ANALYSIS OF LOWER EXTREMITY VENOUS DOPPLER SIGNALS USING SPECTRAL BROADENING INDEX

Semra İçer*, Sadık Kara**

* Erciyes University, Biomedical Devices Technology Dept. Kayseri, Turkey
** Erciyes University, Department of Electrical Engineering, Kayseri, Turkey

ksemra@erciyes.edu.tr

Abstract: This study researches the behaviour of spectral broadening index (SBI) obtained from spectra achived using Short-Time Fourier Transform (STFT) analysis compared to that of SBI based on Autoregressive (AR) Modeling of clinical Doppler lower extremity vein signal. Doppler signals from 12 healthy subjects with eight different physiologic situations were analysed. Sonograms acquired from Doppler signals were used to compare the applied methods in terms of their frequency resolution and their effectiveness for the determination of SBI. The AR based sonograms produced narrower spectra compared to STFT sonograms. Besides, the magnitude of the STFT based SBI was larger than that of the AR based SBI. Furthermore, standart deviations and coefficient of variations of STFT and AR based SBIs changed according to each physiologic situation. The results of this research have also shown that despite the qualitative improvement in the individual frequency spectra, there was no quantitative advantage in using the AR approach over the STFT for the determination of SBI morever there was also an additional computational complexity income connections with AR modeling.

Introductıon

Ultrasonic Doppler flow imaging has become a powerfull tool in clinical applications. The Doppler effect, resulting from interaction of the ultrasonic wave with moving red blood cells, has been extensively used to determine blood flow velocity [1]. By using spectrum analysis techniques, the variations in the shape of the Doppler spectra are presented in the form of sonograms in order to obtain medical information [2-4]. The use of spectrum analysis to display Doppler frequency shift signals provides not only the best means of measuring blood-flow velocity but also information about the presence of disturbed flow [5].

The detection of blood flow is more difficult in veins due to occuring lower frequency shifts. Doppler signals from slow-flowing blood are closer to the noise level and, consequently, largely filtered out by most continuous-wave instruments. This limitation is overcome by transiently enhancing venous flow by the use of augmentation maneuvers [2, 6].

Color Doppler is used for the detection of stenosis, but quantification of its strenght could be done sing an index extracted from the Doppler spectrum such as the spectral broadening index (SBI) [7]. Kaluzynski and Palko (1993) studied the behaviour of SBI and other indices under different conditions for the spectrum analysis of simulated signals and concluded that the instability of the spectral estimates (of simulated data) had only a limited effect on the indices derived from the spectrum. Keeton et al. (1997) also used simulated data and studied the robustness of Fourier-based and AR-based SBI in noise and the behaviour of AR-SBI with model order. They concluded that although AR had better spectral matching characteristics than the FFT approach, there was no significant improvement in the estimation of the SBI by using the AR technique even in the presence of noise [7-9].

A number of spectral estimation methods have recently been developed for Doppler ultrasonic signal processing [10. 11]. Ubeyli and Guler (2004) studied the spectral analysis of ophthalmic arterial Doppler signals using STFT and Wavelet Transform. They demonstrated that despite the qualitative improvement in the individual sonograms, no quantitative advantage in using the WT over the STFT for the determination of spectral broadening index was obtained due to the poorer variance of the wavelet transform-based spectral broadening index and the additional computational requirements of the wavelet transform [12].

The main aim of this paper is that comparison and calculation spectral broadening index through STFT and AR modeling using real clinical Doppler venous signals with different physiologic situations because of select appropriate signal processing method for venous signals and so diagnostic vein disease.

Materials and Methods

The signals were recorded from left common femoral veins of 12 healthy males (mean age, 23 years; range, 20-27 years) by an expert Radiologist. Before the data were obtained, a color and pulsed Doppler ultrasound examination of the left femoral vein was performed in order to exclude a venous pathology by using a color Doppler Ultrasound unit (Toshiba PowerVision 6000). A linear ultrasound probe of 10

ISSN: 1727-1983 © 2005 IFMBE

MHz was used to transmit pulsed ultrasound signals to left common femoral vein. The signals reflected from the vein were recorded for one minute duration. To detect the variability of the data, the signals were recorded in eight different physiologic situations while the subject was lying in supine and upright position:

