Accuracy of surgical guides manufactured with four different 3D printers. A comparative in vitro study

Morón-Conejo, Belén; Berrendero, Santiago; Salido, Maria Paz; Zarauz Yanez, Cristina; Pradíes, Guillermo

How to cite

MORÓN-CONEJO, Belén et al. Accuracy of surgical guides manufactured with four different 3D printers. A comparative in vitro study. In: Journal of dentistry, 2024, vol. 148, p. 105226. doi: 10.1016/j.jdent.2024.105226

This publication URL: https://archive-ouverte.unige.ch/unige:182828
Publication DOI: 10.1016/j.jdent.2024.105226

Journal of Dentistry 148 (2024) 105226

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Accuracy of surgical guides manufactured with four different 3D printers. A comparative in vitro study

Belén Morón-Conejo [a], Santiago Berrendero [a], Maria Paz Salido [a,*], Cristina Zarauz [b], Guillermo Pradíes [a]

[a] Department of Conservative and Prosthetic Dentistry, Faculty of Dentistry, University Complutense of Madrid, Plaza Ramón y Cajal S/N., Madrid 28040, Spain
[b] Division of Fixed Prosthodontics and Biomaterials, Clinic of Dental Medicine, University of Geneva, Rue Michel-Servet 1, 1211 Genève 4, Switzerland

ARTICLE INFO

Keywords:
3D printing
Accuracy
Implantology
Surgical guide
Guided implant surgery
Stereolithography

ABSTRACT

Objectives: The aim of this study was to assess the accuracy of surgical guides manufactured with four different 3D printers..

Methods: Forty-eight surgical guides (BlueSky Plan, BlueSky Bio) were produced using four different 3D printers, with strict adherence to each manufacturer's instructions. The printers used were three digital light processing (DLP) printers (SolFlex170, VC; Nextdent5100, ND, and D30+Rapidshape, RS) and one stereolithographic (SLA) printer (Formlabs3B+, FL). The study evaluated the trueness and precision of the overall surface, the region of interest (RoI) (occlusal and guide zone), the repeatability in several batches, and the guide hole's diameter and xyz axes. The printed guides were digitized and compared with the CAD design control specimen (Control X, Geomagic). Descriptive statistics and Kruskal-Wallis tests with post-hoc Mann-Whitney tests were performed (α=0.05).

Results: Differences in trueness and precision were found between groups in the overall zone and RoI ($p = 0.00$). The ND group demonstrated the highest repeatability. Only the RS group exhibited a comparable guide hole diameter to the master specimen (5.27±2.12 mm; $p = 0.104$). No statistical differences were observed between groups in the x and z axes. However, in the y-axis, the VC group displayed statistically significant differences ($p = 0.01$).

Conclusions: The results showed that the DLP groups had better overall accuracy, while the SLA group had the best results in the RoI. The manufacturer's workflows demonstrated a high reproducibility between batches in the RoI. The RS group had values most similar values to the guide hole diameter of the master specimen, with minimal deviations in guide hole orientation.

Clinical significance: Implant position can be affected by the accuracy of the 3D printed surgical guide. Therefore, it is critical to analyze the final dimensions and the direction of the guide hole using available printing technologies.

1. Introduction

In recent years, dental surgery has undergone a revolution with the development of guided surgery. This includes both static computer-assisted guided implant surgery (s-CAIS) and dynamic computer-assisted implant surgery, i.e., dynamic navigation (DN) [1]. s-CAIS requires a physical surgical guide to transfer the implant position planned virtually, which is designed using CAD (computer-aided design) software [2]. The virtual implant position is determined by considering the prosthetic and anatomical situation in each case. This is achieved by superimposing the digital files, including anatomical structures from the Cone Beam Computer Tomography (CBCT), intraoral surfaces from the digital scanner, and the prosthetic planning from a digital wax up [2]. s-CAIS is associated with an accurate 3D positioning of the implant, reducing surgical time and optimizing prosthetic results [3–5]. Due to this extended planning, the surgical guides are manufactured using computer-aided manufacturing (CAM) procedures that manage milling or 3D printing fabrication [6].

3D printing is a CAM technology that produces physical objects from Standard Tessellation Language (STL) files by adding different materials

* Corresponding author.
E-mail address: mpsalido@ucm.es (M.P. Salido).

https://doi.org/10.1016/j.jdent.2024.105226
Received 20 November 2023; Received in revised form 1 July 2024; Accepted 3 July 2024
Available online 4 July 2024

layer by layer using polymerization or sintering techniques [1,6,7]. This technology offers three significant benefits: the ability to customize manufacturing quickly, the ability to achieve complex geometric, and the reduction of material waste by consuming only the necessary materials [6,8,9]. Recently, dental printers with vat-polymerization technology, such as stereolithography (SLA) and digital light processing (DLP) have become available [10,11]. SLA and DLP are similar in that they both build objects by immersing a build platform in a resin tank containing light-cured liquid resin [12]. However, the key difference between these two technologies is the type of light source used: SLA employs an ultraviolet (UV) laser light to draw a pattern of a cross-section of the 3D object, while DLP uses a digital light projector screen to project the entire cross-section of the 3D object at once [12,13]. One of the main uses of this technology in dentistry is the manufacturer of surgical guides [12]. The affordability of dental 3D printing system has enabled clinicians to produce their own surgical guides, potentially overcoming previous barriers to the widespread implementation of s-CAIS [14,15].

