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Research Article

Stratasys Printed 3-D Mandibular Molar with Tooth Anatomy and Texture

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Abstract

Introduction: We used CBCT scans of a human mandibular molar in concert with the Stratasys 3-D printer to fabricate said teeth with similar texture and hardness to enamel, dentin, and cementum. The printed tooth should also have the same crown and root anatomy, as well as root canal anatomy of the scanned tooth.

Methods: One mandibular first molar was scanned (Carestream Dental CS 9600 CBCT) and printed (Stratasys 3D multi-material printer). A (Micromet 5104) hardness tester was used to test the hardness of the printed tooth. Nine combinations of two different materials (Stratasys' Vero Pure White and Agilus 30 Clear material) were used to print the tooth. A Vickers's hardness test was performed on each of the nine combinations to determine whether or not the printed tooth had a similar hardness to a natural tooth.

Results: This study illustrated that the methods utilized can accurately replicate the root canal and external anatomy of a human mandibular molar [$p>0.05$]. We also attempted to identify a Stratasys printed plastic material with the same hardness as enamel, dentin, and cementum. In the printed tooth all three printed entities were softer than their natural counterparts.

Conclusions: Based on our results, we could not adequately create printed teeth with the same harness as natural teeth [$p<0.05$]. More research and development needs to be invested into this endeavor to accomplish such.

Clinical Significance: CBCT scans with the Stratasys 3D printer fabricates teeth with the same root canal anatomy seen in the actual teeth. Utilization of this technology will aid in the training of dentists and dental hygienists without the use of actual teeth.

***Keywords:** Stratasys, 3D Printing, Carestream, Micromet, Invesalius.*

Introduction

Few studies have been reported utilizing the Stratasys 3-D multi-material printer to fabricate permanent mandibular molars. The Stratasys printer has been used to print resin materials with consistencies that are comparable to the boney exoskeleton, epidermal tissue, and cardiac tissue. We propose to use cone-beam computed tomography system (CBCT) scans in conjunction with the Stratasys 3-D printer of molars to replicate the true anatomy and textures of the teeth. Many studies have been conducted that illustrate the pulpal anatomy of teeth[1–3]. These studies and others have utilized different methods such as Indian ink dispersion, conventional radiographic observations, and sectioning or "dissection" of teeth to observe the pulpal or root canal anatomy of teeth[4–6]. By utilizing CBCT scans with the Stratasys 3-D printer, we hope to fabricate a tooth with the same texture and hardness of enamel, dentin, and cementum, as well as the same root canal anatomy seen in the actual tooth. Utilization of this technology will undoubtably aid in the training of dentists and dental hygienists without the use of actual teeth. We hope by using this technique to "print" teeth, students can get a 3-D printed tooth and practice treatment prior to performing a procedure on a patient. The technology could also be used in remediation.

Materials and Methods

Digital Scans

Twenty extracted permanent mandibular 1st molars were collected and radiographed using a Progeny Dental X-ray unit on the settings: 65 kV, 7mA, 0.125s. One final tooth was selected based on having normal proportioned pulp canals and pulp chamber with no irregular deviations in the anatomy. This tooth was radiographed using a Carestream Dental CS 9600 cone-beam computed tomography system.

The sectioned CBCT scan was reconstructed using InVesalius 3 software. The reconstructed image was then sectioned into three STL files using the software, MeshMixer, to allow "software to print" to recognize a readable file for proper printing using various textures on the Stratasys 3D multi-material printer. (Figure 1)

Figure 1. *3-D rendering of scanned mandibular molar after CBCT slices were combined digitally.*

Specimen Block Preparation

Stratasys' Vero Pure White material was crossed with Agilus 30 Clear material and printed into test blocks with nine different combinations of the two materials based on formulated mixtures preloaded into the Stratasys' software. For each section of the block, nine sections with length, width, and height of 5mm, 5mm, and 20mm, respectively, were used. Each section had a centered, tapered hollow cone with a 1.5mm diameter at the base that extended 15mm in height. The cones simulated the root canal orifice extending to the apical foramen.

Specimen Printed Tooth Preparation

The same materials used in the block preparations were used in the tooth preparations. The three combined STL files that were developed in MeshMixer were imported to Stratasys print software, GrabCAD. Each sectioned tooth was printed with an enamel layer and dentin/cementum layer of the varying materials that were printed in the blocks.

