

Research Paper Dental Implants

Accuracy of augmented reality-assisted versus template-guided implant surgery: an in-vitro comparative study

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Abstract. This in-vitro comparative study aimed to examine the accuracy of augmented reality-assisted implant placement compared to the conventional drilling templates. Twenty maxillary bone models were used to perform 80 implant placements using two different methods. Every bone model received four implants: two were placed using augmented reality (AR-I), and two using templates (TG-I). AR-I was performed using Microsoft HoloLens 2, and TG-I using SMOP Software. Postoperative cone-beam computed tomograms were superimposed with the presurgical planning, measuring the deviation between the planned and placed implant. The primary outcome (angular deviation (degrees)) and secondary outcome (depth deviation (mm)) parameters were measured. Overall, 80 implant surgeries were included in the study. Regarding the primary outcome parameter, a statistically significant difference ($P < 0.001$) between AR-I and TG-I was demonstrated. The mean values were $1.48^\circ (\pm 1.45)$ in the AR-I group and $2.65^\circ (\pm 1.29)$ in the TG-I group. The secondary outcome parameter showed no significant difference ($P = 0.6$) between the AR-I group with $-0.07 \text{ mm} (\pm 0.59)$ and the TG-I group with $-0.08 \text{ mm} (\pm 0.67)$. The results show a high precision for both methods. The AR technology showed even more accurate results, particularly regarding the primary outcome parameter.

Keywords: Computer-assisted surgery; Mixed reality; In-vitro study; Oral surgical procedures, dental implantation.

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Augmented reality (AR) plays an increasingly important role in dental medicine. This technology integrates virtual information into the real-world environment. It opens new

opportunities in various dental fields and provides the user with an enhanced perception of their surroundings.¹ Augmented reality generally is believed to have been developed by Caudell and

Mizell, working with a head-up display, combined with head position sensing and a workplace registration system.^{2,3} With recent commercial products such as Microsoft HoloLens (Microsoft,

Redmond, WA, USA), and Google Glass (Google, Mountain View, CA, USA), optical see-through systems have become broadly available. These head-mounted-displays allow a high degree of flexibility by enabling the user to visualize virtual content that is directly overlaid onto the real-world environment.^{2,4} For this reason, this technology is also referred to as 'mixed reality'.

In the field of dental medicine, AR techniques were already described in 1996 by Wagner et al. for joint motion analysis.⁵ The need for more precise, faster, and minimally invasive treatment techniques has driven the technology to undergo significant advancements over the past few decades. In the field of dental implant surgery, implant placement can rely on two-dimensional imaging and free hand drilling. This procedure is highly dependent on experience, possibly leading to variations in implant positioning and angulation. Implant placement can also be performed using newer technologies such as static drilling templates based on cone-beam computed tomography (CBCT) and intraoral scans which enable high precision of implant placement.⁴ On top of these existing static technologies, emerging dynamic technologies such as AR become of interest to enhance the accuracy, efficiency, and predictability of dental implant procedures.

AR can be utilized to overlay preoperative imaging data (such as three-dimensional (3D) scans) directly onto the patient's anatomy during surgery, allowing a better visualization of critical structures and improving the precision of implant placement. Further, even the digital preoperative planning of the targeted implant position can be overlaid on the patient's anatomy. This technology offers numerous potential benefits, including reduced surgery times, improved treatment planning, and possibly minimized risk of complications and harm to vulnerable anatomical structures.

The application of AR in dental implantology is still not present in clinics. AR is still a developing technique; its intraoral application requires extra small, precise devices and must enable treatment on a conscious and moving patient, compared to other medical fields. Furthermore, clinicians are often accustomed to existing systems, and are wary of the costs and changes new technologies bring.

Therefore, the accuracy of AR-assisted implant surgery (AR-I) was investigated in an in-vitro setting and compared to the established technique of using templates to guide the implant surgery (TG-I). The null hypothesis of no difference between AR-I and TG-I with regard to angular deviation (primary endpoint) and depth deviation (secondary endpoint) was assumed.

Materials and methods

This in-vitro study was conducted at the Clinic of Cranio-Maxillofacial and Oral Surgery at the University of Zürich, Switzerland, between January 2024 to October 2024.

