Original Article

Accuracy of dental implant placement using chairside computer-aided surgery/computer-aided manufacturing-milled guides compared to three-dimensional printed guides

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ABSTRACT

Background: In-office devices are increasingly used in dental practices to mill "chairside" restorations for increased turnover. New functions permit milling implant surgical guides, thus cutting the time and cost of treatment. This study compares the accuracy of chairside-milled surgical guides (CMG) with that of high-accuracy laboratory-based three-dimensional (3D)-printed guides (PGs).

Methods: In this *in vitro* study, 10 bone-level cylindrical implants (4 mm × 13 mm) were placed using both guide types (five for each) in 10 similar prefabricated plastic models with the aid of a specially designed machine. The positions of the placed implant were compared to the planned positions by superimposing postsurgical cone-beam computed tomography scans over the preoperative scans and by measuring the horizontal, vertical, and angular deviations within each study group.

Results: The horizontal deviation at the implant neck was 0.37 mm ± 0.16 for CMG and 0.84 mm ± 0.35 for PG ($P < 0.05$). The horizontal deviation at the apex was greater; 0.76 mm ± 0.49 for CMG and 1.70 mm ± 0.46 for PG ($P < 0.05$). The vertical deviations in both groups were smaller than the horizontal values and almost identical at the neck and apex within each group (0.26 mm ± 0.13) and (0.37 mm ± 0.25) for CMG and PG, respectively ($P > 0.05$). The angular deviation of the implant's long axis for PG (4.10° ± 1.96°) was twice as large as CMG (2.0° ± 1.37°), but the difference was not statistically significant ($P = 0.08$).

Conclusion: Chairside milled guides demonstrated higher accuracy and predictability compared to laboratory-based 3D-PGs.

Keywords: Chairside milled guides, computer-aided surgery, computer-aided surgery/computer-aided manufacturing, data accuracy, dental implants, image-guided surgery, three-dimensional printing

BACKGROUND

Proper implant planning and precise positioning are indispensable to avoid damage to surrounding vital structures and obtain predictable aesthetic and prosthetic outcomes [1,2]. Improper implant positioning will have a detrimental effect on the fabrication of the final substructure in relation to the antagonists and other oral structures, including the lip and tongue [3-6].

Surgical guides are plastic (resin) templates used during the implant surgery to physically control the position, orientation, and depth of the drill during osteotomy [7]. They have become increasingly used due to the improved accuracy, safety, confidence, and speed of the surgery [8,9]. Moreover, restoration-driven implant placement with a surgical template can decrease clinical and laboratory complications [10].

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Surgical guides are used for the placement of single or multiple implants. They can be tooth-supported, mucosa-supported, or bone-supported. They can also be classified as pilot, partial, or complete. The latter permits guidance of both the drills and the implant itself. In contrast, the partial guides only direct the drills, and the pilot guides only help with the pilot drills. Thanks to the advancement of three-dimensional (3D) radiology (e.g. cone-beam computed tomography [CBCT]) and 3D manufacturing, fabrication of accurate surgical guides has become common in dental laboratories, either by milling through computer-aided surgery/computer aided manufacturing (CAD/CAM) technology or by 3D printing.

The CAD/CAM technology involves planning the implant position on CBCT and designing the surgical guide on CAD/CAM software. The design is then transferred to a milling device that mills a block of prefabricated resin material [11,12]. Conventionally, a large, 5-axis milling machine is required to drill holes for implants with different axial orientations [11,13]. Similarly, in the 3D printing method, the implants are virtually planned on the CBCT, and the surgical guide is designed using CAD/CAM software. The data are then transferred to a production center. Different 3D printing technologies are available in the dental field; among these are stereolithography, direct light processing (DLP), and material jetting [14,15].

These techniques require large, expensive equipment that only exists in large dental laboratories. As such, the guides have to be outsourced and are naturally associated with additional waiting time and cost. In-house 3D printers are becoming increasingly popular; however, they can result in an inaccuracy in the implant position in the range of 2 mm [16,17]. which can be detrimental to vital structures in the mouth.

