

Outer Shell Thickness Measuring Tool for Structures with Curved Surfaces

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Abstract

Accurate measurement of surface-to-interface thickness in biological structures, such as cortical bone or root dentine, is important for clinical applications in oral radiology and anatomy particularly in endodontics where inadequate remaining dentine may increase the risk of procedural complications such as perforation. Conventional methods typically rely on two-dimensional sections aligned to fixed global axes, which often fail to account for the natural curvature and complex geometry of three-dimensional (3D) biological models. This study proposes a novel automated software tool for high-resolution thickness mapping of small, highly curved structures. Using the Physics.Raycast function within the Unity 3D development platform, the tool implements a five-stage workflow: slice generation, longitudinal centerline establishment, centerline refinement, surface remeshing, and automated thickness computation. Virtual 2D slices are created at the model origin to establish a longitudinal axis, ensuring that subsequent slices remain perpendicular to the local anatomical curvature. Surface reconstruction through linear interpolation corrects segmentation artifacts and artificial holes, producing a cohesive watertight model. Validation using cylindrical and cuboidal computer-generated models representing morphological extremes demonstrated high precision, with measurements accurate to 0.0001 mm on curved surfaces. Although the software currently requires manually annotated inner and outer surfaces in .obj format, it generates robust numerical outputs and color-mapped visualizations of local thickness. Application of this method enables consistent and reproducible assessment of dentine thickness in complex root morphologies. Beyond dental applications, this framework enables reliable and repeatable quantitative analysis of curved hollow structures, including long bones, the cranial vault, and airway walls.

Introduction

Measurement of surface-to-interface thickness in biological structures has several applications clinically. For instance, measuring cortical thickness or dentine thickness is of critical importance in fields like oral radiology and anatomy. Cortical thickness usually represents the mean spacing between periosteal and endosteal surfaces, measured orthogonally (as the shortest perpendicular distance between cortical boundaries) (Vedi et al., 2011). An analogous structural concept to cortical thickness is the dentine thickness, which relates to the peripheral mineralized layer of the tooth and is measured from the outer load-bearing mineralized tissue to the internal cavity along the root curvature (Meyer et al., 2025).

Measurements from surface-to-interface of biological structures are usually taken from two-dimensional (2D) slices made in a three-dimensional (3D) structure. These sections can either be destructive: sampled directly from the structure or non-destructive by radiological sections. Sections taken directly from the structure may undergo further histological processes and photography to facilitate measurements (Bissinging et al., 2017; Vågberg et al., 2018)

Nowadays, however, we rely more on radiological techniques as they are considered more accurate and deliver more precise measurements than histological methods. Among available 3D modalities, micro-focus X-ray computed tomography (micro-CT) is regarded as the gold standard for dental and bone research due to its superior spatial resolution (MicroCT: 68–106 μm CBCT: approximately 200 μm resolution depending on specimen size) (Schneider & Ochs, 2014; Theye et al., 2022). This variation is particularly significant, as discrepancies of even one or two decimal fractions of a millimeter may have critical clinical implications (Theye, 2022).

To measure surface-to-interface thickness accurately, perpendicular measurements need to be taken. The study by Profico et al. (2021), describes and demonstrates the application of a R package, morphomap, which uses a 3D mesh of long bones. The example used was the femur. Following segmentation, as a default, the program extracts 100 evenly spaced virtual sections along the given femur length perpendicular to the frontal plane. These transverse sections intersect with two meshes: periosteal and endosteal. From the centroid of the cross section, equiangular lines (15 degrees) are projected on to each mesh to place twenty-four semi landmarks on each surface. Cortical thickness can then be calculated from the Euclidean distance between each landmark pair (one on the endosteal surface and the other on the periosteal surface) (Profico et al., 2021).

Unfortunately, perpendicular sections based on a fixed global axis such as the frontal plane which disregards the curvature of the structure, will fail for three-dimensional (3D) models of structures with complicated geometries and natural curves as sections will become oblique when the structure curves.

