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A New Method for the Integration of Digital Dental Models and Cone-beam Computed Tomography Images

Hsiu-Hsia Lin, Wen-Chung Chiang, Lun-Jou Lo, and Chien-Hsuan Wang

***Abstract*—This study introduces a regional-surface-based registration without markers for integration of laser-scanned dental images into maxillofacial cone-beam computed tomography (CBCT) images. The method just needs to manually select three similar areas without artifact on the digital dental image and CBCT image, and then the process is automatically complete the fusion (superimposition) of maxillofacial model and the digital dental model. Then the differences such as mean error and root-mean-square (RMS) error are automatically computed between the 2 images according to the selected surfaces and expressed in a color scale. Experimental results show that the mean errors between the 2 models at the integrated model range from 0.15 mm to 0.45 mm and the RMS errors range 0.18 mm to 0.49 mm. The numbers are similar to the results of previous methods and reach a desirable error. Moreover, it is robust feasibility for especially serious artifacts CBT images. It is worth mentioning that all measurements of intra-operator reproducibility and inter-operator reliability are excellent.**

I. Introduction

A number of studies have been integrated the maxillofacial CT bone model with digital dental models obtained from a laser scanner, enabling a simultaneous 3D representation of the skeletal structure, teeth, and occlusion. Previous research results can be classified into 3 categories: fiducial markers method [1-3], triple CBCT scan method [4, 5] and surface-based method [6-9]. In a fiducial makers method, Titanium spheres, ceramic balls, softened gutta percha or facebow are used in these studies. Although all these techniques suggest an acceptable degree of registration accuracy, the procedures are rather complicated for practitioners. In the “triple” CBCT scan method, their approach did not use fiducial markers for registration while the subjects are scanned with CT more than once. This method involves additional radiation exposure and it should be avoided. The Surface-based method is carried out by using an iterative closest point algorithm, and its errors were evaluated by measuring the 3D Euclidean distances between the surface points on the 2 images. But it is limited by normal occlusion, no missing teeth and no prosthetic crown restorations.

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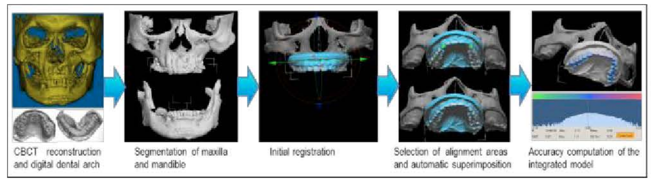


Figure 1. The integration flowchart.

In addition to the above-described problems, these studies either have no easy obtained or identification reference points/areas on dental model can be used as the selected alignment surface for registration. Moreover, no methods have been evaluated the intra-operator reproducibility and inter-operator reliability to show their technological stability and robustness.

The purpose of this study is to introduce a novel and simple regional-surface-based registration without markers for integration of laser-scanned dental images into maxillofacial CBCT images (including dental restorations). We implement the markerless fusion of digital dental model and the dental part of CBCT images (maxilla and mandible are fused separately) in 2 steps: first, dental model is moved to close maxilla/mandible and get an initial registration; then we select at least three similar areas without artifact in the digital dental model and dental part of CBCT and do the superimposition for integration of the two images. In order to evaluate the intra-operator reproducibility and inter-operator reliability, the same procedure is repeated twice by different operator for the same superimposition cases, and the differences over the operator and time are measured.

Our experimental results indicate that laser-scanned dental images can be integrated into the CBCT images with minimal error using the presented regional-surface-based registration without markers. After the registration of two images, the dental part of the CBCT images can be replaced with the digital dental images for clinical use.

II. The Proposed Method

The flowchart of our integration is shown in Fig. 1. To show that the presented method is feasibility in clinical environment, all cases with orthodontic brackets and dental restorations are included in our study. Our dataset contains 10 patients for evaluations who are provided by the Chang Gung Memorial Hospital.

A. Initial Registration

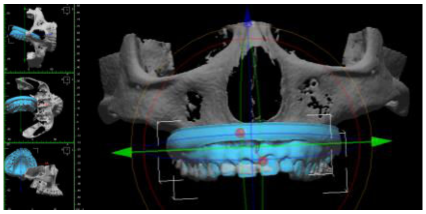


Figure 2. Digital dental model in blue and maxillofacial model from CBCT in gray are manually approached for the initial registration.