1. Neutral breathing in supine position
2. Deep continuous regular breathing in supine position
3. A Valsalva maneuver of 5 seconds' duration initially, followed by neutral breathing in supine position
4. A Valsalva maneuver of 10 seconds' duration initially, followed by neutral breathing in supine position
5. Neutral breathing in upright position
6. Deep continuous regular breathing in upright position
7. A Valsalva maneuver of 5 seconds' duration initially, followed by neutral breathing in upright position
8. A Valsalva maneuver of 10 seconds' duration initially, followed by neutral breathing in upright position

The audio output of ultrasound unit was sampled at 44100 Hz and then sent to a PC via an input-output card [13, 14]. The system hardware was composed of Digital Doppler Ultrasound unit that works in the pulsed mode, a linear ultrasound probe, an input-output card and a personal computer (PC).

STFT Transform

Time frequency representation of the nonstationary Doppler signal was performed using the STFT (Short time Forier Transform). The STFT of x(n) is a set of such discrete time Fourier Transform corresponding to different time section of x(n). The time section for time t is obtained by multiplying $x(\tau)$ with a shifting squence $w(\tau\text{-}t)$. The expression for the discrete time STFT at time t is therefore given by

$$\text{STFT(t,f)}=\left|\int_{-\infty}^{+\infty} x(\tau)w(\tau-t)e^{-j2\pi f\tau}d\tau\right|^2 \qquad (1)$$

where w is referred to as the analysis window or sometimes as the analysis filter. Since a short time section of x(n) is the product $x(\tau)w(\tau\text{-}t)$, it is clear that changing the analysis window will generally change all the short time sections and therefore the STFT [15].

In this study, the STFT was performed using a 256 point Hamming window with an overlap of %50 and no zero padding was used.

AR Modeling

Based on the AR model, the current value of a Doppler signal x(n) can be described by a linear combination of previous values of the same Doppler signal and a white noise input [1]. The AR model of order p is defined as follows:

$$x_n = -\sum_{k=1}^{p} a_k x_{n-k} + e(n) \qquad (2)$$

where, x_n=output squence (Doppler signal), a_k=parameters of the model, e(n)=driving signal. The output power of fitler evaluated on the unit circle, driven by a white noise of zero mean and variance s^2, is equal to the power spectral density of the process x_n:

$$\text{P(f)} = \frac{s^2\Delta t}{\left|1+\sum_{k=1}^{p} a_k \exp(-j2\pi kf\Delta t)\right|^2} \qquad (3)$$

where Δt denotes the sampling period, f frequency, model parameters, p model order and s2 total squared error of the model [16]. In this study for spectral analysis, AR modeling on the Doppler data grouped in frames of 256 data points.

There are a number of criteria to optimize the AR model order. Akaike's final prediction error (FPE) criterion was used to optimize the AR model order in this study [16, 18]. Final Prediction Error, which selects the model order p by minimizing the function FPE(p) defined as:

$$\text{FPE(p)}=s^2\text{(p) x (N+p+1)/(N-p-1)} \qquad (4)$$

Where s^2 is the estimate white noise variance (prediction error power) for the pth order AR model, p is the model order and N is the number of the samples of the output sequences. Selection of the model order was based an examination of the consistency of several order determination methods under noise free conditions for each of the analyzed data length realizations. FPE yielded curves that asymptotically approached a minimum with knee around p=20.

Spectral Broadening of venous signals

The STFT and the AR Model were selected to obtain sonograms which represent the changes in Doppler frequency with respect to time. MATLAB software package was used to form sonograms of the venous Doppler signals. The SBI has been used as the parameter associated with the measurement of flow disturbances. In this study, the SBI was calculated from both the STFT and AR model sonograms. The spectral broadening index is defined as:

$$\text{SBI} = \frac{f_{\max} - f_{mean}}{f_{mean}} \qquad (5)$$

ISSN: 1727-1983 © 2005 IFMBE

where f_{max} is maximum frequency component in the spectrum, f_{mean} is the mean frequency component in the spectrum[7, 12]. The SBI was calculated from both the STFT and the AR-based spectra at peak systole and also by averaging the SBI value of five spectra starting at peak systole.

Results and Discussion

A number of parameters related to the blood flow may be extracted from the sonograms which are of high clinical value. One of the parameters derived from the sonograms is the SBI. Figure 1 (a) and (b) show the sonograms of AR and STFT methods belonging to a healthy subject (subject no: 4) in eight different physiologic situations. There is a distinct difference between the relative spectral widths of the frequency spectra obtained from STFT and AR algorithms. The AR spectra are noticeably narrower.

