APPROACHES TO 3D PRINTING TEETH FROM X-RAY MICROTOMOGRAPHY

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ABSTRACT

Artificial teeth have several advantages in pre-clinical training. The aim of this study is to three-dimensionally (3D) print accurate artificial teeth using scans from X-ray microtomography (XMT). Extracted and artificial teeth were imaged at 90 kV and 40 kV respectively, to create detailed high contrast scans. The dataset was visualised to produce internal and external meshes subsequently exported to 3D modelling software for modification before finally sending to a slicing program for printing. After appropriate parameter setting, the printer deposited material in specific locations layer by layer, to create a 3D physical model. Scans were manipulated to ensure a clean model was imported into the slicing software, where layer height replicated the high spatial resolution that was observed in the XMT scans. The model was then printed in two

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different materials (polylactic acid and thermoplastic elastomer). A multi-material print was created to show the different physical characteristics between enamel and dentine.

INTRODUCTION

A distinct need for hands-on pre-clinical training before treatment of a patient has been widely acknowledged within dental education (Qualtrough *et al.*, 1999). Throughout the years, numerous techniques have been created to teach students to perform different dental treatments. Artificial teeth are widely used and replicated with transparent resins in which the pulp chamber and root canals are distinguishable with different colours (Nassri *et al.*, 2008). Despite this use of artificial teeth, extracted human teeth remain one of the most popular and accurate samples used during pre-clinical endodontic training. Both artificial and extracted teeth have advantages and disadvantages, with the common practice using a combination of artificial root canal models and extracted human teeth during pre-clinical training (Dummer, 1991).The disadvantages of using extracted teeth include the possibility of cross-infection, being potentially infectious to students, the unavailability of these teeth and anatomical variability of extracted teeth, meaning valid assessment for students is not uniform (Tchorz *et al.*, 2015). The benefits of artificial teeth include risk of infection, availability in large quantities, validation of assessment through their uniformity (Bitter *et al.*, 2016), tailoring to offer anatomical challenges and 3D printing into training models for simulation-based medical education (SBME) (San Diego *et al.*, 2013). However, based on previous studies, students reported artificial teeth as unsatisfactory because of a perceived lack of realism of these teeth, offering them a non-realistic simulation to practice on, compared to natural teeth. Despite the reported difficulties, students recognised the advantages and suggested improvements, such as varying geometry, to include real-life imperfections of teeth such as caries (Al-Sudani & Basudan, 2016).

Previous literature studies have shown the ability to convert tomography files into viable 3D printed training models (O'Brien *et al.*, 2016) in order to support the concept of 3D printing artificial teeth. In Longfield, et. al. (2015), computed tomography (CT) scans were taken of 6-month-old patient's temporal bone for a low-cost training method in paediatric surgery (Longfield *et al.*, 2015) and therefore provides a technique for creating realistic 3D datasets. In this study, we present a method of collecting structural biological data and converting into a 3D model, using open source software. The emphasis at this stage of the study is to focus on the geometry of the tooth, with future work looking into mimicking the mechanical properties of the tooth.

MATERIALS AND METHODS

X-Ray Microtomography

A natural mandibular first molar and a plastic replica (Fábrica de Sorrisos, Brazil) were selected as specimens to demonstrate the transition from XMT to 3D print. The specimens were scanned using the 'in-house' TDI (time delay integration) X-ray microtomography scanner (MuCAT-2) at Queen Mary University of London (QMUL), developed by Davis and Elliott (2003). The system uses a charge-coupled detector (CCD) camera (Spectral Instruments, Tucson, Arizona, USA) with a 60 μm thick columnar caesium iodide scintillator (Applied Scintillation Technologies, Ltd., Cambridge, UK) (Davis & Elliott, 2003; Davis *et al.*, 2013). The natural tooth was scanned at 15 μm voxel size at 90 kV 180 μA, 1503 projections were taken within 3 blocks[2], whereas the plastic tooth was scanned at 40 kV, 405 μA, 675 projections within a

[2] Area of view for the camera of 501 slices and 675 slices for the extracted and artificial tooth, respectively.

single block. Time taken for the scans was 26 hrs 52 mins and 5 hrs 8 mins respectively. The projections were reconstructed using a modified Feldkamp cone-beam back-projection algorithm (Feldkamp *et al.*, 1984). Following reconstruction, the files produced were "trimmed" to produce single-byte voxel data containing only the cuboid of interest.

