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Assessment of metal sleeve-free 3D-printed implant surgical guides

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ABSTRACT

Objectives. The aim of the present study was to investigate the adaptation and guide hole tolerance of metal sleeve-free computer-assisted implant surgical guides fabricated with 3D printers.

Methods. An implant surgical guide for full-guided implant placement was designed with a total of eight different guide holes. Ten implant surgical guides ($n = 10$) were fabricated from the same design with each of five in-office 3D printers (D1, FOR, ONE, PER, and ZEN) using compatible printing materials. Ten surgical guides fabricated by the manufacturer of the implant company were used as the control group (CON). The adaptation of the surgical guides was evaluated by the replica technique. The tolerance of the guide holes was evaluated by measuring the degree of diversion with guide drills.

Results. CON and D1 showed superior internal adaptation with a gap distance of less than 1 mm. The mean degree of diversion of the guide holes ranged from 3.45° for ZEN to 6.55° for PER. The tolerances of CON (4.70°) and D1 (4.50°) did not differ at the level of statistical significance at $\alpha = 0.05$.

Significance. The characteristics of implant surgical guides were evaluated *per se*. None of the 3D printers fabricated superior implant surgical guides to those produced by the manufacturer with regard to the internal fit and guide tolerance. However, the potential for the routine clinical use of in-office 3D printers was demonstrated. Further studies are required to determine how the guide hole tolerance and the angular deviation between the preplanned and actual implant positions are related.

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1. Introduction

Radical improvements in digital technology have had a dramatic impact on dental implantology [1,2]. The introduction and development of cone-beam computed tomography (CBCT), dental scanners, computer-aided design (CAD) software, milling machines, and additive manufacturing (AM)—also known as 3D printing—have contributed to successful applications of computer-guided implant surgery [1,3]. In contrast to conventional implant surgical guides, which are usually fabricated by modifying radiographic templates [4–8], a computer-guided approach visualizes anatomical landmarks, reduces surgical time, promotes flapless surgeries, integrates all valuable information in the implant planning software, and enables restoration-driven implant placement [9–11].

In the early 1980s, Charles Hull introduced a novel device called a stereolithography apparatus (SLA) to generate 3D objects [12]. The recent expiration of key patents for AM technology has facilitated a boom in the 3D printer market [13]; the reduced cost and size have now made having 3D printers in clinics affordable [14,15]. These 3D printers are called in-office or personal 3D printers [16,17]. SLA technique-based 3D printers polymerize liquid resin inside the bath *via* a layer-by-layer method with a series of points and lines to create a 3D object [14]. Digital light processing (DLP) technique-based 3D printers act by curing photoreactive liquid resin in a layer-by-layer method, where each layer is projected as a flat image in a given slice of the x-y plane. Hence, it may leave a stair-step trace on the printed material [18]. In contrast, polyjet 3D printers are high-cost industrial-level printers that have a mechanism similar to that of ink-jet printers. A jet of tiny droplets of photocuring liquid photopolymers is cured by ultraviolet light on a tray instead of ink droplets on paper [19]. It can produce complex materials without surface finishing procedures due to the superior resolutions.

Implant surgical guides are one of the products that can easily be fabricated with 3D printers and compatible resin materials for dental usage after being designed in implant planning software [20]. Many studies have reported that implant placements with computer-assisted implant surgical guides have comparable accuracy to implant placements using conventional surgical guides [20–24]. However, these studies focused on the accuracy with regard to deviations between the planned and post-operative implant positions; these deviations are in fact the result of accumulated errors caused by many continual procedures.

There has been a paucity of research on the intrinsic characteristics of computer-assisted implant surgical guides themselves fabricated by AM technology [25]. It is important for implant surgical guides to be precisely adapted to both the cast model and the patient's oral cavity. Another important factor for accurate implant placement in a predetermined position is the tolerance of guide holes in the implant surgical guide; these holes need to be suitable for allowing compatible guide drills [25,26]. Previous studies that measured the guide hole tolerance of computer-assisted implant surgical guides used ones incorporating metal sleeves [25,27,28]. To the best of the authors' knowledge, no studies have compared the tolerance of metal sleeve-free implant surgical guides fabricated with several 3D printers.

The aim of the present study was to evaluate the adaptation of six different 3D-printed metal sleeve-free implant surgical guides and the tolerance of their guide holes. The guide holes were all incorporated in the surgical guides without metal sleeves. The hypotheses were that the internal fit of implant surgical guides and the tolerance of guide holes differ among the 3D printers.

