CBCT-guided 3D Dental Structure Reconstruction from Panoramic X-ray: A Preprocessing Pipeline

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Abstract

Panoramic Radiography and Cone Beam Computed Tomography (CBCT) are the most used imaging techniques for implant treatment and oral surgery. However, it cannot be used frequently due to the high cost and radiation exposure of CBCT. Whereas Panoramic x-rays do not provide the high dimensional information necessary for planning surgery. Our research aims to produce an automated method for reconstructing a 3D dental structure from a single panoramic X-ray. This paper presents a robust preprocessing pipeline of CBCT data which are exploited to train a deep learning model for reconstructing the 3D dental structure from a single 2D panoramic X-ray image. It includes a method of generating a pair of synthetic panoramic X-rays and the corresponding flattened 3D volume as ground truth from CBCT data.

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Abstract *Panoramic Radiography and Cone Beam Computed Tomography (CBCT) are the most used imaging techniques for implant treatment and oral surgery. However, it cannot be used frequently due to the high cost and radiation exposure of CBCT. Whereas Panoramic x-rays do not provide the high dimensional information necessary for planning surgery. Our research aims to produce an automated method for reconstructing a 3D dental structure from a single panoramic X-ray. This paper presents a robust preprocessing pipeline of CBCT data which are exploited to train a deep learning model for reconstructing the 3D dental structure from a single 2D panoramic X-ray image. It includes a method of generating a pair of synthetic panoramic X-rays and the corresponding flattened 3D volume as ground truth from CBCT data.*

Keywords*: CBCT, Panoramic X-ray, 3D dental reconstruction*

1. Introduction

The imaging modality is chosen based on the patient’s clinical needs such that it yields necessary diagnostic information and results in the least radiologic risk. 2D Panoramic X-ray and 3D CBCT (Cone-beam Computed Tomography) are mostly used techniques for planning implant treatment and oral surgeries [1]. However, these imaging modalities have certain limitations which can limit their usefulness in clinical situations. While Panoramic X-rays result in lower radiation doses and costs, they can still fail to provide information on the third dimension. They can only show less severe bone destruction and cannot show the spatial relationship between structures. In contrast, CBCT can provide high-dimensional images, but the radiation risk associated with it and the long time it takes to acquire the images can significantly limit its utility in clinical practice [2].

To address these limitations, there have been a few studies on reconstructing the 3D dental structure from a 2D panoramic X-ray image without requiring any additional scans [3,4,5]. It consists of two major steps: (1) generating a flattened 3D volume from a panoramic X-ray, and (2) registering the flattened 3D volume to a dental arch curve. The first stage is usually based on deep learning which can be trained using a pair of panoramic X-rays and the corresponding flattened 3D volume as ground truth. Song et. al in their work Oral-3D trained a generative network to back project the 2D X-ray image to 3D space, and then restore the bone structure by registering the generated 3D image with the prior shape of the dental arch [4].

In this paper, as an essential part of 3D dental structure reconstruction from panoramic X-ray, we present an efficient data preprocessing pipeline for training a deep learning model of generating a flattened 3D volume from the corresponding single panoramic X-ray image. In particular, we suggest efficient strategies for generating synthetic paired data of a 2D panoramic view and the corresponding 3D flattened volume from CBCT data.

2. Related Works

Flattened CBCT image synthesis can be viewed as a major step in generating the panoramic view from a patient's CBCT data. The synthesizing process depends on various factors - the number of control points chosen for curve fitting, curve fitting equation, the thickness of the dental arch, and so on. Therefore, it is crucial to obtain an accurate estimation of the dental arch curve to avoid artifacts due to inaccurate dental arch detection during image processing steps. Several works have addressed this problem using different approaches for fitting dental arch curves.

Akhoondali et. al [6] used a maximum intensity projection (MIP) based method for mandibular curve creation and then used nine control points with a cubic spline curve fitting algorithm to estimate the dental arch curve. Yun et. al [7] introduced the automatic reconstruction method based on the dental arch thickness. A curved MPR image set was generated based on the arch thickness and cubic spline curve fitting on 11 control points and finally, a synthesis algorithm enhanced the reconstructed panoramic image. Zhang et. al [8] employed a similar mechanism but proposed dental arch curve detection based on axial MIP over different ranges. A non-uniform B spline cubic curve fitting with 13 fitting points was used to extract the dental arch curve. Additionally, to resolve the contrast issues, they altered the strength of the metal implant during the image extraction process to reduce the impact on other tissues.

