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Speckle Reduction and Lesion Segmentation of OCT Tooth Images for Early Caries Detection

Jialin Li, *Student Member, IEEE*, Christopher Bowman, Reza Fazel-Rezai, *Senior Member, IEEE*, Mark Hewko and Lin-P'ing Choo-Smith

Abstract—**The significance of identifying early non-cavitated carious lesions and monitoring the lesion extent has led to increasing prospects for prevention, early diagnosis, and implementation of conservative treatments. This paper emphasizes the importance of speckle reduction and possible lesion segmentation options of optical coherence tomography (OCT) images prior to caries detection. First, a comparison of popular speckle reduction filters is presented. These filtering algorithms were evaluated to measure the ability of different methods for reducing background noise from raw images. Both qualitative and quantitative results (signal-to-noise ratio, contrast-to-noise ratio) are reported. Image segmentation is then applied to multiple tooth images. With proper thresholding, high intensity response regions are outlined with the possibility of assessing caries and monitoring its regression. Our results show that a rotating kernel transformation (RKT) filter with 9x9 kernel size provides a good compromise between noise reduction yet preserving the pathological features of interest as required for subsequent feature segmentation analyses.**

I. Introduction

The predominant reason associated with tooth extraction is dental caries along with periodontal disease. Before demineralization (i.e. decay) of the tooth matrix has reached the underlying dentin, an early stage carious lesion can be repaired by remineralization. However, if the lesion has progressed into dentin, restorative procedures become necessary. Such procedures are generally invasive and present a much higher expense to a patient. Thus, early detection of demineralization is a key element of effective management of dental caries. Current clinical inspection methods rely on visual and tactile examinations, and are highly subjective [1]. Several emerging methods utilizing different imaging techniques have been investigated and developed in recent years for non-subjective detection of early non-cavitated carious lesions. Among the various approaches for early caries assessment, optical coherence tomography (OCT) is a novel optical imaging technique which is capable of acquiring non-invasive, micrometer-resolution, cross-sectional images from translucent sub-surface tissue structures. The OCT technique is based on the coherent cross-correlation detection of the interference fringe intensity of backscattered light. Similar to ultrasound in operation but offering an order of magnitude greater spatial resolution, OCT generates morphological images with 10 μm axial resolution to depths of ~2-4 mm [2]. The application of OCT in medicine and biology has been recognized over the past two decades, with its ability to penetrate biological tissue, even within some highly scattering media, and to image internal microscopic structures in tissue at resolutions beyond the limit of other imaging modalities [3].

The optical properties of tooth enamel and dentin change as a result of demineralization during the caries process. Therefore an OCT system that exploits such changes holds promise for early detection and characterization of the carious lesion [4][5]. The near-infrared (NIR) region from 830 nm to 1550 nm offers the potential for optical imaging due to weak scattering and absorption in dental hard tissues. Despite the attractive advantages of OCT imaging, the presence of speckle noise is the dominant factor in OCT image distortion. Speckle noise reduces image contrast and makes the boundaries between tissues difficult to resolve, especially in highly scattering tissues. Speckle noise gives a grainy appearance to OCT images and has a negative effect on texture based analysis of carious lesions. In addition to OCT imaging, speckles occur in other coherent imaging systems as well including synthetic aperture radar (SAR), medical ultrasound, and radio astronomy. Speckles arise as a result of a coherent superposition of backscattered light waves sampled from different areas containing densely packed scattering particles. Schmitt *et al.* investigated the origin and the formation of speckles together with their influence on OCT images, in which speckles play a dual role both as a noise source and as a carrier of information about tissue structure [6]. A classic model of the speckle sum can be described by a Rayleigh density distribution function [7]:

$$P(A) = \frac{A}{\sigma^2}\exp\left(-\frac{A^2}{2\sigma^2}\right) \tag{1}$$

when $A \geq 0$, otherwise $P(A) = 0$. A is the amplitude constant and σ denotes the standard deviation. The ratio of the standard deviation to the mean produces a speckle contrast. Speckle noise is assumed to have multiplicative error and must be

Jialin Li is with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Manitoba, Canada, R3T 5V6 (e-mail: jialinli@ee.umanitoba.ca).

