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SEQUENTIAL APPROACH TO IMPROVE THE ACCURACY OF 3D PRINTED DENTAL IMPLANTS SURGICAL GUIDES

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ABSTRACT

Objective: To test the accuracy of implant sites drilled using 3D printed sleeve-free surgical guides made following a stepped approach directed to reduce the accumulative errors during the manufacturing process.

Material and methods: Twelve 3D printed surgical guides were constructed to plan twenty-four implants' drilling sites. The desktop 3D printer building platform was leveled. Layer normal exposure time and guide hole tolerance calibration were done. The predrilled casts were scanned, and the 3D models were exported as STL files. The surgical guides were designed, printed, and solidified according to the calibrated parameters. The drilled casts were scanned with the drill bit in the prepared site, and the exported STL post-drilling models were analyzed to measure the linear and the angular deviations of the drilled sites. The results were compared to the findings of previous studies.

Results: The mean and standard deviation of the coronal linear and angular deviation were 0.155 ± 0.095 mm and 1.129 ± 0.323°, respectively. The mean and standard deviation of the apical linear deviation at 5, 10, 15, and 20mm implant lengths were 0.246 ± 0.106 mm, 0.338 ± 0.125 mm, 0.429 ± 0.149 mm, and 0.520 ± 0.176 mm, respectively. The means and standard deviations were lower than that of the compared studies.

Conclusion: Addressing several errors during the manufacture of sleeve-free surgical guides reduces the degree of linear and angular deviation of the drilled implant sites.

KEYWORDS: 3D LCD printers, Accuracy of 3D printed surgical guide, Layer Normal exposure time, Guide hole tolerance.

INTRODUCTION

The advances in dental implantation increase the demand for more accurate implant positioning with improved function and esthetics. Proper planning of implant position and angulation followed by the precise implementation of this plan is crucial for the overall success of the rehabilitation process. Precise implementation is possible by constructing a surgical guide with computer-aided design/computer-assisted manufacture (CAD/CAM) techniques.[1]

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The additive manufacturing techniques done by the union of layers above each other are a part of these CAD/CAM technologies. Additive manufacturing could be either material extrusion, material jetting, powder bed fusion, or vat-photopolymerization.[2]

Vat-photopolymerization utilizes photo-activated resins with different curing light sources. According to the curing light source and the imaging system, photocuring 3D printers could be classified into three categories. These are stereolithography (SLA), digital light projection (DLP), and the latest liquid crystal display (LCD).[3,4] The three types cure the liquid photopolymer selectively layer by layer.[4,5] However, SLA printers utilize laser scanning to cure the resin selectively point by point. While DLP and LCD use ultraviolet (UV) light to selectively cure the entire layer at once, making them faster printers.[2]

Implant installation based on a surgical guide made by photocuring 3D printers shows different degrees of deviation from the planned position and angulation. This deviation results from the summation of several errors that arise during the surgical guide manufacturing steps or the implant site drilling. [6-13] Variation from the intended location and angulation could be significant in clinical cases where the exact position is crucial, such as to avoid damaging the adjacent teeth or vital structures or for better esthetics.[14]

During the surgical guide manufacturing, errors could occur in preprocessing, processing, and postprocessing stages. Preprocessing errors could arise from file conversion in STL format[6] and slicing of the STL files[15]. The processing errors occur from the pallet lifting, laying, resin circulation, projection imaging systems, and build plate leveling. Postprocessing errors are caused by resin shrinkage, deformation during support removal, and deformation during post-curing and surface treatment after printing.[6]

On the other hand, errors during drilling could arise from the improper clearance between the drill and the guide hole, i.e., guide hole tolerance (GHT). GHT of the surgical guide is critical for correct implant positioning. For possible insertion of the drill bit into the guide hole with preserving accuracy, a minimal GHT should be added to the dimension of the hole.[7-12]

Several studies addressed the errors related to desktop photocuring 3D printers and discussed the effects on implant position deviation with different degrees of improvement. However, a flaw of procedures that could minimize the variation of implant position was not addressed. The current study examined a sequential approach that addresses the accumulating errors to achieve higher accuracy in implant site drilled position.