2. Materials and methods

2.1. *Classification of the groups*

The metal sleeve-free computer-assisted implant surgical guides were classified into six groups according to the 3D printers used: CON, D1, FOR, ONE, PER, and ZEN (Table 1). The CON group consisted of implant surgical guides fabricated by the manufacturer of the implant company (Osstem, Busan, Korea) according to a standardized protocol and served as the control group. The other five groups consisted of implant surgical guides fabricated with the in-office 3D printers.

2.2. *Design and fabrication of the computer-assisted implant surgical guides*

2.2.1. *Design of the implant surgical guides*

A definitive cast representing an edentulous maxilla was scanned with a tabletop scanner (Identica Blue, Medit Co., Seoul, Korea). The scanned data in the standard tessellation language (STL) file format were imported into implant planning software (Implant Studio, 3Shape, Copenhagen, Denmark) (Fig. 1). An implant surgical guide for implant placement under complete guidance (OneGuide, Osstem, Busan, Korea) was designed to allocate the sites for a total of eight implants (TSIII, Osstem, Busan, Korea). These represent second molars, second premolars, canines, and central incisors in a symmetrical arrangement (Fig. 1). The design component of the metal sleeve-free guide holes was incorporated in the implant surgical guides. The eight guide holes within each implant surgical guide differed in design with respect to the diameter, angulation, and openness. Their names were designated to reflect these characteristics (Table 2). Four guide holes in the right quadrant were designed for implants with a diameter of 4.5 mm (representative of regular-size implants). The other four holes in the left quadrant were designed for implants with a diameter of 5.0 mm (representative of wide-size implants). The guide holes for the four posterior implants had open sleeves, whereas the sleeves for the remaining anterior four implants had a closed form. The long axes of the middle four guide holes were perpendicular to the corresponding underlying tissue surfaces of the definitive cast; the two most posterior were tilted 30° posteriorly, and the two most anterior had an angulation of 30° toward the anterior side.

Table 1 – Classification of the groups. SLA: stereolithography apparatus. DLP: digital light processing.

Group name	3D printer	Manufacturing method	Setting values for the "Offset from sleeve" option	Printing materials
CON	Objet Eden260VS (Stratasys, Eden Prairie, MN, USA)	Polyjet printing	Not available	MED610 (Stratasys, Eden Prairie, MN, USA)
D1	D1 (Veltz3D, Incheon, Korea)	DLP	0.14	NextDent SG (NextDent, Soesterberg, Netherlands)
FOR	Form2 (Formlabs, Somerville, Massachusetts, USA)	SLA	0.16	Dental SG (Formlabs, Somerville, Massachusetts, USA)
ONE	OneJet (Osstem, Busan, Korea)	DLP	0.14	Dentrial S 2 (DIC Co., Saitama, Japan)
PER	Perfactory Micro Advantage (EnvisionTEC, Dearborn, MI, USA)	DLP	0.14	Dentrial S (DIC Co., Saitama, Japan)
ZEN	Zenith U (Dentis, Daegu, Korea)	SLA	0.12	ZMD-1000 B Clear-SG (Dentis, Daegu, Korea)

