Evaluation of Segmentation Schemes for Noisy and Denoised Dental Cone Beam Computed Tomography (CBCT) Images

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***Abstract*—Segmenting Cone Beam Computed Tomography (CBCT) images is challenging due to high noise levels, artifacts, and limited resolution. This paper evaluates the effectiveness of various segmentation methods on both noisy and denoised CBCT images. We examine the performance of state-of-the-art segmentation techniques on CBCT scans processed with three efficient denoising methods tailored for low-dose CBCT images. Our findings indicate that introducing a denoising step before segmentation significantly enhances the segmentation quality of CBCT images. Additionally, the 3D Slicer approach demonstrates the most robust segmentation performance for both noisy and denoised CBCT images. Among the denoising techniques, Chang et al.'s method proves to be the most effective, yielding promising results across all evaluated segmentation methods.**

Keywords—Cone Beam Computed Tomography (CBCT) images; segmentation; denoising.

I. INTRODUCTION

Cone-Beam Computed Tomography (CBCT) is being widely used in dental imaging since it has low cost, high-quality images, and low radiation exposure which can guarantee patient safety [1]. It has enabled more precise treatment planning by connecting 2D representations with 3D reality [1] [2]. In implant dentistry, CBCT imaging enables accurate assessment of bone quality and quantity for appropriate implant size and placement [3]. It also enhances root canal therapy success by offering comprehensive visualization of complex root canal anatomy [4]. In orthodontics, CBCT images support the evaluation of craniofacial growth and development for more accurate treatment plans and tooth movement predictions [5]. Additionally, CBCT is crucial in diagnosing Temporomandibular Joint (TMJ) disorders, providing detailed images of the joint structure and surrounding tissues, thus improving patient management and treatment outcomes in dentistry [6]. The most difficult task in creating 3D models for orthodontics is currently the segmentation of CBCT images [7]. This process involves dividing CBCT images into different anatomical regions of interest. For instance, segmenting teeth is challenging because the tooth roots have a similar intensity to the surrounding alveolar bone [7]. Moreover, accurately segmenting bony structures is challenging due to high noise levels, limited image resolution, and metal artifacts [8]. To address these issues, denoising methods are essential for enhancing the image quality, thereby facilitating improved segmentation [9].

In recent decades, extensive research has been conducted to denoise and enhance the visual quality of CBCT images. For example, Chang et al. proposed enhancing CBCT images by applying a simple Wiener filter, followed by a sharpening filter to recover details, and finally, a Gaussian filter to further reduce noise [10]. Zhong et al. introduced an effective CBCT enhancement method which classifies wavelet coefficients into irregular and regular categories based on their magnitude sum within a Cone of Influence (COI), then processes them differently with a new noise estimation algorithm [11]. Also, Li et al. suggested a hybrid denoising technique for low-dose CBCT images [12]. Their technique involves separating data into frequency components using wavelet transformation. High frequencies are cleaned with wavelet thresholding, while low frequencies are filtered with Wiener filter. An inverse wavelet transformation recombines these components, and an anisotropic diffusion function further reduces image artifacts. In another study, researchers compared four denoising algorithms for enhancing low-dose CBCT images: total variation minimization, Bayes Least Squares-Gaussian Scale Mixtures (BLS-GSM), Non-Local Means (NLM), and Block Matching and 3D Filtering (BM3D). This study found that NLM and BM3D can offer superior visual quality [13].