In this study, the SBI values were calculated from the STFT and AR based sonograms. The mean value calculated for a particular heartbeat was averaged over a number of heartbeats in order to obtain a statistically valid SBI. A statistically significant maximum and mean frequency values for SBI were obtained using five heartbeats for a particular subject. Figure 2 (a) illustrates the magnitudes of the SBI extracted from the sonograms obtained using the STFT and AR algorithms, respectively, for eight physiologic situations. The magnitude of the AR-SBI was clearly smaller than that of the STFT-SBI as seen in Fig 3 (SBI values for STFT changed from 0,7 to 0,8 as SBI values for AR were between 0,35 and 0,55).

As seen in Figure 2 (b), the standard deviations of SBI values calculated from the STFT and AR were different for each physiological situation. These differences of standard deviation between AR and STFT models were larger in the PS1-PS3, PS5 and PS8. (In the PS1-PS3 (physiological situations in supine) and PS7 (upright with 5 sn valsalva) standart deviation values changed between 0,1and 0,18 in AR modeling. AR based standart deviation values were lower than these of STFT particularly in the upright physiological situations.

Figure 2 (c) shows that coefficients of variation for AR were higher than these of STFT model in the majority of positions (except of physiological situations 5 and 8).

The STFT method is based on a finite record of data and their frequency resolutions are limited by the data record duration, independent of the characteristics of the data. Furthermore, the principal effect of windowing that occurs when processing with the STFT method is to smear or smooth the estimated spectrum. The basic limitation of the STFT method is the inherent assumption that the autocorrelation estimate is zero outside the window. From another viewpoint, the inherent assumption in the STFT method is that the data are periodic. Neither one of these assumptions is realistic.

The model-based methods do not require such assumptions. The modeling approach eliminates the need for window functions and the assumption that the autocorrelation sequence is zero outside the window. The model-based methods spectra have better statistical stability for short segments of signal and have better spectral resolution and the resolution is less dependent on the length of the record. The model-based methods have better temporal resolution and produce continuous spectra. The disadvantages of the model-based methods compared to the STFT method are: the STFT method are more widely available and are the traditional engineering approach to spectrum analysis; the model-based spectra are slower to compute; the model-based methods are not reversible; the model-based methods are slightly more complicated to code; the orders of the model-based methods depend on the characteristics of the signal and the current objective methods for model order determination are not satisfactory [7-9,15-18].

