An Application Framework of Three-dimensional Reconstruction and Measurement for Endodontic Research

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Abstract

The purpose of this study was to customize an application framework by using the MeVisLab image processing and visualization platform for three-dimensional reconstruction and assessment of tooth and root canal morphology. One maxillary first molar was scanned before and after preparation with ProTaper by using micro–computed tomography. With a customized application framework based on MeVisLab, internal and external anatomy was reconstructed. Furthermore, the dimensions of root canal and radicular dentin were quantified, and effects of canal preparation were assessed. Finally, a virtual preparation with risk analysis was performed to simulate the removal of a broken instrument. This application framework provided an economical platform and met current requirements of endodontic research. The broad-based use of high-quality free software and the resulting exchange of experience might help to improve the quality of endodontic research with micro–computed tomography. *(J Endod 2009;35:269–274)*

Key Words

Application framework, MeVisLab, micro-CT, morphology, root canal, 3D

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The study of dental and root canal morphology is a critical theme in endodontic education, training, and treatment (1–7). To that end, three-dimensional (3D) reconstruction from high-resolution data is an increasingly popular and valuable method. It allows the evaluation of effects of root canal preparation and obturation; moreover, it allows assessing aspects of apical microleakage and cutting efficiency and has been used to establish finite element models (8–14).

Micro–computed tomography (micro-CT) data acquisition is nondestructive and allows fast examination of morphologic characteristics of a tooth in a detailed and accurate manner. At this point in time, generating a series of cross-sectional images of a tooth by using a micro-CT scanner is a common technique; however, image analysis and visualization techniques are core issues in the successful application of micro-CT data (15). A series of images generated by micro-CT can be visualized as a 3D structure only after performing a 3D reconstruction process (16). Therefore, 3D reconstruction software is indispensable.

Currently, most micro-CT scanners are integrated with software that provides quantitative morphometric analysis of trabecular bone and reconstructed 3D images (17). Some of the software applications are available for SGI, Sun, and HP platforms and are relatively expensive and not widely used (18). A number of commercial software packages for 3D reconstruction with platforms applicable to PC-Windows have also been used to characterize tooth and root canal configuration, including 3D-Doctor, V-works, VGStudio Max, and Voxblast (7, 19–21). These packages are typically expensive, and their availability to the general research community is limited. Moreover, most of the commercially available packages do not fulfill special functions needed for endodontic research, further diminishing the universal use of 3D reconstruction and micro-CT techniques in general.

Recently, a highly developed software package has become freely available. MeVisLab (MeVis Research, Bremen, Germany) is a framework system for medical image processing and visualization platform for Windows XP (Microsoft Corp, Redmond, WA); it provides an easy to learn modular visual programming interface with a comprehensive suite of image processing and visualization tools. The creation of a user-oriented application framework in MeVisLab is also quite time-consuming and is not an easy task for endodontic researchers (22).

The purpose of this proof-of-principle study was to create a customized application framework by using MeVisLab for 3D reconstruction and assessment of tooth and canal morphology on the basis of micro-CT data. This framework should also serve to evaluate root canal preparation and perform advanced simulation and analyses including virtual canal preparation.

Material and Methods

Preparation of Specimen and Micro-CT Scanning

One maxillary first molar that had been stored in thymol solution before usage was used for subsequent four framework application examples. The molar was accessed and prepared by manual ProTaper instruments (Dentsply Maillefer, Ballaigues, Switzerland) according to the manufacturer's guidelines. The palatal canal was prepared to F3, whereas mesiobuccal and distobuccal canals were prepared to F2. The tooth was scanned before and after preparation by using a micro-CT system (μCT-80; Scanco Medical, Bassersdorf, Switzerland) with an isotropic voxel size of

