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The design of an fast Fourier filter for enhancing diagnostically relevant structures – endodontic files

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ABSTRACT

Background: The endodontic working length is commonly determined by electronic apex locators and intraoral periapical radiographs. No algorithms for the automatic detection of endodontic files in dental radiographs have been described in the recent literature.
Method: Teeth from the mandibles of pig cadavers were accessed, and digital radiographs of these specimens were obtained using an optical bench. The specimens were then recorded in identical positions and settings after the insertion of endodontic files of known sizes (ISO sizes 10–15). The frequency bands generated by the endodontic files were determined using fast Fourier transforms (FFTs) to convert the resulting images into frequency spectra. The detected frequencies were used to design a pre-segmentation filter, which was programmed using Delphi XE RAD Studio software (Embarcadero Technologies, San Francisco, USA) and tested on 20 radiographs. For performance evaluation purposes, the gauged lengths (measured with a caliper) of visible endodontic files were measured in the native and filtered images.
Results: The software was able to segment the endodontic files in both the samples and similar dental radiographs. We observed median length differences of 0.52 mm (SD: 2.76 mm) and 0.46 mm (SD: 2.33 mm) in the native and post-segmentation images, respectively. Pearson's correlation test revealed a significant correlation of 0.915 between the true length and the measured length in the native images; the corresponding correlation for the filtered images was 0.97 ($p=0.0001$).
Conclusions: The algorithm can be used to automatically detect and measure the lengths of endodontic files in digital dental radiographs.

1. Introduction

Endodontic treatment requires the determination of the exact anatomical length of root canals [1]. Electronic apex locators and intraoral periapical radiographs are commonly used to assess endodontic working lengths [2]. However, no algorithms for the automatic detection of endodontic files have been described in the recent literature, and the total lengths of small and conic files in intraoral radiographs cannot be detected with threshold or edge detection algorithms. However, a similar problem of biopsy needle segmentation from ultrasound images has recently been investigated using second-order derivatives of Gaussian filters that exploit the tubular structure of needles prior to segmentation [3].

In image processing, fast Fourier transforms (FFTs) are generally used for designing special spectral filters and for noise removal. This type of image transformation decomposes a given image into its spectral components and is based on the theory that every signal (or image) function can be described as a collection of simple, sinusoidal waves. Using this principle, we can enhance sinusoidal waves of interest after transformation in the Fourier domain, which depicts the frequency spectrum of an underlying image [4]. Certain structures, such as fixed noise patterns, can be removed using Fourier transforms [5], suggesting that the spectral properties of known objects in digital radiographs can be used to enhance these objects' visibility and facilitate their segmentation. Knowing that noise filters with certain designs can alter the appearances of the tips of endodontic files [6], we wanted to determine whether these files' spectral properties could be used to enhance their radiographic images. Therefore, the aim of this study was to assemble a new, self-developed filter that operated in the Fourier domain and to test this filter's effect on the segmentation and display of endodontic files in digital dental radiographs.

2. Materials and methods

If the image is assumed to be a two-dimensional function $f(x,y)$ defined on a Cartesian grid with $0<x<N$ and $0<y<M$, the real-

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valued discrete Fourier transform $F(k,1)$ can be defined as follows:

$$F(k,\mathrm{l}) = \sum_{x-0}^{N-1}\sum_{y-0}^{M-1} f(x,y)e^{-2\pi\left(\frac{yk}{N}+\frac{y1}{M}\right)}$$

The inverse transform under the same conditions can be defined as follows:

$$f(x,y) = \frac{1}{NM}\sum_{k-0}^{N-1}\sum_{\mathrm{l}-0}^{M-1} F(k,\mathrm{l})e^{\mathrm{i}2\pi\left(\frac{xk}{N}+\frac{y1}{M}\right)}$$

Under these conditions, the filtering operations of the filter function $g(k,l)$, which is defined on a Cartesian grid with $0<x<N$ and $0<y<M$, can be applied by multiplying this function by $F(k,l)$:

$$F'(k,\mathrm{l}) = F(k,\mathrm{l})*g(k,\mathrm{l})$$

to obtain a filtered $f(x,y)$ image with suppressed or enhanced frequencies determined by g(k,l), which is the inverse transform of $F'(k,1)$.

Teeth from the mandibles of pig cadavers were accessed using standard diamond burs. Digital radiographs of these specimens were obtained using an optical bench. Pictures were acquired with a Sirona Heliodent DS X-ray unit (Sirona, Bensheim, Germany) and a Sidexis Full Size Sensor (Sirona, Bensheim, Germany). Specimens were then recorded in identical positions and settings after the insertion of endodontic files of known sizes (ISO sizes 10–15). The resulting images were converted into frequency spectra using an FFT to determine the frequency bands generated by the endodontic files (Fig. 1).