Visualisation

Tomview (Version 1.1, QMUL, 2003-2018), a tomography visualisation software specific to MuCAT-2, was used to view 2D slices through the trimmed volume (*.tom file) in any of the three orthogonal planes (XY, XZ and YZ). Tomview was used to create a metadata file (*.pvl.nc file) that was exported to Drishti (Version 2.6.3; ANU Vizlab, 2016), which is a multi-platform, open source volume exploration and presentation tool, written for visualising tomography datasets from various scanning technologies and different tomography file formats. Using Drishti, a mesh was generated in the form of a polygon file format (*.ply), which was opened using Meshlab (Version 2016.12; ISTI-CNR, 2016). The 3D mesh was modified and manipulated in Meshlab to remove any unwanted or excess material or imperfections.

3D Printing

The model file was exported as a *.stl file format with ASCII[3] coding into Cura (Version 2.3.1; Ultimaker, 2016). Cura is a 3D printer slicing application, in which parameters are set and a 3D visualisation of each layer is provided. This information is exported into a G-code file format and fed into the 3D printer. An open-source fused deposition modelling (FDM) 3D printer (Duplicator i3, Wanhao, China), read the numerical control programming language of the G-code to deposit a determined amount of material in a specific location. Modifications

[3] American Standard Code for Information Interchange.

were made to the printer in the form of a Bowden extruder (Landry, 2016) (Flexion™, Diabase Engineering, USA), designed to increase the resolution of the 3D printer from 60 μm to 50 μm. Filaments used for the printing included a hard white polylactic acid (PLA) (3D Prima, Sweden) and flexible thermoplastic elastomer (TPE) (FFF World, Spain).

RESULTS

A variety of images reconstructed from XMT volume datasets are shown in Fig. 1-2. Fig. 1-2 show both the natural and artificial mandibular molar at different cross-sectional planes, visualising difference in structure and material. Further details of the specimens are given in the Figure captions. Fig. 3. demonstrates the result of the 3D surface rendering that is applied to the reconstructed volume data sets achievable in the open-source software. This rendering is required to provide discrete surfaces that can be exported effectively to the 3D printer.

Three models were produced to demonstrate the ability to convert tomography files to 3D prints. Two prints were produced from PLA, for both natural and artificial tooth structures (Fig. 4a), whereas the third print was an assembled model made from the harder PLA representative of enamel and TPE for the dentine and pulp cavity (Fig. 4b).

DISCUSSION

The non-destructive 3D imaging of teeth provides a basis for SBME, using the data for the teaching of dental morphology, operative dentistry, and endodontics (Dowker *et al.*, 1997). Combining this 3D imaging technology with recent advances in modelling and computational power provides the ability to manipulate biological image datasets and export to physical models using complementary 3D printing. Such an approach is appropriate for applications teaching in teaching were physical models for training can be produced and modified on demand. Physical outputs are expected to be further enhanced using virtual reality/augmented reality for SBME, in which sensory feedback is received from simulated environments (Dowker *et al.*, 1997; Wang *et al.*, 2015). However, virtual reality is currently under-developed and has only recently become available in the consumer market, unlike 3D printing with desktop printers now widely available.

