Clin Oral Invest (2009) 13:43–46
DOI 10.1007/s00784-008-0198-4

SHORT COMMUNICATION

Construction of three-dimensional tooth model by micro-computed tomography and application for data sharing

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Received: 17 August 2007 / Accepted: 5 March 2008 / Published online: 3 April 2008

Abstract The study of dental morphology is essential in terms of phylogeny. Advances in three-dimensional (3D) measurement devices have enabled us to make 3D images of teeth without destruction of samples. However, raw fundamental data on tooth shape requires complex equipment and techniques. An online database of 3D teeth models is therefore indispensable. We aimed to explore the basic methodology for constructing 3D teeth models, with application for data sharing. Geometric information on the human permanent upper left incisor was obtained using micro-computed tomography (micro-CT). Enamel, dentine, and pulp were segmented by thresholding of different gray-scale intensities. Segmented data were separately exported in STereo-Lithography Interface Format (STL). STL data were converted to Wavefront OBJ (OBJect), as many 3D computer graphics programs support the Wavefront OBJ format. Data were also applied to Quick Time Virtual Reality (QTVR) format, which allows the image to be viewed from any direction. In addition to Wavefront OBJ and QTVR data, the original CT series were provided as 16-bit Tag Image File Format (TIFF) images on the website. In conclusion, 3D teeth models were constructed in general-purpose data formats, using micro-CT and commercially available programs. Teeth models that can be used widely would benefit all those who study dental morphology.

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Keywords Tooth morphology · Micro-computed tomography (micro-CT) · Three-dimensional tooth model · Data sharing

Introduction

The study of dental morphology is a basic and essential theme in dental science. It is very important for clinicians to understand dental form and internal structure in three dimensions. Various aspects of tooth geometry and size have been investigated for tooth forms. For instance, morphologic studies using contour lines [8] or longitudinal sections of plaster crown models [6] have been performed in order to understand and quantify tooth configuration.

With advances in three-dimensional (3D) measurement devices, geometric data can be obtained more rapidly. Analysis of morphology based on 3D information is efficient, as it enables morphometric evaluation of internal and external structure without sample destruction [1, 4, 10]. In recent years, the mechanism of tooth development, particularly positional information on morphogenesis factors, has been elucidated [5, 7]. Geometric analysis using teeth models is thus vital. However, raw fundamental data on tooth shape require complex equipment and techniques. Therefore, teeth models that are widely available would benefit all people who study dental morphology.

3D teeth models containing anatomical information in versatile data formats are therefore indispensable for use as basic data. Such teeth models may be useful in determining morphogenesis factors in association with geometrical analysis. The aim of this study was to demonstrate the process for constructing teeth models and application for data sharing.

Materials and methods

Acquisition of tooth shape data

The specimen was permanent upper left incisor extracted from a Japanese individual and belonging to the first department of anatomy of Aichi Gakuin University. The specimen had no tooth substance defects or caries. The present study was approved by the Ethics Committee of Aichi-gakuin University (no. 67).

Information on the internal structure of the specimen was obtained using micro-computed tomography (micro-CT; SMX-225CT-SV, Shimadzu, Japan) in cone-beam method from the root apex to the incisal edge, under the following conditions: pixel matrix, 512×512; tube voltage, 70 kV; tube current, 50 μA; 1,200 views; slice thickness, 60 μm. Each voxel consists of a 60-μm isotropic cube. A tooth axis determined by the line passing the tooth center perpendicularly [2] was set up vertically to the stage. The scanning time of the tooth was 55 min. Exported data from the micro-CT machine were in RAW data format. The size of the resulting file was 2.4 GB, and 360 sliced images were obtained. The hardware used to process these data was Dell workstation PWS650 Intel® Xeon (CPU, 3.06 GHz).

3D reconstruction from the sliced images was performed using 3D reconstruction software (VG Studio Max, Volume Graphics GmbH, Germany). Tag Image File Format (TIFF) data were used to import the sliced images to VG Studio Max. There were some artifacts and noise from micro-CT data, and this was corrected by filtering when the images were reconstructed.

Segmentation and conversion of data format

Enamel, dentine, and pulp were segmented by thresholding of different gray-scale intensities. Cementum could not be distinguished from dentine on micro-CT images, as the gray scale is based on degree of calcification. Extracted enamel, dentine, and pulp data were separately exported in STereo-Lithography Interface Format (STL; 3D Systems, USA). STL is used for data transition from Computer Aided Design (CAD) software to 3D modeling software. STL data consist of small triangles, which produce a polygonal model. STL data were converted to Wavefront OBJ (OBJect; Autodesk, USA) file format by means of format-conversion software (VVD2RGL; Medic Engineering, Japan). Wavefront OBJ format, which consists of point coordinates and polygon information, is commonly used for 3D computer graphics (CG) software. Data were converted to Wavefront OBJ from STL, as many 3D CG programs support the Wavefront OBJ format. Simultaneously, overlapping coordinate points were checked and removed automatically by VVD2RGL. A Dell Precision M65 Intel® Core™ (CPU, 2.00 GHz) was used for data segmentation and conversion.