Numerous methods have also been proposed to segment CBCT images for diagnosis purposes. For example, Zheng et al. proposed a Mixed-Scale Dense (MS-D) convolutional neural network for multiclass segmentation of the jaw, the teeth, and the background in CBCT scans [14]. In another study, a semiautomatic method was proposed to segment individual teeth in dental CT images [15]. This method outperformed the standard Dense U-Net in lesion detection accuracy and dice coefficient indices for multilabel segmentation. Another study assessed the segmentation accuracy and reliability of approaches such as 3D Slicer and Blue Sky Plan compared to commercial alternatives, namely Mimics and OnDemand3D. The former approaches could serve as a viable alternative to commercial packages in terms of accuracy and efficiency for threshold-based segmentation [15]. The Insight Toolkit - Segmentation and Non-rigid registration, and Automatic Partitioning (ITK-SNAP) is another approach for medical image segmentation while Priyadharshini et al. utilized its thresholding-function to segment the dental CBCT images for age estimation [16]. The results showed that the maxillary right canine Pulp Volumes (PV) can be used to predict the dental age and ITK-SNAP segmentation serves as a good estimator in determining the PV [16]. While these segmentation techniques have shown promising results on noisy CBCT images, their performance has not yet been investigated on enhanced and denoised CBCT images.

In this paper, we evaluate the performance of three state-of-the-art segmentation methods on CBCT images enhanced by three well-known denoising techniques. Both the denoising and segmentation methods selected are considered cutting-edge approaches for CBCT imaging. Our primary objective is to compare the robustness of these segmentation methods on both noisy and denoised CBCT images.

The rest of this paper is organized as follows. Section II describes the CBCT denoising and segmentation methods selected for this study. In Section III, we compare the performance of different segmentation methods on noisy and denoised CBCT scans and discuss the robustness of each technique. Finally, Section IV presents the conclusion.

II. Our Proposed Method

This paper aims to perform a comparative analysis of three leading segmentation techniques applied to noisy and denoised dental CBCT images. More specifically, we assessed the segmentation accuracy of the 3D Slicer [14], Blue Sky Plan [15], and ITK-SNAP [16] segmentation techniques on CBCT images enhanced by three prominent denoising methods, namely Chang's et al. [10], Li's et al. [11], and Hao's et al. (BM3D) [13], all considered cutting-edge approaches for CBCT denoising.

We utilized 10 3D CBCT images of patients consisting of 440 2D slices from a top view perspective. Initially, the 2D CBCT images are enhanced using the proposed denoising methods, and subsequently, we segment both the noisy and denoised CBCT images using the proposed segmentation techniques.

A. Denoising Techniques

To mitigate the risk of cancer from high radiation exposure in CBCT scanning, dentists and clinicians use lower levels of radiation. However, this reduction in radiation results in increased noise levels and additional artifacts [8]. Therefore, enhancing the quality of CBCT images before using them for segmentation or other treatment purposes is essential. In this study, we employ three well-known CBCT denoising methods, which we describe below.

1) Denoising technique in [10]: This method aims to enhance the visual quality of CBCT images by initially applying a simple Wiener filter to reduce noise. However, this can cause blurring of some details and microstructures. To preserve edges, a Laplacian filter is subsequently used, but it can accentuate both desired edges and unwanted noise. Finally, a Gaussian filter is applied to suppress some of the newly emerged noise.

2) Denoising technique in [12]: This method is a hybrid denoising technique designed to enhance the visual quality of noisy CBCT images. First, a single-level wavelet transform is applied to obtain one set of low-frequency and three sets of high-frequency components. Low frequencies are denoised using a Wiener filter, and high frequencies are corrected using a wavelet thresholding method based on soft thresholding (thresholds are chosen using the Birge-Massart strategy). Then, an inverse wavelet transformation recombines the filtered low- and high-frequency components. Finally, an anisotropic diffusion function further reduces image artifacts while preserving details.

3) Block Matching and 3D Filtering (BM3D) in [13]: BM3D is a denoising algorithm that divides an image into overlapping blocks, finds similar blocks in the image to form 3D groups, and then applies a 3D decorrelating unitary transform to each group. This process transforms the group into a different domain to exploit sparsity, then uses a shrinkage operator to reduce noise while preserving the signal. Finally, the filtered blocks are aggregated to reconstruct the denoised image, resulting in effective noise reduction.