Reza Fazel-Rezai is with the Institute for Biodiagnostics, National Research Council Canada, 435 Ellice Avenue, Winnipeg, Manitoba, Canada R3B 1Y6 and with Department of Electrical Engineering, University of North Dakota, Grand Forks, North Dakota, 58202 (e-mail: reza@und.edu).

Christopher Bowman, Mark, Hewko and Lin-P'ing Choo-Smith are with the Institute for Biodiagnostics, National Research Council Canada, 435 Ellice Avenue, Winnipeg, Manitoba, Canada R3B 1Y6 (e-mails: {Chris.Bowman, Mark.Hewko, Lin-Ping.Choo-Smith}@nrc-cnrc.gc.ca).

reduced before the data can be utilized for boundary detection, image segmentation, pattern recognition, and other image analyses. Otherwise, the incorporated noise degrades the image quality and results.

Previous studies performed on speckle suppression are focused on spatial and frequency compounding by averaging multiple scans which are not practical for real-time clinical image acquisition and assessment [8][9][10]. Once the images are formed, image processing methods and especially digital filtering are considered the predominant tools to reduce speckle noise. In the past, extensive research has been conducted both in the fields of medical imaging and remote sensing for improving speckle reduction. The complexity of the algorithms ranged from a simple mean filter to complex linear and nonlinear models. For example mean filter, median filter, Lee filter, Kuan filter, multi-resolution wavelet analysis, and rotating kernel transformation (RKT) have been shown to effectively reduce speckle noise [8][11]. For the current study, we compared the performance of various digital filters by applying them to OCT images acquired from teeth. A brief description of spatial filters and their effects on speckles are described. Two metrics used to evaluate the quality of the filtered images are then defined.

II. Speckle Reduction and Image Restoration

A. *Image Acqusition*

Enamel, dentin, and cementum are the three hard layers that comprise the solid structure of teeth. Enamel is the outer shell of the crown that is exposed to the environment and dentin is the inner layer beneath the enamel, where is extends to the root of the tooth. The enamel is internally contiguous with the inner dentin at an interface commonly known as the dentino-enamel junction (DEJ).

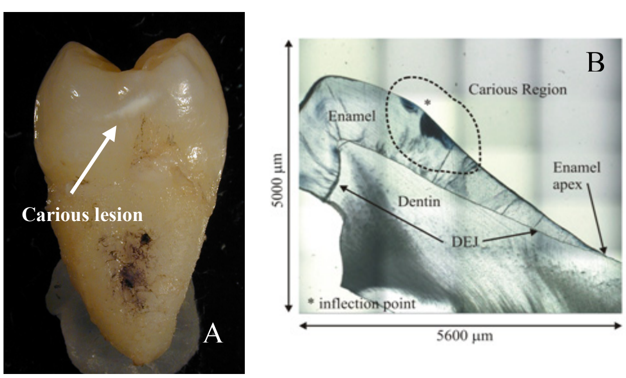

Fig. 1. A) Example of an extracted human tooth with a non-cavitated lesion (white spot), and B) photomicrograph of a histological tooth section revealing a subsurface carious lesion.

Data were collected using a 1310 nm OCT system built in house at the NRC-Industrial Materials Institute (Boucherville, Quebec). Instrumentation details have been previously described in [14]. Images were acquired from the surface of human teeth and were used for MATLAB based speckle reduction analyses. For this study, a total of 35 OCT images from sound enamel and 35 images from carious regions derived from 7 surfaces of 5 extracted human teeth were examined. In Fig. 1, a photograph of an extracted human molar is displayed along with a cross-section image obtained by destructive histological sectioning and light microscopy. A non-destructive cross-sectional depth scan of a tooth is shown in Fig. 2. This two-dimensional view (known as a B-scan) shows the light backscattered signals collected at the OCT detector and details the morphology of a carious lesion, and its surroundings.