Study design

A power analysis was conducted to determine the required sample size, considering a clinically relevant difference of 5° in angle and 1 mm in depth.⁴ A Wilcoxon signed-rank test was chosen to account for the paired nature of the study and its robustness against deviations from the normality assumption. In order to use realistic estimates for the standard deviation, data from a previous study were used.⁴ In the sample simulations, scenarios with larger (150%) and smaller (50%) standard deviations were also explored to assess the sensitivity to this input parameter. With 66 samples (33 TG-I and 33 AR-I), both endpoints were sufficiently powered at a significance level of $\alpha = 0.05$. To ensure a multiple of four (four samples per jaw) and to account for a 15% potential jaw failure rate, the sample size was increased to 80 (40 TG-I and 40 AR-I). Thus, 20 partially edentulous maxillary bone models, simulating natural bone in general in a density D2 with a cortico-spongy architecture (Bonemodells SLU, ESB12874939, 12001 Castellón de la Plana, Castellón España, Spain) giving ideal conditions for implant placement, were used for this study. These models provide four regions simulating a fully healed ridge in regions 14, 16, 25, and 27. The regions 14 and 16 simulate each a single tooth gap with two neighbouring teeth. The regions 25 and 27 simulate a free end situation (Fig. 1a, b).

For the digital planning, CBCT (Morita 3D Accutomo 170; Morita, Osaka, Japan) of every maxillary bone model was performed. For this

purpose, all bone models were placed and aligned centrally on a platform, using the positioning light of the scanner. Every model was scanned in a standard dose protocol (89 kV, 4.9 mA, exposure time 17.5 s, field of view (FOV) 8x8mm, voxel size 0.16mm, slice thickness 1 mm). Additionally, an optical scan (Primescan; Dentsply Sirona, Bensheim, Germany; FOV 16x16mm) of each model was performed.

A pilot study with five bone models was conducted for training and to better estimate the overall cost of this study. A total of 80 dental implants were then placed in 20 maxillary bone models. Every bone model underwent two TG-I and two AR-I. Due to the different conditions of the regions 14, 16, 25, and 27 (single tooth gap and free end situation) the drilling method was fully permuted using a drilling order plan.

Digital planning

Prior to implant placement, a preoperative optical scan (STL file) and a preoperative CBCT image (DICOM file) were performed. The two files were superimposed using the SMOP implant planning software (SMOP, Dental Planning system, Version 2.21.2; Swissmeda, Baar, Switzerland). One team member (T.DG.) virtually positioned a dental implant in each designated implant site (site 14, 16, 25, and 27). The planned implant positions were controlled by an experienced oral surgeon (F.B.) (Fig. 2a, b).

For TG-I, a tooth and bone supported drilling template was designed, and 3D printed using MED610 (Stratasys, Eden Prairie, MN, USA) in collaboration with the SMOP Service Center. The sleeves were not glued into the surgical guide (Fig. 3a-d).

For AR-I, the same digital planning was sent to Increded (Zürich, Switzerland). The digital planning was loaded onto the Microsoft HoloLens 2 Augmented Reality Headset (Microsoft) using the Device Portal web application running on the HoloLens 2. Once the planning resided in the file system of HoloLens, it could be accessed by Increded's navigational Mixed Reality App. Using this tailor-made application, the drilling position and angular direction of the planned drillings were visualized in the AR headset and the surgeon was guided when using the instruments.

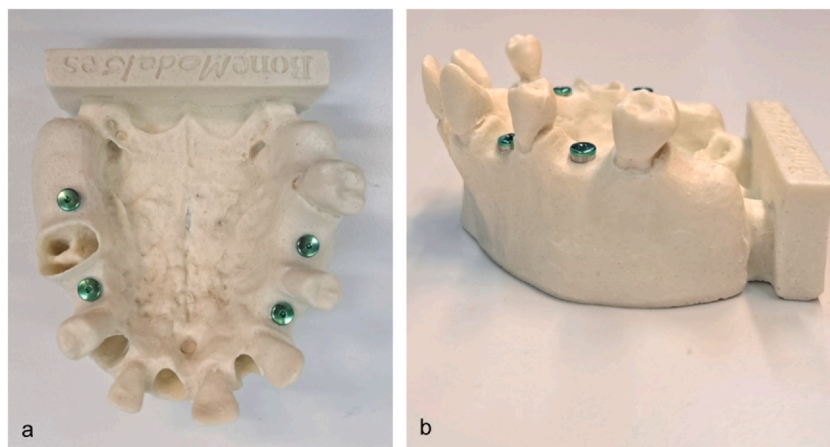


Fig. 1. Maxillary bone model from occlusal (a) and lateral view (b).

