ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 29 (2012) 3434 – 3441
Procedia Engineering
www.elsevier.com/locate/procedia

2012 International Workshop on Information and Electronics Engineering (IWIEE)

Time-Frequency Analysis of Femoral and Carotid Arterial Doppler Signals

M. Latfaoui[a*] , F. Bereksi Reguig[b]

aBechar University, Faculty of Sciences and Technology, Department of Electronics, Bechar, Algeria.
bAbou Bekr Belkaïd University, Faculty of Technology, Department of Biomedical Electronics, Geni-Biomedical Laboratory (GBM), Tlemcen, Algeria.

Abstract

In this study, the short time *Fourier* transform, continuous wavelet transform (CWT) and *S-transform* have been used for spectral analysis of the carotid and femoral arteries Doppler signal. Each of these methods can represent the temporal evolution of Doppler spectra know as the sonograms. Time-frequency analysis by S-transform presents a linear resolution that surpasses the problem of Fourier Transform by a slipping window (STFT) of fixed length and also corrects phase concept in the wavelet transform for the analysis of non-stationary signals. This transform provides a very suitable space for extracting features and the localization of discriminating information in time and frequency in Doppler ultrasonic signals. The sonograms have been then used to compare the methods in terms of their frequency resolution and effects in determining the stenosis of carotid and femoral arteries.

Keywords: STFT, CWT, S-transform, Doppler ultrasound, femoral arterial, carotid arterial

1. Introduction

The Doppler ultrasound is used medically to evaluate the stenosis in the carotid and femoral arteries. The presence of the stenosis can be indicated by the disturbance of the distal flow in the part reached by the stenosis. This causes a spectral broadening of the Doppler signal around the maximum systole. Nowadays the ultrasonic Doppler signals are employed for the detection of the stenosis.

---

[*] Corresponding author..
E-mail address: m.latfaoui@gmail.com

doi:10.1016/j.proeng.2012.01.508

Although the short time Fourier transform has been used for the estimation spectral of the ultrasonic Doppler signals. Many researchers, however, have shown that different spectral techniques can produce better spectral estimates, particularly when short data frames are required. Indeed Keeton *et al.*[8] showed that a better spectral resolution using autoregressive models (AR) can be obtained. S. Kara [4] reported a better execution of the spectral estimate with the discrete wavelet transform(DWT) technique on the spectral advance and resolution; S. Assous [1] addressed the advantages of the use of the spectral estimate by the S-transform for the laser Doppler flowmetry signals. Kaluzynski and Palko [11] studied the behavior of the broadening spectral index (SBI) and other indices under various conditions for the spectral analysis of the ultrasonic Doppler signals and concluded that the instability of the spectral evaluations has only a limited effect on the indices derived from the spectrum.

Keeton and Schlindwein [9] utilized clinical Doppler signals and studied the behavior of the SBI derived from the spectra obtained using autoregressive (AR) modeling compared with that of the SBI obtained by the rapid Fourier transform (FFT). They concluded that although AR had better spectral characteristics than the FFT approach, there was no significant improvement of the SBI estimate by employing the AR technique even in the presence of noise.

Much more methods of spectral estimates have recently been developed for the processing of the ultrasonic Doppler signals [15]. The resolution of the spectral estimator used limit sensitivity for the detection of disturbance-induced spectral broadening. In this study, signals of the carotid and femoral arteries have been examined taking their sonogram into account. Since the flow in the arteries is pulsatile and the red globules have a random space distribution, the Doppler signal is variable and random in time. The short time Fourier transform (STFT), continuous wavelet transform and the S-transform are used for the spectral analysis of the femoral and carotid arterial Doppler signals. These methods are compared in terms of their frequency resolution and their effects in the determination of spectral broadening index in the presence of stenosis for the femoral and carotid arteries.

