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"High-precision, reconstructed 3D model" of skull scanned by conebeam CT: Reproducibility verified using CAD/CAM data

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ABSTRACT

Computed tomography (CT) scanning has recently been introduced into forensic medicine and dentistry. However, the presence of metal restorations in the dentition can adversely affect the quality of three-dimensional reconstruction from CT scans. In this study, we aimed to evaluate the reproducibility of a "high-precision, reconstructed 3D model" obtained from a conebeam CT scan of dentition, a method that might be particularly helpful in forensic medicine.

We took conebeam CT and helical CT images of three dry skulls marked with 47 measuring points; reconstructed three-dimensional images; and measured the distances between the points in the 3D images with a computer-aided design/computer-aided manufacturing (CAD/CAM) marker. We found that in comparison with the helical CT, conebeam CT is capable of reproducing measurements closer to those obtained from the actual samples.

In conclusion, our study indicated that the image-reproduction from a conebeam CT scan was more accurate than that from a helical CT scan. Furthermore, the "high-precision reconstructed 3D model" facilitates reliable visualization of full-sized oral and maxillofacial regions in both helical and conebeam CT scans.

1. Introduction

In the field of forensic medicine, to solve cases involving an unidentified cadaver, as well as to elucidate a cause of death, it is essential to identify the deceased individual. As the recent increase in international travel has rendered foreign visitors of multiple and complex origins more susceptible to becoming victims of crimes or major disasters in Japan, there has been a growing necessity to obtain a diverse range of information, including data from morphological tests, information on DNA polymorphisms, and dental findings, in order to identify an unknown person.

In Japan, all citizens are covered by national health insurance, so the percentage of people receiving dental treatment is high. Dental treatment histories are stored as dental records and in other forms. These data have often been utilized for identification of cadavers. The significant usefulness of dental data was primarily recognized during major disasters, as in the airplane crashes in 1985 and 1994. Additionally, on March 11, 2011, in the Great East Japan Earthquake, more than 15,000 people were killed. According to a report by the National Police Agency released on May 11, 2012 (one year after the calamity), 15,452 cadavers (97.9%) had been identified, and dental information had been used for identification in 7.7% of all cases [1]. Two-dimensional (2D) data (dental charts, oral-cavity pictures, X-ray images, etc.) have often been used for analysis of dental information collected from cadavers.

In the meantime, three-dimensional (3D) reconstruction from computed tomography (CT) imaging has also been introduced to the field of forensic medicine. To date, a few actual cases has been reported on the practical utility of this approach exercising the superimposition technique, based on 2D data, such as facial pictures [2,3]. This approach is expected to be applied more extensively in the future because of its advantages, including the capability to collect internal observations without injuring the body and the possibility of permanent storage in the form of highly reproducible digital information. Meanwhile, the helical and conebeam CT techniques have advanced remarkably in recent years [4–6]. Conebeam CT is known for its high resolution, particularly in the oral and maxillofacial regions. Examples of clinical applications of 3D conebeam CT imaging in the field of dentistry have been reported [7–9]. From the viewpoint of reproducibility, however, conebeam CT does not allow the quantitative evaluation of

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the accuracy of its image reproduction, because, unlike helical CT, conebeam CT scanning does not allow dimensional measurement with CT values. Published reports in the past concerning the accuracy of image reproduction have usually involved a method of averaging the visually measured distances multiple times from the measurement points by using calipers or 3D imaging software [10,11]; to our knowledge, no report has yet described the precise assessment of image-reproduction accuracy using real samples. On the other hand, in order to use conebeam CT data in forensics, a precise assessment of this method's accuracy is necessary. Therefore, such an assessment corroborating 3D conebeam CT images using dental record findings would be immensely useful during the routine work.

In doing so, however, utilizing conebeam CT in reconstructing a 3D image entails a problem of metal artifacts. Many of the dental findings that are useful in identification of cadavers pertain to traces of dental treatments. The presence or absence of these traces on each tooth and the details regarding the forms, materials, etc. of the tooth restorations in any given cadaver must be compared with information collected from antemortem data. Therefore, the probability of identification increases with the number of indicators of dental treatment. However, the metallic materials used for crown restoration cause metal artifacts on CT images. These artifacts make it difficult to assess the maxillofacial area on CT images and affect 3D image reconstruction.

To minimize the influence of metal artifacts and to facilitate acquisition of 3D surface data, a prototype of a CT dataset, in combination with a corresponding plaster-model surface dataset, had been devised in a past study [12]. By using the same method in our previous study, we also created a plaster model of the maxillomandibular dentition. Subsequently, we tried to supplement the dentition data obtained via CT with 3D dentition data, in order to prevent the findings from being influenced by metal artifacts. We reported that this system was able to provide quantitative dental and clinical evaluations of tooth-adjustment configurations [13,14]. We named this technique "high-precision, reconstructed 3D".