MATERIALS AND METHODS

The current in vitro study proposed sequential steps to produce a 3D printed sleeve-free implant surgical guide with improved accuracy and minimized deviation. These steps were directed to reduce errors accumulated during several guide manufacturing stages that affect implant site drilling accuracy.

Calibration of printing platform:

Anycubic Photon-S LCD-based 3D desktop printer (Anycubic-Griesheim-Gustav burg, Frankfurt, Germany) was used in the current study. The printer building platform was leveled according to the manufacturer's recommendation to improve and unify printing results.

Layer normal exposure time (LNET) calibration

LNET was calibrated using the XP2 Validation Matrix model.[16] Four models were sliced with Photon workshop (v 2.1.24) according to resin manufacturer specifications with a layer height of 0.05 mm. The four models were sliced with a different LNET of 2.5, 3, 3.5, and 4 seconds. The models were printed utilizing ABS-like resin (SHENZHEN WEISTEK CO., LTD, Shenzhen, China). The printed models were washed with Isopropyl Alcohol 99.9% (Alkhuraiji-Factory-Pure and Clean-KSA) in an ultrasonic cleaner (Intelligent Ultrasonic Cleaner -600 mL-China) at 50-Watt power for 10 minutes to remove excess resin. The models were then solidified by exposing them to UV resin curing light (Skophy-China) for 30 minutes. According to validation matrix designer recommendations[16], the printed models were compared for the best print. The best LNET was set at 3 seconds. (Fig 1)

Calibration of GHT

The GHT was determined to establish the clearance factor for a 2.4 mm drill bit (Dremel, Wisconsin, US). A 3D template was designed in 3-Matic software (Materialise N V, Technologielaan 15,3001 Leuven, Belgium) with eight cylinders on two rows, four each. The first row was designed with four hollowed cylinders with an outer diameter of 6 mm and an inner diameter of 2.4, 2.5, 2.6, and 2.7 mm. The second row was designed as solid cylinders with 6, 6.1, 6.2-, and 6.3-mm outer diameter. The model was exported as an STL file and sliced with 0.05 mm layer thickness and the determined LNET (3 seconds). The sliced model was printed, washed, and solidified as in step 2. (Fig 2) The 2.4 mm drill bit was inserted into the hollowed cylinders one by one to determine the hollowed cylinder that allowed for smooth insertion without lateral movement of the bit, which was the 2.7mm cylinder. The inner diameter of the selected cylinder was measured using a digital caliper and was 2.45mm. The printed inner diameter was then subtracted from the chosen cylinder-designed inner diameter (2.7mm - 2.45mm = 0.25mm). The difference indicated the GHT, which was 0.25 mm. Software Boolean subtraction clearance factor was adjusted at 0.125 (GHT divided by two). The outer diameter of the second-row cylinders was measured with a digital caliper. The cylinder that measured 6mm was the 6.2mm cylinder. Accordingly, the outer diameter of the guide cylinder would be adjusted to +0.2mm during 3-Matic designing.

Cast scanning

Six casts were scanned to construct 12 surgical guides to plan twenty-four drilling sites. Each cast was scanned before and after drilling. Einscan SP scanner (SHINING 3D, Hangzhou, China) was used for cast scanning. Each cast was placed on the scanner turntable. The turntable was positioned within the scanning range (35-45cm). The scanner software (EXScan S v3.1.0.1) settings were modified so that the complete turn of the turntable was done in 8 steps, and the automatic aligning mode was adjusted to the turntable coded targets. The tripod-mounted scanner head height was adjusted roughly to make a 20° angle to the horizontal turntable plane (Fig 3-E). The scanner head was then tilted to bring the projected cross mark to the center of the cast (Fig 3-A). Following the first scanning, the scanner head was adjusted to a higher level to make roughly a 50° angle to the turntable plane, followed by a second scanning. Registration of the two scans

Fig. (1): LNET calibration, 4 XP2 Validation Matrix models printed with different LNET 2.5, 3, 3.5, 4 seconds, the 3-second LNET print was chosen.

was done automatically. The scanned images were meshed, the cast base was created by manual hole correction, and the 3D model was exported as an STL file.