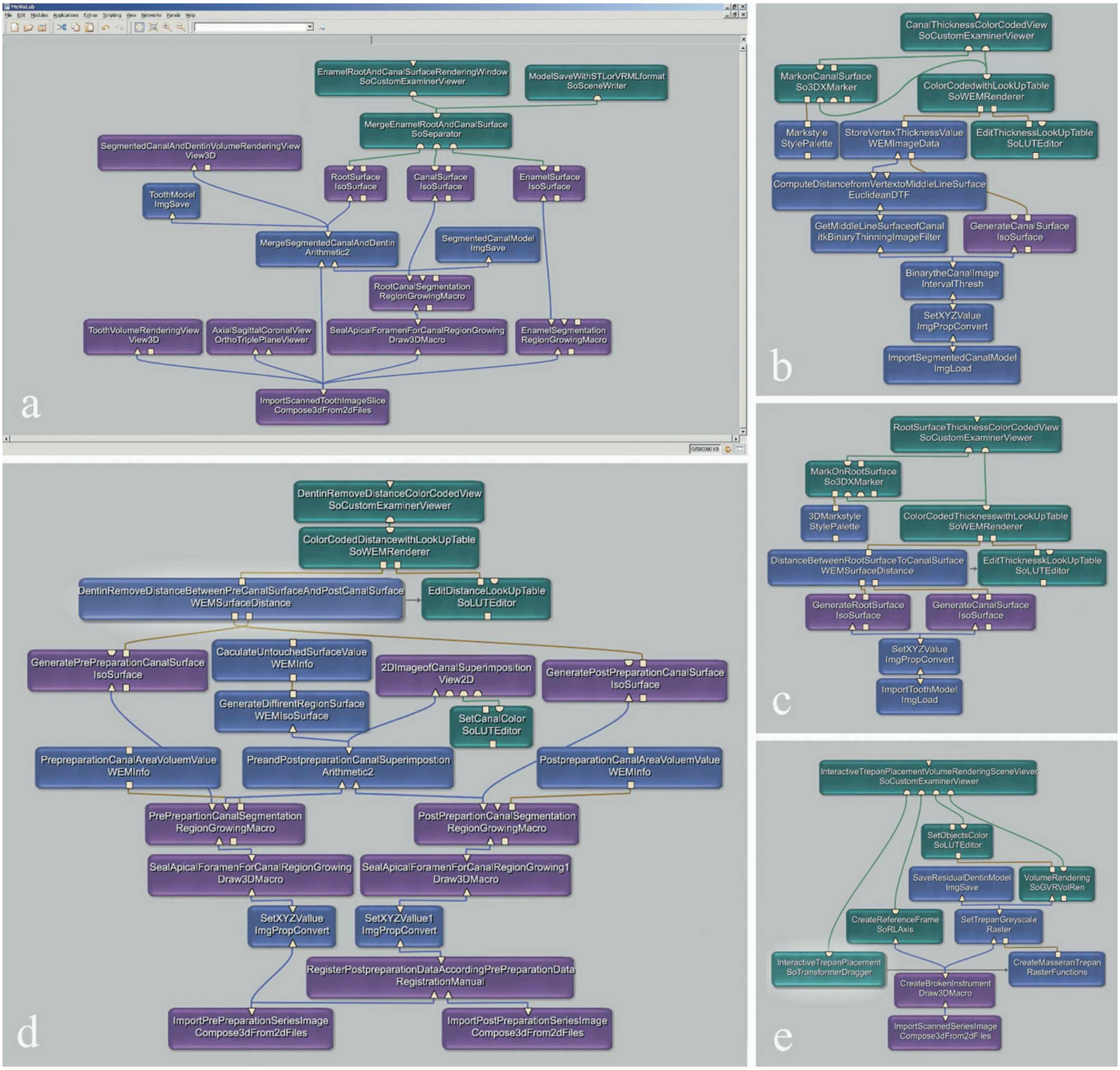

Figure 1. Customized framework example based on MeVisLab. (*a*) A representative MeVisLab network interface, workflow for step I for 3D reconstruction of tooth and canal; (*b*) step II for the root canal thickness measurement; (*c*) step II for the dentin wall thickness measurement; (*d*) step III for evaluation of root canal preparation; (*e*) step IV for risk analysis about virtual removal of broken instrument.