The ISO standard ISO 5725–1: 1994 defines accuracy using two parameters: trueness and precision. Trueness measures the deviation of the printed object from its actual dimensions, while precision refers to the deviation between repeated prints [14,16,17]. Achieving the optimal implant position is crucial for the long-term success of implant therapy, making the accuracy of the 3D printed surgical guide of utmost importance [7,18]. Currently, there is a scarcity of literature on 3D printing that compares the accuracy of different workflows available in the market for the fabrication of surgical guides [8,19]. Additionally, there is a lack of a common standard for comparing printers and their parameters. Studies have demonstrated that guides printed with desktop printers have similar accuracy to those produced with professional 3D printers [5,20]. However, many of these studies do not follow the printer manufacturer's recommendations for resin use. They often combine different materials and use different post-processing protocols, which could significantly affect the quality of the end product.

The aim of this study was to assess the accuracy of four distinct manufacturer workflows for printing surgical guides from the same stl file. The study evaluated dimensional changes of the overall surface and the region of interest (RoI), which included the occlusal and the guide holes. Additionally, the repeatability of the accuracy was assessed across several batches within each printer, as well as the guide hole's diameter and its dimensions in the x, y and z axes. The null hypotheses proposed that the manufacturer workflow of the tested 3D printers did not affect the overall trueness and precision, RoI trueness and precision, accuracy depending on the printing batch within each printer, orientation of the guide hole, and the dimensional changes of the guide holes of CAD-CAM surgical guides.

2. Material and methods

2.1. Master specimen and surgical guide design

A CBCT scan was taken of a patient who attended the Department of Prosthodontics at the Complutense University Postgraduate Clinics. The diagnostic images used in the present in vitro study were obtained with the agreement and Informed Consent of the participant. Additionally, a digital file was exported in stl format using the Trios 4 intraoral scanner (3Shape, Denmark). The STL and DICOM (Digital Imaging and Communication In Medicine) files were aligned using a best fit algorithm in the implant planning software BlueSky Plan 4 (BlueSky Bio, United States). A digital tooth arrangement of the missing premolar was performed using the software's teeth library. A tissue level implant (Premium TG 3.8 × 11.5 mm, Sweden & Martina, Italy) was planned based on prosthetic and anatomical requirements.

A surgical guide was designed based on the virtually design implant position. This guide was then exported and used as the master surgical guide for the comparison. The design settings for the master surgical guide were as follows: a default wall thickness of 3 mm, an offset of 0.5 mm from the teeth, and an offset 0.05 mm from the sleeve of 0.05 mm. For the selected implant, a guide tube of 5 mm (ref. TUBE524–504–4LNF, Blue Sky Bio, United States) was planned, requiring a printed guide hole with a diameter of 5.34 mm.

2.2. 3D impression of the study specimens

Based on previous studies and after calculating the sample size for an expected power of 80 %, an alpha value of 0.05, and an effect size of 1.04 (G*Power 3.1) [1,10]. 12 samples were printed in each study group according to the manufacturer's instructions. The effect size selected was the smallest one with a sample size divisible by three print batches. The study involved printing the stl file 12 times using four different printers, with each printer producing three batches of 4 surgical implant guides (Fig. 1). As a result, the CAD file for the master surgical guide was printed a total of 48 times.

Prior to each batch, the printers were calibrated according to the manufacturer's instructions. The study groups were defined by the four printers included. The study compared the use of four different 3D printers to produce surgical guides: the 3D SolFlex 170 SPM VOCO (VOCO, Germany) in the VC group, the Nextdent 5100 (3DSystem, USA) in the ND group, the D30+ Rapidshape (Rapidshape, Germany) in the RS group with DLP technology and the Formlabs 3B+ (Formlabs, USA) in the FL group with SLA technology. The characteristics of the study groups, including the resin and printing parameters, are described in Table 1. The 3D nesting programs recommended by each manufacturer were used, following the indications for printing with the surgical guide resin. Netfabb software (Netfabb Premium 2020, Autodesk, USA.) was used for the VC group, ND group and RS group, while PreForm (PreForm v3.10.1., Formlabs, USA.) was used for the FL group. In all the study groups, the occlusal surfaces faced away from the build platform to prevent support generation on these surfaces. The recommended supports were inspected to ensure they were not near the guide hole or on the occlusal surfaces. The post-processing and curing protocols specified by each manufacturer's workflow were followed (Table 2).

2.3. Measurements and outcome variables

The surgical guides were digitized using an industrial coordinate measuring machine with a laser 3D resolution of 0.1 µm (Hexagon-Global Silver; ID: GLOE000338IA; Spain). The digitization process was carried out by a certified metrology company (Ditecma S.L., Spain) using a specific clamping piece to place the guides in the measuring machine. The guides were scanned in both upside and downside positions to obtain the point clouds of the specimens. An initial visual inspection was conducted to assess the quality of the point cloud. The point clouds were aligned with the master specimen stl CAD design, and a mesh was generated from the alignment of both point clouds (PcDmis v2021.2, Hexagon-Global, Spain). The resulting mesh was exported to a stl polygon file format.

