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Comparison of Dental Surgical Guides Created by Additive Manufacturing

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Abstract: The presented work deals with the analysis and testing of surgical guidance systems in the dental field, which were created based on available software. When manufacturing dental guidance systems, it is important to consider factors such as the digitization process in the production process, design, selection of the most suitable material and method of implantation. Three types of surgical guidance systems were made by three different devices which work on the principle of additive technology and were closely analysed. Subsequently, the created surgical guidance systems were compared with Standard Triangle Language (STL) files in Gom Inspect software, to determine the accuracy of printed objects. In conclusion, it is important to note that the presented work is a pilot study, which is focused on the design of a methodology to produce surgical guides using 3D printing, taking into account shape accuracy.

Keywords: dental surgery, additive manufacturing, biocompatible materials, CBCT

1. Introduction

Conventional planning for implant placement is based on clinical examination and 2D radiographic imaging. The adoption of 3D radiographic imaging enables a more accurate diagnosis of residual bone dimensions, the intraosseous course of the inferior alveolar nerve, and adjacent teeth [1, 2]. Data from 3D imaging technologies of individual patients is essential for planning the placement of virtual dental implants, using computer-aided design (CAD) and computer-aided manufacturing (CAM) for surgical guidance systems for the correct angle of the drill or implant-supported prosthesis. Anatomical data are derived from CBCT (Cone Beam Computed Tomography), CT (Computed Tomography), and optical scans of teeth and mucous membranes. CBCT has a lower radiation dose (92–118 μSv) than CT (860 μSv) and is therefore often used for planned placement of dental implants [3, 4]. Both CT and CBCT are stored in the universal format for Digital Imaging and Communication in Medicine (DICOM) format.

CT or CBCT does not image the surface of the tooth sufficiently for the assembly of prosthetics and the production of surgical guidance systems. Artifacts such as banding and lost regions occur especially in the presence of fillers [5]. Therefore, CT or CBCT scans and a virtual dental model are obtained either by intraoral optical scan or extraoral scan of impressions or plaster casts before the actual planning of implant placement and are then aligned with each other [6]. Data from intraoral and extraoral optical scans are usually available in the universal stereolithographic STL format. This format contains geometric information about the surface [7]. Virtual dental models can be displayed in 2D along cross-sections and in 3D to assess the mucosal surface from different angles. The process of mutual alignment of multiple imaging datasets is defined as registration [8][9]. Various procedures can be used to achieve accurate registration of CT or CBCT scans and virtual dental models. The tooth surface can be used for registration as a

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common structure shown in both datasets. With standardized markers stored in the software, a single scan of the patient with a radiographic plate is performed (single scan protocol) [10, 11]. In the software, the stored reference mark is registered with the scanned image of the corresponding mark. Custom markers use a double scan protocol. After CT or CBCT acquisition of a patient with a radiographic plate, the radiographic plate itself is scanned [12, 13, 14].

A plate with fiducial markers is not necessary when using the tooth surface as a reference for registration [6, 15, 16]. The software uses an algorithm to register corresponding anatomical surfaces or requires prior selection of corresponding regions by the user to initiate the registration process. Accurate registration of CT or CBCT data and virtual models is crucial for accurate transfer of the prospective implant position to the surgical site [9]. After data import, segmentation and registration, the setting of the prosthetics and the virtual position of the implant are planned. The prosthetic assembly combines the ideal position of the implant-supported prosthesis and considers the design of the abutment with its exit profile, tooth morphology, occlusal and proximal contact surfaces. Using this information, implants can be virtually positioned in cross-sectional images and three-dimensional surface models reconstructed from the radiographic volume. The design of a surgical guidance system can vary depending on its function.

In a fully digital workflow, dental guidance systems are virtually designed by CAD software and manufactured using CAM. CAD/CAM is performed either by the user of the software or in a central manufacturing facility. Dental guidance systems are milled from resin blanks [17, 18] or manufactured by additive technology [19]. Combining analogue and digital techniques, dental guidance systems are adapted from conventionally produced radiographic plates or are produced on plaster casts.