Chairside CAD/CAM machines have been used routinely to fabricate dental restorations in dental clinics [11]. Some of these devices allow the milling of a surgical guide using a small, 4-axis mechanism (CG2 surgical guide with CEREC MCXL unit (Dentsply-Sirona, Bensheim, Germany). As such, these permit the milling of a single-implant tooth-supported guide. Planning two or more implants will generally require different axial orientations, which the 4-axis milling unit cannot provide. Nevertheless, these cases can be made by milling two separate guides.

There have been several reviews of the accuracy and utility of various implant surgical guides [18,19]. The systematic review by Tahmaseb *et al*.[19] showed that computer-aided implant surgery exhibited accuracy within the clinically acceptable range. On the other hand, Henprasert *et al*.[20] showed that there was no statistically significant difference between the accuracy of milled and 3D-printed implant-surgical guides. Hence, with the ever-emerging technologies, there is a constant need to review and compare new modalities. Most studies comparing the manufacturing of surgical guides used laboratory-based 5-axis milling machines. There is a scare literature on the in-house (chair-side) milling devices. This study examines the performance of a chairside milling machine.

MATERIALS AND METHODS

This bench-based study entails the placement of dental implants in standardized prefabricated plastic models using surgical guides constructed by either chair-side CAD/CAM milling or laboratory-based 3D printing. The accuracy of both guide types was assessed by measuring the differences between the achieved implant position and the planned implant position.

The models

Ten standard plastic models of a partially edentulous maxilla were used (Bonemodels, Castellan, Spain) [Figure 1a]. The models were made with resin that simulated D2 and was covered with a silicone-based material to simulate soft tissues.

To facilitate superimposition of the pre- and post-operative model scans, a number of 3 mm holes were drilled into the base of the model using a spherical diamond bur [Figure 1b].

Scanning and implant planning

All models were individually CBCT scanned using the Orthophos SL (Dentsply-Sirona). Consistent parameters were used for all scans. A bespoke CBCT stand was made to locate the models in the same position on the scanning machine accurately and with ease.

Before scanning, the models' teeth were lightly covered with a radiopaque flowable resin (X Resin Flow, Bredent, Germany) to allow a clear definition of the teeth during the merging of the optical scan (digital impression) and the CBCT scan. Once set, the resin was easily removed.

A digital impression was taken of each model using CEREC's Omnicam Acquisition Unit (Dentsply-Sirona), which was used to plan the replacement of the missing tooth (#23). The digital impression (ssi file) was then merged with the CBCT scan to make the implant plan using the GALILEOS Implant software.

Implant planning was undertaken using GALILEOS Implant software, based on the corresponding implant dimensions (detailed below). The plan was then exported as cmg.dxd files to the CEREC machine to design and fabricate five milled surgical guides [Figure 2a] and to the dental laboratory (cmg.dxd files via E-mail) to design and manufacture the printed guides (PGs) [Figure 2b and c].

Fabrication of the milled guides (group one)

The milled guide design was made by a clinician using the CEREC software. The design incorporated a space “sleeve” to house the metal drilling key used to “guide” the drills and to prevent accidental grinding of the plastic guide [Figure 3a]. Once seated in the sleeve, the key also acts as a stopper to prevent the drill from further advancement beyond the desired depth.

Five guides were made by milling transparent thermoplastic poly (methylmethacrylate) blocks using a chairside MCXL milling machine. The milling carbide burs were changed for each mill to ensure consistency.

Fabrication of the printed guides (group two)

The 3D PG design was made at the dental laboratory based on the instructions sent by the above-noted clinician and featured the same configuration as the milled guide. The design was also based on the radiographic dataset transferred as a cmg.dxd file. Five guides were made from a light-curing resin (FotoDentTM guide) using a 405 nm LED-based digital light processing (DLP) System (RapidShape D40, Germany).