Surgical guide designing and printing

The predrilled cast STL file was imported to 3-Matic software. A small cylinder with 2.0 mm diameter and 20 mm length was made and aligned into the proposed first drilling site. The cylinder was duplicated for each drilling site on the same side of the cast. Then the duplicated cylinders were positioned into the planned drilling sites. A large cylinder with (6 + 0.2 mm) diameter and 6 mm length was created and aligned to each small cylinder using the arc-to-arc alignment function. Boolean subtraction operation was done to subtract the small cylinder from the large cylinder with a clearance factor of 0.125 to make the drilling guide cylinder. Several cubes were made and oriented over the teeth. The cubes were positioned apical to the teeth gingival line. The cast was duplicated and subtracted from these cubes with a clearance factor of 0.1 for easy guide insertion and removal. Smaller cubes were made to be fused to the drilling guide cylinders with the Boolean union function.

Another cast duplicate was subtracted from the fused piece with no clearance. The drilling guide and teeth fitting parts were united with the Boolean

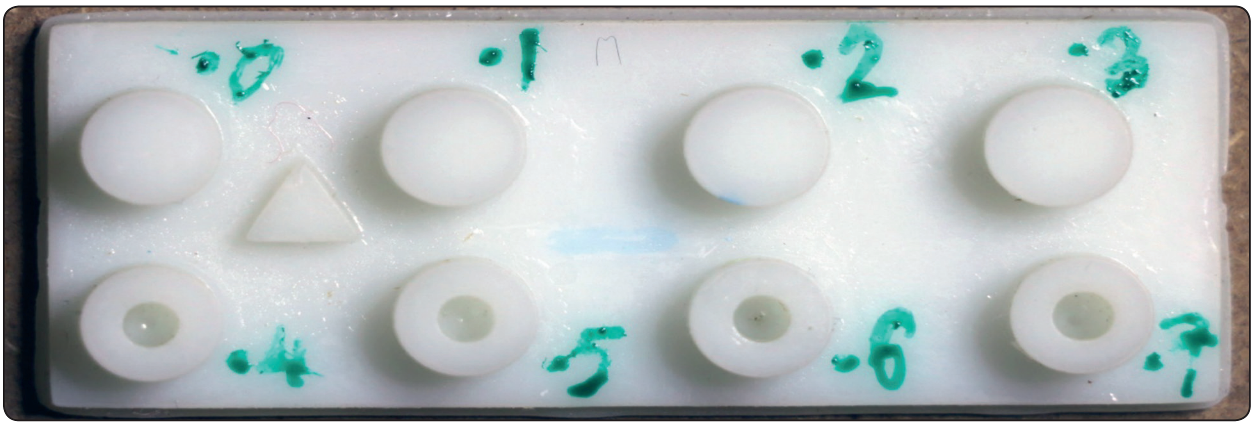

Fig. (2): Calibration model for GHT, the first row of 4 hollowed cylinders with internal diameters of 2.4, 2.5, 2.6, and 2.7 mm, the second row of 4 solid cylinders with outer diameter of 6.0, 6.1, 6.2, and 6.3 mm.

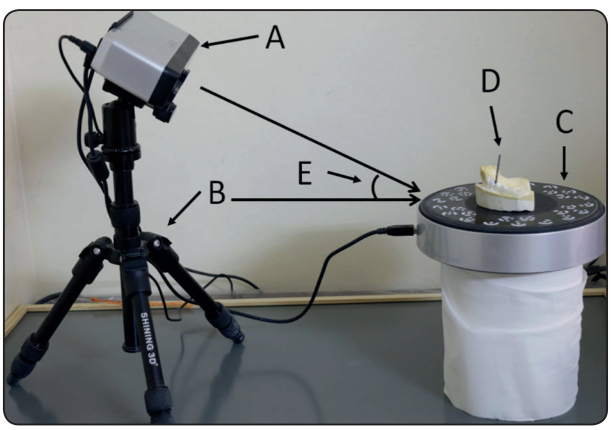

Fig. (3): Post-drilling scanning: A. Scanner head, B. Tripode mount, C. Turntable with build-in marks for automatic registration, D. Painted drill bit, E. Angle between the scanner head and the horizontal plane of the table.