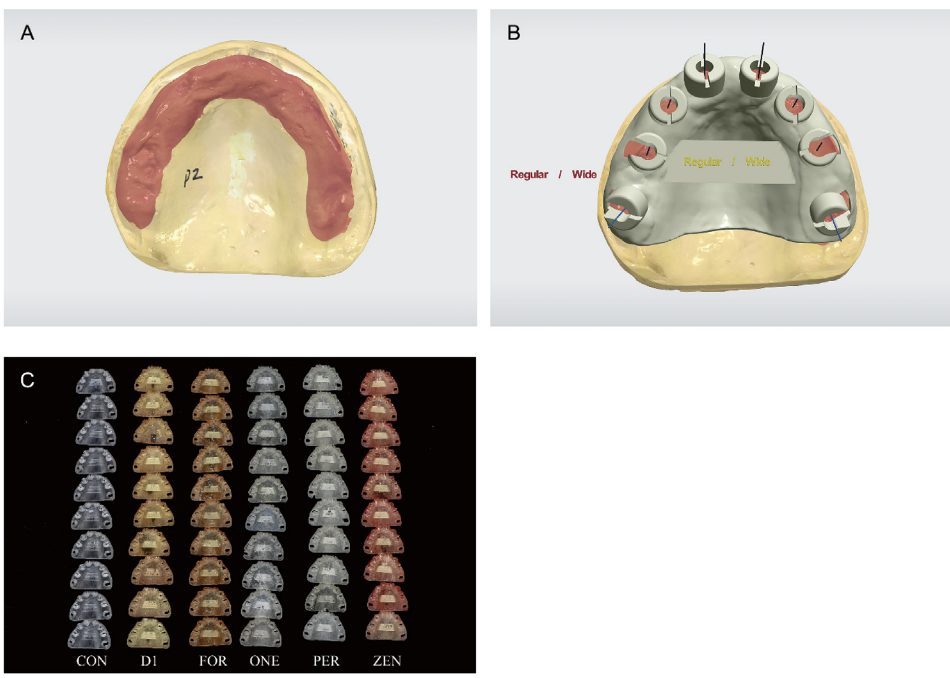

Fig. 1 – Design and fabrication of the computer-assisted implant surgical guides. (A) Scanned definitive cast representing an edentulous maxilla. (B) Design of an implant surgical guide for full-guided implant placement (OneGuide, Osstem, Busan, Korea). The metal sleeve-free guide holes represent second molars, second premolars, canines, and central incisors bilaterally; their characteristics differ from one another with respect to the diameter, angulation, and openness. (C) Surgical guides manufactured with six different 3D printers (*n* = 10 in each group). Those fabricated by the same 3D printer are placed in the same column.

Table 2 – Names of the guide holes according to their characteristics.

Guide hole name	Corresponding tooth number	Angulation	Openness	Diameter
ROT	#17	30° Posteriorly tilted	Open sleeve	Regular (4.5 mm)
ROV	#15	Vertical direction		
RCV	#13	Vertical direction	Closed sleeve	
RCT	#11	30° Labially tilted		
WCT	#21	30° Labially tilted	Closed sleeve	Wide (5.0 mm)
WCV	#23	Vertical direction		
WOV	#25	Vertical direction	Open sleeve	
WOT	#27	30° Posteriorly tilted		

2.2.2. Pilot study to determine the internal diameter of the guide holes for individual five in-office 3D printers

In the last stage of the design procedure with the implant planning software, different parameters (0.12, 0.14, or 0.16 mm) for an "Offset from sleeve" option were selected for each of the five in-office 3D printers. Three surgical guides with different parameters were printed for each in-office 3D printer to produce a total of 15 implant surgical guides. These were used to find the most appropriate parameters for each 3D printer-printing material assembly in a pilot study. The values that allowed the tightest fit with the corresponding drill sizes (either regular or wide) from the drill kit for guided surgery (OneGuide, Osstem, Busan, Korea) were selected for each 3D printer (Table 1).

2.2.3. Fabrication of the implant surgical guides

The STL files of the implant surgical guides were exported from the implant planning software and imported into specific 3D printing preparation software (Preform Software, Formlabs, Somerville, Massachusetts, USA; Materialise Magics, Materialise, Leuven, Belgium; Zenith SW, Dentis, Daegu, Korea) to generate the supports and initiate the manufacturing process. The files were sliced along the z-axis with a resolution of 100 μm. The five in-office 3D printers coupled with their compatible printing materials were used to each fabricate 10 implant surgical guides ($n = 10$) from the same design. The printing materials used were photosensitive liquid resins that showed appropriate photoreactivity within the wavelength range for the light source of each 3D printer. The guides were continuously soaked in isopropyl alcohol for 10 min after they were printed and were additionally cured for 10 min in a post-curing chamber. The supports were removed, and the surfaces were polished. In total, 60 implant surgical guides were used in the study, including those fabricated by the manufacturer of the implant company ($n = 10$; Osstem, Busan, Korea) (Fig. 1). Table 1 summarizes information about the 3D printers and their printing materials.

2.3. *Fabrication of a custom jig*

A custom jig was designed and fabricated to firmly hold the implant surgical guides in order to minimize unintended movements during the tolerance measurement procedures (Fig. 2). The jig held the palatal surface of the implant surgical guides with its beak.

2.4. *Adaptation of the implant surgical guides*

The adaptation of the implant surgical guides was evaluated in terms of the internal fit. The intaglio surface of the surgical guides was coated with a thin intermediate layer of vinyl polyether silicone material (Fit Checker Advanced, GC Corp., Tokyo, Japan). Then, the guide was adapted on the definitive cast with finger pressure for 4 min. A set of vinyl polysiloxane impression materials (Exafine putty type, GC Corp., Tokyo, Japan) was uniformly mixed and applied to the intaglio surface of the surgical guide coated with a vinyl polyether silicone material. The surgical guide was removed after the mixture hardened to leave a silicone complex.