Surgery

One experienced oral surgeon (F.B.) performed the implant placement procedure, after conducting a pilot study on five similar models. As described for each maxillary bone model, two AR-I and two TG-I implants were placed in a permuted protocol.

In this investigation a bone-level type dental implant with a 1 mm polished neck of pure titanium (Grade 4) in two different length was used. The parallel-walled implant is self-tapping with a shallow thread depth, a thread pitch of 1 mm and a superhydrophilic conditioned surfaced INICELL (Element RC 4.0 ×9.5 mm or ×12.5 mm Thommen SPI, Grenchen, Switzerland). The implant placement followed the manufacturer's recommendations using a surgical motor (CA 20:1 L, MX-LED; Chiropro L, Bien-Air Dental SA).

The guide-related surgical components recommended by the manufacturers include the following: surgical drilling with drill-integrated sleeve guidance inserted into the guide.

The currently used AR technology does not compensate optimally for any

movement of the object. Therefore, a special construction for a rigid fixation of the maxilla was used. The maxilla was fixed on a plastic plate with one centrally placed screw. This plastic plate included three optical reference-markers to reference the fixed bone model with the used drilling tool which was also optically tracked. Next the plate itself was mounted via a clamp on a fixed table (Fig. 4). Thus, the construction was immobile and enabled an optimal drilling situation for the AR-I protocol. The application was started by voice command and the 3D registration of the maxilla was the first step of the procedure. For each maxilla, three predefined landmark points were collected by the surgeon with a custom-made pointing device (PD) consisting of a notch, a handle and a tip (Fig. 5).

The AR application recognized this sterile PD with the mounted markers. Using the optical tracking of this sterile marker, the PS App could locate, register, and seamlessly track the 3D location and pose of the pointer tools. Due to the known geometry of the PD, the navigation application can

extrapolate from the markers pose to the position of the tip and thus enable guided navigation (Fig. 5).

After the successful registration, the preoperative surface scan of the maxilla was superimposed on the real maxilla. The surgeon could check the registration by placing the PD at any area of the maxilla and checking the match visually. After approval, the surgical navigation could be started by voice command.

The surgical navigation approach relies on a trackable custom-made navigation device (ND) attached to a standard-angle handpiece. The ND was also mounted with sterile markers that were recognised by the navigation app. The ND is designed in such a way that it allows the surgeon to hold the handpiece onehanded. After starting the navigation, the 3D model of the maxilla was hidden, and an entry point of the planned implant position was shown. By moving the ND, the navigation app registered the markers added to the ND and tracked every movement of the bur. In addition, degrees of deviation in the 3D area were shown virtually, so that the navigation could be performed according to these two guidance methods. When moving the bur, the marker allowed the surgeon to follow the movement, and correspondingly adjust every deviation from the optimal (planned) drilling position and angle. By displaying visual guidance for both, the entry point of the drilling and the angular orientation, the surgeon could navigate the anatomy of the model (Fig. 6a, b). Currently, the measurement of depth is the only missing guidance that cannot yet be virtually shown. For this reason, the present authors measured the depth during drilling classically through the markers on the bur.

For the TG-I methodology no fixation was used. Prior to the TG-I drilling, the fit of the drilling template was checked, and if necessary adjusted. The guided drilling was conducted using the same standard-angle handpiece without permanent water cooling to the depth stop.

After placing the implants (fully guided) every maxillary bone model underwent a postoperative CBCT scan for the verification of the implant position.

