mucosa is not sufficiently visible in CBCT or CT, and the conventional workflow, including prosthetically derived backward planning, recommends the insertion of three pins prior to planning or use of a radiographic template. This, however, raises costs or patient morbidity. This problem is so far unresolved and, to the best of the authors’ knowledge, MRI has not yet been used in combination with the workflow for guided implant surgery presented here. The study therefore was conducted as a proof of principle and has some flaws that need to be addressed: In contrast to human, porcine palatal mucosa shows distinct rugae that aid the matching procedure. Additionally, the mucosa has a thicker structure than in humans, which results in higher alignment with more visible pixels and thus facilitates the matching procedure. Moreover, MRI in the presence of metallic implants is limited. The use of MRI for dental applications has only found limited indications in the past, but is receiving more and more attention. MRI has successfully been used in dental applications for detecting the width of apices of wisdom teeth to estimate a patient’s age. This has an indication, since age estimation is mainly necessary for judicial reasons and, in contrast to CBCT or CT application, it offers a radiation-free imaging technique. Others have used MRI successfully to localize impacted teeth or periodontal structures. However, one reason for the limited indications for using MRI in dental applications relates to the good visualization of soft tissue but limited presentation of hard tissues like bone and teeth. This may also be the reason why MRI has not been used for planning guided implant surgery until now. Recently it was shown that inductively coupled intraoral coils enable high-resolution MRI of dental soft tissue, e.g., visualization of the pulp canal as well as periodontal tissue. Although this group describes the superior quality of soft tissue assessment, the published images impressively show the surrounding bone as well. MRI has successfully been used in earlier research by others for presurgical implant assessment. However, although some authors have described good bone visibility of the jaw with MRI, for planning guided implant surgery improvements in bone, improved visualization is still eligible when subjectively compared to the CBCT quality. Further optimization might be achieved by using dedicated and adapted MRI methods.

It is known that ferromagnetic metals can adversely affect the image quality by distorting the magnetic field. It has additionally been shown that titanium implants do not affect MRI quality but that the insert of magnet keepers for prostheses has to be removed for MR safety before an MRI scan. However, this plays a minor role in edentulous patients. One major drawback to using MRI in edentulous patients for guided implant surgery relates to the high costs that MRI still generates. Aside from cost, MRI requires more time for image acquisition when compared to CBCT or CT, which is another issue that limits the rational indication for using MRI in dentistry. Finally, this study used cadaver jaws, which show no movement during image acquisition. Even if the mean time for MRI were below 5 minutes, movements during MRI cannot be avoided in living humans. The movements might impair the image quality, thus leading to additional inaccuracies.

However, the workflow presented in this study for template fabrication based on matching a surface scan in edentulous patients is almost impossible using CT or CBCT data, and alternatives need to be introduced. In this respect MRI may provide a valuable alternative.

In the present study it was possible to align the MRI image clearly with the surface scan. In three out of five cases (60%) this was even possible with the automated mode, and in two cases (40%) slight manual corrections had to be made. It is reasonable to assume that the need for manual alignment might be even higher in humans, since the rugae are not so prominent and thus an impediment to automatic alignment.

CONCLUSIONS

The workflow described in this study represents a new and alternative way of performing guided implant surgery in edentulous cases. The accuracy calculated is comparable to the alternative workflows for guided implant surgery in edentulous cases. However, additional studies in humans are required to evaluate the benefit of this approach.

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REFERENCES