As existing tools for determining the surface-to-interface thickness does not adequately quantify small curved biological structures like dental roots (Yanık, & Nalbantoğlu, 2022), there is a need for an automated, high-resolution software tool that can accommodate highly curved surfaces in small biological structures. The objective of this research is therefore to propose a new software tool that is specifically designed for small biological structures with pronounced curvatures, such as dental roots. Building on the general principle of radial thickness sampling from virtual sections, where equiangular rays from each section's centroid intersect inner and outer contours to yield thickness values, we introduce the Physics.Raycast in Unity (Unity Technologies, 2023). Physics.Raycast is a 3D development platform with a collision-detection function used for simulation, gaming, and scientific visualization for the surface-to-interface thickness measurement of small curved biological structures. The system uses raycasts which are radially projected virtual straight lines which detects collisions or intersections with a 3D object/mesh. At the intersection, the exact coordinate, the distance from the origin, and the surface normal – the vector perpendicular to the surface at that location are generated (Möller & Trumbore, 1997). Surface-interface thickness can then be computed enabling automated, high-precision measurement (Jones et al., 2006). To our knowledge, Unity's raycast application programming interface has been used in biomedical Unity apps but not for surface-to-interface thickness determination e.g. cortical/dentine thickness quantification (Meulstee, 2022).

Materials and Methods

Ethics approval: Ethical approval for this study was obtained from the School of Medicine Research Committee of the Sefako Makgatho Health Sciences University (SREC) and the Sefako Makgatho Health Sciences University Ethics Committee (SMUREC) (SMUREC/M/443/2024:PG) (13/02/2025)

A digital 3D anatomical mesh representing dentine morphology was constructed and processed for computational thickness analysis. The 3D model was imported into the Physics.Raycast function software (Unity Technologies, 2023) where it was processed through a series of automated steps designed to ensure accurate geometric alignment and high-resolution thickness mapping. A custom automated thickness-measurement algorithm was developed using Python (Python Software Foundation, version 3.11). The script implemented ray-based intersection calculations to compute orthogonal outer-shell measurements from 3D mesh data. Algorithms were implemented using Python (Python Software Foundation) to allow reproducible and automated 3D thickness analysis. The workflow consisted of five main stages: slice generation by establishment of a centerline, centerline refinement, surface remeshing, and thickness computation.

A series of 10 computer-generated models were used to test the accuracy of the tool. In order to represent two extremes of biological structures, both cylindrical and cuboidal models were used to test the program.

As in other studies, 2D slices needed to be made from the 3D model before cross-sectional data (dentine thickness in this example), could be measured. To ensure that 2D virtual slices were created which were consistently perpendicular to the curvature of the dental root (or similar biological structure), a longitudinal centerline or axis needed to be created first that defined the local anatomical axis of the structure and served as the reference for all subsequent slicing and thickness determinations.

1. Generation of the first Two-Dimensional (2D) Slice at the model's origin

The process began with a virtual slice as a 2D plane passing through the 3D structure at the model's origin, from which the center of area of the outer surface contour was calculated to define the first centerline point (P_n). The outer and inner boundaries of the structure were detected using a simulated laser-scanning approach implemented through Raycasting in Unity.

Raycasts are invisible lines that are distributed radially at equiangular intervals around the center of the slice plane (green) to detect collisions with colliders in the scene. The intersection points between the rays and the model surface are recorded (blue points) and used to define the 2D contour of the structure in that plane. Increasing the number of rays increases the surface resolution and accuracy of the slice. Figure 1 depicts a two-dimensional (2D) cross-sectional slice of the model at that first centerline point.

2. Establishing the Longitudinal Centerline

Subsequent slices to the first slice were placed sequentially at a constant specified distance d from the previous point (Fig. 2). The first centerline point was labelled P_n and the center of area of each

subsequent slice was recalculated ($P_{n+1}, P_{n+2}, \dots$). Each new slice plane was rotated so that its normal vector was aligned with the vector between consecutive centerline points (e.g., $P_{n+1} - P_n$), ensuring perpendicularity of each slice to the local axis. This repetitive procedure allowed the slices to follow the natural curvature of the model.

To minimize orientation error when a lower number of slices was used, angular corrections could be applied, by aligning the slice plane normal to the bisector of adjacent centerline vectors (e.g., $P_{n+1} - P_{n-1}$).

3. Centerline Refinement and Smoothing

The centerline based on the outer surface obtained from these processes may contain minor high-frequency variations caused by surface irregularities or noise. To produce a stable and anatomically meaningful centerline, smoothing is applied to the outer centerline and the degree of smoothing can be adjusted by the user (Fig. 3).

A corresponding inner surface centerline is also calculated using the same method but without smoothing. This prevents the inner centerline from being displaced outside of the inner surface boundaries, which could otherwise interfere with accurate radial thickness computation.