36 μm. A total of 580 cross-sectional slice images were acquired (tiff format), and the data were processed on an HP 8510W laptop computer (Hewlett Packard, Palo Alto, CA) running Windows XP.

Architecture and Description of the Application Framework

The MeVisLab package (available from www.mevislab.de/index.php?id=4) provides a visual data-flow program environment on its graphic user interface (GUI) (Fig. 1). The boxes on the GUI are called modules, and the wires connecting them are called data pipes. Each module encapsulates a specific function; it has a parameter panel providing a control to its functions, whereas the data pipes carry input and output data between them. Taken as a whole, the modules and data pipes comprise a data-flow framework.

Different functional application frameworks can be established with different image modules combined to complex image processing networks (Fig. 1). The capabilities and architecture of different frameworks are described in more detail.

Step I-3D: Reconstruction of Tooth and Canal

Segmentation of the root canal system, dentin, and enamel generated accurate 3D models. The individual steps of the workflow are shown in Fig. 1*a*. The major steps include the following: (1) import the scanned maxillary molar image and build 3D dataset; (2) draw a region up to the apical foramen to separate the canal into individual spaces with Draw3DMacro module; (3) segment the canal and enamel with

RegionGrowingMacro module; and (4) create the rendering views of the canal, dentin, and enamel structures.

Step II: Geometry Measurement of Tooth and Canal

Geometry quantification relies on accurate segmentation of root canal and hard tissue, dentin, and enamel. The maxillary tooth canal models were created by step I framework. The geometry measurements including 2 frameworks and the steps of the workflow are shown in Fig. 1*b, c*.

Root canal diameter (thickness) measurement and color coding were done according to these major steps (Fig. 1*b*). (1) Import segmented canal model created in step I. (2) Find a voxel surface in the middle line of the canal model with the itkBinaryThinning module. (3) Generate a polygonal surface of canal with the IsoSurface module. (4) Use the EuclideanDTF module computes for each node distance from the canal middle line surface to the polygonal surface. (5) Use these values with the SoWEMRenderer module to obtain a color with SoLUTEditor module; the color on the surface represents the distance of the region of the surface to the computed middle line surface, with the canal diameter (thickness) acquired accordingly.

The dentin wall thickness measurement was expressed as color-coded reconstructions. The major steps to achieve this included the following (Fig. 1*c*). (1) Import tooth model created in step I. (2) Generate a polygonal surface of canal and external root surface. (3) Calculate the minimal distances from the canal surface to the external root surface with the WEMSurfaceDistance module. These distances are stored in the nodes for a later color-coding and analysis. (4) A 3D mark also can be placed on the surface to obtain minimum canal wall thickness by using set values in SoLutEditor module.

Step III: Evaluation of Root Canal Preparation

The framework was used in the evaluation of root canal preparation. The major steps included the following (Fig. 1*d*). (1) Import the scanned maxillary molar image and then register the pre- and post-preparation 3D dataset with the RegistrationManual module for canal superimposing and subsequent cross-sectional image analysis. (2) Investigate the cross-sectional images before and after canal preparation and calculate the untouched surface in the canal preparation 3-dimensionally. (3) Generate surface of canal before and after canal preparation for a graphic comparison of the change of canal shape, namely the amount of dentin removal during canal preparation.

Step IV: Risk Analysis During Virtual Removal of Broken Instrument

The framework is used in a perforation risk analysis during virtual removal of a broken instrument with the Masseran kit (MicroMega, Besancon, France). The Masseran kit consists of a number of differently sized trepans that cut a narrow parallel space around the broken instrument, allowing it to be released (23).