XMT produces a high-resolution scan of the teeth, both extracted and artificial, which were easily converted into workable 3D models using multiple software (Drishti, Meshlab). The specimens' datasets can be uploaded to a free access database for downloading to be used in 3D printing (websites such as Thingiverse[4,5] (www.thingiverse.com)) and/or virtual reality (Sketchfab (www.sketchfab.com)). Both data collected from extracted teeth and artificial teeth showed the internal and external geometry, with the artificial tooth being scanned as a comparison to show whether the anatomy differs from natural teeth. In the example of the artificial tooth, the internal geometry showed differences in the structure between the enamel and dentine with different types of resin used to distinguish this (Fig. 2).

Drishti allows the isolation of different meshes, such as; enamel, dentine, and pulp. The isolation of different meshes allowed for the ability to print each structure separately and with different materials. With Meshlab, the meshes can be edited, changing the dimensions, and changing the number of triangles and vertices, which in turn alters the resolution of the model and the size of the model file. This combination of programs proved effective in altering the tooth datasets and could be a possible pathway to use in future conversion of XMT data to *.stl files.

[4] Extracted tooth; www.thingiverse.com/thing:2770645
[5] Artificial tooth; www.thingiverse.com/thing:2770647

The software program Cura was used to divide the meshed data into slices (dependent on layer thickness) and allows finite control over the final product, as more parameters can be set and changed compared to other slicing programs. Cura is also compatible with most commercially available 3D printers, making it an ideal choice for exporting the meshed data to a physical output. The XMT data of the artificial tooth was used to produce replicas in white PLA that contained both internal and external structures. The choice of only using one material to recreate the artificial tooth was to prove the concept of translating data into a physical model. The XMT data of the extracted tooth was used to create various models using white PLA. The models proved that it was possible to use a cost-effective 3D printer and produce from XMT data, physical 3D models, but at a lower resolution. Specifically, the MuCAT-2 system has a spatial resolution of around 13 μm whereas the Wanhao Duplicator i3 (with Flexion™ extruder) can only produce a resolution of around 50 μm, thus indicating that the high definition from the imaging was not captured in the physical output. The ability to create multiple meshes for the internal anatomy was taken advantage of, as a multi-material print was created, using PLA as the enamel, and the flexible TPE as the dentine and pulp, to primitively demonstrate the different mechanical properties of real enamel and dentine. The use of dual extrusion would allow for a simultaneous print using multiple materials. However, the print made of a range of parts allows for dismantling which could be a valuable tool in teaching students tooth anatomy especially the different structures that make up a tooth. More advanced multi-material 3D printing technology is however available, but at a much higher cost, compared to the Duplicator i3.

CONCLUSIONS

We have demonstrated 3D models of a tooth, manufactured from tomography files generated from XMT, using various open-source programs. The approach is generic and provides a workflow for 3D printed physical outputs from high-resolution non-destructive XMT scans of biological specimens. This workflow could prove to be invaluable for SBME to exploit the availability of desktop 3D printers, as well as free-access databases that contain tomographic files. Future work following on from this study will aim to mimic the properties of natural teeth using 3D printing. Such an approach has been exploited from XMT imaging bone structures and provided mechanical analogies using multi-material 3D printing (Parwani *et al.*, 2017) but has not been translated into teeth.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest with respect to the authorship and/or publication of this article.