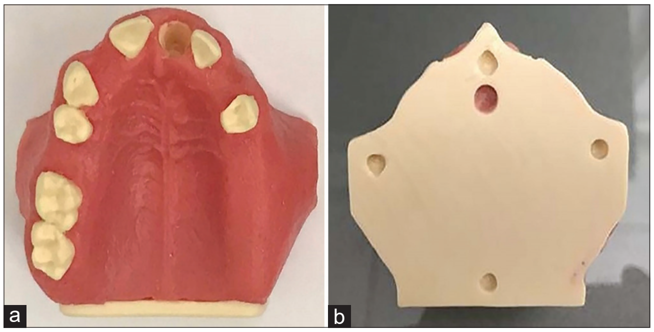

Figure 1: (a) The model used in the experiment. (b) The model’s base showing five landmark holes drilled to facilitate the CBCT super-imposition. CBCT: Cone-beam computed tomography.

Osteotomy and implant placement

Ten identical “dummy” or “training” dental implants (TX 4.0S Astra OsseospeedTM) were used in this study. The implant is parallel, bone-level, 4.0 mm in diameter, and 13 mm in length.

After cutting the “soft tissue” with a scalpel, osteotomy was carried out using a standard surgical motor (Surgybone SB300, Silfradent) at 1000 rpm and under copious saline irrigation. A fresh set of drills was used for each osteotomy to ensure consistency amongst all samples. The drill set consisted of four 25 mm long-guided twist drills for Astra implants, with increasing diameters: 2.0 mm, 3.2 mm, 3.7 mm, and 3.85 mm (Dentsply-Sirona). The drills were guided into the planned position using a series of metal keys that corresponded to the drills and fitted securely in the guides’ sleeves.

To standardize the osteotomy procedures and prevent human (operator’s) errors, the surgical motor’s handpiece was mounted on a custom-fabricated unit (Super Fresart, Amadeal Ltd) [Figures 3b]. Once set in position, the machine allows only a vertical, in-and-out movement of the attached handpiece to the pre-set direction and depth.

At the completion of each osteotomy, the implants were placed using machine-mounted drivers at adjusted speed and torque. The guides were then removed, and the most coronal part of the implants (3 mm) was torqued down by hand as the implants exhibited high resistance to full insertion to “bone-level” with the handpiece. The implants were manually torqued down to 30N as per the manufacturer’s instructions. Full insertion was assessed visually to simulate reality.

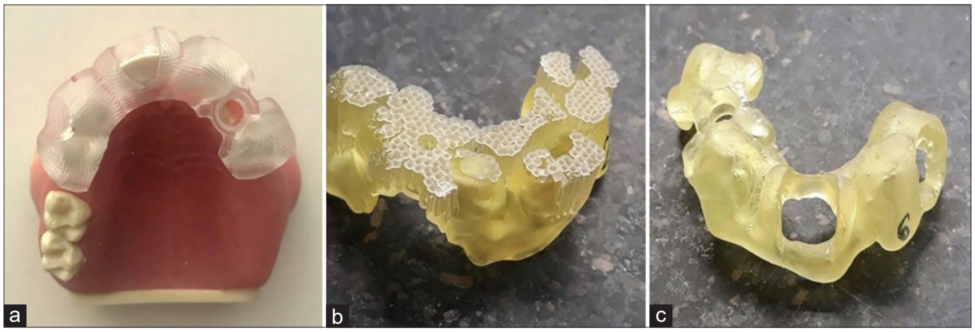

Figure 2: (a) An occlusal view of the CAD/CAM milled guide (b) The 3D printed guide with the support structure (middle) (c) The 3D printed guide with the support structure removed (right). CAD/CAM: Computer-aided surgery/computer aided manufacturing, 3D: Three-dimensional.

Postoperative cone-beam computed tomography scanning of the models

All models were placed in the same position in the CBCT stand, and ten individual scans were taken using the same exposure time and volume used for the preoperative scans. All postoperative scans were exported as a DICOM file to the outcome assessor (a radiology technician) through the SICAT portal (SICAT GmbH and Co. KG, Bonn, Germany) and the corresponding preoperative scans and implant plans.