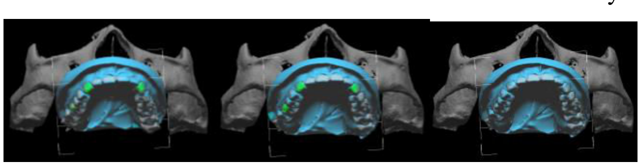
Image registration is the process of overlaying and integrating 2 images by tracing the common features. The features of the objects can be detected and matched manually or automatically based on the area or feature of region, line, and point [10, 11]. Iterative closest point (ICP) algorithm is frequently used to register 2 corresponding point sets generally by calculating the minimal distance for the closest points iteratively [12].

Our regional-surface-based fusion method is based on the iterative closest point (ICP) algorithm which is a registration technique to accurately align the 3D polygon mesh data sets of the digital models. In ICP algorithm, the corresponding points and shapes are searched from the surface information of data sets and then the distance is minimized after rotation and translation between 2 dataset. Before the superimposition processing, we manually conducted the initial registration of the digital dental model and CBCT model by ensuring that the corresponding reference points and shapes on the models are as close as possible. The processes are shown in Fig. 2.

B. Integration of the Digital Dental Model and CBCT Model

In this step, the digital dental model is integrated (superimposed) into the maxillofacial model according to the selected surfaces marked on the digital dental model by using the 3dMD Vultus software. First, at least three similar areas (surfaces) without artifacts are selected corresponding to each laser-scanned image and CBCT image. Subsequently, the presented regional-surface-based registration is automatically processed to finalize the fusion (superimposition) of maxillofacial model and the digital dental model. The process and result are shown in Fig. 3.

Here, regional-surface-based registration is performed with an iterative closest point algorithm, and its errors were evaluated by measuring the 3D Euclidean distances between the surface points on the 2 images, by using the "shell/shell deviation" function in the program [7, 8]. The relative distance values are used as the measurements in this study.



(a) (b) (c)

Figure 3. (a) The three areas are selected and shown in green at the teeth on digital dental image. (b) The superimposition is completed and based on the geometric information of the selected surface of two models. (c) The superimposition result without selected alignment surface visualization.

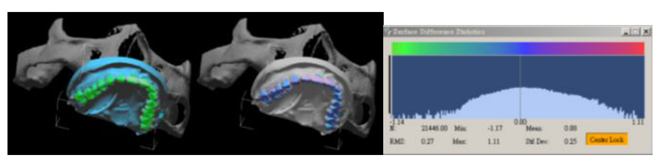
C. Accuracy Computation of the Integrated Digital Maxillofacial-dental Model

After completion of the superimposition, the relative distances (differences) between the selected surfaces (points) of maxillofacial model and the digital dental model are calculated for the evaluation of the integration accuracy. First, select all non-artifact surfaces as much as possible corresponding to each laser-scanned image and CBCT image on the integrated digital maxillofacial-dental model. Then the differences are automatically computed between the 2 images according to the selected surfaces and expressed in a color scale. Likewise, root-mean-square (RMS) error is used to compute the integration accuracy which is defined as the shared image information between 2 images after image fusion and indicated the degree to which the 2 images were superimposed. An RMS error above 0.05 mm is deemed a clinically important departure from the control value [13]. The accuracy computation of the integrated digital maxillofacial-dental model is shown in Fig. 4.

D. Statistical Analysis

To evaluate the intra-operator reproducibility of presented fusion method, all 20 objects superimposition are performed by one single operator and repeated twice by the same operator for the same object on the other day. Likewise, the superimposition is also completed by a different operator for all 20 objects to avoid the inter-operator-related bias.

Statistical analyses referred to here are carried out using SAS program in version 9.2. The analysis of the intra-operator reproducibility and inter-operator reliability is tested by the intra-class and inter-class correlation coefficient. The 2-way Analysis of Variance (ANOVA) is used to compare the mean errors associated with superimposition of the integrated model with different operations and operators for the same object. Wilcoxon Two-sample Test is used to compare the RMS in means with intra-operator and inter-operator for all objects. Differences are considered statistically significant at $p<0.05$.