1.1. Softwares for planning dental guidance systems

There are many software packages available today that can process digital files such as DICOM and STL for virtual implant placement planning, digital design of dental guidance systems, or digital fabrication of implant-supported prostheses (Table1). These software packages are divided into two main groups:

1. *Virtual implant planning software*
2. *CAD/CAM software*

The two digital platforms can also be integrated to facilitate the free exchange of information. The virtual planning software uses the position of the implant with respect to the patient's anatomy and the desired design of the prosthetic implant to select the ideal implant type. Several planning steps are performed on this platform as follows:

1. *Import, segment and align DICOM files*
2. *Setting the panoramic curve*
3. *Pairing of DICOM and STL files*
4. *Digital teeth adjustment*
5. *Selection and planning of a virtual implant*
6. *Selection and planning of the virtual pillar*
7. *Virtual bone augmentation planning*
8. *Digital design of a dental guidance system for controlled implant placement*
9. *Drawing of the operational protocol*
10. *Connectivity with CAD / CAM software [20]*

Table 1: Overview of available 3D software

Software	Manufacturer
Implant Planner	Zirkonzahn
Nemoscan	Nemotec
Implant 3D	NSI
3Shape	Implant Studio
Surgicase	Materialise
BTI – scan 3	BTI
Thommen – Guided Surgery	Thommen Medical
CoDiagnostiX	Diagnostix Corp. – Dental Implantology
Guided Surgery	B&B Dental

2. Materials and Methods

Due to the increase in the use of 3D printing for medical devices to directly treat patients, there is a demand for new materials that provide different biocompatible characteristics for different potential applications. Biocompatibility is a term used for materials specifically designed to interact with living tissue without causing an immunological reaction. Biocompatible materials must be tested and certified with reference to the properties marketed by the manufacturer. In Europe, biocompatibility is assessed according to the ISO 10993 family of standards, which includes 22 sections dealing with a series of reactivity tests, quality, and risk management processes [21].

One of the materials that is coming to the fore is the dental resin, which is characterized by its biocompatibility, wide availability, and resistance to abrasion (Table 2).

Surgical guide resin is a crystal-clear resin suitable for 3D printing of precise dental surgical guides. Class I biocompatibility guarantees that temporary contact with the human body is safe enough for the needs of drilling or other surgical procedures commonly used in dentistry. It also does not react in any way with human body fluids. The surgical guides produced in this way are translucent, which increases visibility during the procedure. Also, high dimensional accuracy guarantees precise placement of implants or guidance of tools used by dentists.

Temporary resin is also among other widely preferred orthodontic materials. With this resin, it is possible to create temporary fillings in the mouth that do not spoil the patient's appearance from an aesthetic point of view thanks to its colour options. The patient can use the temporary implants without any problems until he has a permanent dental solution [22].

2.1. Digitalisation process

A comprehensive diagnostic examination of a patient, including the clinical and photographic analyses, was followed by the preparation of a CBCT scan or an intraoral scan of the relevant quadrant.

After the scanned zones and their occlusion-related characteristics were assessed, the files were exported to the 3Shape Implant Studio software (3Shape, Denmark). Following the initial processing of DICOM files obtained from CBCT, the data were imported to the 3Shape Implant Studio software to combine the scans and create a 3D superposition of the real intraoral situation and the CBCT images.

The 3D digital position of the implant was defined to identify the ideal relationship between the implant and the prosthetics. This was accompanied by the identification of vital structures, such as the inferior alveolar nerve and vascularity, as well as the minimum safety measurements of the bones around the implant.

The two implants were virtually placed in the posterior mandible so that the apical distance between the implants was 2 mm, and the D radial distance between the tooth and the implant was 1.5 mm. The placement was then evaluated in the sagittal and horizontal planes. During the planning, the software changed the colour of the implant from green to red if its position was too close to the anatomic element which should not be interfered with. This facilitated maintaining the plan and ensuring that the subsequent surgical intervention is safe and smooth.