Merging the pre- and post-operative cone-beam computed tomography volumes

The merging process was carried out using the MATLAB 2010 software (The MathWorks, Inc., Natick, Massachusetts, United States). Both scans for each model were overlaid using the predetermined landmarks (holes drilled at the bottom of the model). The quality of the matching process was checked by the use of isocontours within the software [Figure 4a]. The original preoperative implant plan was overlayed on the matched postoperative scan to assess the accuracy of implant placement [Figures 4b and c].

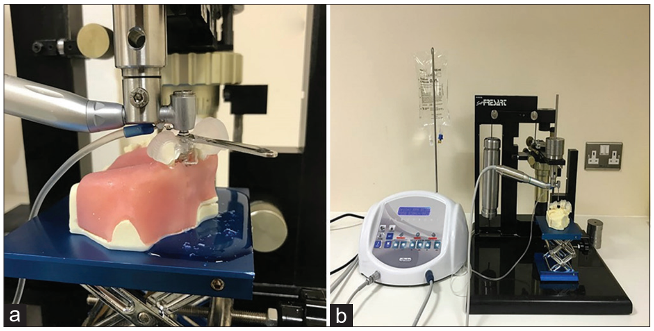

Figure 3: (a) The drill key controlling direction and depth of the osteotom (b) The unit used to carry out the osteotomies.

Outcome assessment

Using the 3D coordinates in the SICAT Implant 1.2 software, measurements were made on the images to determine both linear and angular deviations between the inserted implant position and the planned implant position at the corresponding occlusal and apical ends of the implant[21] [Figure 4c].

The mean (m) and standard deviation (SD) of the positional deviations within each guided group were calculated using Excel 2010 (Microsoft), and the statistical significance of the differences was examined using the open-source calculator OpenEpi Version 3. The study power and required sample size has been estimated using OpenEpi V3 and Graphpad Statmate 2.

Power calculation

The study power, calculated using OpenEpi, was based on the linear deviation at the implant apex (total deviation), as this is the most critical aspect of variation in implant position. The study power measured 86%.

The calculation was repeated based on the total linear deviation at the implant shoulder and was found to be 76%. The GraphPad StatMate 2 application was used to calculate

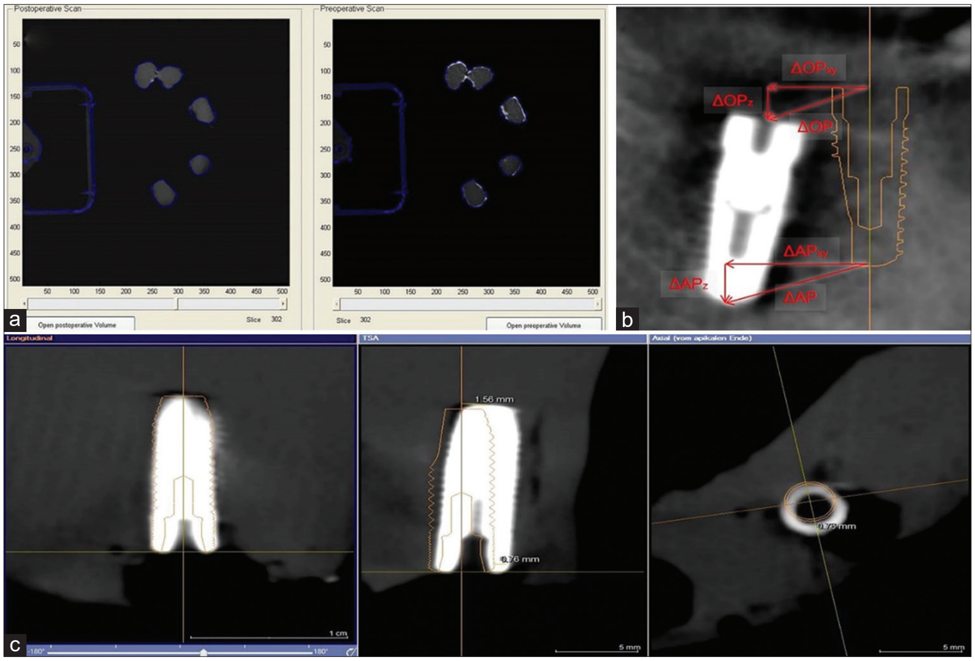

Figure 4: (a) A screenshot of isocontours from the preoperative scan overlayed on the postoperative scan. (b) and (c) Super-imposition of the pre-op implant plan (orange trace) on a CBCT scan of the achieved positions (radiopaque material). The different measurements taken between the two positions are shown at the occlusal end (OP) and the apical end of the implant (AP). CBCT: Cone-beam computed tomography.

the sample size required to obtain a power of 95% to detect a difference of 0.54 mm between the means of the two investigated groups. The estimated size was found to be 12.