4. Surface Reconstruction and Remeshing

This process corrects minor segmentation artefacts and closes artificial holes present in the original scanned models through linear interpolation (Fig. 4).

To ensure compatibility between the radial measurement system and the root canal geometry, the inner surface is reconstructed as convex in two dimensions, enabling consistent radial pairing between inner and outer contours. The final remeshed model therefore represents a coherent, watertight reconstruction of the original 3D geometry, with consistent vertex structure and no surface discontinuities (Fig. 5).

5. Thickness Measurement

For each slice, cortical or dentine thickness is calculated radially at equal angular intervals around 360° . Each thickness value represents the distance between corresponding points on the inner and outer contours. Mean, minimum, maximum, and standard deviation values are computed per slice or across the entire model.

Thickness distributions are color-mapped onto the 3D surface for visual inspection (Fig. 7), and all numerical results can be exported as comma-separated value (.csv) files for statistical analysis.

Results

A series of 10 computer-generated models were used to test the accuracy of the tool. In order to represent two extremes of biological structures, both cylindrical and cuboidal models were used to test

the program. Very accurate and repeatable results were noted in both extremes. In cylindrical models, the tool measured accurately to the nearest 0.0001 mm while in the cuboidal models it measured completely accurately on flat surfaces.

Discussion

The proposed software was designed as an automated framework capable of solving complex geometric problems regarding dimensionality in 3D biological structures. The potential success of the workflow depends on its thorough preservation of the data throughout the entire process, from initial slice generation through to the final thickness computation process. The primary strength is the initial virtualization of the structure, with the initial Raycasting in Unity to determine inner and outer boundary locations of 2D cross sections enabling to scale the resolution by using hundreds of rays, thereby ensuring exceptionally high-resolution contouring (Unity Technologies, 2023).

The construction of a longitudinal centerline is an important step in representing the original curvature of the structure for automatic orthogonal sections. Artifacts that were created during the initial scanning or segmentation process could be addressed by sealing artificial holes and correcting minor surface imperfections through linear interpolation. This produces a final model which is a cohesive, watertight reconstruction and is critical for quantitative surface analysis.

However, the software has some mandatory prerequisites and limitations. The input file should be given in the .obj file format. Most importantly, a fine-grained identification and annotation of the inner and outer surfaces of the object using external software (Blender) is also crucial to avoid problems, and the tool would not be able to run without manually identifying the inner and outer surfaces of the object.

Moreover, there is also a technical restriction, which is the geometric compromise required by complex morphologies - the inner surface (e.g. in cases of root canal splittings) is reconstituted as convex two-dimensionally in order to allow accurate radial pairing; this may not have sufficient geometric agreement with the actual geometry of all features of the body.

Also, the software uses a user-defined smoothing degree for the outer centerline, which adds a degree of subjectivity to the calculation. If not standardized across users or studies, the standard parameter may introduce some variation of the centerline path and the resulting thickness values. It is therefore mandatory that protocols must be carefully designed, tested and detailed to ensure repeatability.

Although this software tool was developed primarily for addressing the need for determining dentine thickness in dental roots accurately, it is potentially applicable to a wide range of curved hollow biological structures where there is a need to determine the thickness of the shell. Potential applications include cortical bone thickness analysis in long bones, cranial vault thickness as well as vascular and airway wall thickness measurements. The software tool may also be useful in implant design.

The software should be developed further with geometric handling of extremely complex internal topologies (e.g. building algorithms for non-convex inner surface reconstruction with a stable radial measurement methodology).

Conclusion

The proposed software successfully provides an automated, robust and highly accurate method for radial thickness measurements on curved 3D models. Not only does the novel five-stage workflow avoid common measurement problems by retaining the true shape and dimensions of the model, but it also corrects surface artifacts and produces a stable measurement axis along the model's natural curvature. This tool represents a significant advancement in quantitative morphological analysis, providing researchers with reliable, high-resolution numerical data and corresponding visual thickness maps for complex biological structures.

Declarations

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Author contributions:

M Meyer: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft, Visualization

Data Availability Statement:

The software tool and demo data described in this study are available on GitHub at <https://github.com/MariscaMeyer/Surface-to-interface-thickness-measuring-tool>. The standalone executable and sample models for testing can be downloaded directly from the Releases section at <https://github.com/MariscaMeyer/Surface-to-interface-thickness-measuring-tool/releases>.

Conflicts of interest: The authors declare that they have no conflict of interest.