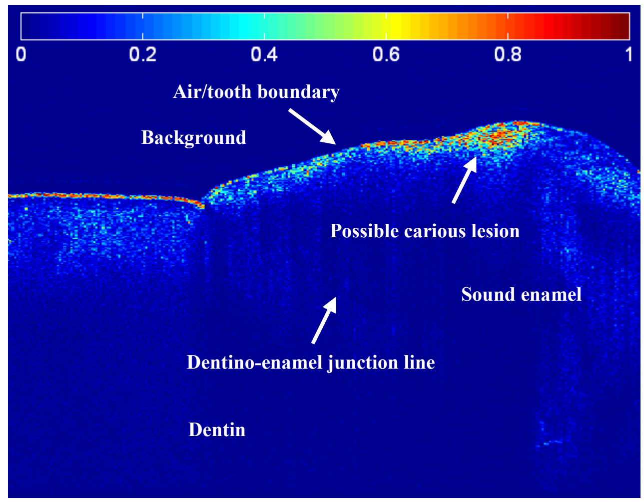

Fig. 2. Original OCT depth image of a human tooth with a carious lesion. Color bar refers to light back scattered intensity (arbitrary units).

B. *Speckle Filtering*

Spatial speckle filtering consists of moving a window kernel across an image and applying algorithms to adaptively compute the center pixel based upon the adjacent pixels. In mean filtering, the center pixel of the kernel is calculated through a mean value in a local neighborhood. The mean filter essentially does not remove the speckle but averages it into data. Generally speaking, the speckle noise reduction results in loss of detail and resolution. However, it can be used for applications where resolution is not the priority. Instead of calculating the center pixel value with the mean of neighboring pixel values, median filter replaces it with the median of those values. Unlike mean filter, median filter does not blur the edges of the regions larger than the size of the window used. The Lee filter utilizes the statistical distribution of the values within the moving kernel to estimate the value of the pixel of interest [12]. This filtering method is based on the assumption that the mean and variance of the pixel of interest is equal to the local mean and variance of all pixels within the moving kernel. Its adaptiveness allows the filter to blur the speckles but preserves the sharp features. The Kuan filter is very similar to the Lee filter by transforming the multiplicative noise into additive noise, but only differs in modeling the multiplicative noise [13]. The rotating kernel transformation operates through selecting the largest filter output at each pixel from a set of templates that consists of kernels with small incremental steps from 0 to 360 degrees.

Two different metrics were used to evaluate the performance of the noise reduction schemes. The first one was the basic signal-to-noise ratio (SNR) which is a quantitative measure of the noise suppression ability.

$$SNR = 20 \cdot \log\left(\frac{\sqrt{\sum f(i,j)^2}}{\sqrt{\sum[f(i,j) - f'(i,j)]^2}}\right) \tag{2}$$

where the top part of the fraction describes the square root power sum of each pixel (*i* and *j* represent the position of each pixel within the image) from the original OCT image and the denominator is the root mean square error between the original image and image after speckle filtering ($f'(i,j)$). While this metric is intuitive and widely used, it does not always provide an accurate visual display of image quality. In order to assure a thorough evaluation, a second metric, the contrast-to-noise ratio (CNR) was also used.

$$CNR = 20 \cdot \log\left(\frac{\sqrt{\sum[f_a'(i,j) - f_b'(i,j)]^2}}{\sqrt{\sum[f(i,j) - f'(i,j)]^2}}\right) \tag{3}$$

where fa' and fb' are selected regions of interests *a* and *b* (usually one region is chosen from the background). The CNR is a distortion measure that predicts image integrity. The CNR is based on a model of human visual processing and generally is a more robust measure compared to SNR as it employs the contrast that perceptually is convenient for humans to detect pattern differences.

