Digital Signal Processing Aids Cholesterol Plaque Detection

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ABSTRACT

In this paper, we describe four new methods for detection of cholesterol plaque deposits inside arteries, using digital signal processing. These methods have been tested on a number of patients. The results obtained are presented and discussed.

An ultrasonic beam is directed towards the examined artery. Signal features obtained from the Doppler signal reflected from the bloodstream contain information about the character of turbulences caused by cholesterol deposits inside the artery. These features can thus provide information about the size, shape, and position of stenosis. Features in both the time and frequency domains were utilized, such as the LPC cepstrum, the exponential time-frequency distribution, the energy waveform and the wavelet transform.

1. INTRODUCTION

Atherosclerosis is a disease in which small blood cells clump together with cholesterol in the walls of the arteries, resulting in a patch called an atheroma which bulges out from the arterial wall and reduces the flow of blood. The phenomena of reduction of lumen diameter due to the atheroma is known as stenosis. Depending on the organ affected, the decrease in blood flow may result in stroke, gangrene, angina, or even a heart attack. The presence of atherosclerosis plaque causes changes in pressure, velocity and flow. Increased velocity of blood results in turbulence. The higher the degree of stenosis, the greater the turbulence during the systolic cycle. Figure 1 shows the presence of turbulence downstream of the stenotic region.

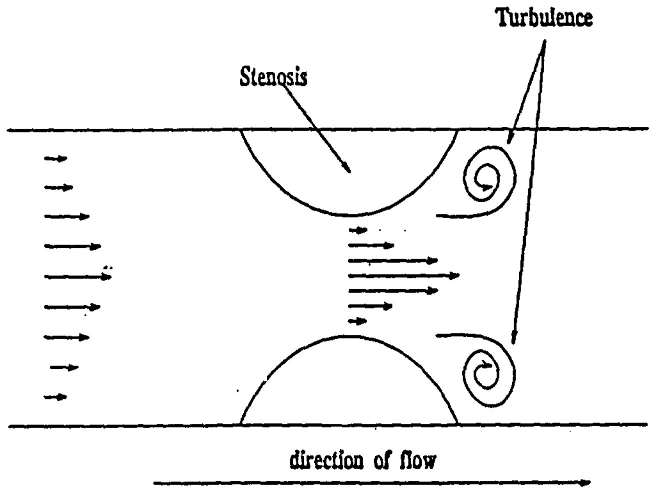

Figure 1.
Formation of turbulence downstream of stenosis

The carotid arteries carry blood from the heart to the brain and face. Carotid arterial stenosis is a vascular disease that is caused by cholesterol deposits inside the artery. These deposits clog the artery, reducing the lumen diameter and preventing the normal flow of blood. During the systolic cycle, the heart pumps blood into the arterial system, the velocity of blood is high, and the flow of blood is turbulent even if there is no stenosis. In the diastolic cycle, the heart does not pump and blood flows slowly. If the artery is "clean", there are no turbulences inside the artery during the diastolic cycle. However if there are deposits inside the carotid artery (stenosis) the flow of blood will be turbulent even during this diastolic cycle.

Various methods have been used to determine the presence and degree of stenosis, such as ultrasonic imaging and arteriography. The ultrasonic monitoring equipment measures the variation of blood velocity along the vessel. The moving red blood cells reflect the ultrasound beam incident on the blood

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flowing through the artery. Due to the Doppler Effect, turbulences in the artery are converted into an electric signal. The frequency spectrum of that signal contains the "signature" of the stenosis. Most of the ultrasonic methods provide the examining physician with an audible signal, the frequency content of which depends on the degree to which the lumen of the vessel has been reduced. In addition to the audio signal, they may also provide a visual display of the cross section of the vessel, a velocity versus time plot obtained from a selected region of the lumen, and the corresponding frequency spectrum (spectrogram). Currently, a physician makes a rather subjective diagnosis based on the sound of the audio signal. In contrast, arteriography has disadvantages such as the risk involved, the expense, and the discomfort to the patient.

Unlike arteriography, the new methods described in this paper are simple, relatively inexpensive, yet quite accurate. In addition, the examination is without risk and with minimum discomfort to the patient. The methods we used to estimate the degree of stenosis were energy waveform analysis, cepstral analysis, time-frequency distributions (exponential distribution), and wavelet transforms. The advantages of these methods are noninvasive diagnosis and inexpensive equipment.