The digital files were analyzed using Control X software (vs. 2018.1.0., Geomagic, 3Dsystems). The master surgical guide stl was imported, and its surface was segmented to obtain two zones of analysis. The first zone includes the analysis of the overall volume of the specimen (Fig. 2A). The second area of analysis was called the region of interest (RoI) and includes the occlusal surface and the guide hole (Fig. 2B). The analysis of this area aimed to prevent any potential distortions resulting from the removal of the 3D printing supports. The master specimen was aligned with the study specimens using the best fit algorithm, with a discrepancy of 1000 µm and a tolerance range of ± 100 µm. The Control X software presents a color scheme that indicates the degree of discrepancy between the printed model and the master specimen. Yellow to red areas indicate that the printed model was larger than the master specimen, while turquoise to blue indicate that the printed surgical guide was undersized.

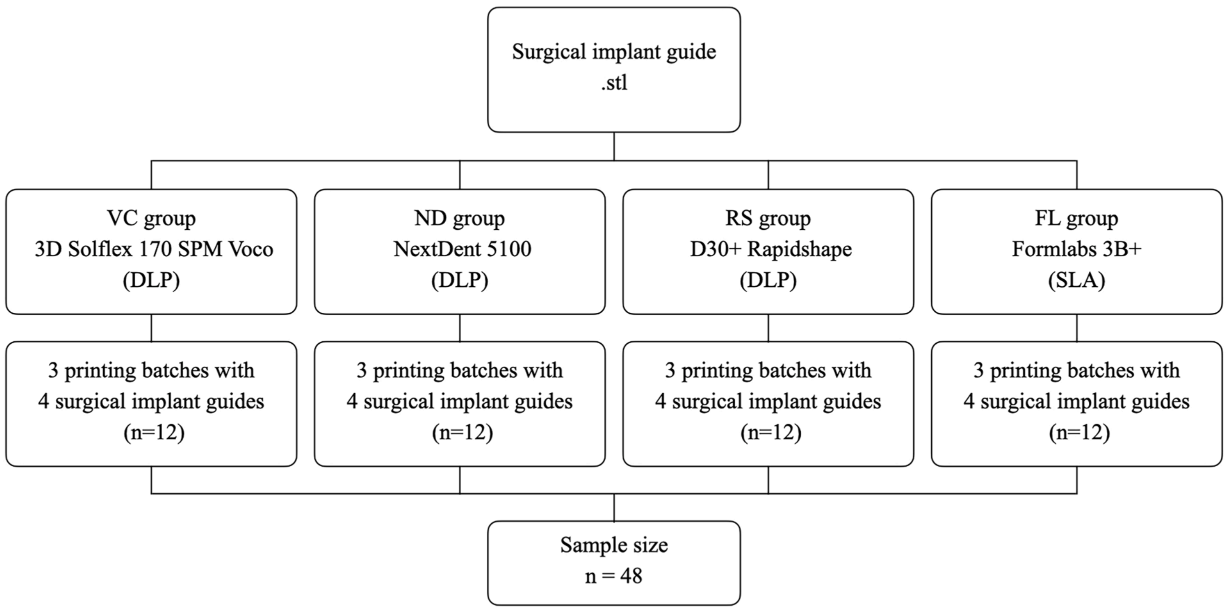

Fig. 1. Study groups and sample size diagram.

Table 1
Study groups characteristics.

Group	Printer	Technology	Wavelength (nm)	Pixel (µm)	Resin	Layer thickness (µm)	Nesting and building angle
VC	VOCO SolFlex 170 SPM	DLP	385	63	V-Print SG	50	30°
ND	Nextdent 5100	DLP	405	65	Nextdent SG	50	0°
RS	Rapidshape D30+	DLP	385	34	SHERAprint-SG	100	0°
FL	Formlabs 3B+	SLA	405	85	Dental SG	50	0°

Legend: nanometers (nm) and microns (µm).

The study recorded two main variables: trueness and precision. Trueness was evaluated using RMS (Root Mean Square) values were, while precision was analyzed using Standard Deviations (SD). To obtain the intergroup differences, the *overall trueness* compared each study specimen with the master specimen of the CAD design. The reproducibility of the results of each study group was evaluated using *overall precision*. To determine the *trueness of the Region of Interest (RoI)*, each specimen's RoI was compared with the master specimen of the CAD design to identify any intergroup differences. To assess *the precision of the RoI* findings for each study group, the SD of the RoI comparisons of the study samples were analyzed.

In addition, the study analyzed additional variables, including the repeatability of each printer, the diameter, and direction of the guide hole. The accuracy and precision of each print batch within each study group were compared to evaluate *the repeatability of the printer* and the influence of human post-processing errors. The *diameter of the guide hole* was identified as a critical factor in adapting the metal tube and could affect the surgical performance. To measure this, the Control X software was used to create a virtual measuring cylinder that conformed to the inner surface of the surgical guide hole. The diameter of each study specimen's guide hole was then compared to that of the master specimen. It was identified that the *direction of the guide hole* could also affect the surgical performance and the final implant position. The study also considered comparing the direction values in the x, y, and z axes of the virtual measuring cylinder obtained with the Control X software of the study specimens to the master specimen.

2.4. *Statistical analysis*

Descriptive statistics, including mean values, standard deviations, medians, and 95 % confidence intervals, were calculated for each group using a statistical software program (SPSS version 28.00; IBM, USA). The reliability of the data was assessed using the Kruskal Wallis and post hoc Mann Whitney tests with a significance level (type one error) of 0.05. To analyze the diameter and direction of the guide hole in the x, y, and z axes compared to the master specimen, a one-sample t-test was conducted against the CAD design parameters was performed.

