Evaluation of Dimensional Accuracy of 3d Printed Mandibular Model Using Two Different Additive Manufacturing Techniques Based on Cone Beam Computed Tomography Scan Data (A Diagnostic Accuracy Study)

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Abstract

Purpose: To compare the dimensional accuracy of stereolithography (SLA) and fused deposition modeling (FDM), using 3D printed mandibular models based on CBCT scan data.

Materials and Methods: In this study, one mandibular model was recruited. Ten measurements were measured directly on the model using digital caliper. Radio-opaque markers were fixed to serve as the reference standard. The model was scanned using CBCT machine (i-CAT by KaVo dental, USA) at 120 KVp, 5 mA, for 8.9 seconds. CBCT scans were exported and accordingly the STL file was generated. The scanned models were saved as STL file format. 3D printing was done using two different additive manufacturing techniques; SLA and FDM. The scanned model was printed 7 times per each printer. Same ten linear measurements were recorded using the same digital caliper for all the printed models.

Results: There was a statistically significant difference in the dimensional error of both techniques in comparison to the reference model. Where the mean relative difference MD was (0.154%, -0.80%) and the mean absolute difference MAD was (0.271 mm, -0.36 mm) for SLA and FDM respectively. Upon comparing the two techniques to each other, the trueness of both showed no statistical or clinical significant difference in the dimensional error, with the MD and the MAD of SLA being lower than that of the FDM.
Conclusion: These results suggest that both printers can be used safely in dental practice and that a low-cost FDM printer provides an accuracy level comparable to the highly professional SLA printer.

Keywords: Mandible, Cone-Beam CT, 3D printing, Accuracy, Stereolithography

Introduction:

Dentistry has changed dramatically as a result of advances in digital technology and manufacturing. The most advanced technology in the manufacturing industry is three-dimensional (3D) printing technology. 3D printing systems utilize a 3D design file to fabricate 3D structures. This novel approach has a set of advantages; as reduction of the production time, cutting off the costs, and enables fabrication of complex structures. Consequently, it has been widely applied and established in the medical and dental fields. 1,2

3D printing, also known as rapid prototyping (RP), is a new technology aimed at assisting dental professionals in the facets of the intended operation visually and tactiley, consequently increasing the precision of diagnosis, preparation performance, and efficiency of the treatment plan. As well as enhancing the outcomes and minimizing the complications, risks, operative time, and overall care costs. 3

According to its machining procedure, fabrication of a 3D model with a computer-aided design/ computer-aided manufacturing CAD/CAM system may fall into one of two
groups: (1) Subtractive manufacturing, also named as milling or (2) Additive manufacturing AM technique, also a synonym to Rapid prototyping or 3D printing. The latter is divided into three steps: (1) Data acquisition, (2) Data processing, and (3) Model fabrication. 3D printing is based on the patient’s oral data acquired with either a 3D imaging modality or an optical scanner. Unnecessary material loss during milling, high machinery maintenance costs, and significant time loss during the manufacturing process are all drawbacks of the milling system which are being spared with this innovative technology, 3D printing. The benefits of 3D printing, on the other hand, include the ability to produce desired 3D objects with a small amount of material and the capability to make several items at once. The ease with which such routine manufacturing can be done greatly improves clinical performance. 4,5

This innovative technology has a specific resonance in the dental sector, and it will become increasingly important as 3D imaging and modeling technologies advance. Computed tomography was undoubtedly the most commonly utilized imaging modality for 3D printing, as well as MRI, 3D ultrasonography, and radioactive isotope imaging. Nowadays, CBCT imaging is the alternative imaging approach for 3D modeling. 6,8

Because of its merits over both the conventional 2D and other 3D imaging modalities in this age of advanced technology, CBCT has gained prominence in the sector of oral radiology. The employment of CBCT for diagnosis and treatment preparation in various specialties of the dental field, as well as its integration into the 3D printing procedure and its various implementations in clinical practice, is rapidly and profoundly growing. 9
With the expanded use of CBCT in dentistry, as well as the fact that 3D printing has become more commonplace, dentistry is poised for a major shift about 3D printing in the coming years.  