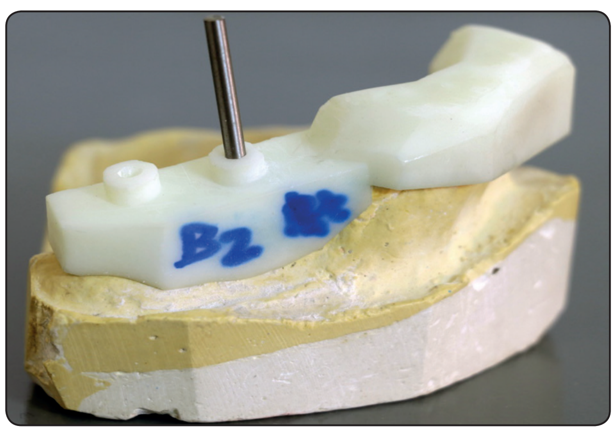

Fig 4: 3D printed sleeve free surgical guide adapted to its corresponding cast with the 2.4 mm drill bit inserted in one of the guide holes.

union. The 3-Matic fixation wizard was then used to optimize the surgical guide triangulation. The surgical guide was then exported as an STL file and imported to the photon workshop software. The model was oriented to make 45° to the build plate with the non-fitting site facing the build plate. Automatic supports were then made, and the supported model was printed, washed, and solidified as before. The supports of the solidified guide were then removed.

Linear and Angular Deviation measurements:

Each guide was adapted to its corresponding cast, and the planned holes were drilled to 15 mm depth by the 2.4 mm drill bit mounted on a Dremel right angle handpiece (Dremel, Wisconsin, US). (Fig. 4) Another 2.4 mm drill bit was sprayed with a thin layer of gray mud paint to eliminate the metal luster for proper scanning. After the complete dryness of the sprayed paint, the sprayed drill bit was inserted into the depth of one drilled hole. The cast with the drill bit was scanned, and the 3D post-drilling model for the specific drilling site was saved as an STL file. (Fig. 3) The same was repeated for each drilled hole in each cast. Each post-drilling STL file was imported to the corresponding 3-Matic file then aligned to the original cast model by point registration followed by global automatic registration. The aligned drilled cast was duplicated and then trimmed so that only the scanned drill pit was left.

An analytic cylinder was created upon the scanned drill pit using an automatic cylinder fitting function. Two cylinders (5mm diameter and 20mm length) were made. The first cylinder was aligned to the designed stent corresponding guide hole, and the second cylinder was aligned to the analytic cylinder using arc-to-arc alignment. Both cylinders were translated along their corresponding long axis so that their top ends were at the crest of the cast ridge. Analysis arches were created on each end of the two cylinders. The distance measuring tool measured the distance between the two cylinders' top and bottom arches' center. An analytic axis was then made for each cylinder, and the angle of deviation (AD) was measured. The top distance was designated to coronal linear deviation (CLD), and the bottom distance was assigned to the apical linear deviation (ALD) at 20mm. (Fig 5) The ALD at 10mm was calculated using the trapezoid midsegment equation (sum of the bases divided by 2). The same was repeated to calculate the ALDs at 5- and 15-mm.

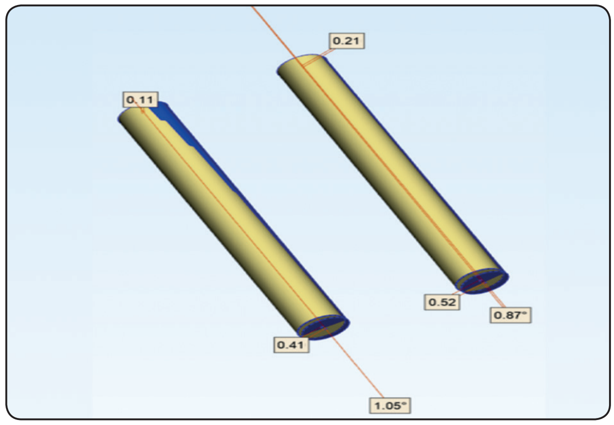

Fig. (5): Measuring linear and angular deviations of the drilled implant sites: the blue cylinders represent the planned position, and the yellow cylinders represent the drilled sites, coronal and apical (at 20 mm) linear deviations, and angular deviations are presented.