2. The short time Fourier transform

The Fourier transform with slipping window is defined in [12] by Portnoff as being the result of the repeated multiplication of the time series *x(t) by* a short window localized in time. Analytically, it is given by the following relation:

$$X(f)=\int_{-\infty}^{+\infty} x(\tau)\,h(\tau-t)\,e^{-j2\pi f\tau}\,d\tau \qquad (1)$$

Where $h(\tau)$ is a selected window function, the action of this window is to locate, in time, the resulting local spectrum. This window of localization is then shifted in time to produce the local spectrum for all the duration of the existence of $x(\tau)$. It should be noted that the width of the window $w(\tau)$ is constant during all the spectral analysis [1].
The discrete version of the STFT is given by:

$$X_k(f)=\sum_m x(m)\,h(k-m)\,e^{-j2\pi mf} \qquad (2)$$

The STFT, simple to calculate and control, was largely used in a broad range of applications. The principal disadvantage of the STFT is the compromise noticed between temporal and frequency resolution. Indeed, if one reduces the width of the function of analysis in order to increase the temporal resolution, one will create a signal of limited duration artificially, therefore with broad spectrum. This compromise is specific to STFT, other methods such as S-transform do not register.

3. Continuous Wavelet Transform

The continuous wavelet transform (CWT) is defined by

$$CWT(a,b)=\int_{-\infty}^{+\infty} x(t)\psi_{a,b}^{*}(t)dt \tag{3}$$

Where *x(t)* represents the analyzed signal, *a* and *b* represent the scaling factor (dilatation/compression coefficient) and the time (shifting coefficient), respectively, and the superscript asterisk denotes the complex conjugation [15]. $\psi_{a,b}(.)$ is obtained by scaling the wavelet at time b and scale a:

$$\psi_{a,b}(t)=\frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right) \tag{4}$$

Where $\psi(t)$ represents the wavelet.

4. The S-transform

The S-transform is a time-frequency representation known for its properties of the local spectral phase. It was published initially in 1996 by Stokwell and his staff [14]. The need for the S-transform is that it combines only one frequency of the time-frequency space and the information of the local phase is absolutely given. That makes it possible to define the significance of the phase in a local spectrum, and to obtain results with much desirable characteristics [1][14].

The S-transform of a function *x(t)* can be defined as a transform in wavelets with a quite specific mother wavelet multiplied by a phase factor:

$$S(\tau,f)=e^{i2\pi f\tau}W(\tau,d) \tag{5}$$

Where $W(\tau,d)$ is the continuous wavelet transform of the signal *x(t)* defined by:

$$W(\tau,d)=\int_{-\infty}^{+\infty} x(t)\,w(t-\tau,d)\,dt \tag{6}$$

Where the mother wavelet is defined by:

$$w(t,f)=\frac{|f|}{\sqrt{2\pi}}e^{-\frac{t^2f^2}{2}}e^{-i2\pi ft} \tag{7}$$

Let us note that the dilatation factor *d is* the reverse of the frequency *f.*

The wavelet in the equation (7) does not satisfy the admissible condition (to have a null average) [1], [14]. Thus the equation (5) is not strictly a wavelet transform. By replacing the equation (7) by the equation (5), one explicitly obtains the following S-transform:

$$S(\tau,f)=\int_{-\infty}^{+\infty} h(t)\frac{|f|}{\sqrt{2\pi}}e^{-\frac{(\tau-t)^2f^2}{2}}e^{-i2\pi ft}\,dt \tag{8}$$

Properties of the S-transform

If the S-transform is indeed a representation of the local spectrum, one can thus hope that the simple operation of average of the local spectra through time would give the Fourier transform. It is certainly the case of the S-transform:

$$\int_{-\infty}^{+\infty} S(\tau,f)d\tau=X(f) \tag{9}$$

Where $X(f)$ is the Fourier transform of $x(t)$. It follows from this that $x(t)$ is exactly recoverable starting from
$S(\tau, f)$:

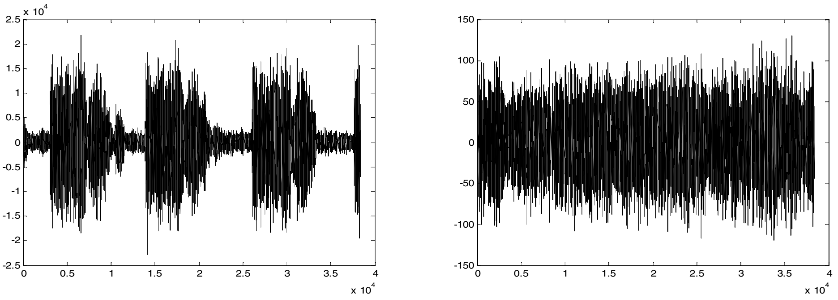
$$x(t) = \int_{-\infty}^{+\infty} \left\{ \int_{-\infty}^{+\infty} S(\tau, f) d\tau \right\} e^{i2\pi ft}\, df \qquad (10)$$

This shows that the S-transform is a generalization of the Fourier transform for the non-stationary signals.