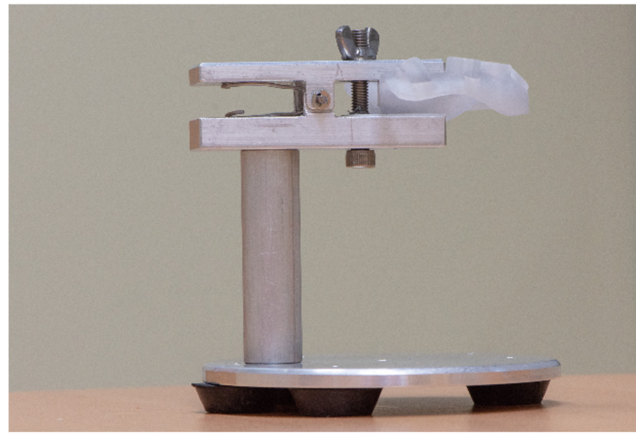

Fig. 2 – Custom jig for firmly holding the implant surgical guides.

Six tiny holes in a 3 × 2 array were created on the palatal surface of one surgical guide fabricated by the manufacturer of the implant company (Fig. 3). This guide was adapted to each of the 60 silicone assemblies, and the spots were marked on the assemblies through the holes with a marking pen. Each silicone assembly was carefully cut parallel to the sagittal plane along the marked spots to be divided into four pieces. The mean thickness of the intermediate vinyl polyether silicone material layer was calculated from six sites of each implant surgical guide under a stereozoom microscope (SMZ168, Motic, Xiamen, China) with image analysis software (ImageJ, National Institute of Health, Bethesda, MD, USA) at 7 × magnification.

2.5. *Measurement of the tolerance of guide holes*

Two drill sizes from the drill kit for guided surgery (OneGuide, Osstem, Busan, Korea) were used to measure the tolerance. The smaller drill (5.0 mm diameter) was used for the holes in the right quadrant, and the larger drill (5.7 mm diameter) was used for those in the left quadrant. The drills were inserted in the low-speed contra-angle handpiece to simulate clinical situations. Grid paper was attached to the head of the handpiece to facilitate future linear measurements.

After the implant surgical guide was secured to the custom jig, the hand-piece was moved far mesially and far distally. Photographs were taken for each trial with a digital single-lens reflex camera (Nikon D750, Shinjuku, Tokyo, Japan). A pair of photographs per guide hole was imported into image-editing software (Photoshop 2018, Adobe, San Jose, CA, USA), and the two photographs were superimposed over each other. A line following the grid paper was drawn on each image, and the angle formed by the two lines from the pair was recorded with a measurement tool in the software. This angle was defined as the degree of diversion (DOD) and represents the tolerance (Fig. 4). The mean DOD from the eight guide holes of each implant surgical guide was calculated. All experiments and measurements were conducted by an experienced clinician (K.C. Oh).