Statistical analysis

The mean and standard deviation of the linear deviation distances at different implant lengths and the deviation angle were calculated using Microsoft Excel 365.

RESULTS

The coronal linear and angular deviation means and standard deviations were 0.155 ± 0.095 mm and 1.129 ± 0.323°, respectively. The means and standard deviations of the apical linear deviation at 5, 10, 15, and 20mm implant lengths were 0.246 ± 0.106 mm, 0.338 ± 0.125 mm, 0.429 ± 0.149 mm, and 0.520 ± 0.176 mm, respectively. (Table No 1) The results of previous studies are represented in table No 2. The linear and angular deviation measurements of the studied casts are presented in table No 3.

TABLE (1): Means and standard deviation of coronal, apical, and angular deviations

	Mean ± SD	Minimum	Maximum
CLD	0.155 ± 0.095 mm	0.029 mm	0.480 mm
ALD at 5mm	0.246 ± 0.106 mm	0.100 mm	0.618 mm
ALD at 10mm	0.338 ± 0.125 mm	0.120 mm	0.755 mm
ALD at 15mm	0.429 ± 0.149 mm	0.135 mm	0.893 mm
ALD at 20mm	0.520 ± 0.176 mm	0.150 mm	1.030 mm
AD°	1.129 ± 0.323°	0.400°	1.741°

TABLE (2): Results of previous studies.

Author	Type of study	Guide type	CLD	ALD	AD
Bell et al. [14]	In vitro	Thermoplastic guide	1.33±0.3mm	1.6±0.29mm At 8 mm	3.4±1.23°
		3D printed guide	0.51±0.24mm	0.76±0.36mm At 8 mm	2.36± 1.38°
De Santis et al. [17]	In vivo	Fully guided sleeves	1.16±0.68mm	1.65±1.17mm	
		Pilot drill guide	1.11±1.05mm	1.7±1.12mm	
Tahmaseb et al. [18]	Systematic review		1.12 mm (maximum 4.5mm)	1.39 mm (maximum 7.1mm)	
Schneider et al. [19]	Systematic review		1.07 mm (95% CI 0.76–1.22 mm)	1.6 mm (95% CI 1.26–2 mm),	5.3° (95% CI 3.94– 6.581)
Van Assche et al.[20]	Systematic review		0.99 mm (range 0–6.5 mm),	1.2 mm (range 0–6.9 mm),	3.81° (range 0–24.9°).

TABLE (3): Linear and angular deviation measurements of the studied casts

Cast	Side	Drilling site	Linear Deviation					AD°
			CLD	ALD at 5mm	ALD at 10mm	ALD at 15mm	ALD at 20mm	
Cast 1	Rt 1	1	0.110	0.185	0.260	0.335	0.410	1.050°
	Rt 2	2	0.210	0.288	0.365	0.443	0.520	0.870°
	Lt 1	3	0.090	0.105	0.120	0.135	0.150	0.400°
	Lt 2	4	0.130	0.238	0.345	0.453	0.560	1.330°
Cast 2	Rt 1	5	0.040	0.100	0.160	0.220	0.280	0.860°
	Rt 2	6	0.230	0.320	0.410	0.500	0.590	1.070°
	Lt 1	7	0.480	0.618	0.755	0.893	1.030	1.740°
	Lt 2	8	0.130	0.253	0.375	0.498	0.620	1.450°