III. Results and Discussion

A. De-noising Images

Fig. 3 shows the speckle filtering results on a representative 1310 nm OCT tooth image, with window sizes 9x9 and 21x21 (for brevity, only the mean, Lee and RKT filtering results are shown). The speckle reduction can easily be seen in these images as compared to the raw image (Fig. 2). For the purpose of evaluating the performance of the filters quantitatively, two quantities of SNR and CNR were used. Fig. 4 shows the numerical values of the speckle reduction with different kernel sizes of the images above. Moreover, the changes of these two parameters with respect to corresponding values are also observed. Indeed a simple mean filter brings relatively poor enhancement and blurs the detail once the window size increases. The median filter erases small features and also creates artifacts. In comparison, adaptive filters such as Lee filter and Kuan filter allow both image enhancement and information conservation. Both Lee and Kuan filters provide good SNR results but very limited CNR enhancement. This can be explained by the fact that biological OCT images are very complex and contains various kinds of speckles. A globally assumed homogeneity does not fit well to different regions within an image of biological tissue. RKT filter smoothes the images and reveal interesting properties and features such as regions of caries and light backscattered intensity response in the lesion area. However, the drawback is that artifacts appear near the air-enamel boundary, once the filter window is large.

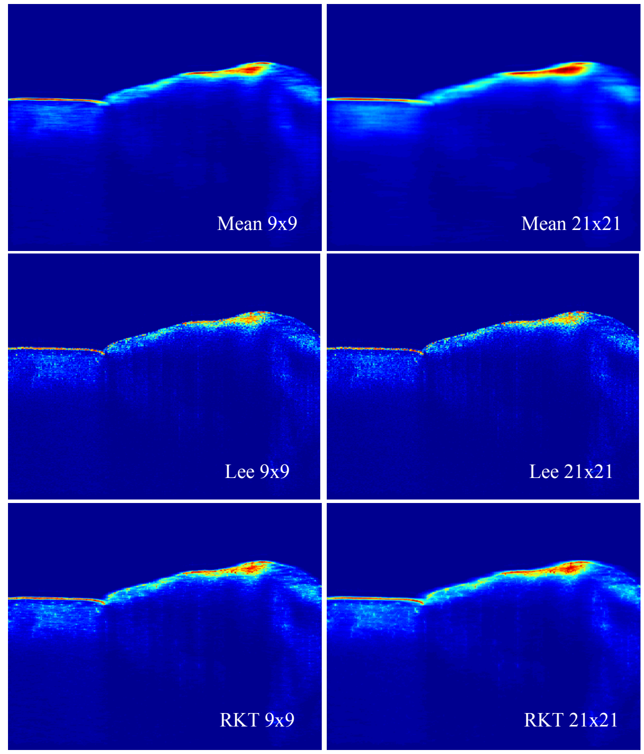

Fig. 3. Representative OCT images filtered with only Mean, Lee and RKT algorithms with kernel sizes of 9x9 and 21x21 pixels.

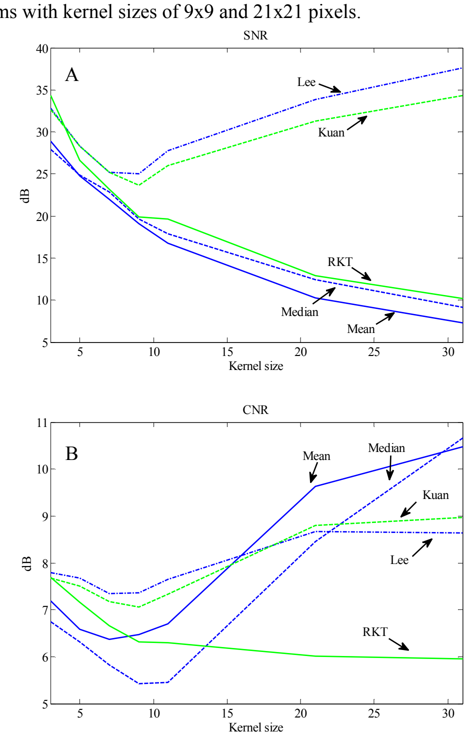

Fig. 4. (A) SNR and (B) CNR plots for different filters with window kernel size increasing from 3x3 to 31x31 pixels.