Accuracy analysis

The accuracy analysis was performed using the SMOP software (Dental

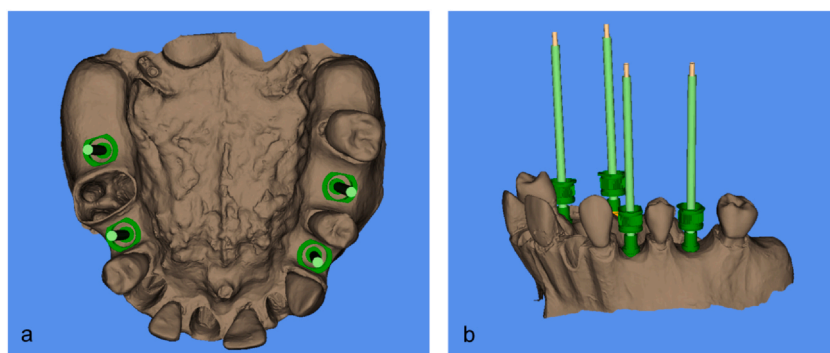


Fig. 2. Digital implant planning from occlusal (a) and lateral view (b).

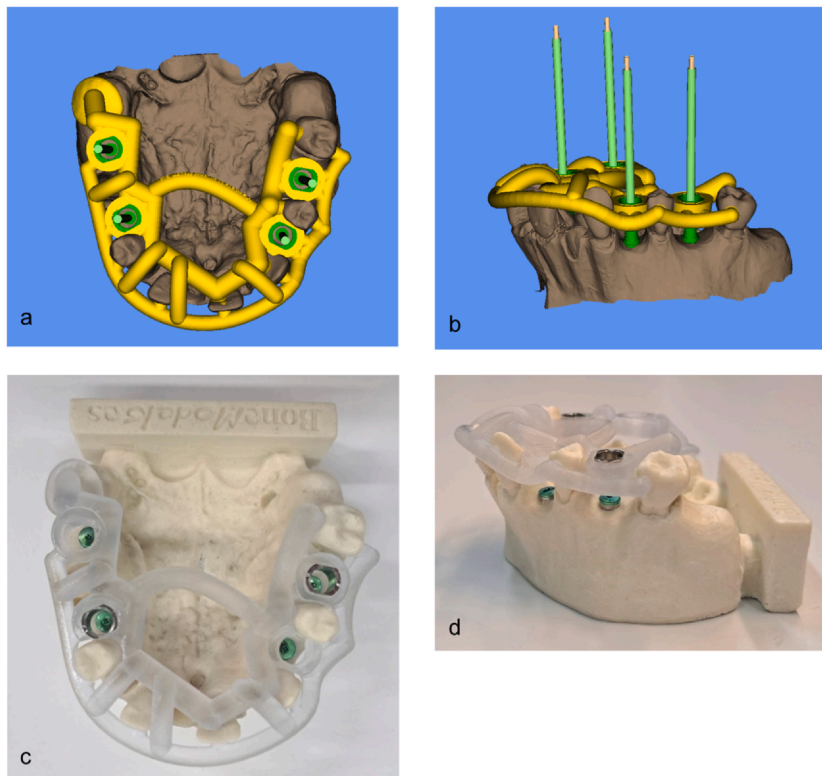


Fig. 3. Digital implant planning with the planned drilling template from occlusal (a) and lateral view (b), printed drilling template on maxillary bone model from occlusal (c) and lateral view (d).

Planning system, Version 2.21.2; Swissmeda, Baar, Switzerland). The preoperative CBCT scan was extracted in STL file format from the initial planning case in the MeshLab software. The surface was then smoothed using the Laplacian smoothing tool. The postoperative CBCT scan was imported as a new case. The accuracy analysis was performed by the SMOP Service Center. Using congruent alignment via conducted surface matching in the SMOP software, the originally planned implant was loaded into the new case. The software computed the deviation between the planned implant and the actual implant (Fig. 7a, b). For the primary outcome angle deviation, solely positive values exist due to the measured difference without taking notice in which direction the deviation was made. The secondary outcome parameter, depth deviation, was measured in two directions. Negative values indicate that the implant overshoot the planned implant position and positive values indicate that the implant was placed too short compared to the planned implant position (0 = length of the planned implant position).

Statistical analysis

Descriptive statistics including mean, standard deviation, median and inter-quartile range were computed for both endpoints. For the boxplot visualization, two measurements for each method and endpoint were mean-averaged and connected by a dashed line with their counterpart for the same jaw, reflecting the repeated-measures design of the study (Fig. 8). In line with the sample size calculation, Wilcoxon signed-rank tests were used for each of the two endpoints to take the paired nature of the data into account. The significance level for the tests was set to $\alpha = 0.05$, in line with the a-priori sample size calculation. All analyses and plots were computed with the software R,⁶ including the package Tidyverse.⁷

Results

Overall, 80 out of 80 implant placements analysable. Therefore, no bone models were excluded. Out of these 80 implant placements, 40 (50%) were performed by TG-I and 40 (50%) by AR-I.