Conclusion

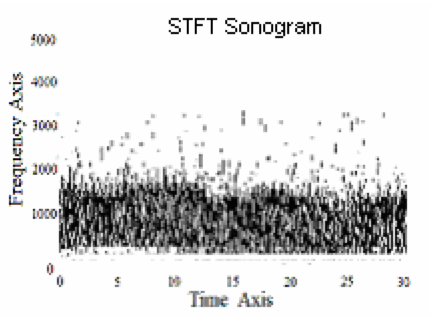
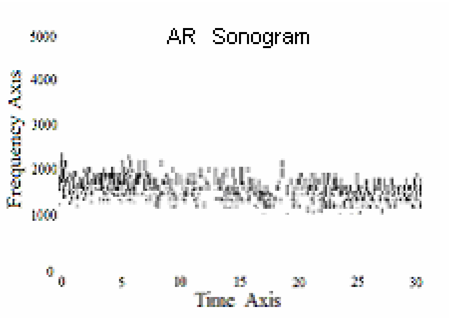
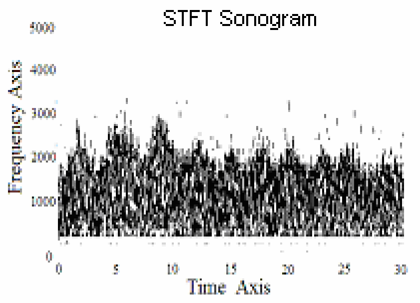
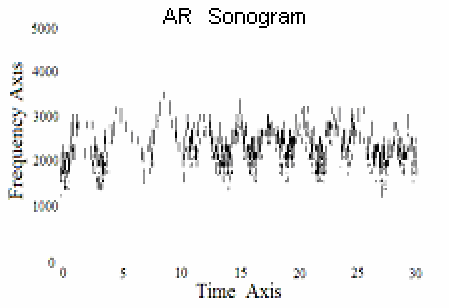
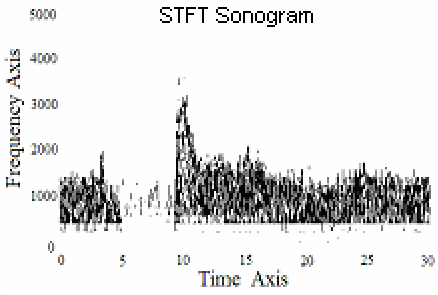
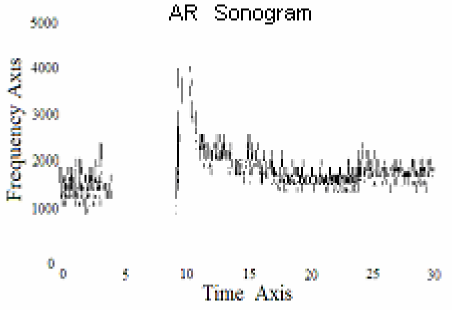
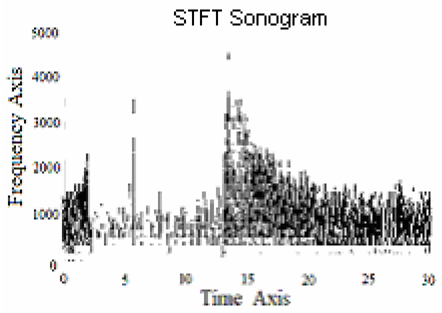
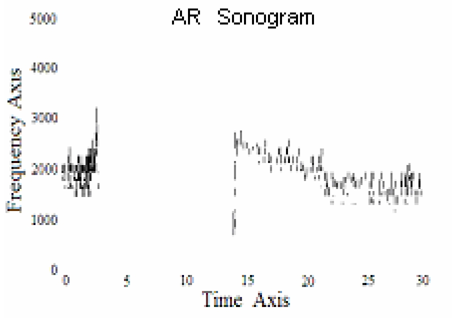
Doppler sonograms of the femoral vein belonging to eight different physiologic position were obtained using the STFT and AR method. These methods were compared in terms of their frequency resolution and their effectiveness for the determination of spectral broadening. The results obtained from the two techniques revealed that the AR approach can help improve the quality of the spectra of clinical vein Doppler signals. The AR sonograms do not influence some of the intrinsic problems that affect the STFT based spectral estimation and hence there was a distinct qualitative improvement in the visualisation of the AR sonograms over the STFT sonograms.

The SBIs calculated from both the STFT and AR based sonograms showed that the magnitude value of the STFT based SBI was larger than that of the AR based SBI. The coefficients of variation of the STFT-SBI and AR-SBI were different for eight different situations. In addition, correlation coefficient between standard deviations and coefficients of variation of AR model and STFT in the upright situations was greater than these of supine physiological situations.

The results of this research have also demonstrated that despite the qualitative improvement in the individual frequency spectra, there was no quantitative advantage in using the AR approach over the STFT for the determination of SBI and there was also an additional computational complexity related to AR modeling.