B. Segmentation Techniques

As previously mentioned, our primary objective is to evaluate the performance of various segmentation techniques on both noisy and denoised CBCT images. Below, we describe the three state-of-the-art CBCT segmentation techniques utilized in our study.

1) ITK-SNAP: The ITK-SNAP segmentation approach, developed by the Penn Image Computing and Science Laboratory, is an open-source medical image processing application. It offers a blend of manual and semi-automatic tools for extracting structures from 2D and 3D image data of various modalities and anatomical regions. This solution is based on the Insight ToolKit library of image analysis algorithms and the Visualization ToolKit library of visualization algorithms and advanced modeling techniques. One of its segmentation tools is based on the Thresholding function, which we used for CBCT segmentation in this paper.

2) Blue Sky Plan: The Blue Sky Plan is a comprehensive segmentation solution tailored for virtual surgical planning and guided surgery, particularly in implant dentistry, oral surgery, and maxillofacial surgery. This approach enables the manipulation of 3D medical imaging data, such as CBCT scans, to plan surgical procedures with high precision. A key feature of the Blue Sky Plan is its advanced segmentation tools, which use sophisticated algorithms and image processing techniques to separate different anatomical structures, such as bone, teeth, and soft tissue, from scan data. This segmentation is essential for creating accurate surgical plans and designing custom surgical guides. In this paper, we employ the Advanced Jaw Segmentation tool in the Blue Sky Plan, which semi-automatically segments the CBCT images based on a predefined minimum density threshold.

3) 3D Slicer: The 3D Slicer is a widely used open-source software package for dental CBCT scans analysis and visualization. It provides a comprehensive set of tools for processing and analyzing 3D CBCT images, making it valuable for researchers and clinicians. One of its key features is its segmentation tools, which offer a variety of manual, semi-automatic, and fully automatic methods for segmenting dental structures or regions of interest. In this paper, we utilize a semi-automatic segmentation method from the Segment Editor