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LIST OF FIGURES

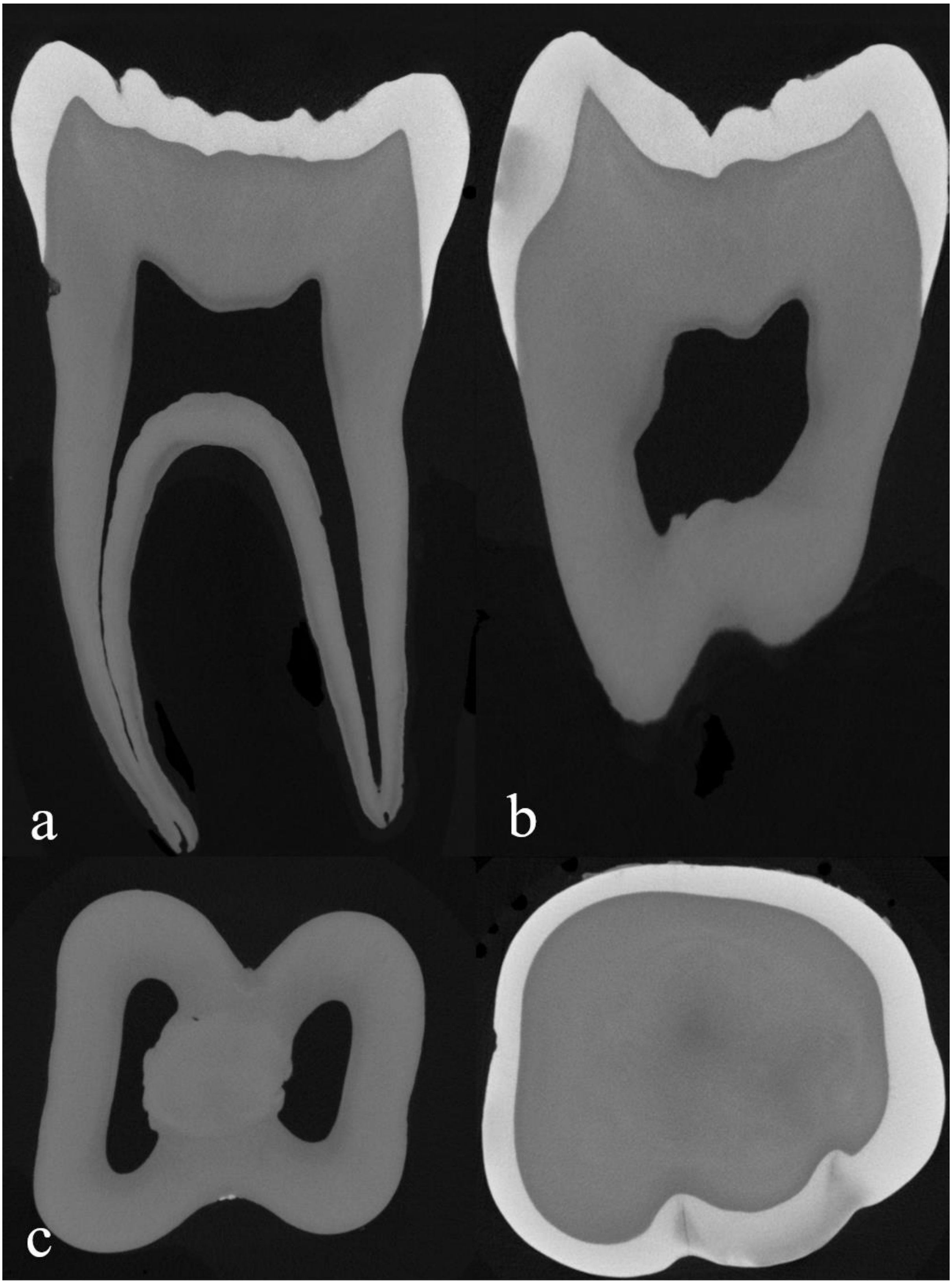


Figure 1.