RESULTS

Overall, the PGs resulted in more deviation at the shoulder, apex, and angle over the CG2 milled guides [Figures 5-7]. Data distribution was checked, and normal distribution was found in all variables. Therefore, statistical significance between the groups was examined with the unpaired two-tail *t*-test using the open-source OpenEpi calculator.

The horizontal deviation at the implant shoulder for CG2 ranged between 0.15 and 0.57 mm (m = 0.37, SD = 0.16) compared to the larger difference noted in the 3D PGs, 0.52–1.36 mm (m = 0.84, SD = 0.35) (*P* = 0.028). The horizontal deviations at the apex were larger for both groups, ranging between 0.28 and 1.52 mm (m = 0.76, SD = 0.49) for the milled guides and 1.03–2.13 mm (m = 1.7, SD = 0.46) for the PGs (*P* = 0.014). The difference between the two guide groups was statistically significant at both ends of the implant.

The vertical deviation was consistently less than the horizontal deviation in both groups. The vertical deviation at implant shoulder ranged between 0.06 and 0.39 mm (m = 0.26, SD = 0.13) for CG2 and 0.00–0.64 mm (m = 0.37, SD = 0.25) for the 3D PGs (*P* = 0.408). The vertical deviation was almost identical at the apex, measuring between 0.06 and 0.39 mm (m = 0.25, SD = 0.13) and 0.00–0.66 mm (m = 0.36, SD = 0.24), respectively (*P* = 0.393). The difference between the two guide groups was not statistically significant.

The total linear deviation of the implant shoulder for CG2 ranged between 0.42 and 0.60 mm (m = 0.48, SD = 0.13) and for the 3D PGs 0.63–1.51 mm (m = 0.94, SD = 0.35) (*P* = 0.027) [Figure 5]. The total linear deviations at the apex were between 0.28 and 1.53 mm (m = 0.82, SD = 0.47) and 1.03–2.16 mm (m = 1.74, SD = 0.49), respectively (*P* = 0.016) [Figure 6]. The difference between the two groups was statistically significant at both ends of the implant.

The angular deviation between the planned and placed implant positions ranged from 0.99° to 4.29° (m = 2°, SD = 1.37°) for CG2, which was half that recorded for the 3D PGs: 1.28°–6.56° (m = 4.10°, SD = 1.96°), but the difference was not statistically significant (*P* = 0.085) [Figure 7].

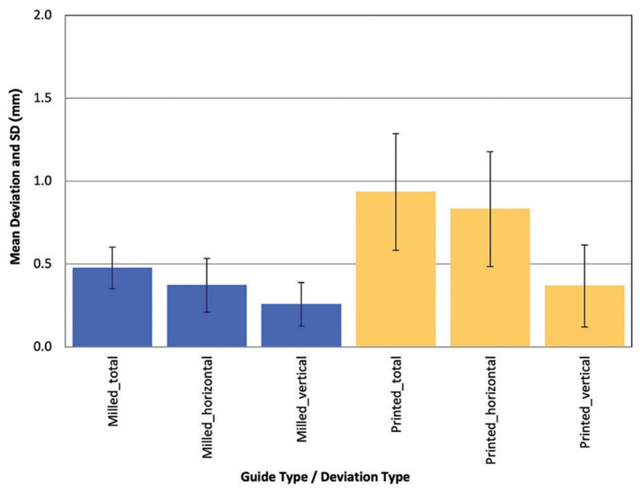

Figure 5: Total linear deviations for the two groups at the implant shoulder.