In dentistry, 3D printing has a broad array of applications and holds a lot of promise for many innovative and exciting therapies and approaches to dental restoration manufacturing. The increased use of 3D printing is due to improved availability, faster processing times, and lower costs. At the same time, the growth of medical applications is increasing. Drilling guides for dental implants, 3D models for prosthodontics, orthodontics, and surgery, and the manufacturing of copings and dental restorations are all examples of 3D printing applications.

3D printing technique encompasses a variety of well-known technologies. The following are some of the most popular 3D printing techniques: Stereolithography (SLA), Selective laser sintering (SLS), Fused deposition modeling (FDM), and Digital light processing (DLP). Each methodology has its own set of merits, drawbacks, and applications when it comes to prototyping.

Unfortunately, one of the most common characteristics of 3D printing is the high cost of the equipment, materials, servicing in addition to the maintenance. Besides the safety concerns and the need for expertise.

Cost-effective 3D printers present a significant opportunity in the medical and dental fields, as they will allow practitioners to use 3D printed models at a very reasonable cost, democratizing their use in a variety of indications. Efforts should be made, however, to create a unified validation protocol for low-cost 3D printed models.

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and rapid prototyping techniques, which includes accuracy in terms of precision and trueness tests.\textsuperscript{16,17}

So, whether 3D models created with a low-cost 3D printer, such as FDM, are dimensionally accurate and comparable to other well-established high-cost professional RP technologies, such as SLA, is still under investigation. The validation of low-cost 3D printers could represent the next step toward better accessibility of RP technologies and making the best out of its countless benefits.\textsuperscript{17,18}

**Study Settings and Ethical Approval:**

The protocol of the current study was registered in the (www.protocolexchange.researchsquare.com) database, with a unique DOI 10.21203/rs.2.9866/v1. The study protocol was approved by the Ethics committee in the Faculty of Dentistry- Cairo University as it complied with the ethical standards of the Research Ethics Committee of the Faculty of Dentistry, Cairo University, Egypt (CREC), (Ref. 19/6/22).

This study is an in vitro diagnostic accuracy prospective study which was held in the Faculty of Dentistry, Cairo University, Egypt.

**Sample Size Calculation**

Sample size calculation was done using Minitab Software output. One-way ANOVA analysis of variance power calculation for more than two groups was used to
detect the proper sample size. Means and standard deviations were determined according to (Petropolis et al., 2015). The results showed that at a power of 80% and a two-sided significance level of 5%; a total sample size of 7 models for each printer will be adequate to reject the null hypothesis.

**Materials and Methods**

1. Selection and Description of the reference model

   A mandibular model with the same radiodensity as the normal average jawbones, totally edentulous, with cancellous and cortical bone tissue, and without dental nerve. The used model was shipped from (Implant Bone Company, Argentina).

2. Reference Model Preparation and Measurement

   14 ball-shaped radio-opaque markers of gutta-percha (size 80, 1.5 mm long) with a diameter of about 0.5 mm were applied on the model, to act as reference points for the measuring procedures on the model, as well as on the 3D printed models later on (Figure 1). The center point of each ball was defined as the most reproducible measuring point. Ten linear measurements, as following (Table 1), were obtained in (mm) using a digital caliper with (0-150) mm measuring range.
Table (1): Allocated linear measurement