3. Proposed Methods

The overall proposed architecture of 3D dental shape reconstruction is shown in Fig. 1. Our model consists of three stages.

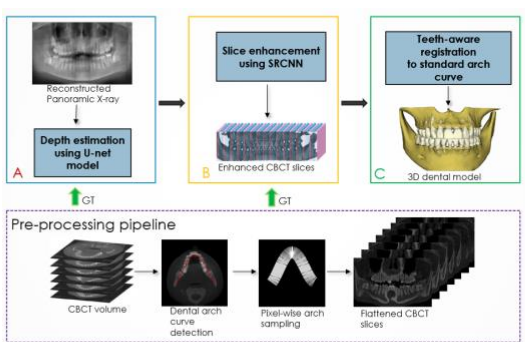

Fig. 1. CBCT Reconstruction using Super-resolution, A: Flattened CBCT synthesis C: Slice enhancement, D: Teeth-aware registration(Adapted from Song et. al. [4])

The first stage A is to generate a 3D flattened volume from a single 2D panoramic X-ray image. A training dataset can be built by generating synthetic data of a 2D panoramic view and the corresponding 3D flattened volume from CBCT data. It can be achieved by densely extracting 2D slices along the dental arch curve from CBCT data and stacking them into a flattened volume.

In the second stage B, a high-resolution flattened volume is generated by increasing the number of 2D slices based on a super-resolution model. In the third stage C, the high-resolution flattened volume is registered to a standard dental arch curve to reconstruct the 3D dental structure.

The scope of this paper focuses on how to build a synthetic augmented dataset from CBCT in the first stage of our overall pipeline. The synthetic augmented data can be generated with three steps: (1) dental arch detection and (2) generating the 3D flattened volume along the dental arch curve, and (3) estimating a 2D panoramic view from 3D CBCT.

A. Dental Arch Detection

Our proposed plan for dental arch detection is outlined in Fig. 2. First, the coronal MIP image of the original CBCT data is generated. Next, we remove any tissue surrounding the teeth by applying some pre-processing techniques such as thresholding.

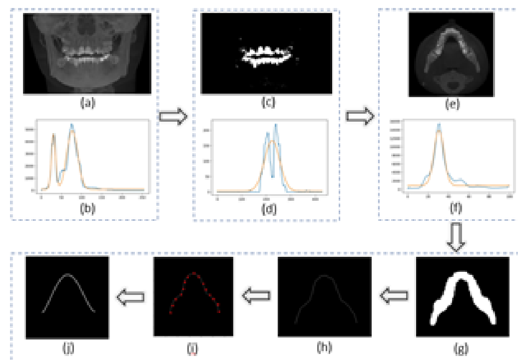

Fig. 2. Block diagram of Dental arch detection (a) Coronal Maximum Intensity Projection (MIP) (b) Intensity histogram with Gaussian curve fitting (c) Coronal binary mask (d) Y-axis histogram (e) Axial Maximum Intensity Projection (MIP) (f) Intensity histogram with Gaussian curve fitting (g) Axial binary mask (h) Dental skeleton (i) Dental arch with 15 curve points (j) Final Dental arch curve

We calculate the intensity histogram of coronal MIP and plot a gaussian curve at peaks of the distribution. The peak with the largest gray value is used to identify the location of the teeth in the image. The mean μ and the deviation σ are obtained for this peak. The threshold is then calculated as (1).

$$T = \mu + 2\,\sigma \tag{1}$$

We then generate a horizontal projection of this binary mask and plot a Y-axis histogram to determine the range of slices for generating axial MIP. We use the same Gaussian fitting method to obtain mean μ and deviation σ and then set the axial slices' start and end as in (2) and (3).

$$A = \mu - 1.2\,\sigma \tag{2}$$

$$B = \mu + 1.2\,\sigma \tag{3}$$

An axial MIP is generated using the slices between A and B. Next, we must segment the axial MIP for dental arch detection using the same method we did for coronal MIP. Here, the threshold T is determined as in (4).