References

1. Bissinger, O., Probst, F. A., Wolff, K. D., Jeschke, A., Weitz, J., Deppe, H., & Kolk, A. (2017). Comparative 3D micro-CT and 2D histomorphometry analysis of dental implant osseointegration in

- the maxilla of minipigs. *Journal of Clinical Periodontology*, 44(4), 418–427.
<https://doi.org/10.1111/jcpe.12695>
2. Jones, M. W., Baerentzen, J. A., & Sramek, M. (2006). 3D distance fields: A survey of techniques and applications. *IEEE Transactions on Visualization and Computer Graphics*, 12(4), 581–599.
<https://doi.org/10.1109/TVCG.2006.56>
 3. Meulstee, J. W. (2022). *Augmented reality and 3D technology in clinical practice with special emphasis on craniosynostosis* [Doctoral dissertation, Radboud University].
 4. Meyer, M., Oettle, A. C., Jonker, C. H., & Rajbaran-Singh, S. (2025). Dentine thicknesses of first molar roots: A review of the literature with illustrative cases. *South African Dental Journal*, 80(2), 95–103.
<https://doi.org/10.17159/sadj.v80i02.20656>
 5. Möller, T., & Trumbore, B. (1997). Fast, minimum storage ray–triangle intersection. *Journal of Graphics Tools*, 2(1), 21–28. <https://doi.org/10.1080/10867651.1997.10487468>
 6. Profico, A., Bondioli, L., Raia, P., O'Higgins, P., & Marchi, D. (2021). morphomap: An R package for long bone landmarking, cortical thickness, and cross-sectional geometry mapping. *American Journal of Physical Anthropology*, 174(1), 129–139. <https://doi.org/10.1002/ajpa.24140>
 7. Python Software Foundation. (2023). *Python* (Version 3.11) [Computer software].
<https://www.python.org>
 8. Schneider, J. P., & Ochs, M. (2014). Alterations of mouse lung tissue dimensions during processing for morphometry: A comparison of methods. *American Journal of Physiology-Lung Cellular and Molecular Physiology*, 306(4), L341–L350. <https://doi.org/10.1152/ajplung.00329.2013>
 9. Theye, C. E. G. (2022). *The effects of aging and tooth loss on the microstructure of the mandible in South Africans* [Doctoral dissertation, University of Pretoria].
 10. Unity Technologies. (2023). *Physics.Raycast* (Version 2023.2.3) [Computer software].
<https://docs.unity3d.com/ScriptReference/Physics.Raycast.html>
 11. Vågberg, W., Persson, J., Szekely, L., & Hertz, H. M. (2018). Cellular-resolution 3D virtual histology of human coronary arteries using X-ray phase tomography. *Scientific Reports*, 8, Article 11014.
<https://doi.org/10.1038/s41598-018-29331-w>
 12. Vedi, S., Kaptoge, S., & Compston, J. E. (2011). Age-related changes in iliac crest cortical width and porosity: A histomorphometric study. *Journal of Anatomy*, 218(5), 510–516.
<https://doi.org/10.1111/j.1469-7580.2011.01340.x>

