Evaluation of the accuracy of cone beam computed tomography (CBCT) generated tooth replicas

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Introduction

Three-dimensional (3D) printing is a fast developing technology that promises to play a significant role in orthodontic diagnosis and treatment planning. In the context of autotransplantation, a duplicated tooth model can be fabricated from prior 3D printing. The use of computer-generated tooth models in autotransplantation yielded three main advantages: the ability to minimize extra-oral dry time (EODT) as the preparation of the alveolus could be done before extraction; multiple fitting attempts of the donor tooth can be avoided; the placement, location and angulation of the transplant can be determined with the replica without damaging the tooth[1]. This then increases the ease and predictability of the autotransplantation procedure.

In order for this novel digital approach to realize its potential, it is critical to address questions as to how reliable and accurate the various printing technologies are. While there exist several papers in the literature that examines the accuracy of printed tooth replicas, most of them were based on cadaveric models or extracted teeth and cannot be reliably extrapolated to a clinical situation [2,3].

Based on the gap of information in the literature, this study proposes to evaluate the accuracy of tooth replicas reconstructed from the patient's CBCT.

Aims

The primary aim of this *in vivo* study is to assess the linear and geometric accuracy of 3D printed replica teeth from CBCT data when compared to the actual tooth.

The secondary aims in this study are (1) to compare the accuracy of three different 3D printing technologies: Polyjet (Objet 3D, Strataysys, Eden Prairie, Minn), SLA (Form2, Formlabs, Somerville, Mass), and DLP (RapidShape D30II, RapidShape, Heimsheim, Germany), as well as to (2) evaluate the dimensional changes of the printed tooth replicas after sterilization.

Materials & Methods

Protocol for accuracy assessment

The study group comprised 7 subjects, with a total of 16 teeth being collected from patients seen at the National Dental Centre (Singapore).

CBCT files were exported to a software for segmentation. This was then saved as an STL file and sent to three different printers to generate physical tooth replicas (Fig 1). The printers used were: Objet 30 Connex3 [OJ] (Stratasys, Ltd., Eden Prairie, Minnesota), Form2 [FL] (Formlabs, Berlin, Germany) and D30II [RS] (RapidShape, Heimsheim, Germany).

The 3D printed tooth replicas and the actual extracted tooth was then scanned using the Trios 3 (3Shape Dental Systems, Copenhagen, Denmark) intraoral scanner. The tooth replicas were then further subjected to sterilization via steam heat in an autoclave. Post-sterilization replicas were scanned again using the intra-oral scanner

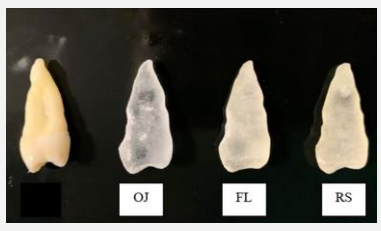

Figure 1: Depicts the extracted tooth as well as the printed OJ, FL and RS replica respectively

Outcome Measures

1. *Linear Measurements:* The length of the tooth from the buccal cusp to root apex was measured using an electronic caliper.
2. *Geometric Measurements:* The scans of the extracted tooth and that of the printed replica were superimposed with a software. Root mean square (RMS) deviation and qualitative color maps were generated to display areas of deviation between surface scans.

All outcome measurements were taken once pre-sterilization, and once again post-sterilization.

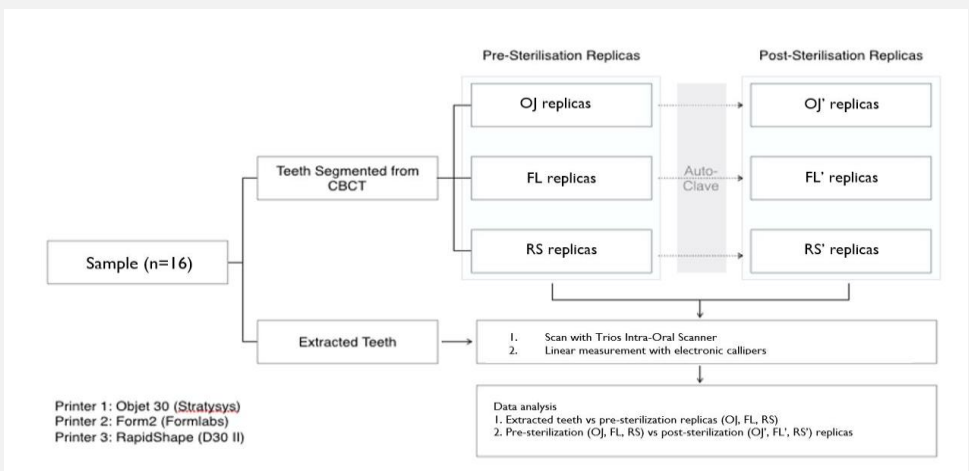

Figure 2: Summary of Methodology

Results

Accuracy of tooth replicas vs actual tooth

(1) Linear Measurements: There was an overall mean difference of 0.36mm (SD 0.203) (Table 1). Models printed with OJ showed the least mean deviation, while models printed with FL and RS had higher deviations.