<table>
<thead>
<tr>
<th>D1: Inter-condylar distance</th>
<th>(From Tip of the right condyle to the tip of the left one)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D2: Inter-coronoidal distance</td>
<td>(From Tip of the right coronoid to the tip of the left one)</td>
</tr>
<tr>
<td>D3: Inter-mandibular notch distance</td>
<td>(From the lowest point of the right notch to the lowest point of the left one)</td>
</tr>
<tr>
<td>D4: length of the Right Ramus</td>
<td>(From Tip of the right condyle to the right angle of the mandible)</td>
</tr>
<tr>
<td>D5: length of the Left Ramus</td>
<td>(From Tip of the left condyle to the left angle of the mandible)</td>
</tr>
<tr>
<td>D6: Length of the body of the mandible at the midline</td>
<td>(From the crest of the ridge to the inferior border of the mandible at the midline)</td>
</tr>
<tr>
<td>D7: Length of the mandibular body at area of right last molar</td>
<td>(From the crest of the ridge to the inferior border of the mandible at the area of last right molar)</td>
</tr>
<tr>
<td>D8: Length of the mandibular body at area of left last molar</td>
<td>(From the crest of the ridge to the inferior border of the mandible at the area of last left molar)</td>
</tr>
<tr>
<td>D9: Right Condyle-Coronoid distance</td>
<td></td>
</tr>
</tbody>
</table>
(From the tip of the right condyle to the tip of the right coronoid)

D10: Left Condyle-Coronoid distance
(From the tip of the left condyle to the tip of the left coronoid)

3. Reference Model Scanning

CBCT images were acquired by i-CAT (by KaVo dental, USA) with the following protocol; 120 KVP, 5 mA, 8.9 seconds. (Figure 2)

Figure 2: Scanning the model using i-CAT
4. Data Processing and Segmentation

Digital Imaging and Communications in Medicine (DICOM) images were imported to an open-source “InVesalius 3” software (by InVesalius, Brazil) and “Meshmixer 3.5” (by Autodesk, USA) for segmentation and generation of the corresponding STL file. The scanned models were saved in STL file format. (Figure 3).

![Figure 3: Finished STL file of the model ready for 3D printing](image)

5. Sample Model Fabrication (3D printing)

3D printing of the scanned model’s STL file was done using 2 different additive manufacturing techniques (SLA and FDM). The scanned model was printed 7 times per printer. For SLA; printing was done using “Form 2 printer” (by Formlabs, United States)
and grey photopolymer resin (Acrylonitrile Butadiene Styrene “ABS” resin). While for FDM; “Zortax M300 printer” (by Zortax, Poland) and Z-PLA filament (polylactic acid filament) were utilized.

6. Sample Models Measurement

The same ten linear measurements (previously mentioned, table 1) were recorded in (mm) using the same digital caliper for all the printed models (7 SLA printed models & 7 FDM printed models).

Data collection

All the measurements were recorded by 3 oral radiologists with different experiences to ensure inter-observer reliability. Each radiologist repeated the measurements 3 times per model to ensure intra-observer reliability.

Statistical analysis

Statistical analysis was performed using SPSS 20®, Graph Pad Prism®, and Microsoft Excel 20163. Data were represented as the mean and standard deviation for quantitative data. Data were explored for normality by using Shapiro Wilk and Kolmogorov-Smirnov normality test which revealed that all data is parametric data (P-value > 0.05). Accordingly, comparison between two groups was performed by independent t-test, while comparison between more than 2 groups was performed by One Way ANOVA. Mean difference was calculated by the following equation (mean difference = tested group – original group), while mean relative difference % was calculated according to the following formula [(V2-V1/V1) x 100] (were V1: Mean of the
tested group, V2; mean of the original group). Also, Inter-observer and intra-observer reliability coefficients were calculated using (Kappa test) to evaluate the agreement between three radiologists (Inter-observer reliability) and three different readings of each radiologist separately.

Results

Trueness of SLA

Comparison between reference and SLA models was performed by using an Independent t-test which revealed a significant difference between them as P < 0.05 regarding D1, D2, D3, D4, D6, D7, D8, D9, D10 with an insignificant difference for D5 as presented in (Table 2). Also, mean difference and mean relative difference % were calculated and revealed that SLA models were significantly higher than reference models in D1, D2, D3, D4, D9, and D10. On the other hand, SLA models were significantly lower than the reference model regarding D6, D7, and D8, and insignificantly lower for D5 as presented in (Table 2).