Based on theoretical considerations, it has been well established that high Fourier coefficients in spectra are generally orthogonally aligned to the orientation of sharp edges or wavefronts [4,5]. The axes of a spectrum (Fig. 1, middle images) have an origin in the center of the image and denote the spatial frequencies $f(x)$ and $f(y)$. The logarithm of power is represented by pixel brightness, and spatial frequency is proportional to the distance from the center of the spectrum [7,8]. Therefore, radiographic images of endodontic files could be enhanced by determining the orientation of the spike caused by a file. File orientation can be determined using the Hough transform after an initial step of simple segmentation. The orientation obtained with this approach can be used to enhance a small, spindle-shaped orthogonal cluster of high Fourier coefficients in the spectrum (Fig. 1, red arrow). As observed in images obtained by subtracting FFT power spectra from images containing endodontic files, the filter function $g(k,1)$ must be a line-shaped structure orthogonal to the orientation α of the endodontic file in $F(k,1)$. This function can be obtained from the orthogonal angle $\bar{\propto}$ of the endodontic file, the amplification factor f and the following equation:

$$g(k,\mathrm{l})\begin{cases} f \text{ if } \mathrm{l} = \tan\ \bar{\propto} \cdot k \\ \quad 1 \text{ else} \end{cases}$$

This finding was used to segment the endodontic files. The file angle α is easily obtained by applying a simple global threshold to the original image and performing a subsequent Hough transform [9,10] on the binary image (Fig. 2).

The frequencies corresponding to the encountered spindle-shaped cluster of high Fourier coefficients for endodontic files were enhanced before application of the inverse Fourier transform. Segmentation of the files could then be completed by applying a simple threshold to the enhanced inverse Fourier transform of an underlying image.

For performance evaluation purposes, the gauged lengths (measured with a caliper by an independent observer) of the visible endodontic files were measured in native images and in the

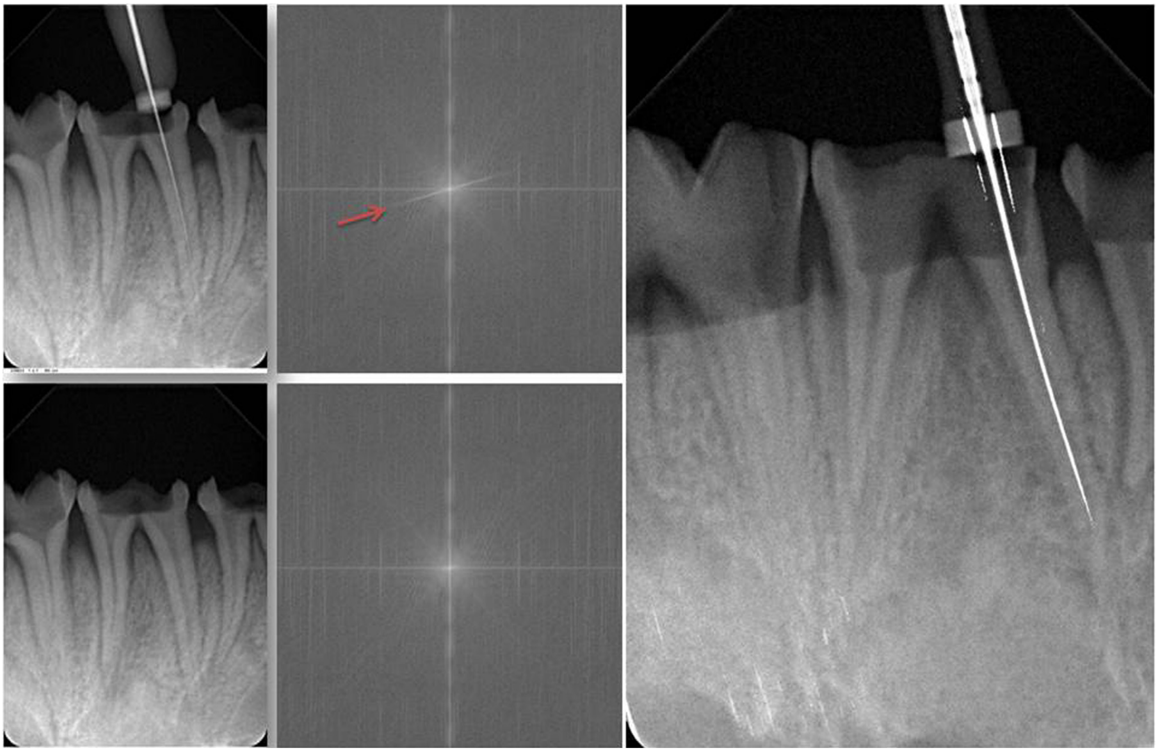

Fig. 1. The determination of an endodontic file's frequencies in the Fourier domain (red arrow) by simply inserting this file into an otherwise identical scene (left images). The enhancement of this special spectral band can be used to simplify the detection of endodontic files in digital dental radiographs (right image). The axes of a spectrum (middle images) have an origin in the center of the image and denote the spatial frequencies $f(x)$ and $f(y)$. The logarithm of power is represented by pixel brightness, and spatial frequency is proportional to the distance from the center of the spectrum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)