The steps of the workflow included the following (Fig. 1*e*). (1) Build a 3D dataset from the scanned maxillary molar image. (2) Create virtual broken instrument in the canal by using the Draw3Dmacro module. (3) Create virtual trepan and set the size of needed trepan by RasterFunctions0 module. (4) Interactively place the virtual trepan to a proper position around the broken instrument with the SoTransformerDragger0 module, and dentin is cut to form a narrow parallel space accordingly. (5) Save the residual dentin model for perforation risk analysis, namely the dentin wall thickness analysis by framework II.

Results

In step I, a 3D model of tooth and canal was constructed by manipulating high-resolution tomographic images. The 3D modeling and manipulation environment was able to present the model at high visualization quality (Fig. 2*a*) by using common hardware along with various rendering techniques. The step II framework provided 3D quantitative information with a color-coded map about the diameter (thickness) of root canal and the dentin wall thickness, which quantify the characteristics of the internal and external anatomy of a tooth, and evaluated the effect of treatment procedure on dentin thickness (Fig. 2*b*, *c*). This thickness information was visualized as a color-coded thickness map on the object's surface, allowing intuitive interpretation and measurement. Root canal thickness varied from 60 to 1233 μm; the thickness was the largest in the palatal canal and the smallest in the distobuccal. Radicular dentin wall thickness was greatest in the cervical portion of root (around 2800 μm) and least in apical portion of root (varied from 30–1000 μm).

In step III, the framework provided a 3D platform to study root canal preparation. Manual registration allowed a precise fusion between pre-preparation and post-preparation without using a special mounting apparatus, as indicated by subtraction of color-coded preoperative and postoperative images. Quantitative information about the volume and surface of canal, the volume of dentin removed, and the untouched surface during canal preparation was obtained; volume and area for mesiobuccal, distobuccal, and palatal canals, respectively, were 3.93 mm^3 and 40.44 mm^2, 1.96 mm^3 and 18.44 mm^2, and 5.01 mm^2 and 26.59 mm^3 preoperatively and 5.24 mm^3 and 43.1 mm^2, 3.19 mm^3 and 20.97 mm^2, and 5.75 mm^3 and 28.1 mm^2 postoperatively. Superimposition images of preoperative and instrumented canals revealed that 60.8% of the canal surface remained unchanged during preparation (Fig. 2*d–f*). Detailed morphologic changes of the canal shaped were assessed with a color-coded map.

The step IV framework can provide an environment that allowed interactively creating a canal preparation based on a typical Masseran kit trepan shape to simulate the course of broken instrument removal. Perforation risk and dentin thickness under different broken instrument depths and sizes of trepan chosen were simulated. An intuitive color-coded thickness map was generated for the visualization and measurement of residual dental wall thickness after instrument retrieval (Fig. 2*g*, *h*); in the present example, minimal dentin thickness was 682 μm.

Discussion

Quantitative tooth and root canal images allow better understanding of the anatomic features and variability in all 3 dimensions, which is essential to endodontic treatment and research (24). On the other hand, even though impressive qualitative results are obtained in most studies, some special quantitative outcomes are often missing. This restriction is understandable, considering the lack of available software for this purpose (15).

The package used in this proof-of-principle, MeVisLab, contains a large set of powerful functions and allows the researcher to customize the application for their specific requirements with a user-friendly and easy to use interface. In this study, an application framework was introduced; thus no statistically supported conclusions were drawn concerning the instrumentation techniques used.

The present experimental results illustrated the performance of the framework and usefulness of the results for medical image analysis applications. In fact, some data generated for the example tooth were quite similar to those reported earlier with dedicated measurement software such as fully custom programs and VGStudio Max (Volume-Graphics, Heidelberg, Germany) used by others (15, 25).