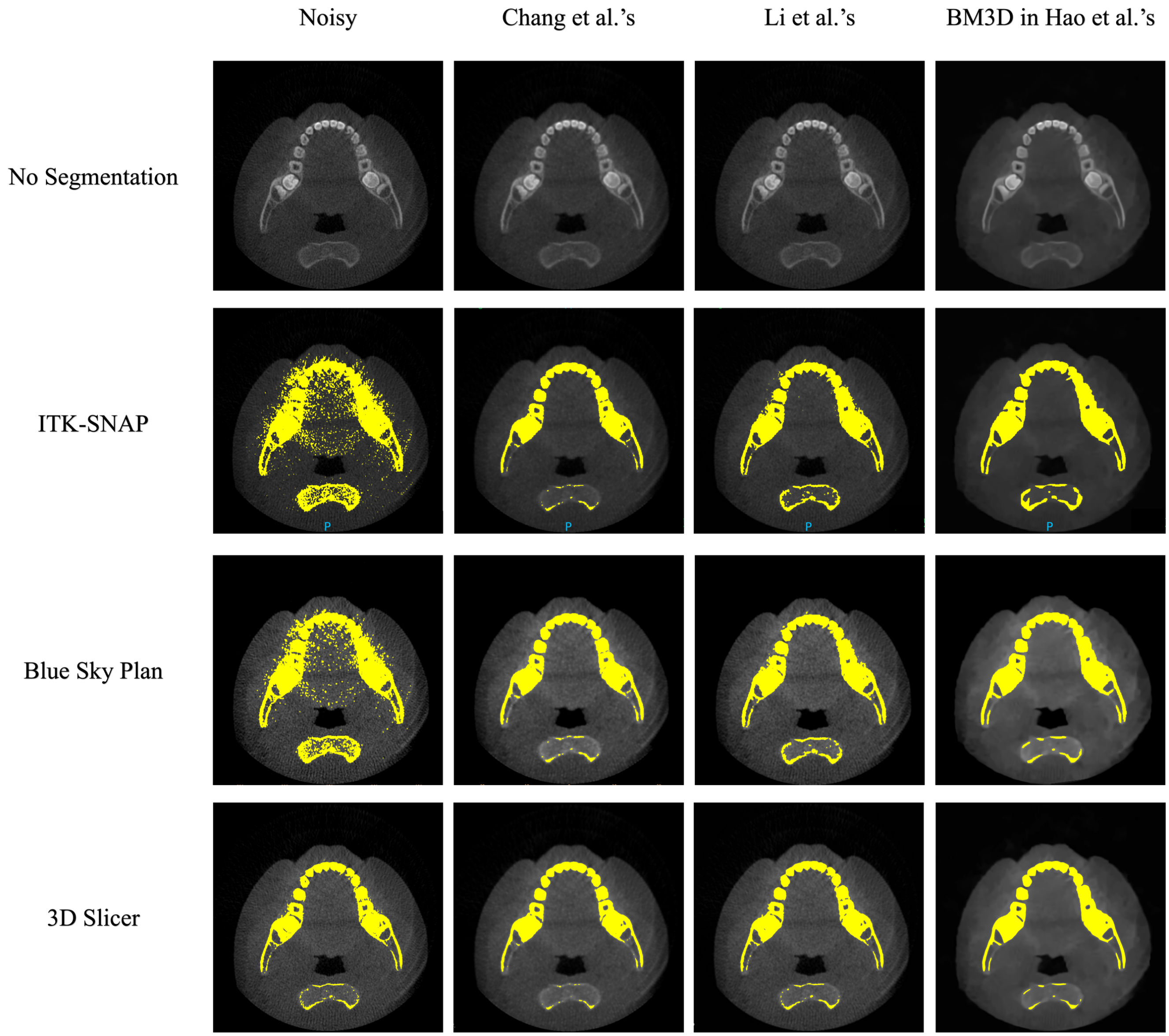

Figure 1. Results of the different segmentation methods on noisy and denoised CBCT images.

module in 3D Slicer, which segments the CBCT scans based on a thresholding technique.

III. Experimental Results And Evaluation

We conducted a subjective test to compare the performance of three state-of-the-art segmentation methods on CBCT images, assessing their effectiveness on both noisy and denoised datasets. Twenty participants, aging from 22 to 35 years, participated in the subjective tests. All of them were screened for visual acuity and color blindness. Since subjective tests are highly dependent on the proper training of the subjects, each subject was trained by means of a short practice (training) session demonstrating the range of qualities to be expected in the test in order to become familiar with the presentation scoring process. The latter follows the ITU-R BT.500-14 recommendation, with scores from 0 (low quality) to 10 (high quality) [17]. All subjects were shown 440 2D slices from a top view perspective of 10 3D CBCT images of real patients. Table I shows the average results of the subjective tests, comparing and ranking the different denoising and segmentation methods.

We observe that the 3D Slicer demonstrates superior accuracy in CBCT segmentation, exhibiting robustness across both noisy and denoised images. In summary, the 3D Slicer's segmentation technique outperforms both Blue Sky Plan and ITK-SNAP, while Blue Sky Plan demonstrates superior performance compared to ITK-SNAP. Moreover, Chang et al.'s method emerges as the best denoising strategy, as all three segmentation methods achieve better performance after using this denoising method. This is due to the fact that Chang et al.'s method effectively removes a significant amount of noise while maintaining edges, resulting in improved image quality.

TABLE I. COMPARISON AND RANKING FOR DIFFERENT DENOISING AND SEGMENTATION METHODS.

		Excellent	Good	Fair
Denoising Techniques	Chang et al.'s	✓		
	Li et al.'s			✓
	BM3D		✓	
Segmentation Techniques	ITK-SNAP			✓
	Blue Sky Plan		✓	
	3D Slicer	✓		

The BM3D denoising approach ranks second in terms of enhancing image quality for better segmentation. As shown in Figure 1, only two segmentation methods (Blue Sky Plan and 3D Slicer) show acceptable performance on the CBCT image denoised by BM3D technique. However, some segmentation errors are still visible since the BM3D method oversmoothed the CBCT image.