Tables

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The overall distance comparison between reference and SLA models revealed that SLA models were significantly higher than the reference model (P<0.05) with a 0.154% mean relative difference as presented in (Table 2). So, it is concluded that the

<table>
<thead>
<tr>
<th>Reference (n=9)</th>
<th>SLA (n=63)</th>
<th>Mean Difference</th>
<th>P value</th>
<th>Mean Relative difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>D1</td>
<td>84.842</td>
<td>0.142</td>
<td>86.218</td>
<td>0.359</td>
</tr>
<tr>
<td>D2</td>
<td>67.479</td>
<td>0.188</td>
<td>68.483</td>
<td>0.454</td>
</tr>
<tr>
<td>D3</td>
<td>84.623</td>
<td>0.181</td>
<td>85.720</td>
<td>0.389</td>
</tr>
<tr>
<td>D4</td>
<td>49.503</td>
<td>0.245</td>
<td>50.080</td>
<td>0.420</td>
</tr>
<tr>
<td>D5</td>
<td>55.370</td>
<td>0.138</td>
<td>55.308</td>
<td>0.400</td>
</tr>
<tr>
<td>D6</td>
<td>18.983</td>
<td>0.107</td>
<td>17.963</td>
<td>0.319</td>
</tr>
<tr>
<td>D7</td>
<td>14.321</td>
<td>0.174</td>
<td>13.025</td>
<td>0.280</td>
</tr>
<tr>
<td>D8</td>
<td>17.372</td>
<td>0.213</td>
<td>16.331</td>
<td>0.268</td>
</tr>
<tr>
<td>D9</td>
<td>28.350</td>
<td>0.243</td>
<td>29.766</td>
<td>0.405</td>
</tr>
<tr>
<td>D10</td>
<td>30.188</td>
<td>0.150</td>
<td>30.845</td>
<td>0.358</td>
</tr>
<tr>
<td>Overall</td>
<td>45.1031</td>
<td>0.078</td>
<td>45.173</td>
<td>0.0365</td>
</tr>
</tbody>
</table>

M: mean    SD: standard deviation    MD: mean difference

*significant difference.
overall trueness between the SLA printed models and the reference model is statistically significant with 0.154%-dimensional error.

2. Trueness of FDM

Comparison between reference and FDM models was performed by using an Independent t-test which revealed a significant difference between them as \( P < 0.05 \) regarding all distances except D7, D9, D10 as presented in (Table 3). Also, mean difference and mean relative difference % was calculated and revealed that FDM models were insignificantly higher than the reference model regarding D7 and D9 while were significantly higher than the reference model regarding D4. FDM models were significantly lower than the reference model regarding D1, D2, D3, D5, D6, and D8. On the other hand, FDM models are insignificantly lower than the reference model regarding D10 as presented in (Table 3).

Table (3): Mean difference and relative mean difference between reference and FDM:

<table>
<thead>
<tr>
<th>D</th>
<th>Reference (n=9)</th>
<th>FDM (n=63)</th>
<th>Mean Difference</th>
<th>P value</th>
<th>Mean Relative difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>D1</td>
<td>84.842</td>
<td>0.142</td>
<td>84.263</td>
<td>0.404</td>
<td>-0.579</td>
</tr>
<tr>
<td>D2</td>
<td>67.479</td>
<td>0.188</td>
<td>66.494</td>
<td>0.430</td>
<td>-0.985</td>
</tr>
<tr>
<td>D3</td>
<td>84.623</td>
<td>0.181</td>
<td>83.987</td>
<td>0.828</td>
<td>-0.636</td>
</tr>
<tr>
<td>D4</td>
<td>49.503</td>
<td>0.245</td>
<td>50.128</td>
<td>0.454</td>
<td>0.625</td>
</tr>
</tbody>
</table>
The overall distance comparison between reference and FDM models revealed that FDM models were significantly lower than the reference model (P<0.05) with a 0.80% mean relative difference as presented in (Table 3). So, it is concluded that the overall trueness between the FDM printed models and the reference model is statistically significant with 0.80%-dimensional error.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5</td>
<td>55.370</td>
<td>0.138</td>
<td>54.557</td>
<td>0.230</td>
<td>0.813</td>
<td>0.092</td>
<td>0.001*</td>
<td>-1.468</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D6</td>
<td>18.983</td>
<td>0.107</td>
<td>18.390</td>
<td>0.234</td>
<td>0.593</td>
<td>0.25</td>
<td>0.001*</td>
<td>-3.123</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D7</td>
<td>14.321</td>
<td>0.174</td>
<td>14.324</td>
<td>0.265</td>
<td>0.003</td>
<td>0.091</td>
<td>0.97</td>
<td>0.020</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D8</td>
<td>17.372</td>
<td>0.213</td>
<td>16.869</td>
<td>0.278</td>
<td>0.503</td>
<td>0.38</td>
<td>0.001*</td>
<td>-2.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D9</td>
<td>28.350</td>
<td>0.243</td>
<td>28.389</td>
<td>0.382</td>
<td>0.039</td>
<td>0.009</td>
<td>0.766</td>
<td>0.137</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>D10</td>
<td>30.188</td>
<td>0.150</td>
<td>30.022</td>
<td>0.396</td>
<td>0.166</td>
<td>0.024</td>
<td>0.212</td>
<td>-0.549</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>45.103</td>
<td>0.178</td>
<td>44.742</td>
<td>0.390</td>
<td>0.361</td>
<td>0.1168</td>
<td>0.008*</td>
<td>-0.80</td>
<td></td>
<td></td>
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</tbody>
</table>

M: mean  SD: standard deviation  MD: mean difference  *significant difference.
Discussion

The current study compared the dimensional accuracy of two of the most popular 3d printing techniques; SLA & FDM. Aiming to evaluate whether the FDM being a consumer low-cost 3d printer, is of a comparable accuracy to the SLA which is well known as a professional 3d printer. The accuracy was evaluated in terms of the trueness of 3d printed mandibular models based on CBCT scan data.

The statistical analysis of the collected data showed promising results. The precision of both SLA and FDM showed no statistically significant difference reflecting their high ability of repeatability. Regarding the trueness, there is a statistically significant difference in the dimensional error of both techniques in comparison to the
reference model. Where the mean relative difference is (0.154%) & (-0.80%) and the mean absolute difference is (0.271 mm) & (-0.36 mm) for the SLA and FDM respectively.

However, the above-mentioned dimensional errors are within the accepted range and have no clinically significant difference. According to several studies held by (1,19–21), the clinically significant difference between the models was defined as a measurement discrepancy of greater than 0.5 mm. In other words, a difference in dimensions between models equal to or less than 0.5 mm is improbable to have a significant clinical impact.

Upon comparing the two utilized 3d printing techniques to each other, the trueness of both the SLA and FDM showed no statistical or clinically significant difference in the dimensional error, with the mean relative difference and the mean absolute difference of SLA being lower than that of the FDM. A high level of agreement in the repeatability of the measurements was demonstrated in this study, with strong intra- and inter-observer reliability.

Several studies investigated the accuracy of the SLA (stereolithographic) additive manufacturing technique, in this regard, the following was demonstrated:

In another comparative study, Rebong et al., 2018 assessed the dimensional accuracy of fused deposition modeling FDM and stereolithography SLA produced models by comparing them to traditional plaster casts. The results showed the mean difference of FDM and SLA to be -0.22mm and 0.34mm respectively, where the FDM printed models had undergone shrinkage, while the SLA models experienced
expansion. The results were aligned to ours as the MD of the FDM and SLA was -0.36 mm and 0.271 mm, respectively. In the process of FDM 3D printing, the resin materials may experience expansion and/or shrinkage, in both studies, the FDM 3D printed models experienced shrinkage. Also, the discrepancy between the MD in both studies may be attributed to the type of the used resin, yet the difference was clinically insignificant. Regarding the SLA, the mean difference was in accordance. The 3D printed models tended expansion. It was found that the usage of colored SLA models is preferable to the clear or transparent color, as the landmark identification is much easier, which leads to more accurate measurements on the resin models. Furthermore, the mentioned study reported a statistically significant difference regarding the trueness of both FDM and SLA, however, it has no clinically significant impact (below 0.5 mm). These results come from the findings of the current study affirming the safe usability of both SLA and FDM interchangeably as FDM models are not inferior compared to professional printing technologies and can be useful within the dental profession. 19

Jaber et al., 2020 researched to compare the commercial FDM and high professional photocuring printer regarding the accuracy through the fabrication of dental models. Reference points were placed on plaster models, followed by scanning and printing of these models using both techniques. Forty measurements were made on these models using a digital caliper. The overall mean difference was - 0.11 mm (range from 0.17 to -0.49 mm) for FDM and 0.00 mm (range from 0.5 to -0.42 mm) for the professional printer, reporting no statistical or clinically significant difference between both printers. As opposed to the current study, it was noticed that results for both FDM and the professional printer fall in the same range of dimensional error, and conclusions
were consistent. Meanwhile, Jaber et al., 2020 registered a superior dimensional accuracy with no statistical difference recorded between the printed and the reference cast, this variation in the reported results could be due to the difference in the number of the compared distances recorded; 40 versus 10 linear measurements for both the aforesaid and the current study, which may affect the results. . ²⁰

In the same context, Msallem B. et al., 2020 demonstrated contradicting results to the present study. Proceeding the comparison between SLA and FDM, the authors assessed the accuracy regarding trueness and precision. For the trueness, the SLA and FDM showed MD of 0.23 mm and -0.01 mm respectively. This was contrary to the results of the current study as the FDM was superior to SLA. In both studies the FDM 3D printed models exhibited shrinkage, which is a feature to be expected in this type of additive manufacturing, because of the process’s mechanism regarding the used thermoplastic resins, melting, and setting. This is to be taken into account while using the FDM 3D printing technique. . ²²

Because of the foregoing, C. R. Hatz et al., 2020 performed a study to determine whether an in-house printed mandible model fabricated by FDM is sufficiently accurate for daily clinical practice. The results reported a dimensional error was 0.055mm which is almost negligible. Upon reviewing the methodology of that study, it was shown that it was comparable to that of the current study regarding the 3D printing technique; FDM, and the employed resin material; PLA polylactic acid, as well as the scan data was CT based. The difference mainly was in the 3D printer brand, as in the aforementioned study FDM 3D printer (MarkerBOT, USA) was used. This sheds light on the new generations of FDM 3D printers as they propose a new level of accuracy. Consequently,
drawing the attention towards further research on these recent series which combine the ease of technicality and low cost of the FDM technology together with the superior accuracy corresponding to that of professional-grade 3D printers.  

Conclusion

From the current work, the following conclusions could be reached:

1. Both SLA and FDM printers offer prominent accuracy in terms of precision and trueness, indicating their ability to produce 3D models repeatedly and accurately.  
3D printing has been well established that it became the leading treatment line and will pave the way for a safe dental practice.

2. Low-cost FDM printer exhibited an insignificant clinical dimensional error, hence it can be used interchangeably with professional SLA printers,
3. CBCT offers high resolution and accurate images that can be used in conjunction with 3D printing technology to fabricate reliable 3D printed mandibular models.

**Clinical Significance:**

These findings and similar comparative studies will allow dentist to choose the most compatible 3D printing technique considering both accuracy and cost. Also, it defines the margin of dimensional error that the dentist could expect from 3D printed parts, to consider this error during the treatment or the surgical planning.

**Reference**


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