Application of 3D tooth model and online publication

Wavefront OBJ data were imported into 3D CG software (Shade 8.5 Professional; e-frontier, Japan). The sequence of tooth model construction is shown in Fig. 1. Data were then posted online in order to demonstrate the feasibility of this model.

Results and discussion

The sizes of the Wavefront OBJ data files for enamel, dentine, and pulp were about 8.5, 8.0, and 1.8 MB, respectively. A 3D tooth model was successfully developed and converted to a versatile format using various applications. Wavefront OBJ data for enamel, dentine, and pulp in the permanent upper left incisor were imported into 3D CG software. All data were located on the same axis of coordinates. Surface information on the tooth was not obtained from the gray-scale image data. The tooth model had only geometric information. Therefore, we set up colors and textures using color and material mapping. There is another method using texture mapping with 2D photos. However, color and material were arbitrarily adjusted in the 3D CG software in the present study. Pulp is visible by specifying high transparency in enamel and dentine. The model was rendered after these configurations were adjusted. Moreover, the tooth model was converted to Quick Time Virtual Reality (QTVR) format using Shade 8.5 Professional. The QTVR model enables the user to freely manipulate solid images from various directions.

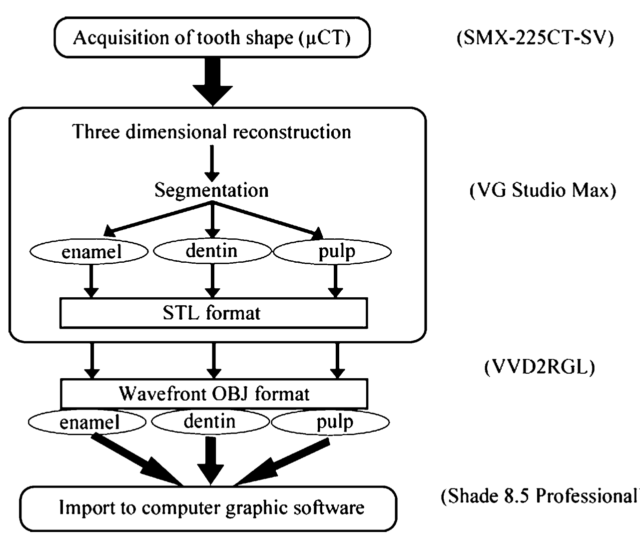

Fig. 1 Scheme for construction of tooth model. Software is listed on the *right*

Wavefront OBJ, QTVR data, and 359 original 16-bit TIFF images were then uploaded onto the Internet (http://www.agu.ac.jp/~a-kato/English/index.html; Fig. 2).

In recent years, applications of image analysis systems have spread dramatically in clinical practice and laboratory study. Cone-beam CT is used for preoperative planning of implant placement [3], for instance, or diagnosis of periapical lesions [12]. However, assessment of narrow space such as periodontal ligament space is accurately performed with conventional radiography [9]. Meanwhile, using innovative micro-CT techniques, the internal structure of small objects such as teeth can be investigated non-invasively. In geometric teeth models obtained using micro-CT, the surface areas or volumes of dental tissues in molars have been calculated [4, 10]. Micro-CT has been also successfully used to measure enamel thickness in teeth [13]. The 3D data obtained by micro-CT thus allow geometric analysis, as described above.

Data captured by micro-CT are presented as several hundred slices of image data. These images are retrieved by 3D reconstruction software and are visualized as a 3D