Finally, Li et al.'s method ranks the lowest in denoising CBCT images. As shown in Figure 1, Li et al.'s method fails to effectively remove all noise, resulting in inaccurate and noisy segmentation, particularly by ITK-SNAP and Blue Sky Plan. Only 3D Slicer manages to achieve acceptable segmentation results on the images enhanced by Li et al.'s method.

For visualization purposes, we show in Figure 1 the 315th slice to of a 3D CBCT image after denoising and segmentation. The first row, from left to right, displays the noisy low-dose CBCT image followed by the denoised images produced by the methods of Chang et al., Li et al., and Hao et al. (BM3D). Rows 2 to 4 present the segmented images produced by the state-of-the-art methods ITK-SNAP, Blue Sky Plan, and 3D Slicer, respectively, for both the noisy CBCT image and the denoised images from Chang et al., Li et al., and Hao et al.

In the first column of Figure 1, the segmentation outcomes on noisy CBCT images are displayed using the three approaches. Notably, 3D Slicer excels at accurately highlighting teeth and bony structures despite the presence of noise and artifacts. In contrast, ITK-SNAP and Blue Sky Plan perform sub-optimally on noisy CBCT images, mistakenly detecting noise as teeth and bones around these structures.

The second column of Figure 1 shows the segmentation outcomes on a CBCT image denoised using Chang et al.'s method. In this scenario, all three segmentation techniques demonstrated improved accuracy, as the visual quality of the CBCT image was enhanced by this noise removal and edge preservation method. The second column clearly illustrates that all three segmentation approaches yield promising results on the denoised image, effectively detecting and highlighting teeth structures. In a more detailed comparison, 3D Slicer and Blue Sky Plan exhibit superior performance compared to ITK-SNAP, which incorrectly identifies the space between the third and fourth teeth as bone.

The third column deals with CBCT images denoised by the Li et al.'s method [12]. This column demonstrates that the proposed denoising method can enhance CBCT images, leading to improved segmentation compared to the noisy images in the first column. We observe that while both Blue Sky Plan and ITK-SNAP achieved higher accuracy in segmenting the denoised CBCT images compared to the noisy ones, they still fall short of the superior segmentation results produced by 3D Slicer.

The last column in Figure 1 illustrates the segmentation results of three proposed software options on the CBCT image denoised using the BM3D method described in Hao et al.'s paper [13]. Here, we can observe that both 3D Slicer and Blue Sky Plan software achieve higher segmentation accuracy compared to ITK-SNAP. The BM3D denoising method oversmoothed the CBCT images, leading to some segmentation errors, such as highlighting areas between two completely separate teeth, particularly noticeable in the ITK-SNAP tool.

IV. CONCLUSION

This paper provides a comprehensive comparative analysis of three leading segmentation techniques applied to noisy and denoised dental CBCT images. We assessed the accuracy of 3D Slicer, Blue Sky Plan, and ITK-SNAP on CBCT images enhanced by three prominent denoising methods, all considered cutting-edge approaches for CBCT imaging. Our study highlights the challenge posed by high noise levels and limited resolution in CBCT scans, which diminish segmentation accuracy. However, we demonstrated that incorporating denoising techniques significantly enhances the performance of segmentation tools for CBCT images.

Our findings underscore 3D Slicer's superiority as the most robust segmentation tool for CBCT images, consistently outperforming its counterparts on both noisy and denoised images. Additionally, Chang et al.'s denoising method emerged as the most efficient technique, consistently delivering superior results across all segmentation tools compared to other denoising methods. These results emphasize the critical role of denoising in improving segmentation accuracy and highlight the potential of 3D Slicer and Chang et al.'s method in enhancing CBCT image quality for clinical applications in dentistry and maxillofacial surgery.

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