The results show that adaptive filters can significantly reduce the speckles and increase SNR. However, it is also evident from the results that there is always a trade-off between speckle suppression and edge/feature preservation. The inverse relationship between filter performance and the outcomes of the speckle reduction has allowed us to optimize filter selection depending on whether retaining edges and features (both linear and point features), or aggressive speckle suppression is required. At moderate de-noising level, images filtered with a 9x9 RKT window were chosen for further region segmentation analyses.

B. Carious Lesion Segmentation

Noise-reduced tooth images were first converted to multiple gray level scales. By applying a simple threshold, gray scale images were then transformed into binary images. A combination of dilation and erosion methods reconstructed the binary images into segments of region of interest (ROI). A label was then assigned to each region based upon the shape and intensity. The criteria used for this assignment is related to the knowledge that natural carious lesions typically appear cone shape with high sub-surface OCT light backscattered intensity. Figure 5 shows four B-scans from two tooth samples. According to the above criteria, Fig. 5 (A) and (C) have ROIs confined to the tooth surface, as expected for sound enamel. In contrast, Fig. 5 (B) and (D) have ROIs with significant lesion depth into the enamel. In Fig. 5 (C) and (D), other ROIs (white contour) were also indentified by the algorithm. However these are not considered carious lesions, because these are areas of dental calculus deposited on top of the tooth surface.

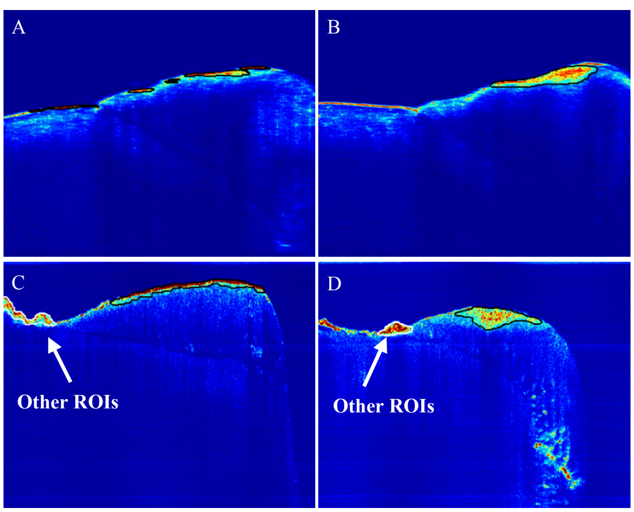

Fig. 5. OCT images from two tooth samples. (A) and (C) show scans of sound enamel from tooth 1 and 2 respectively. (B) and (D) are OCT images acquired from carious infected regions of tooth 1 and 2, respectively.

IV. Conclusion

We presented comparative tests on several standard speckle filters that are widely used. The quantitative performance of the filters was evaluated as well. Speckles have dual roles, i.e. being a source of noise in addition to carrying information. Speckle interference presents an opportunity to apply various de-noising algorithms due to the complexity of the noise itself. Obtaining clinically relevant parameters from OCT images which rely on image processing results should not lead to over-diagnosis of caries and possible over-treatment, but are required to assist dentists in detecting caries at a threshold that requires preventive intervention. In many ways, the de-noising procedures can be based on applying different filters. However, in the grand scheme of lesion detection, accurate information extraction from images is required for clinical utility. Speckle reduction and lesion segmentation of OCT tooth images are only the preliminary ground work leading to more sophisticated caries detection and monitoring analyses involving classification and registration of these images.

Acknowledgments

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