3. Results

3.1. *Trueness and precision of the overall zone of each study group*

Statistically significant differences in trueness and precision were found between groups ($H = 2.793$, $p = 0.00$ and $H = 28.025$, $p = 0.00$, respectively) (Table 3). The post hoc test revealed that RS-ND (RS: 123.4 ± 12.5 µm; ND: 102.9 ± 6.9 µm; $p = 0.006$), ND-FL ($p = 0.00$), and VC-FL (VC: 103.4 ± 20.7 µm; FL: 130.6 ± 9.4 µm; $p = 0.002$) had significantly different trueness values, while VC-RS (VC: 100.0 ± 20.0 µm; RS: 120.0 ± 10.0 µm; $p = 0.005$), ND-FL (ND: 90.0 ± 10.0 µm; FL: 110.0 ± 10.0 µm; $p = 0.001$), and ND-RS ($p = 0.00$) had significantly different precision values.

Table 4 shows the results for the trueness and precision repeatability of the three printing batches of each printer. High trueness repeatability was observed in the VC and ND groups ($p = 0.116$; $p = 0.367$), while statistically significant differences were found between the batches in the RS and FL groups ($p = 0.024$; $p = 0.024$). Statistically significant differences were observed in the VC and FL groups for precision repeatability ($p = 0.0128$; $p = 0.023$). No statistically significant differences were found in the ND group and RS group ($p = >0.05$), (Table 4).

Table 2
Post-processing protocols of each manufacturer: washing and curing indications.

Group	Platform detachment	Washing protocol	Supports removal	Cure or post-polymerization protocol
VC	Before the washing protocol.	Isopropanol (>98 %) ultrasonic bath. 2 stages of 2 min.	Before post-polymerization.	Otoflash G171 xenon photoflash (VOCO, Germany). 2 stages of 2000 flashes. Cooling off period of >2 min with the lid open after the first stage.
ND	Before the washing protocol.	Isopropanol (>90 %) ultrasonic bath. First stage: 3 min. Second stage: 2 min.	After post-polymerization.	NextDent LC 3D Printbox (3DSystem, USA) light box for 10 min.
RS	Before the washing protocol.	Isopropanol (>90 %) ultrasonic bath. First stage: 3 min. Second stage: 2 min.	After post-polymerization.	RS Cure (Rapidshape, Germany) for 10 min.
FL	After the washing protocol.	Form Wash (Formlabs, USA) with Isopropyl alcohol (98 %). One stage of 5 min.	After post-polymerization.	Form Cure (Formlabs, USA) for 30 min at 60 °C.

Legend: Study groups: VC (Voco Solflex 170), ND (Nextdent 5100), RS (Rapidshape DS30+), FL (Formlabs 3B), microns (μm).

3.2. Trueness and precision of the ROI of each study group

Statistically significant differences in trueness and precision were found between groups in the RoI, which includes the occlusal zone and guide hole ($H = 26.402$; $p = 0.00$ and $H = 28.909$; $p = 0.00$, respectively) (Table 3). Specifically, there were significant differences between RS-FL (RS: 102.00 ± 14.8 μm; FL: 49.5 ± 9.0 μm) and RS-ND (ND: 63.8 ± 19.3 μm) in trueness ($p = 0.00$) and between VC-RS (VC: 70.0 ± 30.0 μm; RS: 110.0 ± 30.0 μm), VC-FL (FL: 40.0 ± 20.0 μm), ND-RS (ND: 70.0 ± 10.0 μm), and RS-FL in precision ($p < 0.05$).

Table 4 shows the results for the trueness and precision repeatability of the three printing batches of each printer. High trueness repeatability was observed in the VC group ($p = 0.116$) and ND group ($p = 0.995$), while statistically significant differences were found between the batches in the RS group ($p = 0.05$) and in the FL group ($p = 0.024$). Precision repeatability did not show any statistically significant differences in any of the groups (Table 4).

3.3. Guide hole diameter and direction of each study group

The diameter and direction of the guide hole printed in each sample from the study groups were studied in the x, y and z axes (Table 5). The mean diameter results and p-values were compared with the master specimen for each test specimen: 5.2326 ± 0.0344 mm ($p = 0.00$) for the VC group, 5.3214 ± 0.0274 mm ($p = 0.031$) for the ND group, 5.2768 ± 0.1255 mm ($p = 0.104$) for the RS group, and 5.2534 ± 0.0199 mm ($p = 0.00$) for the FL group. Only the RS group showed a comparable diameter with the master specimen. There were no statistical differences between groups in the x and z axes. However, in the y axis, the VC group exhibited statistically significant differences ($p = 0.01$).

4. Discussion

The aim of this study was to evaluate the accuracy of surgical guides printed using four different manufacturer workflows. All null hypotheses were rejected, as the 3D dental printer influenced the overall and RoI trueness and precision, printing batch repeatability within each printer, and guide hole orientation and diameter accuracy.