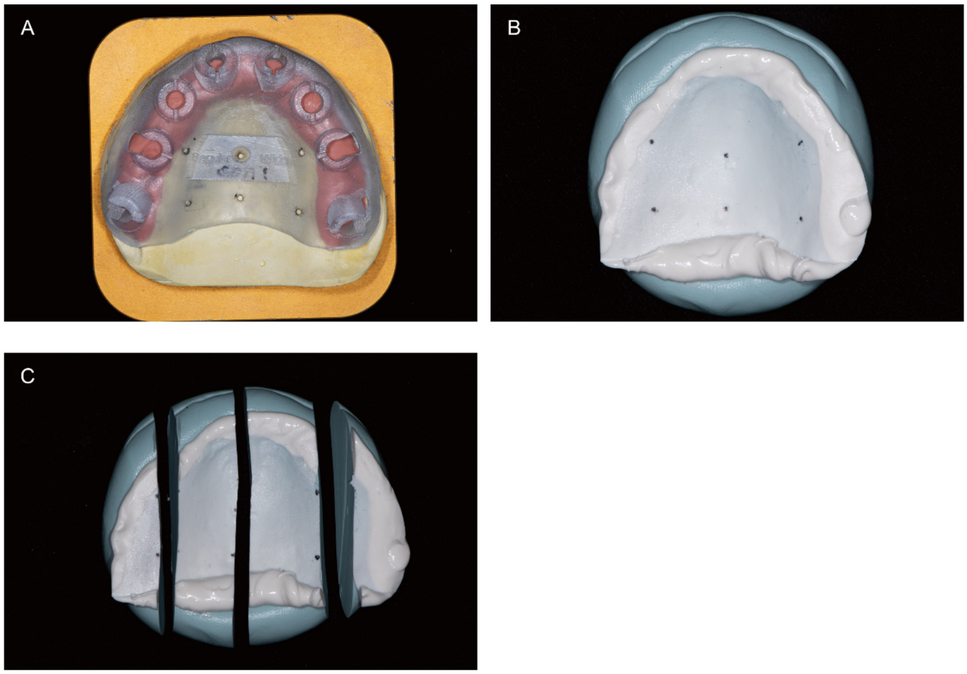

Fig. 3 – Measurement sites for calculating the thickness of the intermediate vinyl polyether silicone material (Fit Checker Advanced, GC Corp., Tokyo, Japan). (A) Six holes created on the implant surgical guide. (B) Six spots marked on the intermediate vinyl polyether silicone material through the holes. (C) Four pieces of silicone assembly.

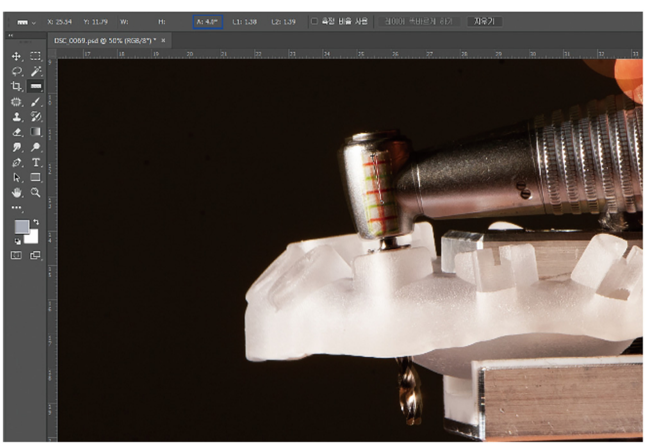

Fig. 4 – Guide hole tolerance (expressed in terms of the degree of diversion (DOD)) measured with a tool in the image-editing software (Photoshop 2018, Adobe, San Jose, CA, USA). The angle marked with the blue rectangle in the upper menu indicates the DOD.

2.6. *Statistical analysis*

All data were expressed as the mean ± standard deviation. One-way analysis of variance was used to compare the mean values among groups. Tukey's honest significant difference test was used for post hoc comparisons. The data were analyzed with statistical software (IBM SPSS Statistics v23.0, IBM Corp., Armonk, NY, USA), and the graph was generated with another software program (GraphPad Prism 7.04, Graph Pad Software, La Jolla, CA, USA). The level of significance was set to $\alpha = 0.05$.

3. Results

3.1. *Adaptation of the implant surgical guides*

All 60 implant surgical guides were successfully fabricated with their corresponding 3D printers. The thickness of the vinyl polyether silicone intermediate layer showed statistically significant differences among the groups (Figs. 5 and 6). The CON group (0.89 mm) and D1 group (0.78 mm) showed the smallest mean gap thickness at less than 1 mm, while the ONE group (1.88 mm) and ZEN group (1.90 mm) showed the largest mean gap thickness. The mean gap distance of the ZEN and ONE groups was more than twice that of the CON and D1 groups ($P < 0.05$).

3.2. *Measurement of the tolerance of guide holes*

Fig. 7 summarizes the tolerances of the guide holes, which are expressed as DODs. The ZEN group had the lowest average DOD of the guide holes (3.45°); it was significantly lower than those of the other groups ($P < 0.05$). The PER group showed the highest average DOD (6.55°), which was significantly higher than that of the other groups ($P < 0.05$). The tolerances of the CON and D1 groups did not show statistically significant differences ($P > 0.05$). The maximum DOD was 11.2° for the ROT guide hole of the PER group, and the minimum DOD was 0.8° for the RCV guide hole of the ZEN group.