(2) Geometric Measurements: An overall mean difference of 0.56mm was found (Table 1). Results of a one-sample t-test showed that the RMS of all printed teeth were significantly different to 0mm (p-value < 0.008). The effect of the printer was significant (p < 0.001). OJ models had the highest accuracy followed by FL, while RS models were least accurate.

Printer	Linear- Absolute Length difference				Geometric – RMS difference			
	Mean (mm)	SD	95% CI	p-value	Mean (mm)	SD	95% CI	p-value
OJ	0.34	0.182	[0.24, 0.44]	<0.001	0.50	0.167	[0.41, 0.59]	<0.001
FL	0.38	0.219	[0.26, 0.50]	<0.001	0.55	0.178	[0.46, 0.65]	<0.001
RS	0.37	0.215	[0.25, 0.49]	<0.001	0.62	0.186	[0.52, 0.72]	<0.001
Overall	0.36	0.203	[0.30, 0.42]	<0.001	0.56	0.180	[0.50, 0.61]	<0.001*

Ho: RMS = 0 vs Ha: RMS ≠ 0
α = 0.008 by Bonfferoni correction

Table 1: Geometric and Linear differences between actual & printed tooth

(3) Location of discrepancies: Colour maps showed that discrepancies tended to occur on crowns or occlusal surfaces of the models, as well as near the root apex (Fig 3). The models also appear to be generally larger in size than the scan of the actual tooth. Greater deviation was observed in RS and FL models compared to OJ models.

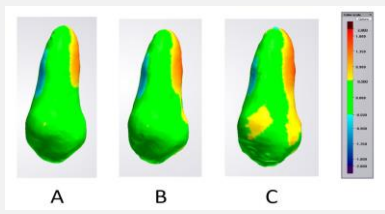

Figure 3: Colour maps showing quantitative differences between the actual and printed tooth. (A) OJ model; (B) FL model; (C) RS model

Accuracy of pre- vs post-sterilization tooth replicas

Overall, a mean absolute length difference of 0.10mm and RMS difference of 0.12mm was found. This difference is unlikely to be clinically significant. Analysis of colour maps generated similarly indicate no major deviations between pre- and post-sterilization models.

Discussion

This in-vivo study is the first to investigate the entire computer aided rapid prototyping (CARP) process from CBCT segmentation to printing of tooth replicas.

Overall, while this study reflected a significant difference in the tooth replica (in both linear and geometric measurements), this error may be acceptable in the clinical situation. Firstly, the width of the periodontal ligament must be taken into account. A larger socket would allow for physiologic tooth movement which may benefit periodontal healing [4]. Secondly, autotransplantation is generally carried out for teeth with incomplete root form. Hence, consideration must be given to the increase in root length that occurs between the time of the CBCT radiograph and the actual surgery.

Secondly, results also showed that the Polyjet printing technique employed by the Objet printer produced more accurate models, which corresponds to other studies in the literature.

Lastly, there was no clinically significant effect of heat sterilization on dimensional stability of the tooth replicas. It can hence be inferred that autoclave sterilization is a safe procedure to carry out for 3D printed tooth models.

Conclusion

- There are statistically significant differences in the linear and geometric measurements of 3D printed tooth replicas when compared to the actual tooth. On average, there is a mean absolute length difference of 0.36mm and a mean geometric (RMS) difference of 0.56mm.
  Qualitative analysis showed that the replicas were generally larger in size, which may be beneficial in this clinical context.
- The Objet printer which makes use of Polyjet technology was able to produce more accurate models than Form2 or RapidShape printers.
- Printed tooth models demonstrated clinically insignificant changes after heat sterilization

As CBCT segmentation error is a contributory factor to the accuracy of 3D printed replicas, a potential way to optimize accuracy would be to reduce the CBCT voxel size while limiting the field of view to the area of interest. This would allow the clinician to obtain the necessary information at a sufficient resolution while minimizing radiation exposure.

References:
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