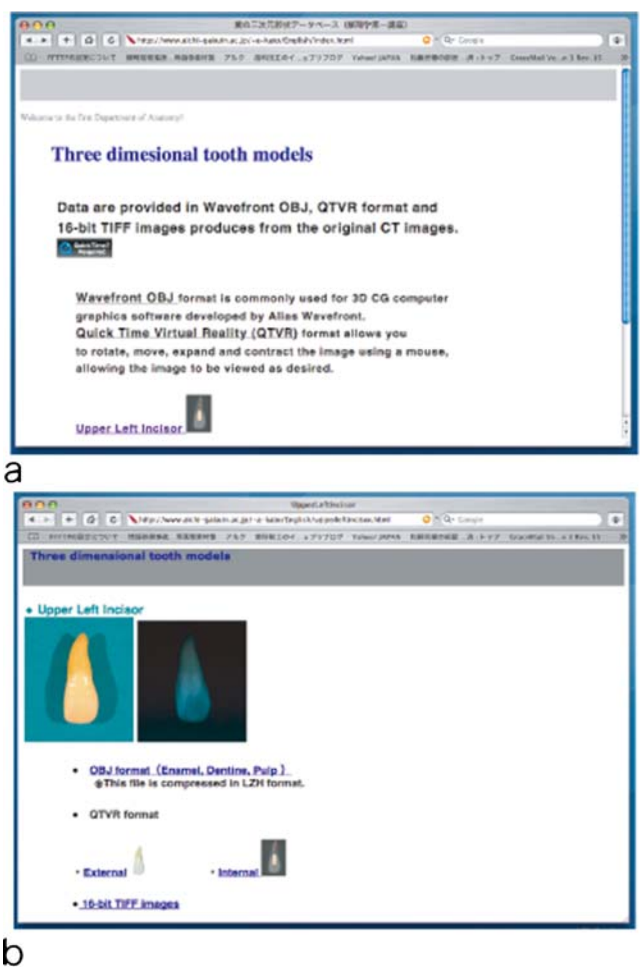

Fig. 2 Data were made available on the Internet. Figure shows the download site (**a**, **b**)

structure only after this reconstruction process. To visualize the data, 3D reconstruction software is required. Moreover, it is difficult for users with different software to share these data. Therefore, the format of 3D tooth model data must be versatile, and it may then be saved as a basic resource. Brown and Herbranson established a huge 3D database of human dentition for use in dental education (http://www.brownandherbranson.com/index.shtml). They constructed 3D teeth models and developed interactive computer programs. In contrast, we constructed 3D teeth models for sharing as basic geometrical data. We converted the data to Wavefront OBJ from STL. STL data consist of coordinates and normal triangles. Vertices of the triangle need to be shared with other triangles. Therefore, STL data files are very large. In the present study, the size of each STL file was about 13.6 MB for enamel, 13.0 MB for dentine, and 3.0 MB for pulp. Common file formats other than Wavefront OBJ include Drawing eXchange Format (DXF, Autodesk, USA), which is also used in CAD and CG software. However, DXF has a different file structure with different versions of Autodesk, and the description of data structure is complex when compared with Wavefront OBJ, while data file size is also large. Therefore, we used Wavefront OBJ file format in the present study.

A series of 16-bit TIFF images produced from the original CT images are also provided on the website. It would be more useful if continuous images were available for 3D reconstruction using volume graphic software. Such 3D geometric data and teeth models would therefore have various applications in dental research, particularly in facilities lacking expensive equipment.

There have been several reports on the development of 3D teeth models using micro-CT. Finite element models of mandibles and dentures have been constructed using micro-CT [11]. In that study, STL data were converted to Initial Graphics Exchange Specification (IGES), which is a commonly used format for 3D CAD software. At the same time, 3D finite element models with resin restoration were successfully developed and tested in order to study the optimal design and geometry of restorations [14]. In that report, the data format was not described, but the model was said to be “too detailed and complex when variations in the geometry of teeth and restorations are considered.” Therefore, such models must be simplified in order to reduce the quantity of data, particularly when publishing these models online. We also created QTVR images of teeth models for use as educational tools. QTVR allows the image to be viewed from any direction, and the 3D image can be rotated using a mouse or be made to spin.

At present, model quality is insufficient, and various aspects need to be improved. First, 3D reconstructed surface models appear as contour line-like level differences. These are called ‘rings’ artifacts. To make the models smoothly curved, data smoothing must be performed during reconstruction. In addition, the created wire frame models are crude, and the size and shape of triangles are irregular. When the model is used for geometric analysis, the number of polygons has to be integrated, and the mesh needs to be corrected.

In the present study, we only described the sequence from acquisition of data to developing the model to explore the basic methodology. In conclusion, a 3D tooth model was constructed from data obtained by micro-CT. These data were converted to a general-purpose format in combination with various applications and can be shared over the Internet, which allows for widespread utilization.

Acknowledgments We would like to express our sincere gratitude to Mr. Masahito Natsuhara of Shimadzu Corporation for assistance with the micro-computed tomography system. This work was supported by a grant-in-aid for the "High-Tech Research Center" Project for Private Universities, with a matching fund subsidy from the Ministry of Education, Culture, Sports, Science and Technology of Japan, 2003-2007 (no. 2003).

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