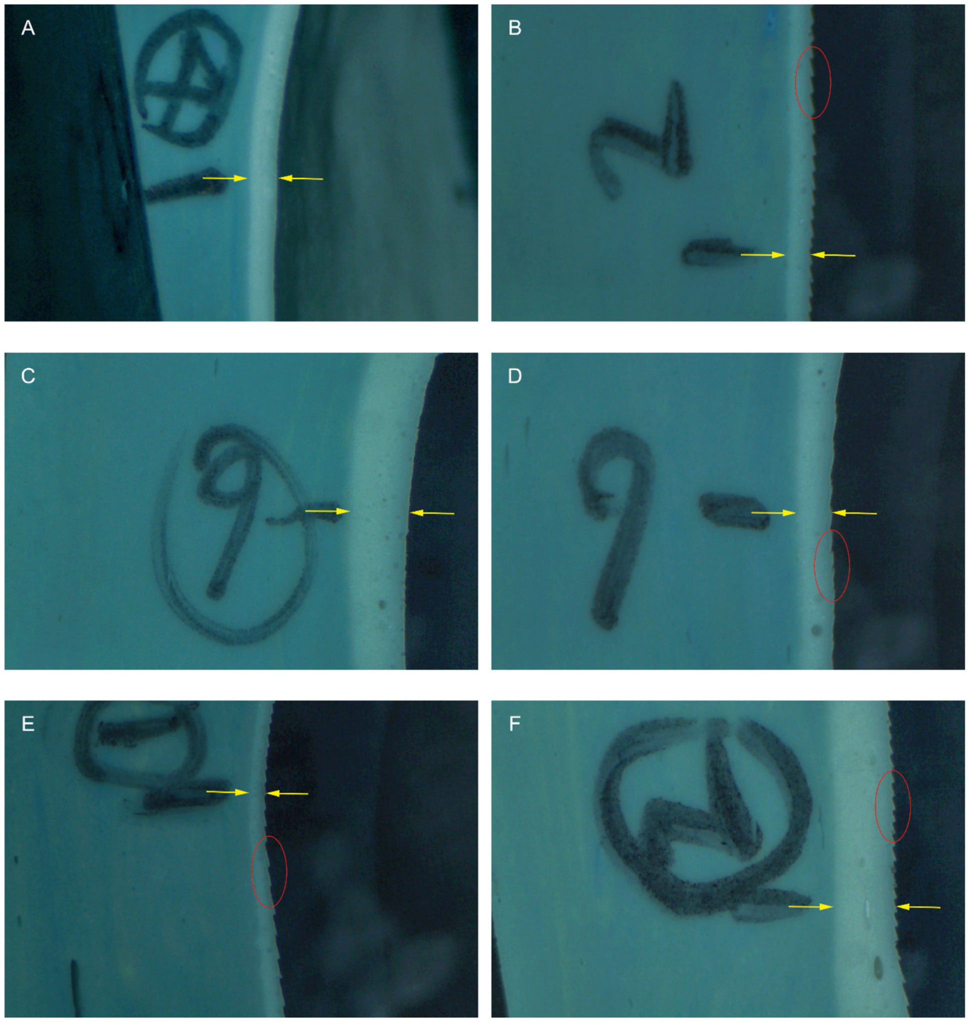

Fig. 5 – Representative cross-sectional views of the silicone assembly from each group. The thickness of the intermediate vinyl polyether silicone material was measured as the shortest distance between the pair of yellow arrows. The stair-step traces are marked with red circles. (A) CON group. (B) D1 group. (C) FER group. (D) ONE group. (E) PER group. (F) ZEN group.

4. Discussion

The hypotheses were partially proven: some guides differed in terms of the adaptation and guide hole tolerance. In fact, the tested hypotheses have higher clinical significance than null hypotheses. Among the many available 3D printers, in-office 3D printers that employ either SLA or DLP techniques were used in the present study because they have shown versatility with many resin systems for dental usage [19].

All implant surgical guides were successfully printed; there were neither partial prints nor delamination of the layers. The most appropriate inner diameters of the guide holes for the individual 3D printers were found in the pilot study through trial and error. The distribution, numbers, and thickness of the supports differed among the printers depending on the support-generating software used.

The replica technique has been validated for examining the internal fit of prostheses, regardless of the measurement site, because of its easy use for measuring gap dimensions [29–32]. A previous study on the accuracy of fit in removable partial denture (RPD) frameworks measured the gap between the palatal surfaces of the RPD frameworks and a metal dental cast at two points along the midline [33]. Six measurement sites were selected on the palatal area in an array in order to measure multiple sites to increase the reliability of the results.