2. SIGNAL FEATURES

A 5 MHz pulsed ultrasonic beam is directed from a transmitting transducer towards the examined artery. The signal reflected from the bloodstream is received by another transducer. Pulsed Doppler was used to enable the examination of specific areas of the artery. A timing circuit enables a receiver to receive the Doppler signal reflected from a particular region (sample volume) of the bloodstream. The received signal consists of a range of frequencies, each frequency corresponding to one part of the sample volume. Since the velocities of the blood in a particular sample volume are changing with time, the frequency spectrum of the received signal is also changing from instant to instant. This results in a time varying nonstationary signal.

Our research has included the common, internal, and the external carotid arteries. Our system was tested on 30 live patients. In addition, we built experimental physical models which consisted of plastic tubes to represent the arteries. These tubes were attached to a Blood Pump which provided the required pulsatile blood flow. Blood was simulated by a mixture of milk and iron powder having a mean diameter of 5 microns. The iron powder simulated the erythrocytes, and it reflected the incident ultrasound beam. The tubing was placed in a tray of jelly, which was used to simulate the tissue through which the ultrasound beam must pass before it reaches the blood vessels. We used these models to establish the correlation between the various contours of stenotic plaque and features obtained from the Doppler signal.

Due to the Doppler effect, the received signal contains a low frequency component that is within the audible range. The signal collected from human patients or from the experimental models are stored on an audio cassette. The recorded data is then sampled at 10 KHz and stored on a computer where feature extraction and pattern recognition algorithms are utilized.

The Doppler signal of a patient with a normal artery contains higher frequency components during the systolic cycle than during the diastolic cycle. Both systolic and diastolic regions are clearly distinguishable. However, for a patient with a high degree of stenosis, the Doppler signal contains high frequency components even during the diastolic cycle. In this case, the systolic and diastolic cycles may not be easily distinguishable.

We observed differences between normal and stenotic arteries using the following three analysis methods:

1) Energy waveform. The energy waveforms for both normal and stenotic arteries are quite different. We observed the variation in energy for a period of 5 seconds, which corresponds to several heart cycles. For highly stenotic arteries, the energy during the systolic and diastolic cycles does not change much. For normal arteries, the difference is clearly evident.

2) Time-frequency distributions. (Wigner-Ville or Exponential Distribution). Time-frequency distributions allow the visualization of changes of the signal spectra with time. These distributions are particularly useful in the analysis of time varying nonstationary signals. We preferred the Exponential Distribution (ED) [1], which was named after its exponential kernel function. The advantage of using the ED is that by a suitable choice of parameters of its exponential kernel, it reduces the cross-terms, retaining at the same time the desirable properties of time-frequency distributions.

Plots of the ED for stenotic and normal arteries are shown in Figures 2 and 3. An entire heart cycle is represented along the time axis. Certain features extracted from these plots appear to give a good indication of the degree of stenosis. Features that we found to be useful are the number of peaks during the systolic and diastolic cycles, the width of the frequency band, and the variation in the peak frequency.

3) Other spectral related features. These features include Linear Predictive Coding (LPC) cepstrum, amongst others. Best results were obtained with the LPC cepstrum due to their good clustering property which enabled reliable classification.

In order to verify our results, autocorrelation analysis was performed in the time domain. For patients with stenosis, a higher correlation between systolic and diastolic cycles in the Doppler signal was observed. Results agreed with those obtained using our aforementioned methods.

4 Wavelet Transforms. We performed a full-tree wavelet analysis to accurately determine which specific wavelet coefficients were of significance. At every level of the tree, the data was filtered using lowpass and highpass quadrature mirror filter banks, and then decimated by a factor of 2.

The first plot in each of figures 4 and 5 show the time signals obtained from a normal and a stenotic artery respectively. We see that the signals are periodic, with the amplitude increasing during systole and decreasing during diastole. The second and third plots show the 2-dimensional and 3-dimensional representation of the wavelet transform calculated from one of the diastolic cycles shown in the time signals. We note that because of the turbulence due to stenosis, there are more higher frequency components in the signal obtained from the stenotic artery. This is clearly evident in the wavelet transform representations.