Vickers Hardness Test

A Micromet 5104 Hardness Tester, Buehler model 1660-5122VKA durometer with a 1 micrometer reading power, 200gF was used for the hardness tests. Stratasys' Vero Pure White material crossed with Agilus 30 Clear material, test blocks were printed with nine varying combinations of the two materials to analyze hardness compared to enamel, dentin, and cementum. Using a Vickers's hardness test, we measured each material combination as well as the hardness of enamel, dentin, and cementum. (Figure 2&3)

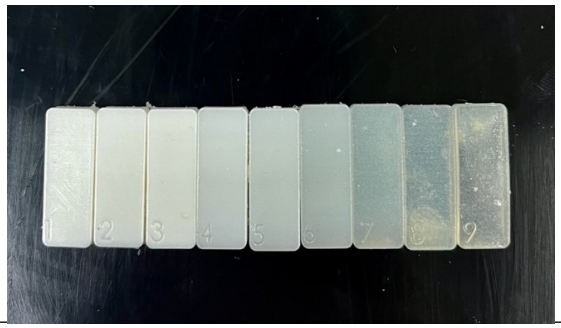

Figure 2. *Test samples used in Vickers Hardness Test.*

Figure 3. *Stratasys printed 3-D teeth.*

Results

Vickers Hardness Values

The hardness values of each digital material and tooth material are listed in Table 1. The hardness of materials FLXA9785-DM, FLXA9770-DM, FLXA9760-DM, FLXA9750-DM, FLXA9740-DM, FLXA-MT-S95-DM, FLXA-MT-S85-DM, FLXA-MT-S70-DM, FLXA-MT-S60-DM, FLXA-MT-S50-DM, FLXA-MT-S40-DM, FLXA-MT-S35-DM, and FLXA-MT-S30-DM were not able to be calculated. (*: The durometer could not get an accurate reading due to the softness of each sample.)

For each of the 3D models, all observations had lower VHN than the mean VHN values reported for each model type. The Wilcoxon rank sum p-values testing whether the Enamel value was less than 390.2 was .049, Dentin value was less than 70.6 was .063, Cementum value was less than 53.4 was .125. Even though the dentin and cementum medians were not significantly different from those reported in the literature, since they were all far less than the reported values, we expect that a larger sample size would lead to significance.

A one-sided one-sample Wilcoxon rank sum test was performed to determine if the enamel, dentin, and cementum VHN median values were smaller than what has previously been reported in literature for teeth. (Table 1)

Table 1. Mechanical properties from hardness tests of each of digital materials.

Digital Material Name	Description	Impact (J/m)	Elongation at Break (%)	Hardness (Shore A)	Hardness (VHN)
RGDA8430-DM	PP-like	30	25-35		12.5,12.5,11.9,12.1
RGDA8425-DM	Balanced Rigidity	25	20-30		8.2, 9.1, 8.4, 8.1
FLXA9795-DM	Rubber-like			95	11.5,10.2,12.0
FLXA9785-DM	Rubber-like			85	*
FLXA9770-DM	Rubber-like			70	*
FLXA9760-DM	Rubber-like			60	*
FLXA9750-DM	Rubber-like			50	*
FLXA9740-DM	Rubber-like			40	*
FLXA-MT-S95-DM				95	*
FLXA-MT-S85-DM				85	*
FLXA-MT-S70-DM				70	*
FLXA-MT-S60-DM				60	*
FLXA-MT-S50-DM				50	*
FLXA-MT-S40-DM				40	*
FLXA-MT-S35-DM				35	*
FLXA-MT-S30-DM				30	*
Enamel					390.2±40.5[7,8]
Dentin					70.6±8.8[3]
Cementum					53.4±7.9[3]

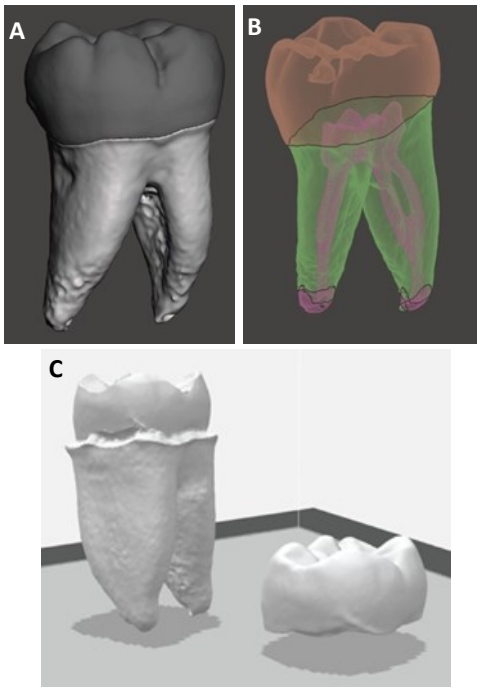

Figure 4. (A) *Scanned 3-D mock-up with layers combined.* ***(B)*** *Scanned 3-D mock-up with layers outlined.* ***(C)*** *Scanned 3-D mock-up with crown and root layers separated.*