Several systematic reviews have evaluated the accuracy and survival rates of s-CAIS, which are comparable to conventionally placed implants. According to the literature, Multijet printers are considered industrial and have been found to produce the best dental models and surgical guides [6,10,14,20]. Wegmüller et al. [20] conducted a study comparing the trueness of surgical guides manufactured with an industrial MultiJet printer to those produced with dental printers and found no significant differences ($p > 0.05$). Several studies have concluded that current SLA and DLP dental printers are accurate enough for clinical applications [1,6]. Rouzé et al. [1] conducted a study on SLA and DLP dental printers and achieved better accuracy results than the Multijet industrial printer ($p > 0.05$) in analyzing the same RoI as our study. The RoI includes the occlusal surface and the guide hole, and determines the fit, retention, and implant position. In our study, the FL group that used SLA technology achieved the highest RoI accuracy while the ND group obtained the highest accuracy for the DLP technology. The Rouzé et al. [1] study reported results comparable to those found in our study for the DLP technology (trueness of 64.28±7.95 μm and precision

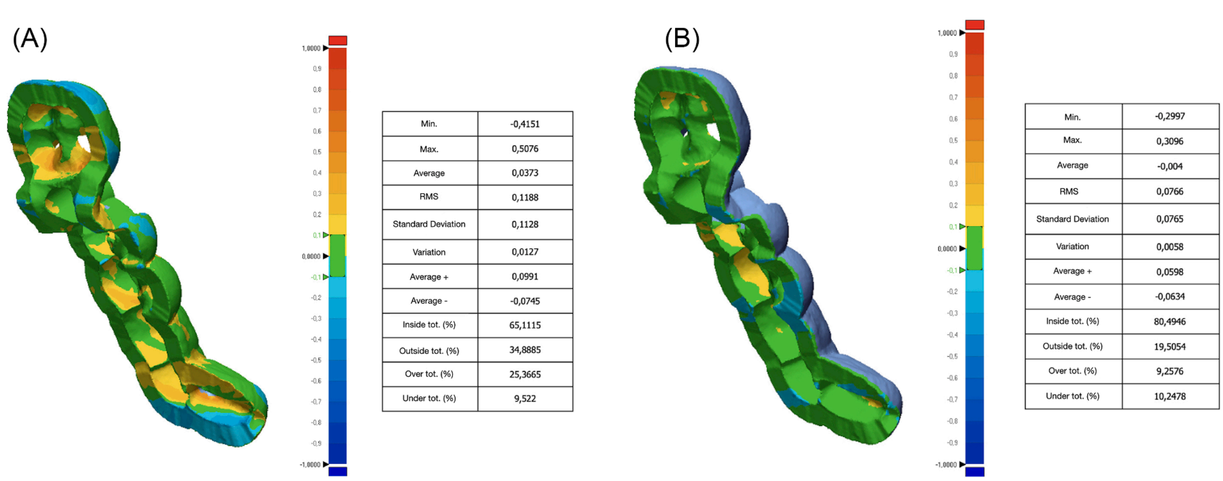

Fig. 2. A) 3D analysis of the overall volume of the specimen with Control X, Geomagic. B) 3D analysis of the region of interest (ROI) of the specimen with Control X, Geomagic.

Table 3
Trueness and precision of the printed surgical guide's Overall Zone (OZ) and Region of Interest (RoI) in microns (µm).

Group	Trueness (RMS ± SD)		Precision (SD mean± SD)		Trueness MW p value		Precision MW p value	
	OZ (µm)	RoI (µm)	OZ (µm)	RoI (µm)	OZ	RoI	OZ	RoI
VC	103.4 ± 20.7 $p = 0.01$*	74.6 ± 27.3 $p = 0.00$*	100.0 ± 20.0 $p = 0.00$*	70.0 ± 30.0 $p = 0.00$*	ND: 1.00 RS: 0.09 FL: 0.002*	ND: 1.00 RS: 0.07 FL: 0.04*	ND: 1.00 RS: 0.005* FL: 0.53	ND: 1.00 RS: 0.04* FL: 0.034*
ND	102.9 ± 6.9 $p = 0.00$*	63.8 ± 19.3 $p = 0.00$*	90.0 ± 10.0 $p = 0.00$*	70.0 ± 10.0 $p = 0.00$*	VC: 1.00 RS: 0.006* FL: 0.00*	VC: 1.00 RS: 0.01* FL: 0.22	VC: 1.00 RS: 0.00* FL: 0.001*	VC: 1.00 RS: 0.03* FL: 0.062
RS	123.4 ± 12.5 $p = 0.00$*	102.0 ± 14. 8$p = 0.00$*	120.0 ± 10.0 $p = 0.00$*	110.0 ± 30.0 $p = 0.00$*	VC: 0.091 ND: 0.006* FL: 1.00	FL: 0.00* ND: 0.01* VC: 0.07	VC: 0.005* ND: 0.00* FL: 1.00	VC: 0.04* ND: 0.03* FL: 0.00*
FL	130.6 ± 9.4 $p = 0.00$*	49.5 ± 9.0 $p = 0.00$*	110.0 ± 10.0 $p = 0.00$*	40.0 ± 20.0 $p = 0.00$*	VC: 0.002* ND: 0.00* RS: 1.00	VC: 0.04* ND: 0.22 RS:0.00*	VC: 0.53 ND: 0.001* RS: 1.00	VC: 0.034* ND: 0.062 RS: 0.00*

Legend: Overall Zone (OZ); Region of Interest (RoI), RMS (root mean square), SD (standard deviation), * for statistically significant differences ($p < 0.05$). MW (Mann Withney Test). Study groups: VC (Voco Solflex 170), ND (Nextdent 5100), RS (Rapidshape DS30+), FL (Formlabs 3B), microns (µm).

Table 4
Differences of trueness in the different printing batch of each study group analyzing the Overall zone and the Region of Interest (RoI).