5. Doppler Signals Analysis

In this paper we have studied eight Doppler signals (including 4 signals of the femoral arteries and 4 others of the carotid arteries) beforehand recorded at S^t Marie's hospital in Leicester (England). These signals have a sampling frequency equal to *10240 Hz*. Figures *(1.a)* and *(1.b)* respectively present an example of the Doppler signals of the femoral and carotid arteries. The flow of blood in the arteries can circulate in opposite direction in two cases:

- The artery is of high downstream resistance type.
- The artery presents a tight stenosis.



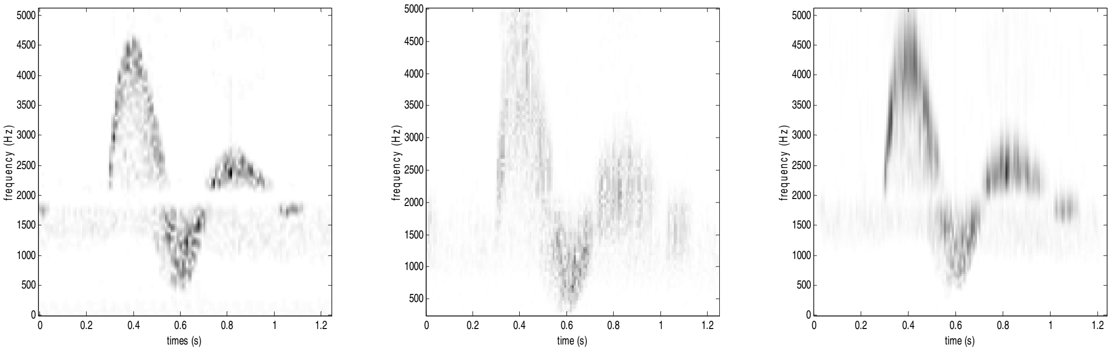
(a) **(b)**

Fig.1. Ultrasonic Doppler signal of: (a) the femoral artery, (b) the carotid artery.

6. Results and discussion

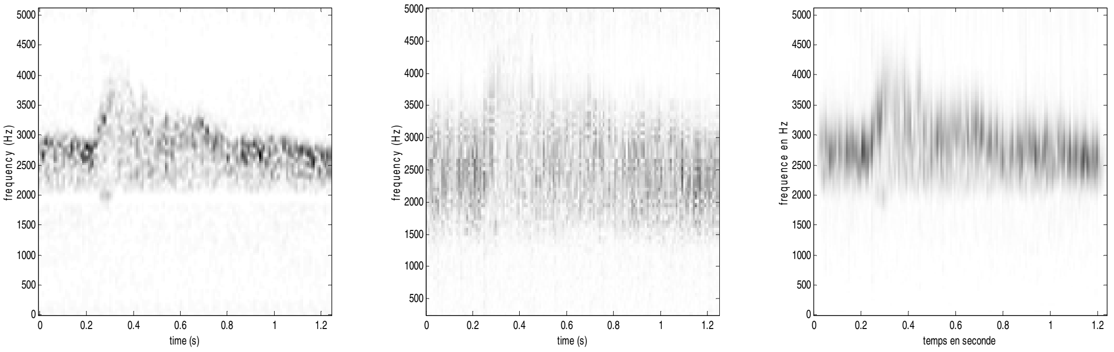
The ultrasonic Doppler signal contains a great deal of information on blood flow occurring in a sample volume of the Doppler ultrasound. The most complete manner to show this information is to make a spectral analysis and to have the results in the form of sonograms. Sonograms show the periodic beats of the heart and in each beat it is possible to visualize the systolic and diastolic flow because the heart contracts and then relaxes.

The following Figures represent the sonograms of the flow in femoral and carotid arteries obtained by the STFT, CWT and the S-transform.



(a) (b) (c)

Fig.2. Femoral arterial Doppler sonograms: (a) using STFT, (b) using CWT(c) using S-transform.



(a) (b) (c)

Fig.3. Carotid arterial Doppler sonograms: (a) using STFT, (b) using CWT, (c) using S-transform.

