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EFFECT OF WAVELET DENOIZING ON TIME-FREQUENCY AND TIME-SCALE ANALYSIS OF QUADRATURE EMBOLIC DOPPLER SIGNALS

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Abstract- **Early and accurate detection of emboli is important for monitoring of preventive therapy in stroke-prone patients. One of the problems in detection of emboli is the identification of an embolic signal caused by very small emboli. The amplitude of the embolic signal may be so small that advanced processing methods are required to distinguish these signals from Doppler signals arising from red blood cells. Time-frequency and time-scale analysis have been widely used in analysis and detection of embolic signals. In this study we use wavelet denoising to improve analysis and detection of embolic signals. Results demonstrate that considerable improvements can be achieved by wavelet denoising.**
Keywords – **Time-frequency analysis, time-scale analysis, wavelet transform, Doppler ultrasound, embolism**

I. INTRODUCTION

Asymptomatic circulating cerebral emboli, which are particles larger than red blood cells, can be detected by transcranial Doppler ultrasound [1]. In certain conditions, such as carotid artery stenosis, asymptomatic embolic signals appear to be markers of increased stroke risk and may be useful in patient management [2]. Time-frequency (TF) and time-scale (TS) analysis have been widely used in analysis and detection of embolic signals [3],[4]. Inter-observer reproducibility studies have demonstrated that there is an overall high level of agreement in identifying embolic signals. However, this is poorest for embolic signals of low relative intensity [5]. Agreement would be improved by any method of signal analysis, which improves the embolic signal to background signal ratio (EBR). Embolic signals reflected by an embolus, has some distinctive characteristics when compared to the Doppler signals from normal blood flow and artifacts. In this study we used wavelet denoising [6] to improve TF and TS analysis of embolic signals.

Wavelet denoising involves taking discrete wavelet transform (DWT), estimating noise level and an appropriate threshold, shrinking the coefficients, and taking inverse DWT. A DWT yields a countable set of coefficients, which correspond to points on a two dimensional grid of discrete points in the time-scale domain. The DWT is defined with respect to a mother wavelet and maps finite energy signals to a two dimensional grid of coefficients.

The windowed Fourier transform (WFT), which is an implementation of TF analysis based on the FFT, has been widely used by commercial Doppler ultrasonic systems. The WFT introduces time dependency in the Fourier transform by pre-windowing the signal $s(t)$ around a particular time t, and calculating its FFT. This is repeated for each time instant t. The WFT of $s(t)$ is given by

$$F_s(t,f) = \int_{-\infty}^{+\infty} s(\tau) g^*(\tau - t) e^{-j2\pi f\tau} d\tau \qquad (1)$$

where $g(t)$ is a short time analysis window function.

The wavelet transform (WT) decomposes a time series into TS space and enables one to determine both dominant modes of variability and how those modes vary in time. It is performed by projecting a signal $s(t)$ onto a family of zero-mean functions deduced from an elementary function $\Psi(t)$ by translations and dilations, and given by

$$W_s(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} s(t) \psi^*\left(\frac{t-b}{a}\right) dt \qquad (2)$$

where $\psi^*(t)$ is the analyzing wavelet.

II. METHODOLOGY

50 embolic signals from patients with symptomatic carotid stenosis were used for analysis. Recordings were made from a middle cerebral artery using an axial sample volume of 5 mm. The quadrature ultrasonic Doppler signals had been recorded using a transcranial Doppler system (EME Pioneer TC4040). The sampling frequency was 7150 Hz and the data length was 2048 point (286 ms). For wavelet denoising, Daubechies 8th order wavelet with 8 scales was used. Doppler signals were analyzed using both a 128 point complex FFT with Hanning window and a 64 scale complex Morlet WT [7]. The TF and TS representations of embolic signals before and after denoising were compared by calculating EBR, half width maximum of the embolic signal power increase in the time domain (HWM) as an estimate of temporal resolution, and absolute time of embolic signal onset (ESO) as an estimate of the accuracy of temporal localisation [4]. The parameter calculations were done by an automated software as used in detection. Wavelet denoising rules were specifically adapted to reject or suppress Doppler speckle and artifacts caused by prob tapping, tissue movement, speech etc, by utilising embolic signal characteristics [8].