To find the degree of stenosis, the full tree wavelet transform was performed up to a depth of 4 levels on the diastolic cycle, resulting in 16 (2^4) bins. We used Daubechies' 16-tap filters and a window size of .2048 seconds (by selecting 2048 samples at a sampling rate of 10 KHz) in the diastolic cycle. Thus every bin consisted of 128 (2048/16) wavelet coefficients, with each bin corresponding to a specific region in the frequency domain. For example, bin 1 contained the coefficients with indices 1-128, bin 2 contained the coefficients with indices 129-256...... and bin 16, the coefficients with indices 1921 - 2048.

We found that bin 7 (x-coordinates 896-1023) contained important information related to the degree of stenosis of an artery, whereas bin 4 (x-coordinates 385-512) had relatively constant features for both normal and stenotic arteries. The ratio of the energies in these two bins gives a measure of the degree of stenosis. The correlation between the ratios observed and the degree of stenosis as diagnosed by a doctor can be obtained by plotting a graph of these two values, and fitting a curve between the points.

3. CONCLUSION

The experiments demonstrated the reliability of the described methods in determining the shape, size and the position of stenosis. Clear differences between signals from healthy and stenotic patients were obtained.

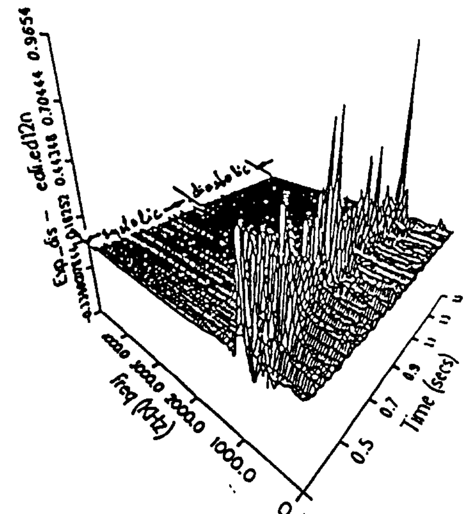

Fig. 2
Exponential Time Frequency Distribution for a Stenotic Artery.

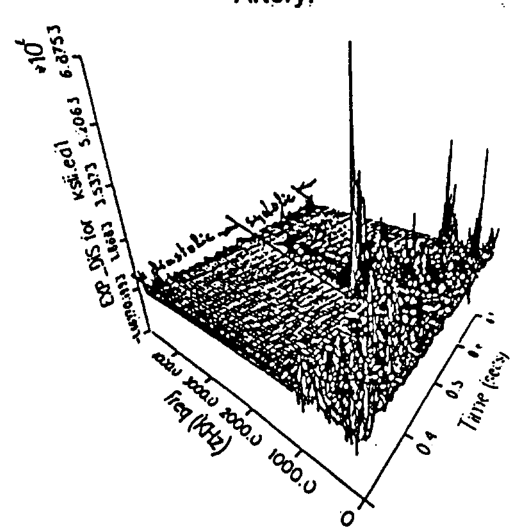

Fig. 3
Exponential Time Frequency Distribution for a Normal Artery.

4. REFERENCES

1) Hyung-Ill Choi, Pattern Recognition for Nonstationary Signals, Ph.D. dissertation, University of Michigan, 1987.