Group	Trueness (RMS ± SD)		p value	Precision (SD mean ± SD)		p value
	OZ (µm)	RoI (µm)		OZ (µm)	RoI (µm)	
VC	PB1: 86.30 ± 5.9	PB1: 80.1 ± 5.9	OZ: 0.116 RoI: 0.116	PB1: 90.0 ± 10.0	PB1: 80.0 ± 10.0	OZ: 0.018*
	PB2: 118.5 ± 11.7	PB2: 93.4 ± 37.1		PB2: 110.0 ± 0.0	PB2: 90.0 ± 40.0	RoI: 0.116
	PB3: 105.5 ± 26.0	PB3: 50.4 ± 5.3		PB3: 90.0 ± 20.0	PB3: 50.0 ± 10.0	
ND	PB1: 107.2 ± 7.7	PB1: 68.3 ± 4.8	OZ: 0.367 RoI: 0.995	PB1: 90.0 ± 10.0	PB1: 70.0 ± 0.0	OZ: 0.981
	PB2: 101.1 ± 8.0	PB2: 68.3 ± 6.6		PB2: 90.0 ± 10.0	PB2: 70.0 ± 10.0	RoI: 1.00
	PB3: 100.5 ± 4.2	PB3: 55.9 ± 34.3		PB3: 90.0 ± 10.0	PB3: 70.0 ± 10.0	
RS	PB1: 136.7 ± 11.6	PB1: 116.7 ± 13.6	OZ: 0.024* RoI: 0.05*	PB1: 130.0 ± 10.0	PB1: 120.0 ± 10.0	OZ: 0.058
	PB2: 116.5 ± 6.9	PB2: 97.4 ± 7.3		PB2: 110.0 ± 10.0	PB2: 120.0 ± 60.0	RoI: 0.118
	PB3: 117.0 ± 6.3	PB3: 92.0 ± 11.0		PB3: 110.0 ± 10.0	PB3: 90.0 ± 10.0	
FL	PB1: 141.7 ± 125.7	PB1: 38.3 ± 2.1	OZ: 0.024* RoI: 0.024*	PB1: 120.0 ± 0.0	PB1: 30.0 ± 20.0	OZ: 0.023*
	PB2: 125.7 ± 6.7	PB2: 55.9 ± 4.5		PB2: 110.0 ± 10.0	PB2: 40.0 ± 30.0	RoI: 0.084
	PB3: 124.5 ± 4.4	PB3: 54.2 ± 4.9		PB3: 110.0 ± 0.0	PB3: 50.0 ± 0.0	

Legend: RMS (root mean square), SD (standard deviation), * for statistically significant differences ($p < 0.05$). Study groups: VC (Voco Solflex 170), ND (Nextdent 5100), RS (Rapidshape DS30+), FL (Formlabs 3B), Overall Zone (OZ); Region of Interest (RoI); microns (µm).

of 64.02±7.17 µm) and SLA technology (trueness of 67.75±10.63 µm and precision of 64.3 ± 9.83 µm). These improved RoI analysis results in both studies are due to the fact that manual removal of the supporting structures does not affect this region. Repeatability is another important parameter when comparing the results of each print batch with each

Table 5
Diameter and direction in axis x, y and z of the surgical guide hole's.

Group	Diameter Mean ± SD and P value	Direction (Mean ± SD and P value)		
		Axis X	Axis Y	Axis Z
VC	5.232 ± 0.034 P 0.00*	0.060 ± 0.008 P 0.884	−0.015 ± 0.006 P 0.01*	0.998 ± 0.0006 P 0.959
ND	5.321 ± 0.027 P 0.03*	0.152 ± 0.215 P 0.166	−0.020 ± 0.003 P 0.358	0.997 ± 0.000 P 0.332
RS	5.276 ± 0.125 P 0.10	0.048 ± 0.026 P 0.155	−0.025 ± 0.042 P 0.718	0.831 ± 0.576 P 0.340
FL	5.253 ± 0.019 P 0.00*	0.062 ± 0.004 P 0.162	−0.025 ± 0.042 P 0.753	0.997 ± 0.0003 P 0.461

Legend: SD (standard deviation), * for statistically significant differences ($P < 0.05$). Study groups: VC (Voco Solflex 170), ND (Nextdent 5100), RS (Rapidshape DS30+), FL (Formlabs 3B).

printer and when assessing the influence of human post-processing errors. The ND group exhibited the greatest repeatability and stability among the printing batches for all variables ($p > 0.05$). In terms of guide hole diameter, only RS showed similar values to the master stl. However, the RS group had the lowest overall and RoI trueness and precision ($p < 0.05$), and reduced trueness repeatability within print batches ($p < 0.05$). The deviations of the guide holes in the xyz axes were minimal in all groups. Only the VC group showed a deviation from the master stl in the y axis. Although statistically significant dimensional differences were observed between groups, none of the printers performed better than the others in all variables and the absolute values were small and may be negligible from a clinical point of view.