Fig. 4. Fixation technique of the jaw model with custom-made pointing device for registration.

Primary outcome (angular deviation)

The mean values overall were in favour of the AR-I group ($1.48^\circ \pm 1.45^\circ$) compared to the TG-I group ($2.65^\circ \pm 1.29^\circ$) ($P < 0.001$) (Table 1, Fig. 8). The spread of the data is comparable for both technologies.

Secondary outcome (depth deviation)

The mean values are overall comparable between the AR-I group (-0.07 ± 0.59 mm) and the TG-I group (-0.08 ± 0.67 mm) ($P = 0.6$) (Table 1, Fig. 8).

Negative values indicate that the drilling overshoot the target site (0 = target). The trend shows that, on average, the surgeon is more likely to overshoot the target.

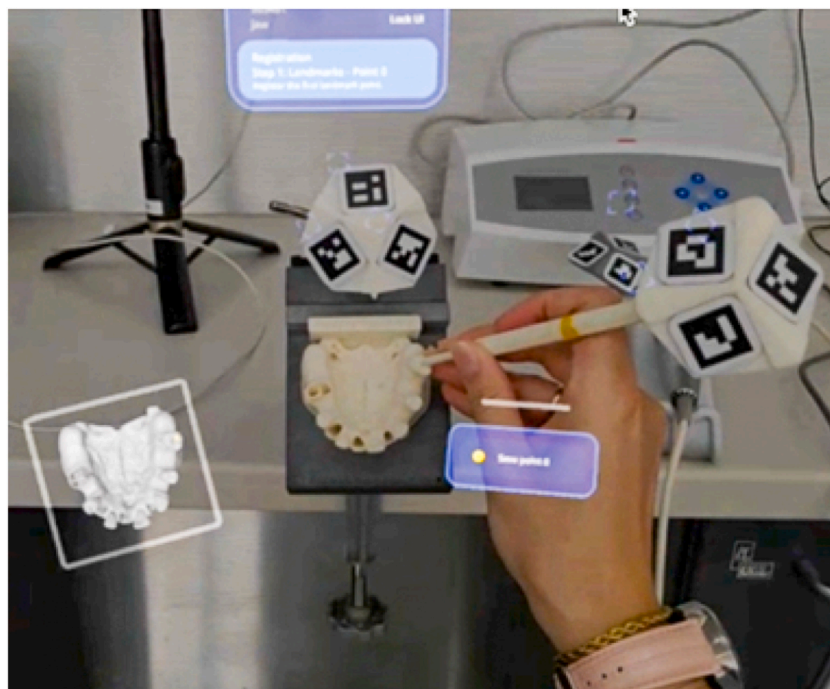


Fig. 5. Successful registration of the bone model: view through augmented reality glasses.

Discussion

The aim of the present in-vitro study was to investigate whether the application of AR in implant surgery shows significant differences compared to the established template-guided methodology. Regarding the accuracy (trueness and precision), the AR technology performed comparably to the applied drilling template. Regarding the primary outcome parameter angle, it even performed slightly (yet statistically significantly) better than the established template-guided technology. The results show for both technologies in terms of the surgical procedure well-performing parameters within medically relevant trueness and precision. It was our aim to assess the magnitude of

error from a surgeon's point of view. Other variables, such as directional analysis of angular deviation or localisation, could be assessed in further studies to provide additional information for prosthetically demanding cases.

The data suggest that the AR technology enables a very precise placement of dental implants in this in-vitro setting.

Few studies have investigated the use of AR in dental medicine and even more rarely in the field of oral implantology. Applying the same technology, Bosshard et al.⁴ showed that both methods (AR and TG) show similar accuracy in an ex-vivo model performing apicoectomies of teeth. Bochet et al.⁸ used the AR technology to improve education in the field of oral

implantology. Two implants were placed in a 3D-printed model of a patient. The angle deviation of the placed implant to the originally planned implant position was with 3.1° and respectively 4.5° worse than in our experiment. Pellegrino et al.⁹ showed in two clinical cases an angular deviation of 3.05° and 2.19° . In general, these studies show that results are even better using a fixed model. Similar to Bochet et al., the models in our study were each placed on a table thus easily accessible for the surgeon. They could have been fixated in a phantom head instead to simulate the clinical setting and make the surgical procedure more challenging.