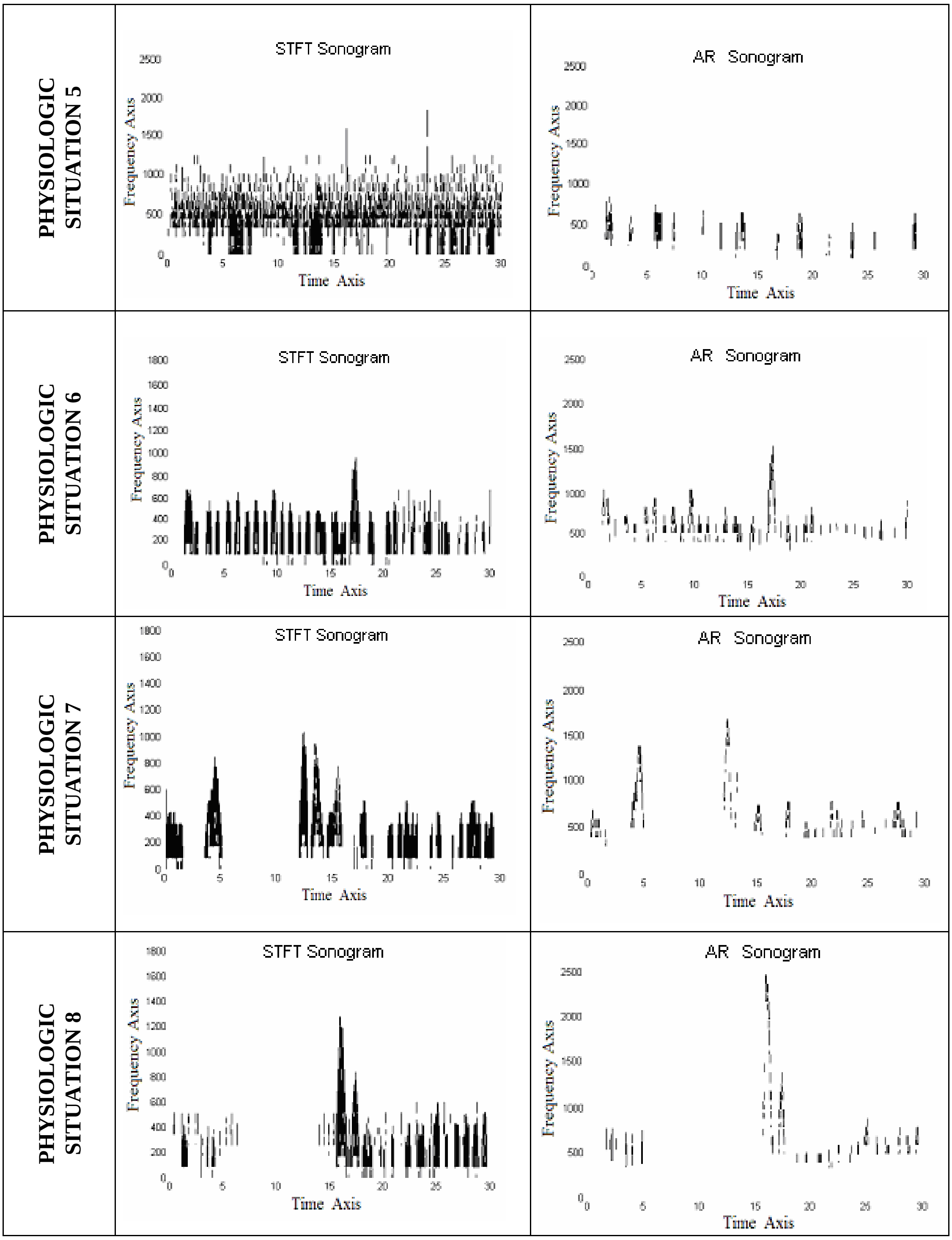
Acknowledgement

This project was supported as Post-Graduate Education and Research Project by Erciyes University (Project no. FBT-04-25).

PHYSIOLOGIC SITUATION 1		
PHYSIOLOGIC SITUATION 2		
PHYSIOLOGIC SITUATION 3		
PHYSIOLOGIC SITUATION 4		

(a)