The accuracy of impression workflows can be affected by various factors, including printer technologies [1,20], object orientation [10,21,22], and the type of resin used [5,23]. Studies on surgical guides have shown that the most important variable is accuracy, which can be affected by the orientation for the impression in relation to the build platform [1,10,15,21,23]. Impression orientation is directly related to shape and volume of the printing supports, which vary depending on the study group. The surgical guides in this study were printed in a horizontal position in the ND, RS, and FL groups, as recommended by the manufacturer's workflow. For the VC group, the surgical guides were recommended to be placed at a 30° angle to the build platform. Previous studies have reported that the guides achieve maximum accuracy when the guides were printed horizontally at 0° or with their largest dimension parallel to the print platform, providing the greatest amount of support structure relative to the impression platform [10,21]. The trueness values of Tahir et al. [10] (100.7 ± 9.7 μm) when analyzing the horizontal orientation with a DLP printer were similar to our DLP groups (VC, ND and RS groups). Additionally, the type of resin used is a variable that can affect the accuracy of 3D printing protocols [5,6,15]. The resin used in surgical guides must have necessary properties such as biocompatibility and heat steam sterilizable. There is currently no agreement on the impact of sterilization on the final dimensions of surgical guides [5,24]. Kebler et al. [5] found that the use of a surgical guide resin specifically designed for the printer, resulted in the most effective outcomes before and after sterilization. To create surgical guides suitable for surgery, it is essential to use the recommended resin, appropriate supporting structures, nesting software, and post-processing procedures in conjunction with the dental printer. However, few studies have compared impression workflows designed specifically for dental printers and surgical guides [1,10,20]. The present study evaluated four certified impression workflows for surgical guides with dental printers. The ND group demonstrated the highest level of stability and reproducibility in the impression workflow, achieving the most consistent outcomes in accuracy.

This study has limitations due to its in vitro design. One limitation of this study is that it does not assess the impact of the accuracy of printed surgical guides on the final implant position. The direction of the guide hole obtained was evaluated as the closest approximation to the direction of the final implant position. The literature describes this situation in different studies; however, it would be of great interest to conduct future in vitro and in vivo research to control the final positioning of the implant in certified dental printer workflows. When evaluating the results of this study, it is important to consider the surgical guide extension that was designed. The evaluated surgical guide was tooth-supported and designed for a single implant. Therefore, caution should be exercised when extrapolating the results to larger surgical guides or those with mucosal support. While previous studies have evaluated various printing and post-processing parameters, few have assessed complete flows certified by dental printer manufacturers. The use of mesh comparison software in analysis methodology has been widely documented in recent literature [1,5,6,10,20]. However, it is important to note that this software may have intrinsic limitations. To the best of the authors' knowledge, no studies have been conducted to compare the different software used. Further studies may be required to analyze the interaction of different printing parameters and post-processing protocols to optimize the specific workflow of each printer.

5. Conclusions

The in vitro study revealed variations in accuracy among surgical guides printed using four different manufacturer workflows. The DLP technology demonstrated superior results when considering the overall zone, while the SLA group performed better in the region of interest. This region of interest determines the fit and retention of the guide, as well as the position of the implant when analyzing the guide hole. In all groups, the guide's hole orientation deviation in the xyz axes was minimal in all the groups. The manufacturer's workflows showed high reproducibility, with no statistically significant differences found between the different batches in the region of interest. Although the dimensional differences in absolute values were small and may not be clinically significant.

CRediT authorship contribution statement

Belén Morón-Conejo: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Funding acquisition. **Santiago Berrendero:** Resources, Formal analysis, Conceptualization, Data curation. **Maria Paz Salido:** Investigation, Funding acquisition, Data curation, Conceptualization. **Cristina Zarauz:** Writing – review & editing, Conceptualization, Validation. **Guillermo Pradíes:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the dental laboratory DENTAL ESTHETIC (Jaen, Spain) for the technical support and their contribution in 3D print part of the surgical guides.