In orthopaedic surgery the values differ from the dental field due to larger surgical sites. An ex-vivo cadaver study performing the complex procedure of the pelvic osteotomy of Ganz¹⁰ in 14 human cadavers showed mean angle deviations between 6° and 7° . Viehöfer et al. performed an osteotomy to correct hallux valgus. An inexperienced surgeon performed more accurate osteotomies with AR with a mean angle of 6.4° compared to freehand 10.5° ; however, an experienced surgeon showed no significant difference performing this osteotomy with AR or freehand (both 3°).¹¹

Pedicle screws are inserted in vertebrae. Dennler et al.¹² proved in another model that the additional anatomical information of the AR technology improved the precision of drilling pilot holes for pedicle screws and decreased the effect of the surgeon's experience.

One advantage of AR implant planning in comparison to drilling templates is that there is no need for a physical template and access to a 3D-printer. Further, the surgeon has a direct view on the implant site, which is generally prevented by a drilling template. In patients with reduced mouth opening, an implant insertion in the posterior area could be performed under AR guidance while in these cases drilling templates are often too bulky to be inserted together with the drill. An advantage of a drilling template is that the bur is physically guided without a risk of slipping away at sharp edges or possible false angulations.

Possible downsides of AR technologies need to be discussed. The technology depends on hard- and software, which need to be serviced, including relevant updates. Further, the

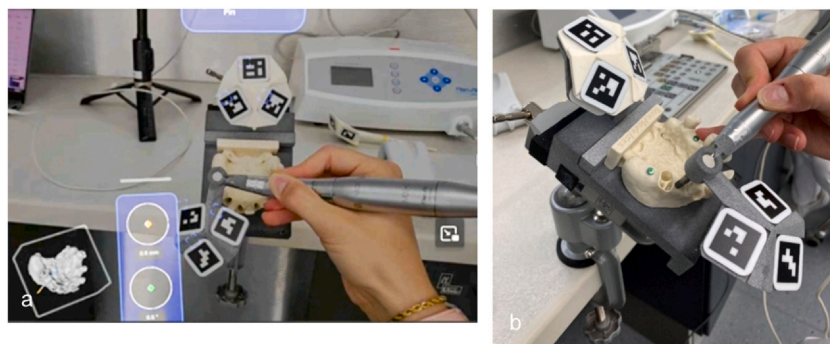


Fig. 6. Augmented reality (AR) implant placement from occlusal: view through AR glasses (a) and lateral view (b).

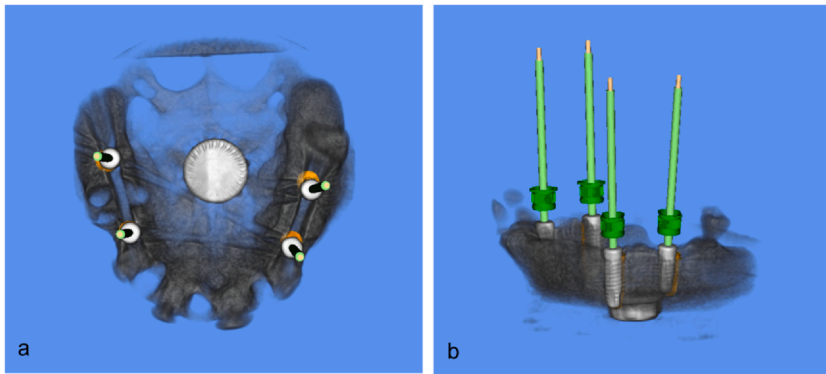


Fig. 7. SMOP Dental Planning system analysis: orange (planned position) from occlusal view (a); green (placed implant) from lateral view (b).