Table 2: Overview of commonly used resin materials in dentistry [23]

Manufacturer	Material type
NextDent	NexDent-SG
Stratasys	MED610
EnvisionTec	E- Guide Tint
Formlabs	Surgical Guide Resin
Zortrax	Raydent Surgical Guide Resin
BEGO	VarseoWax Surgical Guide
SHERA	SHERAprint-sg
DentalMed	3Delta Guide S
Carbon	Whip Mix Surgical Guide
SprintRay	SprintRay Surgical Guide 2
Shining 3D	Resin Shining 3D Surgical Guide
Prodways Tech	PLASTCure Clear 200
DMG	LuxaPrint Ortho
UNIZ	zSG (Surgical Guide) Resin
3Dresyns	Dental 3Dresyns OD
Makex	Surgical Guide
VOCO	V-Print SG

The planning was carried out using the intraoral surface scanning with the concurrent CBCT 3D reconstruction control. This facilitated achieving the optimal implant position and preventing the

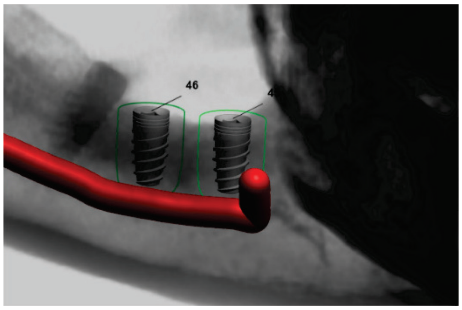

Figure 1: Final position and the implantation axis based on the design in the 3D reconstructed virtual model

fenestration or dehiscence of the bones or lesions of the vital structure (Figure 1).

2.2. Proposed CAD design of surgical guides

A surgical guide was designed by drawing the contour of the future surgical guide on the mandible scan. As soon as the contour was enclosed, any part of the design could be adjusted, except for the positions of the openings for a drilling tool. The offered features also included the addition of the patient's name or ID. The last step was the positioning of a pair of square or rectangular openings onto the occlusive surface of the surgical guide. The openings are used by a surgeon to control whether the guide is correctly positioned and attached to the remaining teeth. The surgical guide modelling was followed by generating the .stl file (Figure 2) which was then imported to 3D printers.

2.3. Manufacture of surgical guides

In the present study, the surgical guides were manufactured by using three types of biocompatible materials (Figure 3). The first one was the photopolymer Dental LT Clear (Formlabs, USA), the second material was biocompatible polyamide PA12 (HP, USA) and the last one was E-GUARD resin material (EnvisionTEC, USA). The surgical guides were manufactured using three 3D printers, Formlabs Form 3B (Formlabs, USA), EnvisionTEC Vida (EnvisionTEC, USA) and HP Jet Fusion 5200 (HP, USA).

Designing the model of a surgical guide was followed by the production of the 10 printouts. In the first case, Formlabs Form 3B 3D printer was used, and the production lasted 3 hour and 20 minutes, with a layer thickness of 100 μm. After the printing, the auxiliary material was simply removed by a high-pressure water jet. Subsequently, the surgical guide was immersed into 96% isopropyl alcohol for the 5 minutes period to completely remove the auxiliary material. After the guide was dried, it was necessary to perform the final photopolymerization with a UV lamp.

In the second case, the guides were produced by using Envisiontec 3D printer, and the production lasted 2 hours and 35 minutes, with a layer thickness of 50 μm. After the guide was produced, it was necessary to mechanically remove the auxiliary material and immerse the guide into 96% isopropyl alcohol for the 10 minutes period of 10 to eliminate the excess unhardened material. After the guide was dried, it was necessary to perform the final photopolymerization with a UV lamp with the wavelength of 410–500 nm.