Figures

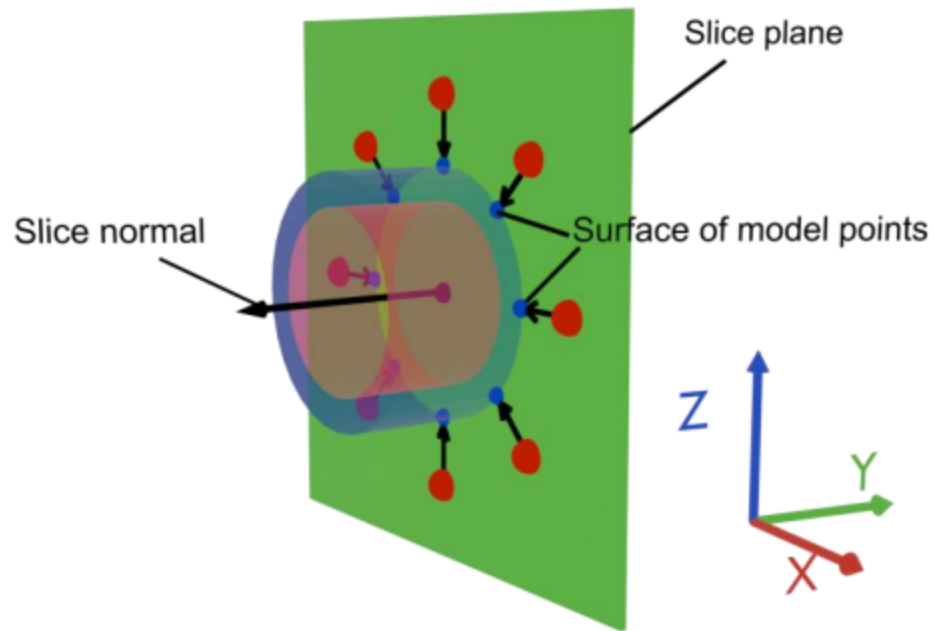


Figure 1

A schematic representation of a two-dimensional (2D) cross-section of the first slice.

Slice plane: The slice plane at the model's origin

Slice normal: The vector that is perpendicular to the slicing plane. A stable reference for defining radial directions within the slice

Red is the internal contour

Blue is the external contour

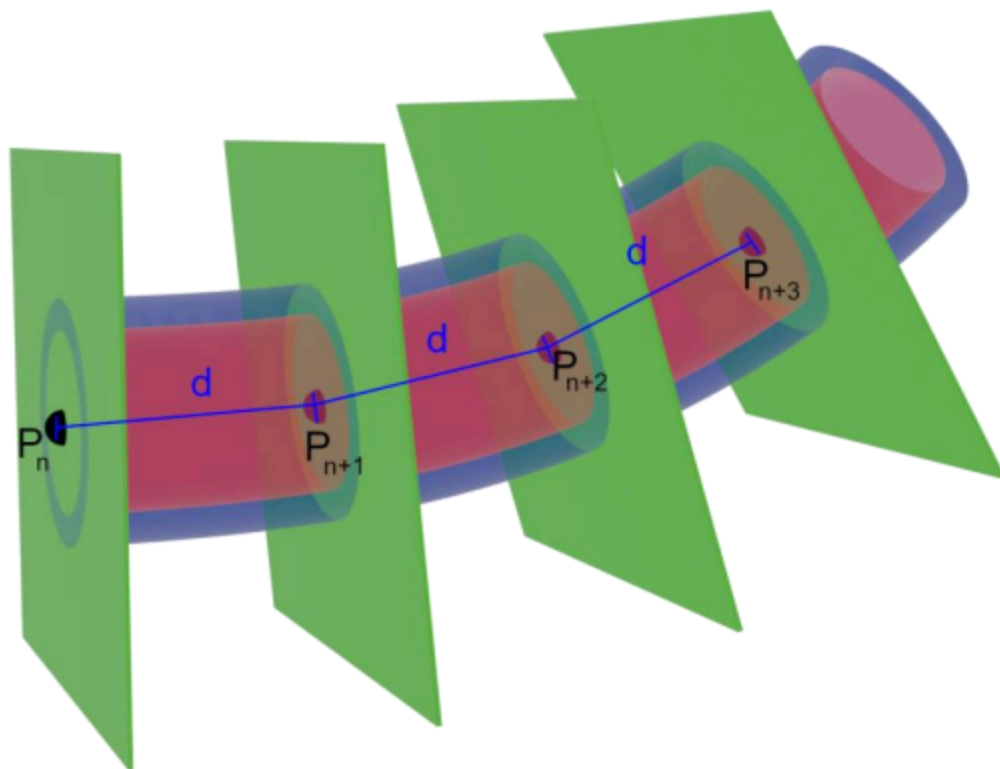


Figure 2

Sequential placement of slice planes along the model's longitudinal axis.