References

[1] F. Rouzé l'Alzit, R. Cade, A. Naveau, J. Babilotte, M. Meglioli, S. Catros, Accuracy of commercial 3D printers for the fabrication of surgical guides in dental implantology, J. Dent. 117 (2022) 103909, https://doi.org/10.1016/j.jdent.2021.103909.
[2] H. Herstell, S. Berndt, C. Kühne, S. Reich, Accuracy of guided implant surgery obtained using 3D-printed surgical guides – An in vitro comparison of four evaluation methods, Int. J. Comput. Dent. 25 (2022) 161–172.
[3] V. Arisan, Z.C. Karabuda, T. Ozdemir, T, Accuracy of two stereolithographic guide systems for computer-aided implant placement: a computed tomography-based clinical comparative study, J. Periodontol. 81 (2010) 43–51, https://doi.org/10.1902/jop.2009.090348.
[4] K. El Kholy, R. Lazarin, S.F.M. Janner, K. Faerber, R. Buser, D. Buser, Influence of surgical guide support and implant site location on accuracy of static Computer-Assisted Implant Surgery, Clin. Oral. Implants. Res. 30 (2019) 1067–1075, https://doi.org/10.1111/clr.13520.
[5] A. Keßler, M. Dosch, M. Reymus, M. Folwaczny, Influence of 3D-printing method, resin material, and sterilization on the accuracy of virtually designed surgical implant guides, J. Prosthet. Dent. 128 (2022) 196–204, https://doi.org/10.1016/j.prosdent.2020.08.038.
[6] T. Kim, S. Lee, G.B. Kim, D. Hong, J. Kwon, J.W. Park, et al., Accuracy of a simplified 3D-printed implant surgical guide, J. Prosthet. Dent. 124 (2020) 195–201, https://doi.org/10.1016/j.prosdent.2019.06.006, e2.
[7] Y. Sun, Q. Ding, F. Yuan, L. Zhang, Y. Sun, Q. Xie, Accuracy of a chairside, fused deposition modeling three-dimensional-printed, single tooth surgical guide for implant placement: a randomized controlled clinical trial, Clin. Oral. Implants. Res. 33 (2022) 1000–1009, https://doi.org/10.1111/clr.13981.
[8] N. Martelli, C. Serrano, H. van den Brink, J. Pineau, P. Prognon, I. Borget, et al., Advantages and disadvantages of 3-dimensional printing in surgery: a systematic review, Surgery 159 (2016) 1485–1500, https://doi.org/10.1016/j.surg.2015.12.017.
[9] A. Barazanchi, K.C. Li, B. Al-Amleh, K. Lyons, J.N. Waddell, Additive technology: update on current materials and applications in dentistry, J. Prosthodont. 26 (2017) 156–163, https://doi.org/10.1111/jopr.12510.
[10] N. Tahir, J. Abduo, An in vitro evaluation of the effect of 3D printing orientation on the accuracy of implant surgical templates fabricated by desktop printer, J. Prosthodont. 31 (2022) 791–798, https://doi.org/10.1111/jopr.13485.
[11] G. Pradíes, B. Morón-Conejo, F. Martínez-Rus, M.P. Salido, S. Berrendero, Current applications of 3D printing in dental implantology: a scoping review mapping the evidence, Clin. Oral. Implants. Res. 6 (2023), https://doi.org/10.1111/clr.14198.
[12] M. Revilla-León, M. Sadeghpour, M. Özcan, An update on applications of 3D printing technologies used for processing polymers used in implant dentistry, Odontolog 108 (2020) 331–338, https://doi.org/10.1007/s10266-019-00441-7.
[13] M. Vercruyssen, I. Laleman, R. Jacobs, M. Quirynen, Computer-supported implant planning and guided surgery: a narrative review, Clin. Oral. Implants. Res. 26 (2015) 69–76, https://doi.org/10.1111/clr.12638.
[14] B. Morón-Conejo, J. López-Vilagran, D. Cáceres, S. Berrendero, G. Pradíes, Accuracy of five different 3D printing workflows for dental models comparing industrial and dental desktop printers, Clin. Oral. Investig. 27 (2022) 2521–2532, https://doi.org/10.1007/s00784-022-04809-y.
[15] L. Chen, W.S. Lin, W.D. Polido, G.J. Eckert, D. Morton, Accuracy, reproducibility, and dimensional stability of additively manufactured surgical templates, J. Prosthet. Dent. 122 (2019) 309–314, https://doi.org/10.1016/j.prosdent.2019.02.007.
[16] A. Ender, M. Zimmermann, T. Attin, A. Mehl, In vivo precision of conventional and digital methods for obtaining quadrant dental impressions, Clin. Oral. Investig. 20 (2016) 1495–1504, https://doi.org/10.1007/s00784-015-1641-y.
[17] F. Emir, S. Ayyildiz, Accuracy evaluation of complete-arch models manufactured by three different 3D printing technologies: a three-dimensional analysis, J. Prosthodont. Res. 65 (2021) 365–370, https://doi.org/10.2186/jpr.JPOR_2019_579.
[18] P. Smitkarn, K. Subbalekha, N. Mattheos, A. Pimkhaokham, The accuracy of single-tooth implants placed using fully digital-guided surgery and freehand implant surgery, J. Clin. Periodontol. 46 (2019) 949–957, https://doi.org/10.1111/jcpe.13160.
[19] D.N. Tatakis, H. Chien, A.O. Parashis, Guided implant surgery risks and their prevention, Periodontol 81 (2019) (2000) 194–208, https://doi.org/10.1111/prd.12292.

[20] L. Wegmüller, F. Halbeisen, N. Sharma, S. Kühl, F.M. Thieringer, Consumer vs. high-end 3D printers for guided implant surgery - an in vitro accuracy assessment study of different 3D printing technologies, J. Clin. Med. 10 (2021) 4894, https://doi.org/10.3390/jcm10214894.
[21] D.D. Rubayo, K. Phasuk, J.M. Vickery, D. Morton, W.S. Lin, Influences of build angle on the accuracy, printing time, and material consumption of additively manufactured surgical templates, J. Prosthet. Dent. 126 (2021) 658–663, https://doi.org/10.1016/j.prosdent.2020.09.012.
[22] F. Kernen, G.I. Benic, M. Payer, A. Schär, M. Müller-Gerbl, A. Filippi, et al., Accuracy of three-dimensional printed templates for guided implant placement based on matching a surface scan with CBCT: accuracy of printed templates, Clin. Implant. Dent. Relat. Res. 18 (2016) 762–768, https://doi.org/10.1111/cid.12348.
[23] W. Piedra-Cascón, V.R. Krishnamurthy, W. Att, M. Revilla-León, 3D printing parameters, supporting structures, slicing, and post-processing procedures of vat-polymerization additive manufacturing technologies: a narrative review, J. Dent. 109 (2021) 103630, https://doi.org/10.1016/j.jdent.2021.103630.
[24] H.F. Marei, A. Alshaia, S. Alarifi, N. Almasoud, A. Abdelhady, Effect of steam heat sterilization on the accuracy of 3D printed surgical guides, Implant. Dent. 28 (2019) 372–377, https://doi.org/10.1097/ID.0000000000000908.