Superimposition and facial restoration as to the morphological applications were generated by 3D-CT image reconstruction. Therefore, the aim of this study was to confirm the reproducibility of the "high-precision, reconstructed 3D model" obtained from conebeam CT as a forensic method. We assessed the reproducibility by comparing the performance with helical CT data, using a marker of computer-aided design/computer-aided manufacturing (CAD/CAM) respectively. CAD/CAM system has made a rapid progress in the field of dentistry. The technology is used for the making of dental restorations and prostheses that are highly complex and delicate, and requires high precision and measuring in the digitizing of the three-dimensional space [15,16]. By setting the reproduced marker on the measuring point using this system, we are able to more accurately verify the reproducibility. In addition, we evaluated the influence of the size and extent of metallic materials, as well as the metal artifacts on reproducibility.

2. Materials and methods

The Department of Anatomy, Tsurumi University School of Dental Medicine provided three dry skulls for this study. We selected skulls that had many residual teeth and that differed from each other in terms of dental treatments, including metal contents, and labeled them skull A, skull B, and skull C respectively. Skull A had no trace of treatment with metals. Skull B contained a small number of metallic restorative materials, such as a metal inlay and a crown. Meanwhile, skull C contained many restorative materials (crowns, bridge prosthetics, etc.) in the residual maxillomandibular teeth (Fig. 1).

2.1. Data collection

On each sample, 47 points of measurement were set [17]. A waterproof film (0.047 mm) (ASO Pharmaceutical Co, Ltd. Kumamoto, Japan) was attached to each sample, and a stainless-steel marker (3 mm, JIS) was placed over it by using Aron Alpha adhesive (TOAGOSEI CO, LTD, Tokyo, Japan). Occlusion before death was reproduced, followed by fixation of the upper and lower teeth and the temporomandibular joints (Fig. 2).

2.2. Original size measurement

While each sample skull was kept fixed on the working table, we measured five places of coordinates about each marker plotted on the skull using a Faro Gage Plus (FARO Technologies, Inc, Lake Mary, FL, USA). From the coordinates of these 5 sites, the center-of-mass coordinate of the markers was calculated. To determine the original size of each skull, the distances between each pair of measurement points (Table 1) were measured as center-of-mass distances.

2.3. CT scanning and segmentation

Each sample was scanned by conebeam CT (Conebeam CT, Alphard, Asahi Roentgen Ind Co, Ltd, Kyoto, Japan) and helical CT (RADIX-Prima, Hitachi Ltd, Tokyo, Japan). Then, the threshold was set using Amira 4.1 (Mercury Computer Systems, Chelmsford, MA, USA) for automated bone-surface processing and subsequent manual processing of artifacts on the images. Three-dimensional image reconstruction was carried out using this approach.

2.4. Preparation of high-accuracy reconstructed 3D images

The next step was to take an impression of the teeth in each sample skull, in accordance with the method described by Ikawa et al. [14], to yield a working model. Using a 3D scanner (Tsurumi University Prototype, Shofu Inc, Kyoto, Japan), 3D surface data from the working model were collected. The original data of the maxillomandibular teeth in the reconstructed 3D model were, then, replaced with this model surface data taken from the working model. In registrating the two data sets of the 3D models, namely the original model and the working model, we used ICP algorithm performed by a three-dimensional image processing software (EZ Scan, Solutionix Soal, Korea), and merged the two data sets using three-dimensional modeling software (FreeForm, SensAble NC, USA), thus, completing a "high-precision, reconstructed 3D model".

2.5. Measurement of the high-accuracy reconstructed 3D images

The 47 markers on the bone were reconstructed in 3D from the CT images. These markers were subsequently converted into CAD/CAM data, 3 mm in diameter, to determine the center-of-mass coordinates in the image processing software (Fig. 3). We also measured the distance between each pair of measurement points on the "high-precision, reconstructed 3D model" using CAD/CAM markers placed on the corresponding points with VRMesh v4.1.2 Studio (VirtualGrid, Seattle City, WA, USA).

2.6. Accuracy assessment

The measurement data from the "high-precision, reconstructed 3D model" obtained from the conebeam and helical CT images were compared with the original sizes calculated in Section 2.2. The reproducibility of conebeam CT and Helical CT was compared by Wilcoxon-Signed Rank Test. These analyses were carried out SPSS Ver22.0 software (IBM, Somers, NY, USA).