It is clearly noted that in Figure (2), there is a certain qualitative improvement of the sonograms obtained by the S-transform compared to that obtained by the STFT and CWT. The sonograms obtained by the STFT have false frequencies, whereas the spectral analysis by the STFT does not produce clear sonograms, because in the analysis by STFT, the application of the FFT on a slipping window leads to a distortion of the spectral estimate.

The advantage of the S-transform compared to the STFT and CWT is the optimization of the time-frequency resolution, and the dynamic localization of the spectrum on the time-frequency level. The second advantage of the S-transform is its better localization of the systolic peaks in order to determine the spectral broadening index (SBI).

The time-frequency representation of the carotid and femoral artery Doppler signals is more uniform, they vary between the mean minimal and maximal limits, resulting in the mean, minimal and maximal frequency components (f_{min}, f_{max} and f_{mean}). The temporal evolution of these frequencies represents envelopes that will be exploited to determine the SBI.

Envelopes are determined according to the minimal, maximal and mean frequency components for each frequency spectrum in a well-chosen threshold.

The point at which the spectrum amplitude surpasses the specified threshold value is defined in the first place as f_{min} and the last one that surpasses this value is f_{max}.. The mean frequency f_{mean}, is defined as the first order moment (average) frequency spectrum *g(f)* comprised between f_{min} and f_{max} frequencies (equation 11) [8].

$$f_{mean} = \frac{\sum_{f=f\min}^{f_{\max}} f.g(f)}{\sum_{f=f_{\min}}^{f_{\max}} g(f)} \qquad (11)$$

The equation (11) permits to eliminate all frequency components situated outside of the band (f_{min}, f_{max}) that we consider as noise, while the components situated inside this frequency band will be exploited to calculate the mean frequency component f_{mean} and then the SBI.

The implementation of an appropriately chosen threshold is necessary to separate the useful information (Doppler signal) of the noise. The threshold applied to sonagrams is determined according to the value of the maximal component for every frequency spectrum as the shown in Fig.6 and Fig.7.

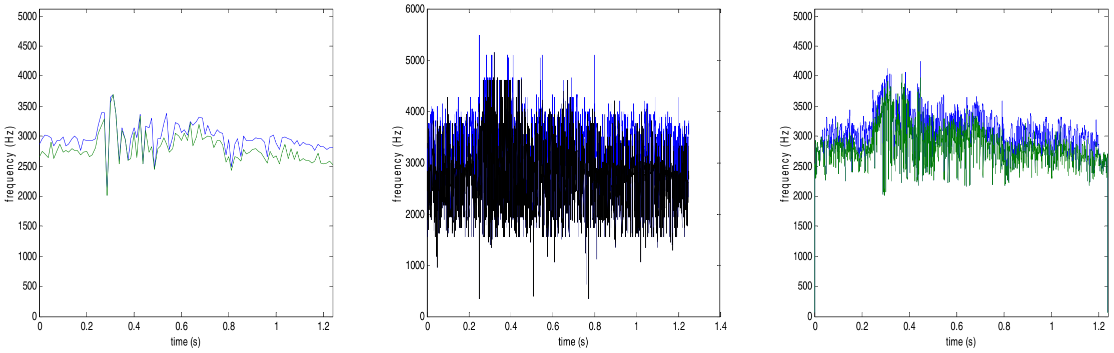
One thus notices that the increase of the threshold permits to increase the shift between the two frequency envelopes f_{min} and f_{max}. In this case, the maximal frequency increases, and this influence the SBI value.

The optimal thershold must be capable of eliminating the maximum noise without provoking an important distortion of the useful information (Doppler signal). An experimental study on the optimal threshold choice was made by P.I.J.Keeton on several cases of known stenosis: his choice was carried on the threshold of -6 dBs [7]. Similarly, the results obtained show that frequency envelopes are drowned in noise.

For a better determination of the systolic picks, and to estimate the SBI index, it is necessary to filter the spectral envelopes in order to smooth them.