In the third case, the guides produced by 3D printer HP Jet Fusion 5200 lasted 2 hours and 4 minutes

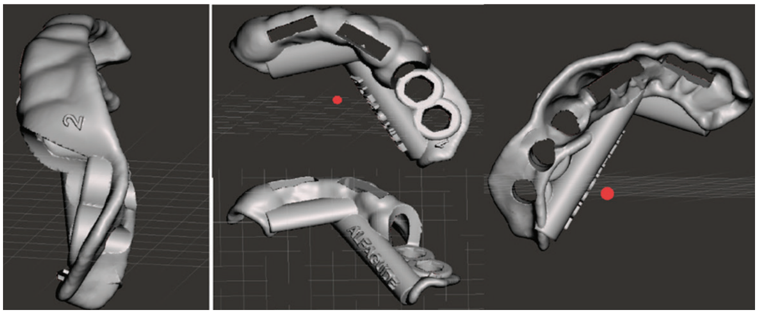

Figure 2: Designed surgical guide in STL format

Figure 3: Surgical guides made by additive manufacturing a) Formlabs Form 3B b) HP Jet Fusion 5200 c) EnvisionTEC Vida

After the guides production the 3D scans of the models were made for the purpose of analysing the production accuracy. The scans were made using a 3D scanner intended for dental models, Dental System D700 (3Shape, Belgium). Data similarity was measured in the GOM Inspect interactive software. The data of the main STL model were imported and selected as the reference values. The data from the Dental System E2 scanner were imported to the software and selected as the real values. The prealignment feature of the software was used to automatically overlap the selected models. The "Local Best Fit" feature was used to improve the overlap accuracy. After the fusion of the models, the "Surface Comparison" feature was used with a color map of overlaps.

3. Results and Discussion

The deviations were visualised by applying the "Equidistant Deviations Labels" feature. Figure 4 shows the colored map of differences in the shapes of one out of ten measured surgical guides. In total, 10 guides were printed for each additive manufacturing technology.

Table 3: Comparison of surface deviations of models produced by different types of 3D printers

Unit [mm]	Formlabs Form 3B	EnvisionTEC Vida	HP Jet Fusion 5200
1.	0.1249	0.1568	0.0810
2.	0.1410	0.2487	0.0816
3.	0.1333	0.1923	0.0847
4.	0.1139	0.2001	0.0863
5.	0.1352	0.2079	0.0814
6.	0.1112	0.2094	0.0695
7.	0.1339	0.1836	0.0636
8.	0.1192	0.1898	0.0664
9.	0.1445	0.3266	0.0748
10.	0.1279	0.1591	0.0674

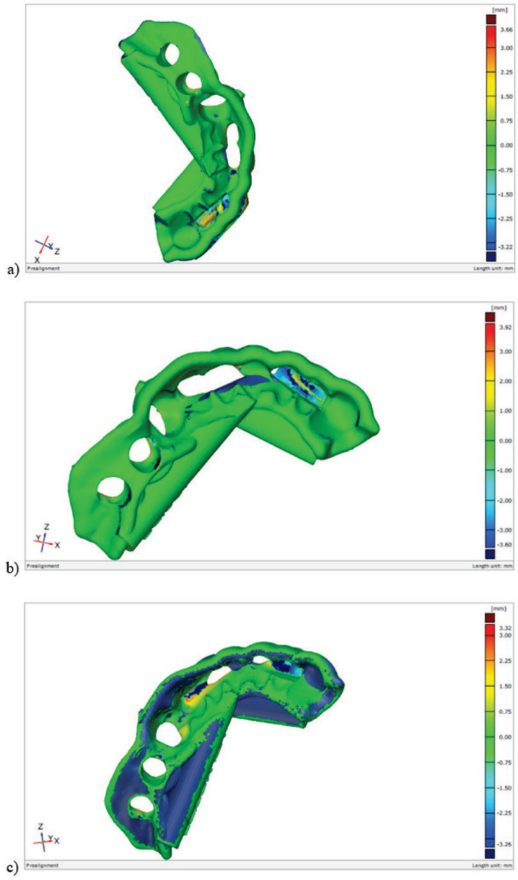

Figure 4: Color map of differences a) EnvisionTEC Vida b) Formlabs Form 3B c) HP Jet Fusion 5200