(a) (b) (c)

Figure 4. (a) Non-artifact surfaces are selected and shown in green at the teeth on the digital dental image for superimposition. (b) Integration accuracy is computed according to the marked surfaces and expressed in a color scale. (c) The color-coded visualization charts show the differences between the 2 selected surfaces after superimposition.

III. Results

A. 3.1 The Visual Results

After integration of each digital dental image into the CBCT image, the accuracy of the integrated model is determined by measuring the discrepancies (in relative distances) between the 2 models, which are marked in color from blue (minimum, 0 mm) to red or green (maximum) as well as measured at some specific teeth point without artifacts.

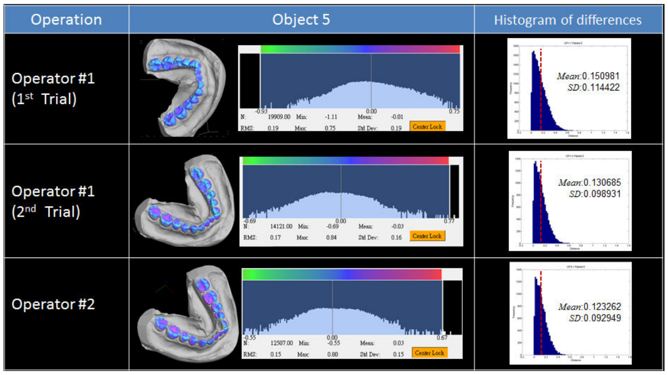


Figure 5. An example of registration result of maxillofacial model without artifact and the digital dental model.

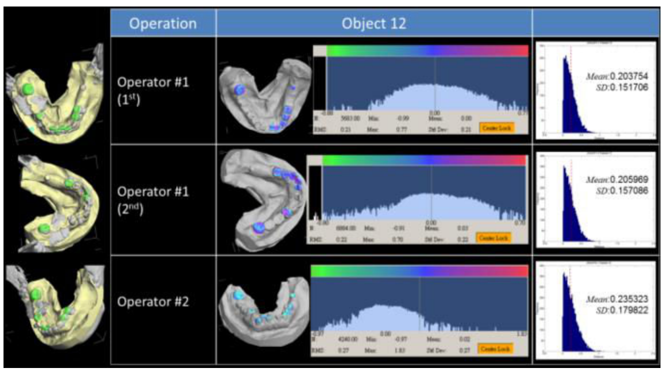


Figure 6. An example of registration result of maxillofacial model with serious artifacts and the digital dental model. The areas without artifact are selected and shown in green at the teeth on digital dental image for superimposition.

We give some examples of registration result of maxillofacial model and the digital dental model using the presented regional-surface-based fusion method, which are shown in Fig. 5 and Fig. 6 for non-artifact and serious artifacts in CBCT images, respectively. In this study, we take the absolute value for all differences since the absolute distance is a general representation for the discrepancies between the 2 images. Then the original color-coded visualization chart is changed into the histogram of absolute distances and the mean and standard deviation are computed.

In our approach, all 20 objects superimposition are performed by one single operator (called operator #1) and repeated twice by the same operator for the same object on the other day to evaluate the intra-operator reproducibility. The superimposition is also completed by different operator (called operator #2) for all 20 objects to evaluate inter-operator reliability. In order to present the results statistically meaningful, we divide all objects into three groups: non-artifact, serious artifacts and very serious artifacts group. However, not all of the objects can be successfully integrated. There are four objects with very serious artifacts on all tooth surfaces in the very serious artifacts group, which are failed to integrate in our experiments.

B. The Statistical Analyses

In addition to the visually representation, the means (absolute value) and RMS (see Fig. 5 and Fig. 6) are also be computed and used to quantitatively and objectively evaluate the distance between 2 images after superimposition. In our statistical approach, the 28 maxilla and mandible objects are divided into two groups according to artifacts for the distinction. These two groups are non-artifact and serious artifacts. Errors between operations and operators are measured and compared to verify the intra-operator reproducibility and inter-operator reliability.

The mean errors of intra-operator and inter-operator for non-artifact group, there is no significant difference between operations and operators (for all $p>0.05$) conditions on 2-way ANOVA.

The mean errors of intra-operator and inter-operator for serious artifacts group, there is also no significant difference between operations and operators (for all p>0.05) conditions on 2-way ANOVA.