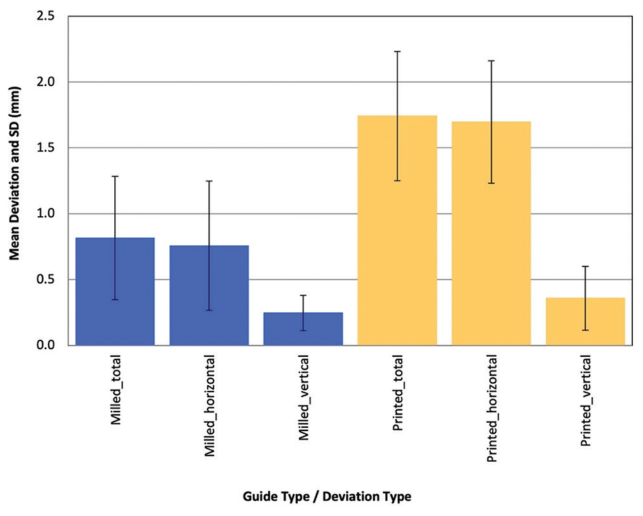

Figure 6: Total linear deviations for the two groups at the implant apex.

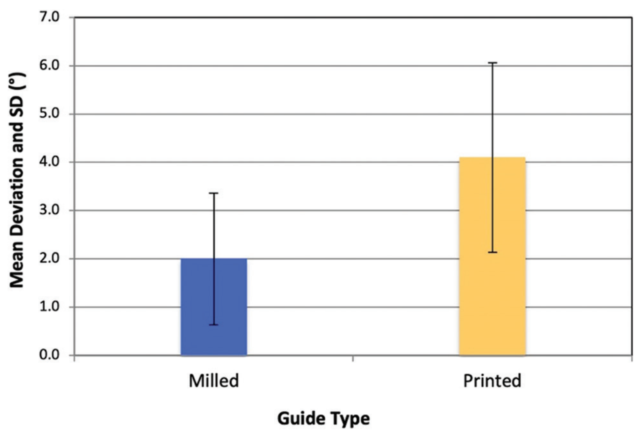

Figure 7: Angular deviations for the two groups.

In summary, all differences were statistically significant, except for the vertical and angular deviation. Another observation was a generally higher variability (SD) within the results of the PGs compared to the milled ones.

AQ9 **Table 1: The study variables and *P* values of the *t*-test statistical significance**

Measure	Description	*P*
Delta OP	The total linear deviation between the mid-point of the occlusal (shoulder/top) end of the implant's planned position and achieved position. This total deviation is made of a horizontal vector (Delta_OPxy) and a vertical vector (Delta_OPz)	0.02728
Delta_OPxy	The horizontal deviation between the mid-point of the occlusal aspect of the implant's planned position and achieved position	0.02824
Delta_OPz	The vertical deviation between the mid-point of the occlusal aspect of the implant's planned position and achieved position	0.4081*
Delta AP	The total linear deviation between the mid-point of the apical (bottom) end of the implant's planned position and achieved position. This total deviation is made of a horizontal vector (Delta_APxy) and a vertical vector (Delta_APz)	0.01631
Delta_APxy	The horizontal deviation between the mid-point of the apical aspect of the implant's planned position and achieved position	0.01407
Delta_APz	The vertical deviation between the mid-point of the apical aspect of the implant's planned position and achieved position	0.3938*
Delta_Alpha(°)	The angle between two lines crossing the implants along their long access: one through the planned implant and one through the placed implant	0.08518*

AQ8 *Satistical insignificance. OP: ???, AP: ???

DISCUSSION

Dental clinics have been increasingly using chairside CAD/CAM machines to fabricate dental restorations. Extending the use of existing chairside equipment to mill surgical guides would be very beneficial. This both cuts down the costs and the time required for the availability of the outsourced technician and eliminates the need for additional investment in chairside printing equipment. Despite the great improvement in the accuracy of implant placement brought by surgical guides, inevitably, a degree of inaccuracy is expected in all computer-assisted fabrication methods. It is, therefore, important to quantify these errors and understand their causes. A systematic review of guided implant surgery concluded that an inaccuracy of up to 2 mm is to be expected [22], which is considerably large in clinical practice. In another study, 3D surgical guides have demonstrated significantly larger "maximum" deviations of 1.58 mm horizontally, 1.68 mm vertically and 8.51° angular compared to guides made by a 5-axis milling unit in the dental laboratory (0.68 mm, 0.41 mm, and 3.23°, respectively) [23].