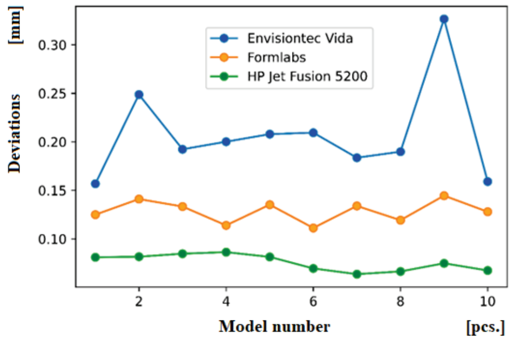

Figure 5: Representation of results achieved from GOM Inspect software

Figure. 5 represents the deviation between produced dental guidance systems. In the case of EnvisionTEC Vida printer the higher deviation values could be caused by an incorrect cut in the software, which was used to scan the model and process it into 3D model. With the dental guidance systems that were created on the Formlabs and HP 3D printer, we can observe stable and low deviations.

Table 4 consist of the prices of the materials that were used to make the dental guidance systems. For the E-Guard Resin material for the Envisiontec Vida 3D printer, the price is 250€ including VAT for 1 liter. We used the DENTAL LT Clear FLDLCL01 material for the Formlabs printer. This material is sold at a price of 162€ including VAT for 1 liter. The material HP PA

12, used in HP Jet Fusion printer, is sold only in a 300-liter package at a price of 8 112€ including VAT. Converted, the price for 1 litre is 27,04€ including VAT.

Table 4: Prices for serial production of dental surgical guides

3D printer	Pieces	Price
Formlabs	10	131.50 €
Envisiontec Vida	10	110.50 €
HP Jet Fusion 5200	10	74.80 €

After collecting the results from the analysis and testing of ten guidance systems for the dental field, the printing accuracy was evaluated, where the HP Jet Fusion 5200 produced the lowest possible deviations, based on which the accuracy was evaluated as the highest with an average value of 0.0757 mm. For the samples from the Formlabs printer, the value of the average deviation was 0.1285 mm, and for the samples from the Vida printer, the average deviation was 0.2074 mm.

From the point of view of printing accuracy and affordability of the printing material the HP Jet Fusion 5200 seems to be the most suitable 3D printer, on the other hand from the point of view of the technology itself, as well as the time required for post-processing, the most suitable choice to produce dental surgical guidance systems is the Formlabs Form 3B 3D printer with the biocompatible material Dental LT Clear. As one of the disadvantages of HP Jet Fusion 5200 3D printer is the greyish colouring of the material, which can lead to complications in the guidance of the implant and the impossibility of monitoring the bleeding effects during surgery.

3.2. Discussion

The current trend in the implant surgery indicates further improvement of these clinical procedures and a reduction of the total duration of recovery with the application of less invasive surgical techniques. Dental surgical guides might facilitate for clinical physicians the simplification of the procedures, from the diagnostics stage to the stage of the final prosthetic reconstruction [17, 18]. The first, and probably the most important stage of the development of these novel clinical procedures was the introduction and propagation of the 3-dimensional (3D) imaging technique and computer technology [16]. Surgical guides produced by the additive manufacturing technology have been used since 2000 [17, 18], and more novel additive manufacturing technologies and related materials are currently being developed [19, 24].

The key parameter for the application of the surgical guides produced by the additive manufacturing technology is the accuracy of production and the subsequent seating. Several studies have been performed in this field [25, 26, 27]. Jung et al. [16] carried out a systematic investigation in the accuracy and clinical performance of the applications of digital technology in dentistry with surgical implants.

The output of this study, based on the requirements from clinical practice, was the description of the process of data collection and the subsequent designing and modelling of the dental surgical guide. This was followed by the production of the modelled dental surgical guide using the additive manufacturing technology. In the study, three different additive manufacturing technologies were applied – Formlabs Form 3B, Vida EnvisionTEC and HP Jet Fusion 5200. The final printouts were then scanned using the 3Shape E2 dental scanner and compared to the reference model in the Gom Inspect software. The measurements performed in individual models were used to calculate the arithmetic means and identify the print deviations for used types of additive manufacturing. In the future, to complete the results that would be relevant in clinical practice, it is necessary to subject the produced surgical guides to mechanical testing and to compare the obtained results with the parameters that are typical for the conventional production of surgical guides.

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