TABLE I
MEAN (AND STANDARD DEVIATIONS) OF THE EBR, HWM, AND ESO FOR THE 50 EMBOLIC SIGNALS

	EBR(dB)	HWM(ms)	ESO(ms)
WFT	15.31(2.65)	11.98(11.77)	57.82(22.91)
WFTdenoise	21.90 (3.44)	10.77(11.07)	67.76(7.67)
WT	15.45(2.37)	22.00(47.46)	53.07(28.10)
WTdenoise	22.40(4.23)	13.21(27.41)	68.39(7.70)
ESO measured from time domain signals			67.85(7.64)

III. RESULTS

Mean and standard deviations of the EBR, HWM, and ESO for the 50 embolic signals are presented in Table I. From the table it is apparent that the improvement in the TF and TS analysis of embolic signals after wavelet denosing is significant. Improvement in the EBR is approximately 5 dB in both analyses. Time localization also more accurate after denoising. A plot of these parameters are shown in Fig. 1. As seen in Fig. 1b and 1c, several wrongly estimated HWM and ESO values were corrected after denoising.

IV. DISCUSSION AND CONCLUSION

In embolic signal detection it is important to suppress artifacts and Doppler speckle. Most of the low frequency artifacts can be removed by simply discarding higher scale coefficients during reconstruction. Main difficulty arises when an embolic signal and Doppler speckle resides on the same scale. In this case careful threshold selection is required. In some cases very litle improvement in the EBR was achieved as seen in Fig 1(a). These were the signals in which embolic signals and Doppler speckles occupy the same scales. Therefore, in such an application denoising algorithms must take into account unique specifications of a signal being analysed. Nevertheless, we have evaluated numerous embolic signals using the DWT in order to define required parameters for denoising [8]. As a result we have implemented a denoising algorithm and attained a considerable improvement on anlysis and detection of embolic signals.

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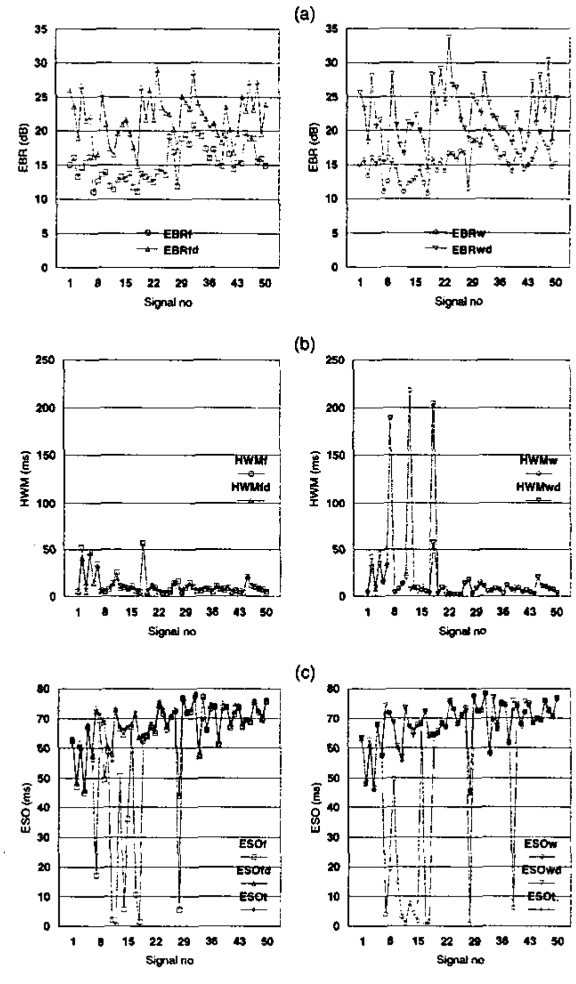

Fig. 1. Plots of (a) EBR, (b) HWM, and (c) ESO before and after denoising. (EBRf: EBR for WFT before denoising, EBRw: EBR for WT before denoising, EBRfd: EBR for WFT after denoising, EBRwd: EBR for WT after denoising, HWMf: HWM for WFT before denoising, HWMw: HWM for WT before denoising, HWMfd: HWM for WFT after denoising, HWMwd: HWM for WT after denoising ESOf: ESO for WFT before denoising, ESOw: ESO for WT before denoising, ESOfd: ESO for WFT after denoising, ESOwd: ESO for WT after denoising, ESOt: ESO measured from time domain signal).