In the first example, a framework was designed to build 3D tooth and canal models. These models can be used for more advanced appli-

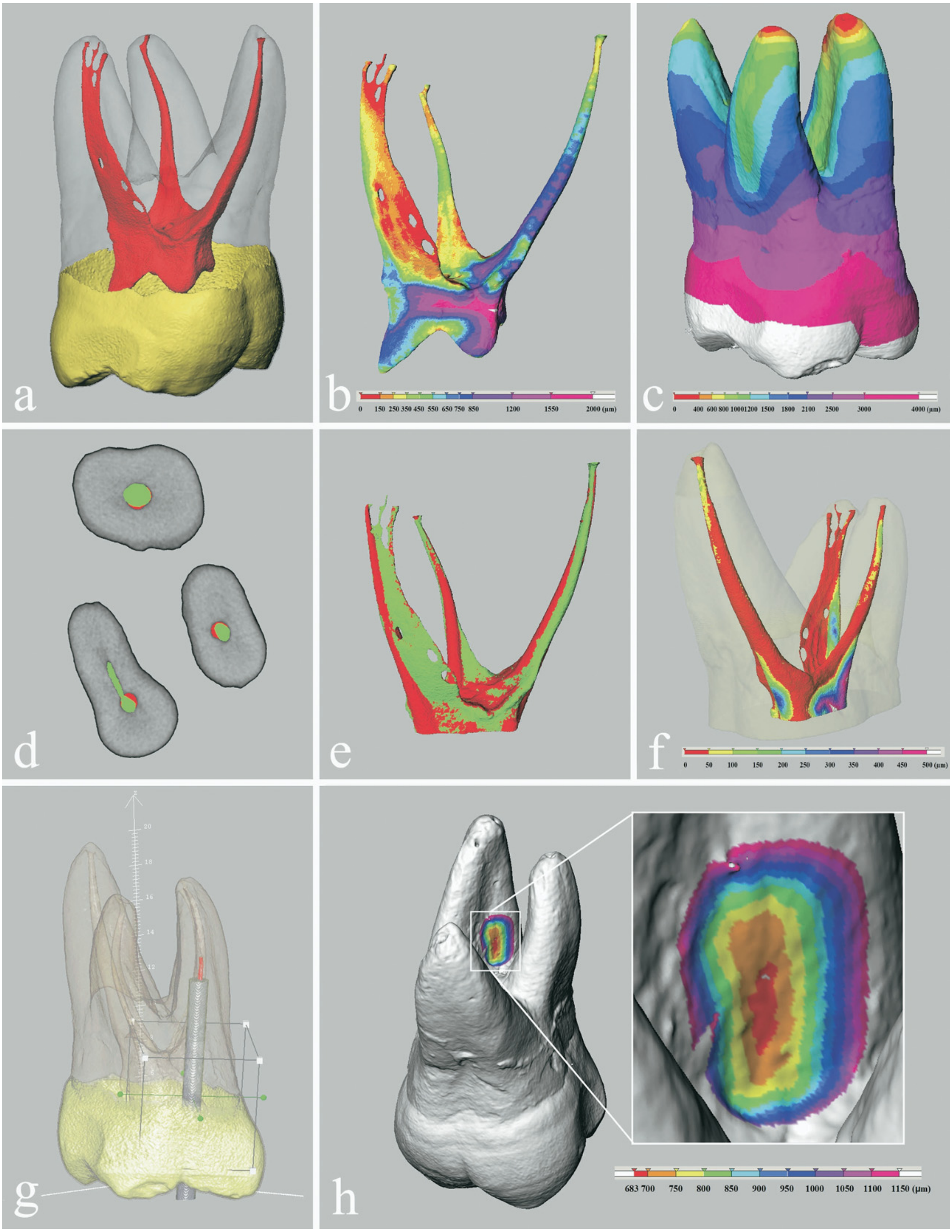

Figure 2. Morphologic reconstruction and measurement potential. (*a*) 3D image shows the enamel, dentin, and root canal with surface rendering. (*b*) 3D color-coded image shows the canal thickness distribution; the bar indicates the thickness expressed in μm. (*c*) 3D color-coded image shows the thickness distribution between tooth external surface and canal surface. (*d*) Canal shape changes of post-preparation cross sections (red) superimposed with pre-preparation canal shapes (green). (*e*) 3D color compound figures: (red), the change of canal shapes in post-preparation; (green), pre-preparation canal systems. Mixed colors indicate summation; the green color shows the untouched surface during shaping. (*f*) Color-coded distance image of the change of canal shape during the instrumentation, and the distance also shows the amount of removed dentin. (*g*) Placement of a virtual Masseran trepan around the artificial broken instrument. (*h*) 3D color-coded image of residual dentin thickness distribution around the narrow parallel space in root dentin created by virtual Masseran trepan. Note the red areas, which indicate the danger zone of dentin.

cations. Thickness information is intuitively useful when considering root fractures and perforation of dentin. However, because of limitations in previous methods, the thickness relationship between the external and internal morphology of the root complex is, in general, poorly understood. Thickness measurements in previous works were based on 2D processing (26–29) rather than utilizing the full 3D potential of micro-CT data.

Root canal dimensions expressed as thickness can be directly related to file size and represent the diameter of the reconstructed root canals (30). In this study, the framework allowed rapid calculation and visualization of 3D thickness information of dentin and canal, including a color-coded map providing a useful and intuitive tool in education, research, and clinics to study the morphology of canal and tooth.

Micro-CT is an ideal tool for research assessing the effects of root canal instrumentation techniques on canal shape. In the present study, the ability to geometrically register the image data before and after instrumentation was an indispensable aspect for superimposition and the precise evaluation of the changes of canal shape. This procedure is mandatory for quantitative comparison and was easier than the previously described procedures that rely on a special mounting device for superimposition (8). After the superimposition of the canal models (pre- and post-preparation), an effort was made to measure instrumentation characteristics quantitatively in 3D. Accordingly, numeric values for canal surface area, volume; volume changes, untouched surface, and the thickness of dentin removed were obtained. Preparation errors such as zipping, canal straightening, ledging, or elbow formation can also be readily evaluated by using the color-coded reconstruction.