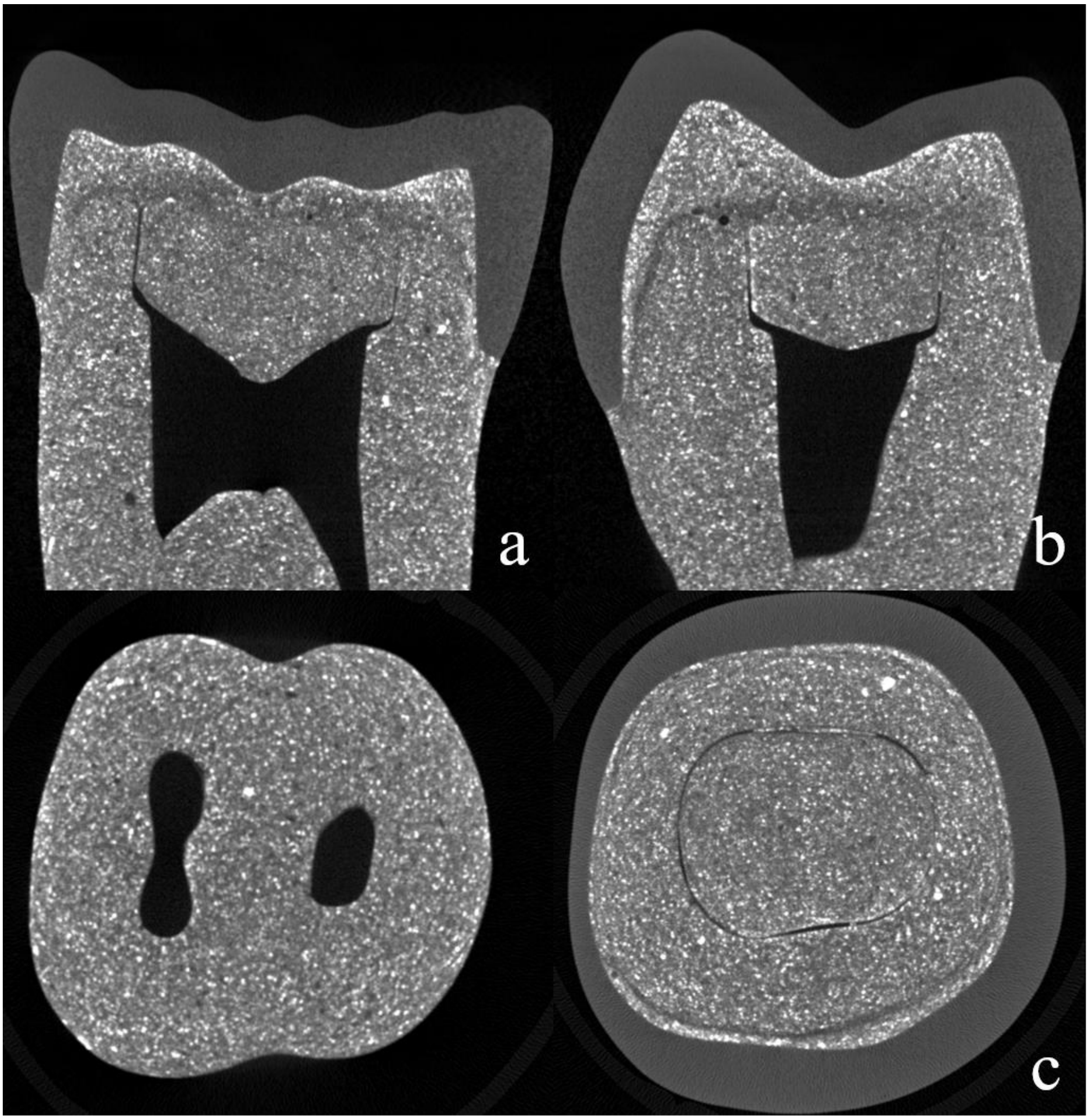
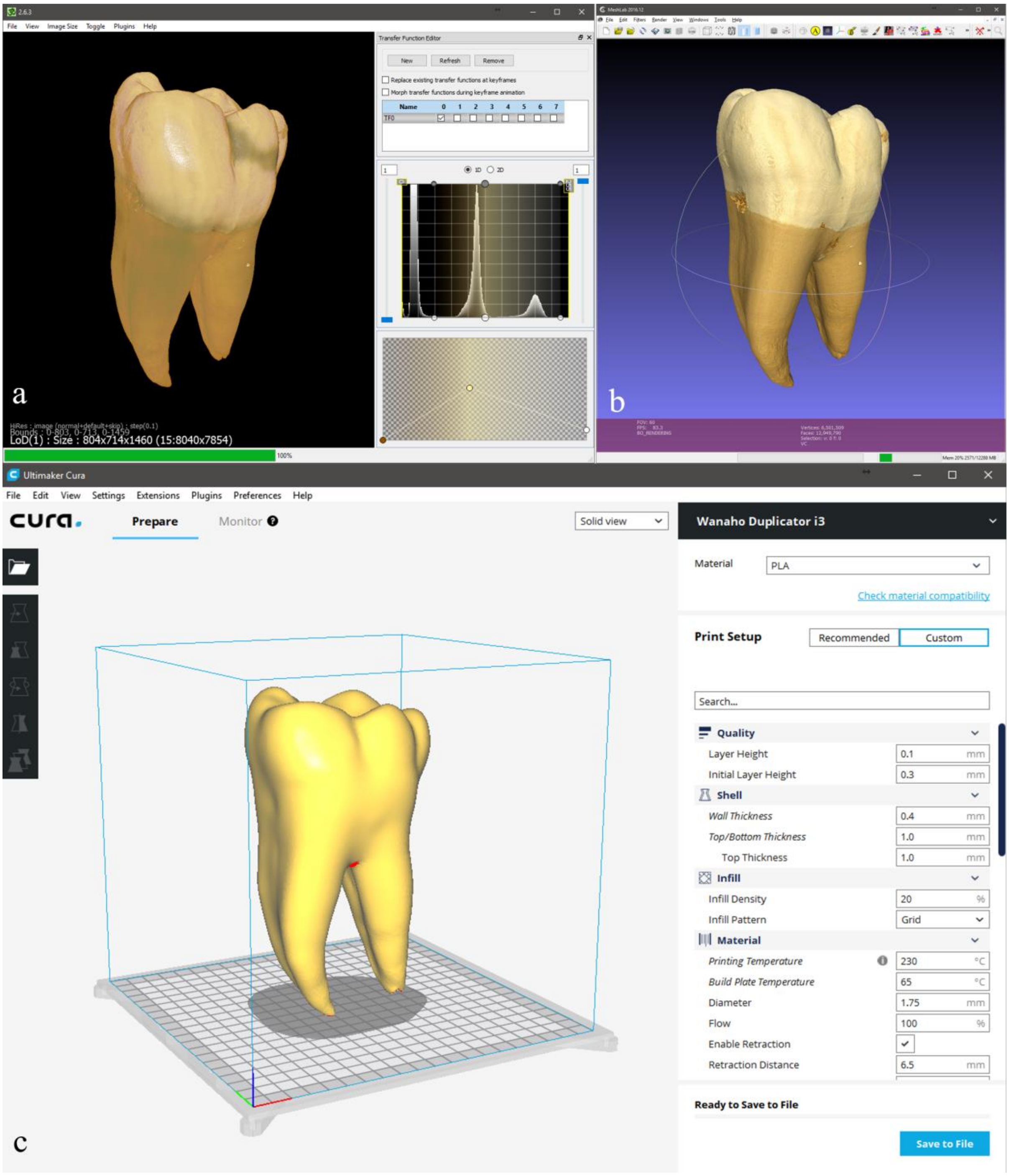


Figure 2.

Figure 3.

Figure 4.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Save to File

Figure 5.

LAY ABSTRACT

Objectives: Trainee dentists practice procedures using artificial teeth that are far from real teeth. Using x-rays and 3D printing technology the project will re-create a real tooth, artificially.

Methods: X-rays produce a 3D image that can be printed out as a physical replica, after several conversions of files. Different settings can be used to allow the printed model, to be as accurate as possible. Data was collected on the forces from a dental drill on a tooth's surface, to measure hardness and resistance.

Results: Multiple teeth replicas were printed with a high accuracy. The materials printed did not mimic actual tooth properties, but using the data from real teeth, materials can be tested in future.