Cast	Side	Drilling site	Linear Deviation					AD°
			CLD	ALD at 5mm	ALD at 10mm	ALD at 15mm	ALD at 20mm	
Cast 3	Rt 1	9	0.130	0.185	0.240	0.295	0.350	0.660°
	Rt 2	10	0.140	0.275	0.410	0.545	0.680	1.520°
	Lt 1	11	0.220	0.358	0.495	0.633	0.770	1.600°
	Lt 2	12	0.120	0.221	0.323	0.424	0.525	1.130°
Cast 4	Rt 1	13	0.040	0.110	0.180	0.250	0.320	0.850°
	Rt 2	14	0.110	0.213	0.315	0.418	0.520	1.170°
	Lt 1	15	0.122	0.224	0.326	0.428	0.530	1.140°
	Lt 2	16	0.151	0.289	0.428	0.566	0.704	1.741°
Cast 5	Rt 1	17	0.190	0.292	0.394	0.496	0.598	1.196°
	Rt 2	18	0.029	0.137	0.244	0.352	0.459	1.261°
	Lt 1	19	0.228	0.303	0.378	0.453	0.528	1.035°
	Lt 2	20	0.126	0.203	0.281	0.358	0.436	1.046°
Cast 6	Rt 1	21	0.287	0.316	0.345	0.374	0.403	0.998°
	Rt 2	22	0.071	0.171	0.271	0.371	0.471	1.008°
	Lt 1	23	0.139	0.244	0.350	0.455	0.560	1.123°
	Lt 2	24	0.195	0.265	0.335	0.405	0.475	0.845°

DISCUSSION

The improvement of desktop 3D printers and the emergence of new affordable technologies allowed the possibility of producing surgical implant guides by the clinician. However, there is a degree of deviation of the placed implants position from the planned one. This deviation results from the accumulation of several errors that occur during guide manufacturing that affect the accurate position of implants drilling sites. The current in vitro study was held to examine the accuracy of 3D printed sleeve-free implant surgical guides following suggested steps directed to minimize the possible manufacturing errors that accumulate, resulting in a deviation of the placed implant's site drilling.

The current study utilized a sleeve-free 3D printed surgical guide to eliminate possible errors from guide sleeves insertion or the utilization of drill hold or handheld sleeve inserts. Several studies indicated the metal sleeves and sleeve inserts as a source of errors during the manufacture of the surgical guide.[10,21] One study showed a mean deviation angle of 4.7° in stereolithographic surgical guides arising from the guide sleeves.[21] Another in vitro study reported mean deviation angles accompanying drill hold and handheld sleeve inserts of 5° and 4.5°, respectively.[10] Moreover, several studies indicated accuracy in implant placement utilizing metal sleeve-free surgical guides.[7,22-24]

The current study showed mean CLD, mean ALD (at 10 mm), and mean AD were 0.155 ± 0.095 mm, 0.338 ± 0.125 mm, and 1.129 ± 0.323°, respectively. An in vitro study done by Bell et al.[14] to compare the accuracy of implant placement utilizing two types of surgical guides. The study showed CLD, ALD at 8mm, and AD for group one using ten implants placed with a thermoplastic guide to be 1.33±0.3mm, 1.6±0.29mm, and 3.4±1.23°, respectively. While in group two utilizing ten implants placed with the 3D printed guide, the findings were 0.51±0.24mm, 0.76±0.36mm, and 2.36±1.38° for CLD, ALD at 8mm and AD, respectively. The current study obviously showed lower means of CLD, ALD at 10mm, and AD when compared to Bell et al.'s results. Bell et al. measured ALD at a shorter implant length (8mm), reducing the linear deviation. Moreover, the current study standard deviations of the given results are lower than that of the Bell et al. results indicated fewer spread-out results in the present study.