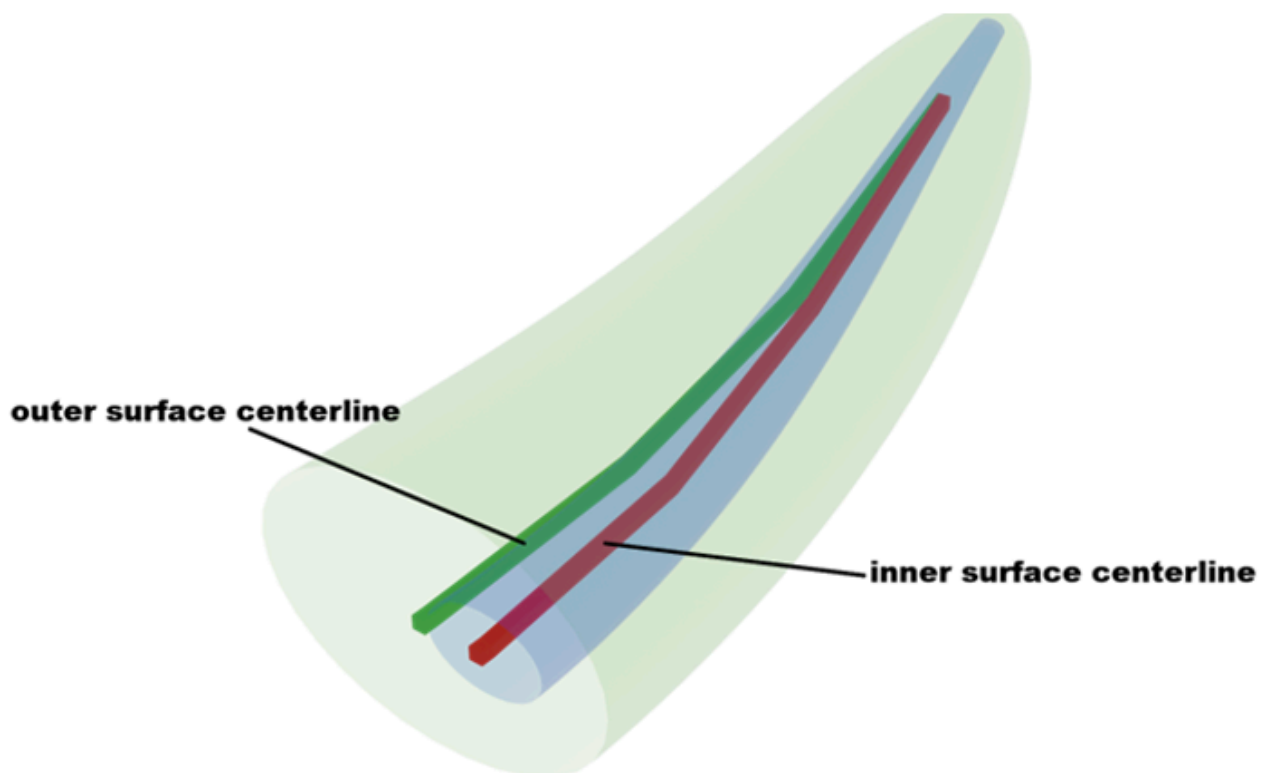


Figure 3

Depiction of outer and inner surface centerline

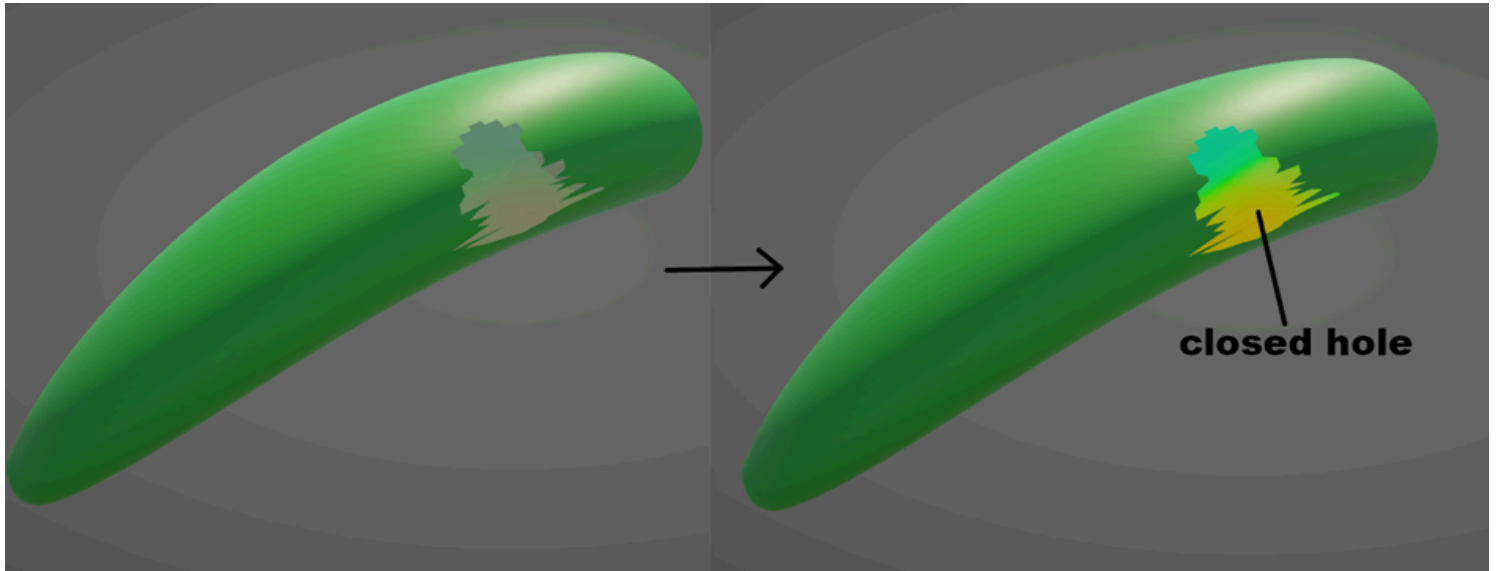


Figure 4

Surface reconstruction and remeshing. (A) Original model with segmentation artefacts and