The adaptation of the implant surgical guides varied considerably depending on the 3D printers used. The adaptation of the D1 group, which employed the DLP technology, was comparable to that of the CON group, showing less than 1 mm gap distance. In contrast, the gap distances for the other four groups exceeded 1 mm. It was not possible to evaluate the superiority of either the SLA or DLP technology and to draw general conclusions because the results were not consistent. Although the stair-step trace was confirmed in the case of the DLP printers in the present study, the trace was too small (microscale) to affect the outcomes, given the limitation of analyzing the replica silicones in only specific spots. Moreover, DLP printers have the antialiasing function to help them to overcome this limitation; however, the effectiveness of this antialiasing function varies for different printers. Therefore,

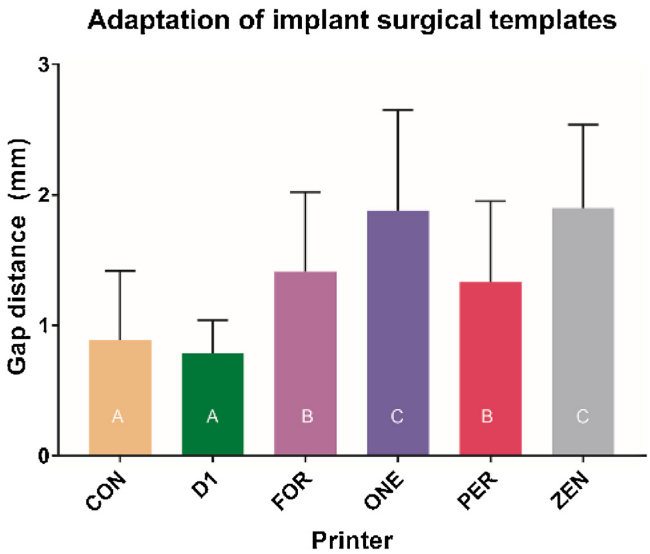

Fig. 6 – Adaptation of the implant surgical guides, as expressed by the thickness of the intermediate vinyl polyether silicone material, or gap distance. The data are shown as the mean ± standard deviation. The different superscript letters within each bar indicate statistically significant differences ($P < 0.05$).

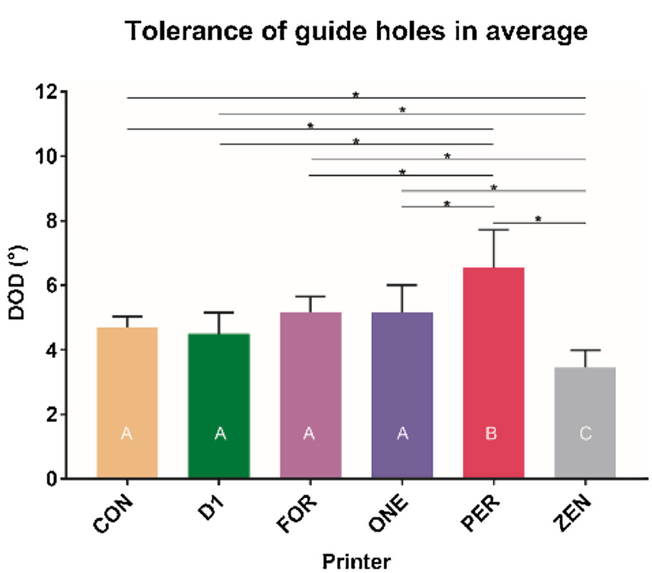

Fig. 7 – Guide hole tolerance expressed in terms of the degree of diversion (DOD). The data are shown as the mean ± standard deviation. The different superscript letters within each bar indicate statistically significant differences ($P < 0.05$).

different outcomes may be obtained with different DLP printers. Differences in the amount of polymerization shrinkage may also explain the differences in the gap distance values among the groups, considering the large amount of resin used to produce full-arch-scale implant surgical guides [34]. The results can also be attributed to the fact that the forces applied to the guides may have differed among the groups and that the implant surgical guides were adapted onto the hard dental cast model as opposed to the soft gingiva.

Previous studies commonly used implant systems that required metal sleeve inserts and drill keys when measuring the guide hole tolerance [25,28]. One of these studies reported a mean deviation in angulation of 4.7° from the sleeves in a stereolithographic surgical guide [25]. Another *in vitro* study reported a mean deviation in angulation of 5° for the drill hold sleeve inserts (guide sleeves) and 4.5° for handheld sleeve inserts (drill keys) using stereolithographic surgical guides [28]. In a previous *in vitro* study, in-office fabricated implant surgical guides showed an accuracy similar to those of laboratory- or manufacturer-prepared surgical guides [20]; however, statistical descriptive analysis was not performed in that study.