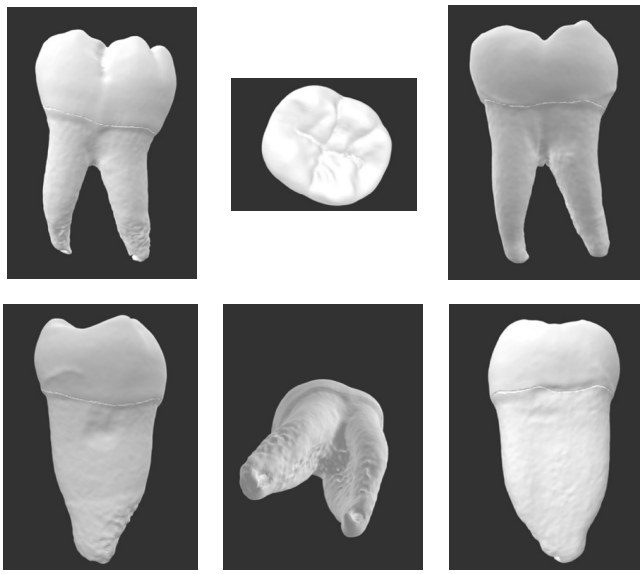

Figure 5. *Final mockup of scanned tooth before print.*

Discussion

In dental education, extracted human teeth have long been the student's first experience in operative dentistry. Students learn the cavity preparation guidelines first set forth by GV Black over 100 years ago[9]. Then they matriculate to a preclinical laboratory to complete cavity preparations. Once competency is achieved a student proceeds to clinic experiences on patients.

Pre-Clinicals

Often, a clinician practices a specific procedure on a tooth with unique anatomy and has no anatomically comparable extracted tooth to practice on before treating their patient. By taking a CBCT image of a tooth and printing it on the Stratasys printer, the clinician can then get a spatial replica of the tooth for practice. According to our study, the texture and hardness of the plastic materials still must be developed more, but the anatomy is extremely comparable.

Remediation

Along with pre-operative practice for an actual patient, this technology could also be used to remediate unacceptable cases that a student has treated. Along with pre-operative practice for an actual patient, this technology could also be used to remediate unacceptable cases that a student has treated. Consider that a student could remediate on a tooth that has a similar problem as the one they had issues. Instructors can then describe proper treatment and give the student a second chance to develop that skill or technique.

A post-operative CBCT could be used to further examine any clinical errors that had taken place. Examples such as a perforated canal during an endodontic procedure, could be further examined with a 3-D printed model of the unsuccessful treatment.

Licensure

To practice dentistry, one must obtain a license from the state or regional Board of Dentistry of their location. To get said license, a candidate must pass a written and clinical examination. Most of these dental examination boards have converted to plastic teeth on mannequins, instead of live patients for their examinations. By developing the plastic materials' hardness and texture to mimic actual human enamel and dentin, the Stratasys printer can quickly and economically print replicas of the examination teeth for practice.

Infection Control

Lastly, extracted teeth may be inhibited by numerous microbes that can cause medical problems for the practicing clinicians. Examples of such problems could be aerosolization of particles that may cause operators an upper respiratory tract infection, especially if they are not utilizing a properly fitted mask. The secondary reinfection of an open wound of the operator is another potential hazard.

The COVID 19 pandemic has forced society to readdress hand washing, mask wearing, and vaccine administration, as well as cultural compliance of these issues. In this environment we must do all we can to belay the fears of reinfection by anything that we can. Moving from extracted to computer replicated teeth can only help in that endeavor.

Conclusion

Primarily, this study proved that the Stratasys 3-D printer can replicate the root canal and external anatomy of a human tooth utilizing CBCT technology. This study had attempted to identify a Stratasys printed plastic material with the same hardness and texture of natural teeth, specifically enamel and dentin. Based on the results of this study, more research and development of Stratasys materials needs to be addressed before we can exactly replicate these natural properties. With the development of new materials, the opportunities to utilize this technology in dental education will set the bar higher for clinical studies.

Preliminary studies have been started using various levels of torque in electric dental handpieces to make these printed materials more comparable in cutting properties to enamel and dentin.

Acknowledgments

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Statement of clinical relevance

CBCT scans with the Stratasys 3D printer fabricates teeth with the same root canal anatomy seen in the actual teeth. Utilization of this technology will aid in the training of dentists and dental hygienists without the use of actual teeth.

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