In this study, the milled guides showed less deviation than the commonly used 3D guides in all variables. The difference between the two groups was statistically significant for the horizontal and total linear deviations and nonstatistically significant for the vertical and angular deviations.

The horizontal deviation noted with the PGs reached a maximum of 1.36 mm at the implant shoulder and a maximum of 2.13 mm at the apex. These results are in agreement with other studies [19,20]. The greater amount of horizontal deviation at the apex is obviously the result of the angular deviation. These values could be detrimental to adjacent structures. Three out of five 3D PGs (cases 04, 08, 10) had to be slightly modified in the circumferential area of the sleeve due to an excess amount of material around the sleeve preventing the full insertion of the drill key. These cases presented the highest angular deviations of 6.56°, 5.14°, and 3.58°. As only the circumference of the sleeve was adjusted and not the height, the increase in horizontal and angular deviations can be expected in this group. For the remaining two 3D PGs, the drill keys had to be almost forced into the sleeve, and this propagated small cracks around the sleeve leading to another possible inaccuracy. This was not experienced with any of the milled guides.

In contrast, errors in the vertical dimension were much smaller than the horizontal errors, which can be due to the accurate vertical position of the drill key within the guide compared to the horizontal leeway. We did not note an increase in the vertical error between the two implant ends.

Causes of inaccuracy

Inaccuracies are caused by inherent errors, both intrinsic (technical) related to the fabrication process or extrinsic caused by handling the surgical guides before and during surgery [24,25]. In this experiment, the accuracy of both guide types could have been affected by a number of intrinsic factors, including image visualization and registration and guide distortion and fit.

Visualization of small details is limited in CBCT images. It is recognized that borders of structures smaller than 100–150 µm blur out. This is due to the modulating transfer function, the volume's voxel size, and the 3D interpolation algorithm of grey values between the voxels [24]. This limited detail accuracy is an inherent limitation of defining the borders of reference markers and borders of implants, which can therefore lead to registration impairments. A potential error of 0–450 µm can be introduced on the basis of limited visualization accuracy and visual artifacts [13,24]. The present study used holes in the model as nonradiopaque reference markers for merging the two datasets (see below), which ensured an artifact-free and accurate matching process.

Distortion and ill-fit of the guide

Distortion can result from a number of errors in the fabrication process. In 3D printing, these can include errors in the scan parameter settings, errors in the inter-slice distance, potential dimensional change during polymerization, and general operator functioning [26]. In the present study, all guides fitted well on the models, and none exploited any rocking. However, the sleeves in the PGs were too tight to accommodate the drill keys and had to be widened during the surgery, or the keys had to be forced in. This may explain the increased horizontal errors in the PGs.

Extrinsic errors in the guides include the leeway between the drill key and sleeve, the leeway between the drill and drill key, guide support type, and guidance of implant insertion.

An optimal fit between the sleeve and the drill key is essential to restrict the degree of freedom of the drill. On the other hand, a minimal difference in diameter must be present between the sleeve and drill key to allow a passive fit and a free maneuver and rotation of the key. A leeway of 120 µm is expected, which can lead to deviation at the apical end of the inserted implant of 400 µm or more [24]. The leeway between the drill and the drill key is determined by the manufacturer and was exactly the same for both study groups, as the same drilling system was used for all guides. The guide's support and retention method can also affect the accuracy [27]. In the present study, we elected to use tooth-supported guides to avoid the inaccuracy caused by the fit and retention of bone-supported or mucosa-supported guides [28].