Another in vivo study done by De Santis et al.[17] compared 23 implants installed with fully guided sleeves versus 27 implants placed with a pilot drill guide. Group one showed 1.16±0.68mm and 1.65±1.17mm while group two showed 1.11±1.05mm, and 1.7±1.12mm for CLD and ALD, respectively. Moreover, several systematic reviews showed different degrees of deviations. A systematic review done by Tahmaseb et al. [18] showed CLD of 1.12 mm (maximum 4.5 mm), ALD of 1.39 mm (maximum 7.1 mm). Another systematic review done by Schneider et al. [19] showed CLD of 1.07 mm (95% CI 0.76–1.22 mm), ALD of 1.6 mm (95% CI 1.26–2 mm), and AD of 5.3° (95% CI 3.94– 6.581). A third systematic review is done by Van Assche et al. [20] showed CLD of 0.99 mm (range 0–6.5 mm), ALD of 1.2 mm (range 0–6.9 mm), and AD of 3.81° (range 0–24.9°). The current study showed obvious lower means and standard deviation of CLD and AD than these results. However, ALD could not be compared due to the lack of unified implant lengths indicated in the presented studies.

The present study suggested several steps that minimized the accumulative errors. It starts with proper leveling of the printer base plate, which is a critical issue in vat-photopolymerization printing. Proper adjustment according to the manufacture's recommendations ensures high printing quality.

The next step is to determine the proper LNET. Printing LNET is affected by different factors such as resin composition, stains, and resin viscosity. Resin viscosity should not exceed 5Pa/s. Increasing viscosity reduces the resin flow and increases the required LNET and total printing time.[25] Higher room temperature reduces resin viscosity and the needed LNET.[26] Moreover, the intensity of LCD light affects the LNET. Therefore, photocured resin manufacturers recommend a range of LNET. Several methods are used for printing LNET calibration. The XP2 Validation Matrix model was chosen in the current study as it is a simple, rapid method for calibrating printing LNET with minimal resin consumption.[16]

Layer thickness is a critical factor during STL file slicing that affects printing quality and time. Utilizing thinner thicknesses increases layers number, improves print resolution in the z-axis, and increases total printing time.[27] Proper layer thickness differs according to printing technologies. It was indicated that the appropriate layer thickness for DLP and LCD is 0.05 mm[27] and that for SLA is 0.1 mm.[28] The current study utilized an LCD printer, so the layer thickness was adjusted to 0.05 mm.

Post-printing solidification is another crucial factor in all calibration and printing steps. Printed models show unreacted or partially reacted resin. Post-printing solidification by exposure to UV resin curing light is required to completely solidify the printed models and enhance their mechanical properties. However, the length of exposure affects the properties of the solidified model. Over-curing could occur with prolonged exposure and increase resin shrinkage.[25] In the current study, LNET templates and clearance adjustment templates were hardened utilizing the same UV resin curing light source for an equal length of exposure to standardize the solidified prints properties and the degree of shrinkage. The same parameters were applied during printing the tested guides.

The following step is to determine the proper GHT. Several studies emphasize the importance of the determination of the proper clearance gap.[7-12,29] Designing the inner diameter of the guide cylinder with a fixed clearance gap carries two challenges. Shrinkage of photocured resins during printing and solidification modifies the designed guide-hole diameter. This shrinkage will result in smaller GHT hindering smooth drill bit insertion. In contrast, creating a larger GHT will allow for lateral movement of the drill bit, increasing the deviation angle. The current study utilized a simple method to determine the proper clearance gap. The 3D GHT calibrating templet was printed, washed, and solidified using the same determined parameters as what would be applied in preparing the guide. This allowed for accurate estimation of clearance gaps in the studied surgical guides.

Another factor that could affect the installed implant deviation is the height of the drill hole wall. Longer walls will allow a more centric position and parallelism of the drill bit to the hole walls.[10] This will reduce the deviation angle and improve the implant placement accuracy.[10,21] The current study utilized holes height of 6 mm. Dimitrios and Georgios, in 2018[9], held a study to offer equations and reference tables to speculate the maximum deviation of implant positioning according to the mechanical properties of the surgical guide. The included table indicated that the minimal hole wall height with minimal variation is 6 mm.

CONCLUSION

According to the findings of this study, addressing several errors during the manufacture of sleeve-free surgical guides reduces the degree of drilled implant site linear and angular deviation. Leveling the building platform, selecting proper layer thickness, calibrating LNET and GHT, and standardizing the post-printing treatment parameters are critical steps in the accuracy of the drilled implant sites.

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