$$T = \mu + 5\,\sigma \tag{4}$$

The values of weights (w=2,1.2,5) for calculating the thresholds have been empirically determined from experiments. The resulting axial binary mask then undergoes some morphological operations such as hole filling and closing. A circular-shaped disk of radius 15 is used for performing the closing operation. This retains the circular nature of the dental arch. The resulting image will have some burrs on the boundaries. So, we first erode it, and then Gaussian smoothing is applied to smoothen the boundaries. To ensure that only the teeth area is extracted, we further apply the largest connected component and then skeletonize the resulting image. This gives us the dental skeleton required for further processing (Fig. 2. h).

The skeletonized dental arch cannot be directly used for flattening the CBCT dataset. For this, we first choose 15 equidistant control points on this skeleton and plot a fourth-degree polynomial curve using these points. This gives us the final dental arch (Fig. 2. i). The choice of the fitting curve has also been determined from experiments.

B. Generating a 3D flattened volume

Once we have finalized the dental arch curve, the next step is to flatten the CBCT slices along the determined dental arch. To facilitate the stitching process, we first need to pre-process the cone beam CT data to align the images along a common coordinate system. For this, we first define a set of normal to the dental arch at each pixel position the arch passes through and then project the normal pixel values to a rectangular grid image. The formula of a line perpendicular to the curve at a point (a, b) is calculated as in (5):

$$(x, y) = (a, b) + k * (1, m) \tag{5}$$

Where m is the slope of the curve at the point (a, b). If you know the length of the normal d, then k can be determined as (6):

$$k = \pm\, d \,/ \sqrt{(1 + m2)} \tag{6}$$

These normals are used in all slices to obtain the final flattened CBCT images. The flattened image set will have a height equal to the number of slices in the dataset, and a width equal to the number of pixels the curve passes through.

C. Estimating 2D Panoramic View

These flattened slices can also be used to generate Panoramic X-rays for data augmentation. Mostly used synthesis algorithms are the ray-sum algorithm, where we add all values along the specified direction of the MPR image set to generate a panoramic image, and normal X-ray imaging emulation in which the X-ray attenuation formula is used to calculate the final value at a particular pixel location.

3. Results

We have conducted our experiments on 366 CBCT datasets collected from the Chosun School of Dentistry in Gwangju, South Korea. The datasets were formatted in a raw DICOM format as a series of 16-bit grayscale images with a resolution of 673x 673 pixels. Each sample had 429 slices and a slice thickness of 0.25mm. All patients had occlusion forks in their mouths while scanning.

In Fig. 3. (a), the result of finding all normal can be seen overlaid on a blank image. Fig. 3. (b) shows the results of flattening the CBCT slices along the dental arch curve. The flattened volume had the size of 429 x (600~700) x 200.

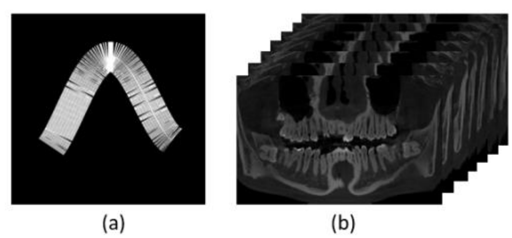

Fig. 3. (a) pixel-wise normal (b) flattened CBCT

The results of panoramic view synthesis from CBCT using the ray sum method are shown in Fig. 4. The generated synthetic panoramic image had the size of 429 x (600~700).

Fig. 4. (a) Ray sum panoramic image (b) Original panoramic X-ray

4. DISCUSSION AND CONCLUSIONS

In this paper, we introduce our framework for 3D dental structure reconstruction from panoramic X-rays and present a simple yet robust data preprocessing pipeline for building a synthetic training dataset from CBCT data that can be exploited to generate a flattened 3D volume from a single panoramic X-ray image.

The experimental results show that CBCT data can be used to create a synthetic augmented dataset for training a deep learning model. In future works, we plan to make use of the synthetic dataset to develop advanced deep learning models for not only the flattened volume generation but also its super-resolution, to achieve elevated data quality and higher accuracy in reconstruction tasks.

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