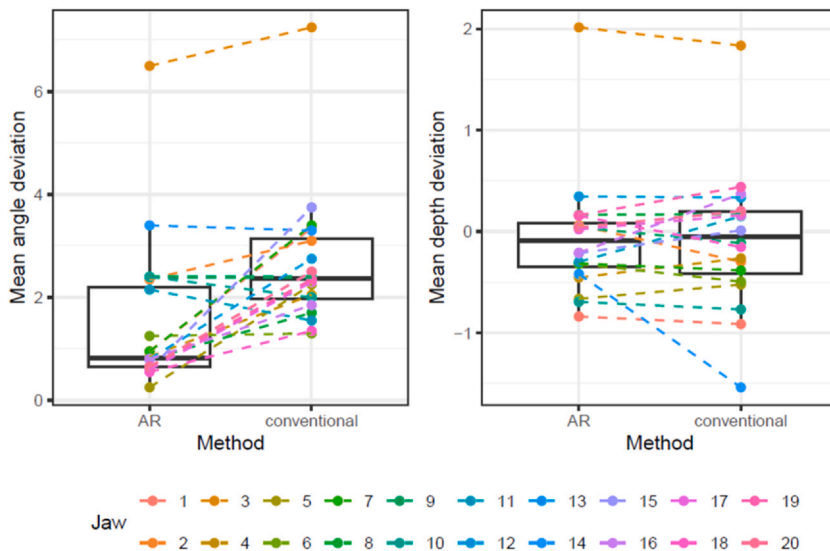


Fig. 8. Box plot regarding the two outcome parameters. Every jaw had four measurements for each of the two endpoints, two for augmented reality-assisted (AR) and two for template-guided (conventional) implant placement. The two measurements for each method and endpoint were mean-averaged for better visualization and connected by a dashed line with their counterpart for the same jaw.

workflow needs to be established in clinical surroundings. Possible risk factors, for example a mismatch of virtual and real data, need to be considered to avoid any possible harm to the patient. This needs to be leveraged against the possible downsides of drilling templates. Although drilling guides appear to guide the surgeon very precisely, they do not allow any correcting movements. In case there is a planning error or in case the template would not

exactly fit on the teeth, it would guide the drill in a false position. Therefore, the surgeon needs to be alert and control these steps. The template itself also limits his view on the surgical site.

Discussing the possible transfer to the patient, it needs to be mentioned that this would demand small, precise devices and real-time motion tracking, as no rigid fixation of a patient is possible. This especially applies to dental medicine, as most

procedures are performed in local anaesthesia with a moving patient and a mandible moving in relation to the maxilla.

The next step will be the application of real-time motion tracking during placement in order to be closer to clinical reality. Furthermore, it would be interesting to integrate the feature of depth measurement into the current software application (Increment Zurich, Switzerland), which is possible but requires more funding.

It is also clear that the success of the AR technology also depends on the surgeon's experience and being familiar with the AR procedure itself. Most clinicians are used to current static implantation systems, lower acquisition costs, and training is required.

With digital development and with further studies providing reliable precision, it seems that AR technology has great potential and its value in implantology will grow in the future.

As a possible weakness we could have chosen bone models in density D3, which is more prevalent in the upper jaw.¹³ It was not the aim to introduce another variable (e.g. localisation, primary stability) but to assess the magnitude of error from a surgical point of view.

In conclusion, the results show a very high precision for both of the implant placement technologies. Under the applied study setup, the AR technology shows even more accurate results, particularly with regard to the primary outcome parameter angle deviation.

Patient consent

Not required.

Ethical approval

No.

Funding

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Table 1. Primary and secondary outcomes of augmented reality-assisted (AR-I) and template-guided (TG-I) implant placement.

Placement type	Angle deviation (°)					Depth deviation (mm)				
	Distal	Mesial	Left	Right	Overall	Distal	Mesial	Left	Right	Overall
AR-I	1.67 ± 1.80	1.28 ± 1.11	1.53 ± 1.54	1.43 ± 1.47	1.48 ± 1.45	0.03 ± 1.14	-0.17 ± 0.54	0.25 ± 0.46	0.11 ± 1.16	0.07 ± 0.59
TG-I	2.88 ± 1.26	2.42 ± 1.84	3.14 ± 1.66	2.15 ± 1.34	2.65 ± 1.29	-0.25 ± 0.55	0.09 ± 1.03	0.26 ± 0.70	0.10 ± 0.94	-0.08 ± 0.67

Values are mean ± standard deviation.

Competing interests

None.

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