surface holes. (B) Remeshed and interpolated surface showing smooth, watertight geometry with consistent vertex structure.

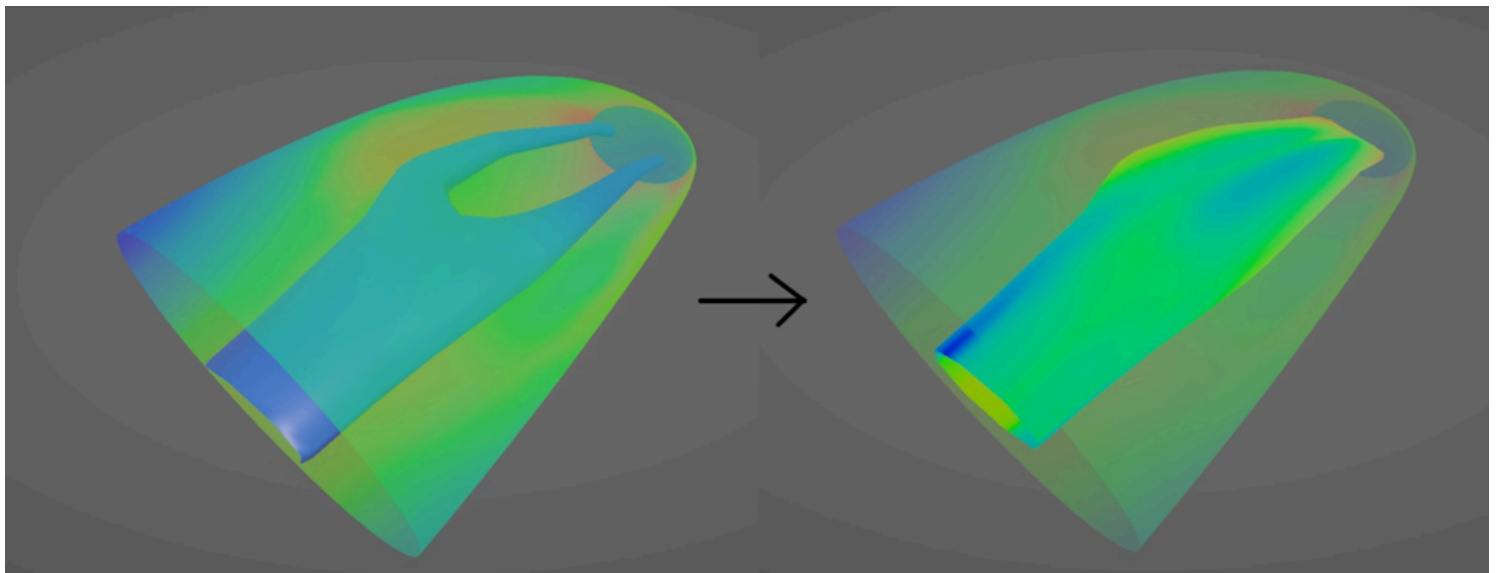


Figure 5

Reconstruction of root canal splittings into a single convex structure.