An experimental *in vitro* study indicated that using implant surgical guides causes significantly higher heat generation during implant site preparation than conventional drilling procedures [35]. Hence, some researchers believe that a certain amount of tolerance between the guide drill and sleeve was inevitable to provide a passageway for irrigation and cool down after heat production [25]. This tolerance was defined as an intrinsic error of the surgical guide [27]. Profound irrigation should accompany implant surgery when using the implant surgical guides from the ZEN group since they showed the smallest DOD. However, the heat production due to a small tolerance can be prevented by using newer guide drills. Previous studies suggested discarding the initial drills after 25–50 uses [35–37]. Further improvements can be achieved by developing drill materials that produce less heat or by improving the performance so that the drill can work equally well at a lower speed [38]. In contrast, a higher tolerance may be a more important issue because a misplaced implant makes it difficult to restore a prosthesis or damages adjacent teeth, which leads to medical accidents. Hence, the surgical guides that show lower tolerance can appear to be more appropriate for clinical application. More careful manipulation is required when the implant surgical guides from the PER group are used because of the relatively higher tolerance.

The mean tolerance of the guide holes in the CON group (4.70°) was comparable to that of previous studies which examined the tolerance of guide holes incorporated with metal sleeves [25,28]. Although the tolerance of the CON group is not an absolute guideline, the printers that produced the D1, FOR, ONE, and ZEN groups are acceptable for surgical guide fabrication considering the similar tolerance values. In terms of the internal fit of the implant surgical guides, however, the FOR, ONE, and ZEN groups showed statistically significant differences compared to the CON group. In contrast, the internal fit of the D1 group was similar to that of the CON group. Hence, the D1 printer showed potential for routine use in daily clinical practice.

The present study inherited a limitation that the angle may differ depending on how the photographs were taken and the accuracy of the superimposition. In an effort to increase the accuracy, a jig was used to firmly grasp the guide, and the photographs were taken with the camera being mounted on a tripod with a self-timer function set at a 2 s interval. The extent of lateral displacement at the drill tip was not assessed because it depends on the drill length for geometric reasons [39]. The forces given in the mesiodistal directions by manual pressure may have varied from hole to hole. The tolerance was measured in the static state: the guide drill was not rotating at each extreme position. Hence, the actual tolerance in clinical situations where the drill is rotating at high speed may differ from the static situation. Although passive guidance of the guide drill may be hard to achieve in clinical circumstances because of the presence of oblique cortical surfaces, the tolerance in a static state was evaluated since the aim was to focus on the characteristics of the surgical guide *per se* [39]. Moreover, the evaluation of the surgical guide *per se* is of great value because the outcome may be aggravated if the wrong initial path is chosen at the extreme direction in a surgical guide with a larger tolerance.

Further research on the internal adaptation of surgical guides inside the oral cavity is required to assess the clinical applicability of in-office printed implant surgical guides. In addition, the tolerance needs to be measured in simulated clinical situations with an underlying bone structure and rotating drills to evaluate how the guide hole tolerance and the angular deviation between the preplanned and actual implant positions are related.

5. Conclusion

The present study provides insights on achieving accurate implant placements with regard to implant surgical guides. The internal fit of metal sleeve-free computer-guided implant surgical guides and the tolerance of the guide holes, which are prerequisites for accurate implant placement, were examined. No superior in-office 3D printers were identified that satisfied both requirements for fabricating implant surgical guides compared to the manufacturer-produced implant surgical guides. However, the D1 group corresponding to the DLP system had characteristics comparable to those of the manufacturer-produced implant surgical guides with regard to both internal adaptation and guide hole tolerance. Although further investigations are required to draw general conclusion about the superiority of SLA or DLP-type 3D printers for in-office usage owing to the inconsistent outcomes, the results indicate that the D1 printer has a potential to be used in clinics. Further analyses of various kinds of SLA- or DLP-type 3D printers will help in identifying cost-effective in-office printers with outcomes comparable to those of polyjet printers. This will save laboratory costs in the long term. Further studies are required to determine how the guide hole tolerance and the angular deviation between the preplanned and actual implant positions are related.

Acknowledgments

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