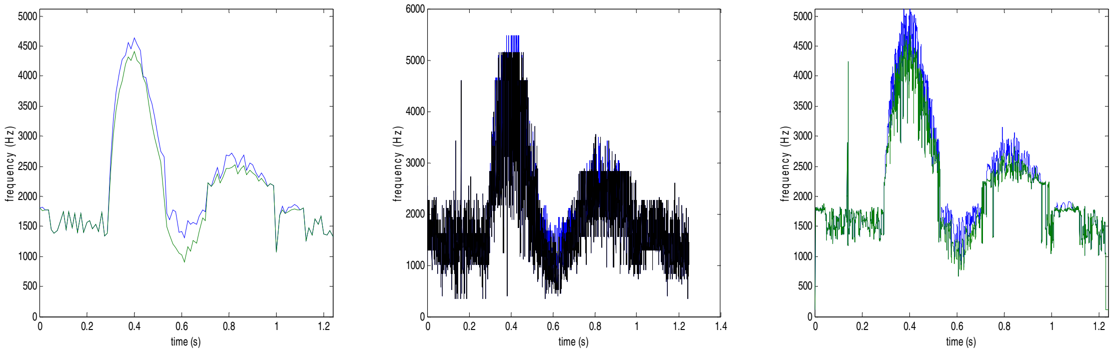
The filter used in this study is an averaging 5-point filter defined by:

$$y(nT) = \frac{1}{5}\sum_{i=0}^{4} x((n-i)T) \qquad (12)$$



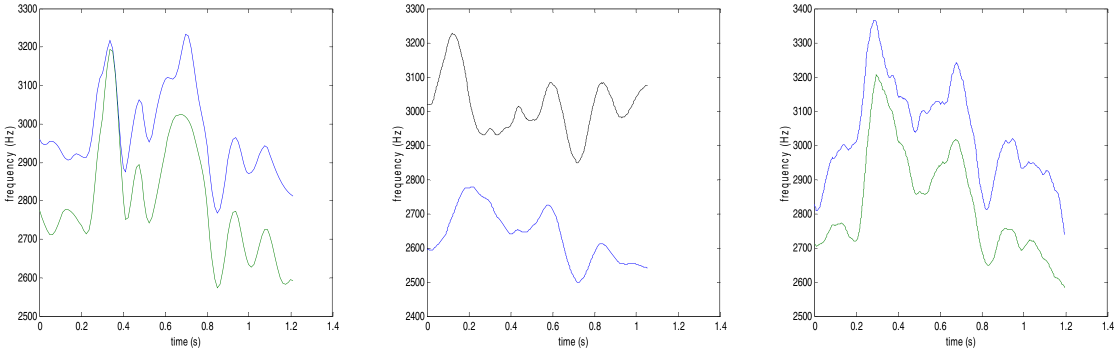
(a) (b) (c)

Fig.4. Maximum and mean frequency envelopes of the carotid arterial extracted from (a) STFT, (b) CWT, (c) S-transform sonograms.



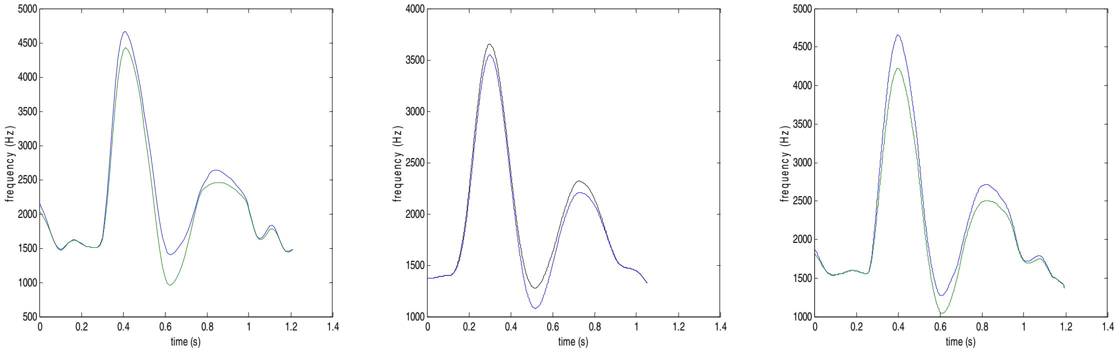
(a) (b) (c)

Fig.5 . Maximum and mean frequency envelopes of femoral arterial extracted from (a) STFT, (b) CWT, (c) S- transform sonograms .



(a) (b) (c)

Fig.6. Filtered envelopes f_{max} and f_{mean} of the artery femoral snogramms: (a) using STFT, (b) using CWT, (c) using S-transform.