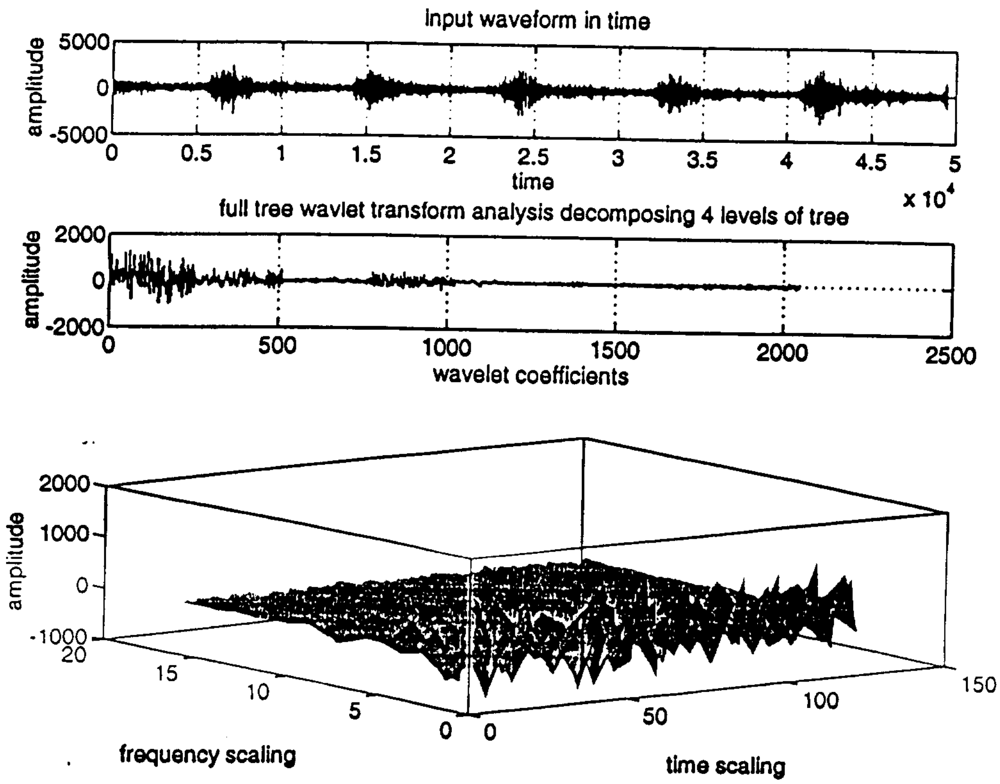

Fig. 4
Time waveform and wavelet transform for the signal obtained from a normal artery

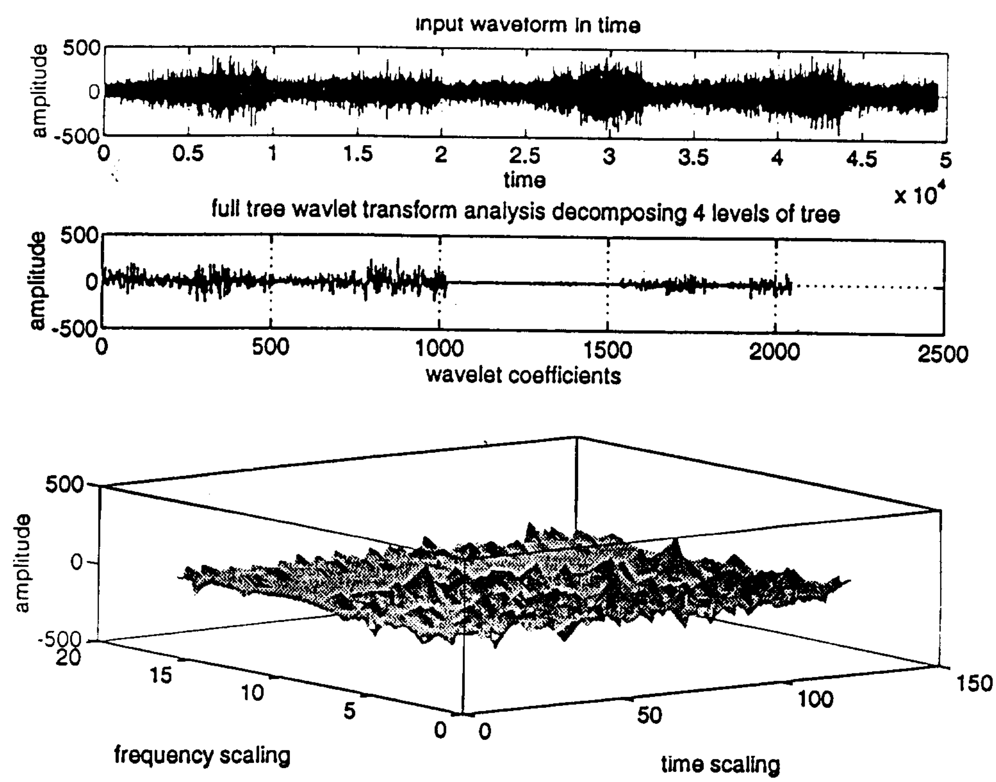

Fig. 5
Time waveform and wavelet transform for the signal obtained from a stenotic artery