Minimizing variability and optimizing the quality

To eliminate variability between the two study arms, all materials and procedures were identical for both study arms except for the fabrication of the guide itself. Therefore, the sample size (*n* = 10) was sufficient to generate results with a very good study power. However, to help future research, we calculated the sample size required to examine a minute positional deviation of 0.5 mm and found that a sample size of 12 would generate an excellent study power.

The study design addressed potential bias. Allocation bias was not possible as all models were manufactured in the same way by the same company. There was no way to differentiate between the models, and they were allocated to both groups randomly. With regards to operator bias, it was not possible to blind the operator when performing the osteotomy and implant placement since the guides were visibly distinctive. However, the risk of performing the procedures differently (i.e. in favor of one guide type over the other) was minimized by removing the human role in the osteotomy. In addition, to avoid any risk of operator bias, a separate operator was assigned to carry out the osteotomies and implant placement independently in each group. Measurement bias was eliminated by making the outcome assessor (radiology technician) blind to the guide type associated with the images being assessed.

The experiment required a model that can mimic bone in terms of ability to drill, radiopacity (to show on the CBCT), and contrast against the inserted implant. The plastic models that simulated D2 bone were routinely used in teaching courses and met the above radiographic criteria. On the contrary, the model teeth did not possess sufficient radiopacity, which hindered an accurate merging between the CBCT and optical impression. This was the reason for coating the plastic teeth with a radiopaque barium sulfate acrylic resin. This product is commonly used on patients' existing dentures as radiographic stents during CBCT scanning.

Superimposing the pre- and post-operative CBCT scans was a very challenging procedure. Although different software applications have been used in the past to overlay full CBCT volumes, for example, Rhinoceros 4.0 and Geomagic Studio [28,29], these applications can only overlay CBCT volumes in the same file format (DICOM). The virtual plan is in a different format that cannot be read by these applications. After much deliberation, we managed to merge the preoperative and postoperative volumes and the plan using a matching algorithm based on mutual information (similar landmarks) in MATLAB 2010.

Surgical guides are an integral component of implant treatment planning procedures. This study provides insights into the efficacy of using chairside, CAD/CAM milled surgical guides compared to traditionally use laboratory-based 3D printers, which not only offer time-saving but are also accurate and would help in dental implant treatment outcome and longevity.

Study limitations

While the *in vitro* design may limit generalizability to clinical practice, this design was chosen to provide optimal and uniform working conditions and eliminate the noncontrollable patient and operator variables commonly encountered *in vivo*, such as bone quality and patient movement. Varying outcomes have been previously reported in the literature when the same operation was undertaken in different media, i.e. plastic models, cadavers, or live humans 21. A newer version of the milling software was released during the preparation of this manuscript.

CONCLUSION

Different computer-aided guides are available. Each has its own inherent fabrication and handling shortcomings. Several sources of error during the sequential fabrication steps may accumulate and influence the accuracy of implant placement through a surgical guide. 3D PGs are commonly used and have many clinical advantages. However, their production is associated with considerable inaccuracy compared to milled guides.

The new chairside CAD/CAM milled guide CG2 allows rapid fabrication of the guides in the surgery, cutting down considerably the cost, time, and errors of a lab-made 3D-PG. However, CG2 guides are limited to tooth-supported single-implant applications. Hence, the null hypothesis, that there would be no difference in the accuracy of chairside CAD/CAM milled and 3D printed surgical guides, is rejected. Future studies should focus on determining the long-term stability and clinical life of dental implants placed using chairside milling and laboratory-based 3D printers.

Authors' contribution

MAM– concept, design, the definition of intellectual content, data analysis, manuscript preparation.

KG– literature search, experimental studies, data acquisition, data analysis.

GZ– data analysis.

NS– statistical analysis, manuscript editing.

MA– design, the definition of intellectual content, manuscript review.

Ethical statement

This is a bench-top study that involved no human or animal subjects or samples.

Data availability statement

Data will be provided upon request.

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Conflict of interests

The authors disclose no conflict of interest or financial gain from any of the manufacturers or suppliers of the materials and equipment used in this study.

The manuscript has been read and approved by all the authors. The requirements for authorship have been met, and each author believes the manuscript represents honest work.

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