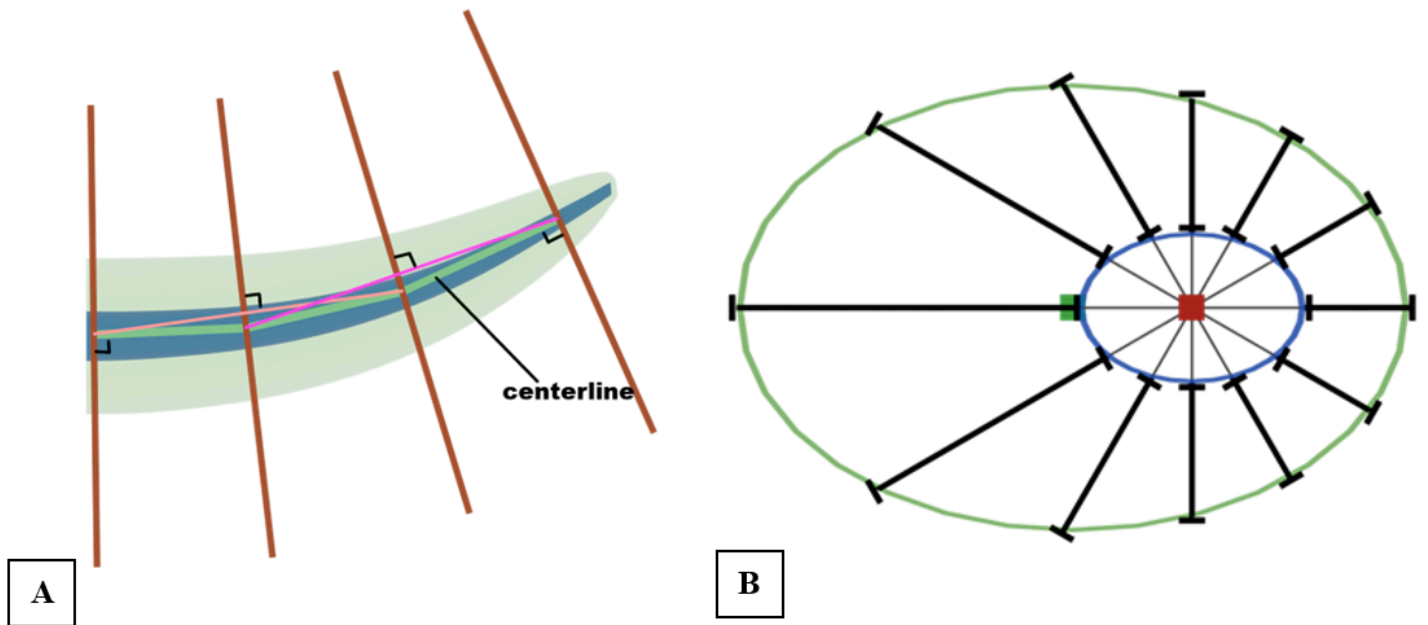


Figure 6

(A) Longitudinal section of perpendicular measurement slices

(B) Radial measurement lines projected from the inner surface centerline toward the outer contour.

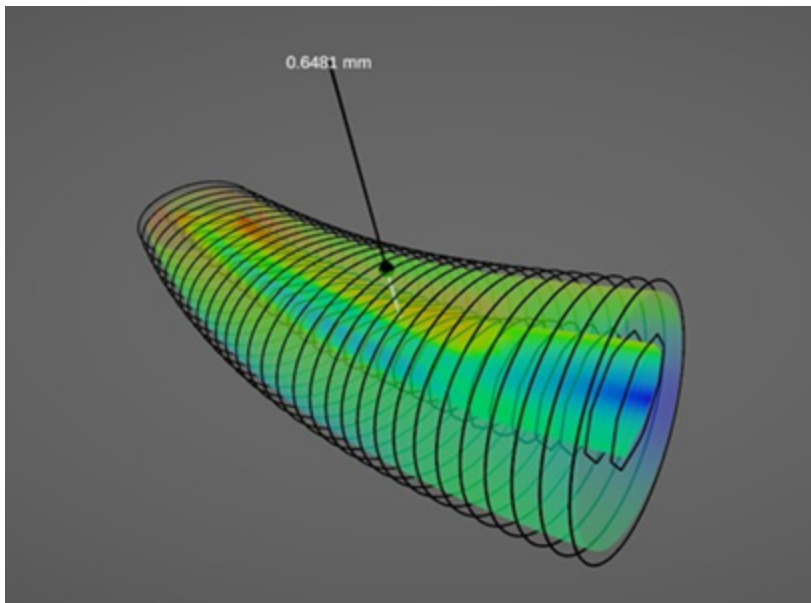


Figure 7

Color-mapped 3D model representing local thickness values, where warmer colors indicate greater thickness.