(a) (b) (c)

Fig.7. Filtered envelopes f_{max} and f_{mean} of the artery femoral snogramms: (a) using STFT, (b) using CWT, (c) using S-transform.

7. Conclusion

The Doppler signals sonograms of the femoral and carotid arteries were obtained starting from the spectral analysis by the STFT, CWT and the S-transform. These methods were compared in terms of their ability of frequency resolution and their effects in determining the spectral broadening in the presence of the stenosis in the femoral and carotid arteries. On the Basis of the results obtained by the three techniques, it is clear that the S-transform can help to improve the quality of the sonogram of the femoral and carotid arteries Doppler signals. The S-transform does not suffer from some of the intrinsic problems which affect the STFT and consequently there is an unquestionable qualitative improvement of the visualization of the sonograms generated by the S-transform compared to those generated by the STFT and CWT.

References

[1] S. Assous, *Analyse temps-fréquence par la transformée en S et interprétation des signaux de fluxmétrie laser doppler applications au diagnostic clinique*, Doctoral Thesis, Ecole Nationale Supérieure d'Arts et Métiers, Angers Centre, France, 2005.

[2] E.O. Brigham, *The Fast Fourier Transform,* Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1974.

[3] M. Ceylan, R. Ceylan, F. Dirgenali, S. Kara,Y. Özbay, “Classification of carotid artery Doppler signals in the early phase of atherosclerosis using complex-valued artificial neural network”, *Computers in Biology and Medicine* 37, pp. 28 – 36, 2007.

[4] F. Dirgenali, S. Kara, ¸S. Okkesim , “Estimation of wavelet and short-time Fourier transform sonograms of normal and diabetic subjects’ electrogastrogram”, *Computers in Biology and Medicine* 36, pp.1289–1302, 2006.

[5] K. Kaluzynski, T. Palko, “Effect of method and parameters of spectral analysis on selected indices of simulated Doppler spectra”, *Med. Biol. Eng. Comput.* 31 pp. 249–256, 1993.

[6] S. Kara, A. Güven, M. Okandana, F. Dirgenali, “Utilization of artificial neural networks and autoregressive modeling in diagnosing mitral valve stenosis”, *Computers in Biology and Medicine* 36, pp. 473–483, 2006.

[7] S. Kara, S. İçer, N. Erdogan, “Spectral broadening of lower extremity venous Doppler signals using STFT and AR modelling”, *Digital Signal Processing* 18, pp.669–676, 2008.

[8] P.I.J. Keeton, F.S. Schlindwein, D.H. Evans, “A study of the spectral broadening of simulated Doppler signals using FFT and AR modelling”, *Ultrasound in Med & Biol.*, Vol. 23, No 7, pp .1033–1045, 1997.

[9] P.I.J. Keeton, F.S. Schlindwein, “Spectral broadening of clinical Doppler signals using FFT and autoregressive modelling”, *European Journal of Ultrasound* 7, pp. 209–218, 1998.

[10] F. Latifoglu, S. Şahan, S. Kara, S. Güneş, “Diagnosis of atherosclerosis from carotid artery Doppler signals as a real-world medical application of artificial immune systems”, *Expert Systems with Applications*, 2006.

[11] B. Lesniak, K. Kaluzynski, D. Liepsch, T. Palko, “The discrimination of stenosed carotid bifurcation models with smooth and irregular plaque surface. Part I. Laser and ultrasonic Doppler flow studies”, *Medical Engineering & Physics* 24, pp. 309–318, 2002.

[12] M. Portnoff. “Time-frequency representation of digital signals and systems based on short-time Fourier analysis”. *IEEE Trans. on Acoustics, Speech, and Signal Processing*, Vol. ASSP-28, No. 1, 1980.

[13] C. Simon, M. Schimmel, J.J. Dañobeitia, “On the TT-Transform and Its Diagonal Elements”, *IEEE Trans. Signal Process.*, VOL. 56, NO. 11, pp. 5709-5713, November 2008.

[14] R. Stockwell, L. Mansinha, and R. Lowe, “Localization of the complex spectrum : The S-transform”. *IEEE Trans. on Signal Processing*, Vol. 44, No. 4, pp. 998-1001, 1996.

[15] E.D. Übeyli, İ. Güler, “Spectral broadening of ophthalmic arterial Doppler signals using STFT and wavelet transform”, *Computers in Biology and Medicine* 34, pp 345-354, 2004.