The RMS errors of intra-operator and inter-operator for non-artifact group, there is also no significant difference between operations and operators (for all p>0.05) conditions on Wilcoxon Two-sample Test.

The RMS errors of intra-operator and inter-operato for serious artifacts group, there is also no significant difference between operations and operators (for all p>0.05) conditions on Wilcoxon Two-sample Test.

In our experimental results, all operations (inter-operator and intra-operator) have an RMS error of less than 0.05 (range from 0.0602 to 0.9074) so there are no clinically significant errors at our presented regional-surface-based fusion without markers method. Moreover, the results of p value for the intra-operator and inter-operator evaluation are within clinically acceptable margins.

IV. Discussion

Interocclusal relationship of maxillary and mandibular is very important in treatment plan of orthognathic surgery or the fabrication of surgical splints. However, the CBCT imaging does not precisely depict details of the tooth surface owing to some streaking artifacts caused by metallic dental restorations and orthodontic brackets. The 3D digital dental model obtained from a laser scanner can provide an accurate Interocclusal relationship of teeth for surgical planning. Combining CBCT model with digital dental model is a reasonable approach to correct metallic artifacts, allowing precise assessment of the tooth surface and accurate surgical simulation.

Previous studies have developed different methods for replacing the teeth in 3D CBCT model with plaster dental model and then the dentition in the CBCT images is replaced with the digital dental images. These methods include fiducial markers method, triple CBCT scan method and surface-based method; Swennen et al. use spherical gutta percha cone and the mean errors range from 0.1 mm to 0.3 mm; Gateno et al.

use titanium spheres and the mean errors range from 0.1 mm to 0.5 mm; Uechi et al. use ceramic balls and the RMS errors range from 0.01 mm to 0.3 mm. Noh et al. use Surface-based registration on the patients without metal attachments, such as orthodontic brackets and the mean errors ranged from 0.27 mm to 0.33 mm. They are successful in producing an accurate integrated digital maxillofacial-dental model. However, there remained some practical problems relevant to the clinical setting owing to its complexity, involving multilevel process for participants or good tooth surfaces in maxillary and mandibular model. In this study, we present a novel method to reduce the complex process of integration while maintaining its accuracy called regional-surface-based fusion without markers for the integration of digital dental models and CBCT images. Our results show that the mean errors between the 2 models at the integrated model range from 0.15 mm to 0.45 mm and the RMS errors range 0.18 mm to 0.49 mm. The worse results of mean error and RMS error are seen in the serious artifacts group. In contrast, the non-artifacts group shows excellent accuracy, with largest mean error of 0.28 mm and the largest o RMS of 0.33 mm. The numbers are similar to the results of previous methods.

Actually, some cases will fail to integrate in our experiments. All of the tooth surfaces have very serious artifacts causes we cannot find at least three independent regions as the fusion alignment on the segmented maxilla or mandible arches (an example with very serious artifacts is shown in Fig. 7). For this type of very serious artifacts, the fiducial markers method should be the only solution.

In conclusion, our method is robust simple to use in clinics then the process is automatically complete the fusion. The procedure just needs to manually select at least three similar areas without artifact on the digital dental image and CBCT image, and then the process is automatically complete the fusion (superimposition) of maxillofacial model and the digital dental model. Another important finding of this study is that all measurements of intra-operator and inter-operator have no statistically significant difference. In other words, our method is robust against operator/operation dependent variability for the integration of the digital dental model and CBCT model. This finding indicates that the study is reproducibility reliability. The accuracy of the integrated model seems to be sufficient for reasonable virtual a treatment plan of the post-operative dental occlusion and orthognathic surgical simulation. By using the presented method, digital dental models with accurate occlusal relationships can be directly incorporate into a CBCT model and then the dental part of the CBCT image can be replaced with the digital dental image for clinical use, such as a good treatment plan, more credible orthognathic surgery simulation., improvement in prediction of the treatment results and more realistic simulation of the post-treatment outcome.

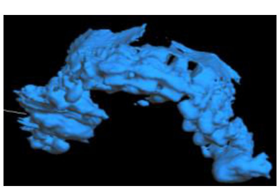


Figure 7. The maxilla with metal restorations causes very serious artifacts..

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