The use of subtracted red-green images clearly demonstrated where material had been removed during instrumentation and where no changes occurred during preparation. Cross-sectional images could be used to demonstrate and measure canal transportation. The effect of both instrumentation and preoperative canal anatomy on dentin wall thickness also can be analyzed quantitatively by the illustrated system. With the use of framework shown in step III, researchers can evaluate and refine canal preparation techniques, enabling manufacturers to improve product design.

For many tasks in computer-aided dental visualization, it is not sufficient to display the visualization of tooth data; there is an increasing demand for performing simulations on the basis of 3D data for therapy planning and evaluation (31).

The success of broken instrument removal from root canals depends on several factors. Among them are the length and site of the fragment and the diameter and curvature of the canal (32). Step IV in the framework used here provided a powerful platform in editing, manipulation, and simulation of these factors in different conditions in 2D and 3D; it also permitted the quantification of the theoretical effect of an instrument removal attempt on radicular wall thickness. With the technological advances of recent years, in vivo cone beam computed tomography (CBCT) has been used for several clinical and investigational purposes in endodontics. It offers relatively high-resolution images in comparison with medical-grade CT images for effective evaluation of root canal morphology, root and alveolar fractures, and presurgical planning in root-end surgeries (33–35). CBCT has a lower radiation dose than in vitro micro-CT or in vivo peripheral quantitative CT (4); together with the framework based on MeVisLab, CBCT will enable endodontists to clinically simulate procedures, to select tools and techniques, and to perform a benefit/risk analysis before removal of a separated instrument.

In conclusion, the application framework based on MeVisLab enables a standardized method of 3D reconstruction and measurements of canal and teeth scanned by micro-CT. This provides powerful and promising tools widely available for solving 3D problems in contemporary endodontic research.

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