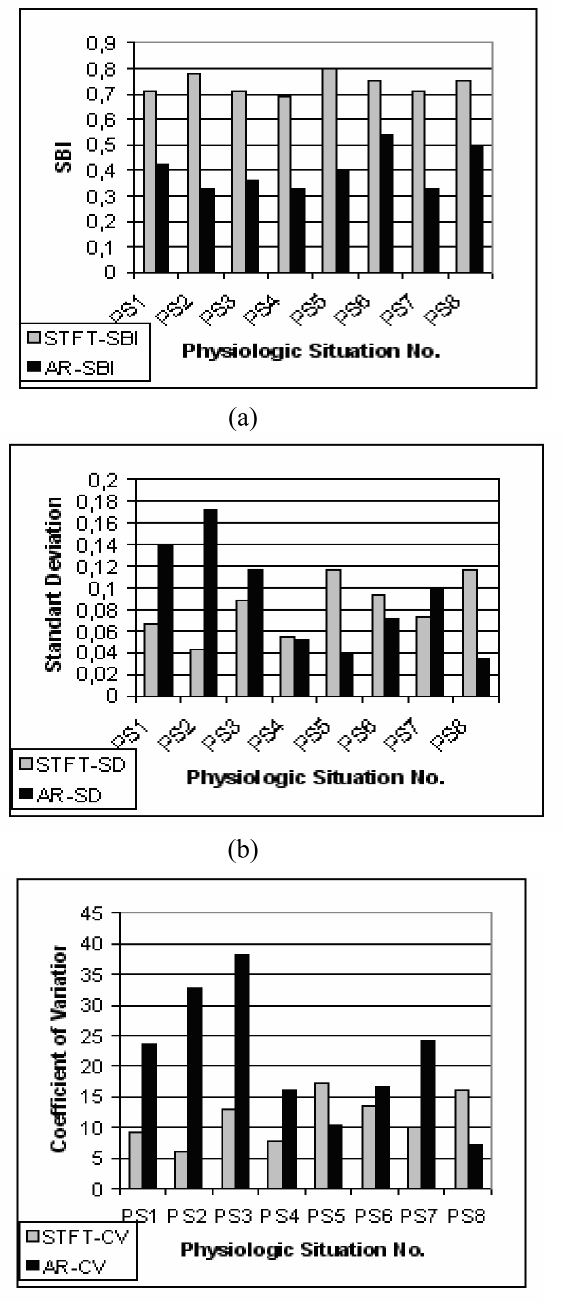
ISSN: 1727-1983 © 2005 IFMBE



(b)

Figure 1 The STFT and AR-derived sonograms of cilinically venous Doppler signals obtained with eight different position. (a) supine positions, (b) upright positions.

ISSN: 1727-1983 © 2005 IFMBE



(a)

(b)

(c)

Figure 2 (a) Magnitude of SBI (b) Standar deviation of SBI for each situation (c) Coefficient of Variation (CV) of SBI for each situation.

References

[1] YEH, C. K. and LI, P. C. (2002): 'Doppler Angle estimation of pulsatile flows using AR modeling', *Ultrasonic Imaging,* **24**, pp. 135-146.

[2] SIGEL, B. (1998): 'A Brief History of Doppler Ultrasound in the Diagnosis of Peripheral vascular Disease', *Ultrasound in Med.&Biol.*, **24,** No. 2, pp. 169-176.

[3] EVANS, D.H., MCDICKEN, W.N., SKIDMORE, R., WOODCOCK, J.P.(1989): 'Doppler Ultrasound: Physics, Instrumentation and Clinical Applications', Wiley, Chichester.

[4] GÜLER, İ., HARDALAÇ, F. and ÜBEYLİ, E. D. (2002): 'Determination of Behcet disease with the application of FFT and AR methods', *Computers in Biology and Medicine*., **32**, pp. 419–434.

[5] GREEN, P.S., (1964): 'Spectral broadening of acoustic reverberation in Doppler shift fluid flowmeters'. *J Acoust Soc. North Am*., **36**, pp. 383-1390.

[6] EVANS, D. S., COCKETT, F.B.,(1969): 'Diagnosis of deep vein thrombosis with an ultrasonic Doppler technique'. *Br Med J.*, **2**, pp. 802-804.

[7] KEETON, P.I.J., SCHLINDWEIN, F.S., (1998): 'Spectral broadening of clinical Doppler signals using FFT and autoregressive modelling', *European Journal of Ultrasoun,* . **7**, pp. 209–218.

[8] KALUZYNSKI, K., PALKO, T., (1993): 'Effect of method and parameters of spectral analysis on selected indices of simulated Doppler spectra'. *Med Biol Eng Comput*, **31,** pp. 249–56.

[9] KEETON, P.I.J., SCHLINDWEIN, F.S., EVANS, D.H., (1997): 'A study of the spectral broadening of simulated Doppler signals using FFT and AR modelling'. *Ultrasound Med Biol*. **23**, pp. 1033–45.

[10] CARDOSO, J.C.S., RUANO, M.G., FISH, P.J., (1996): 'Nonstationarity broadening reduction in pulsed Doppler spectrum measurements using time-frequency estimators', *IEEE Trans. Biomed. Eng.*, **43**, No.12, pp.1176–1186.

[11] GIRAULT, J.M., KOUAME, D., OUAHABI, A., PATAT, F., (2000): 'Micro-emboli detection: an ultrasound Doppler signal processing viewpoint', *IEEE Trans. Biomed. Eng*., **47**, No.11, pp. 1431-39.

[12] ÜBEYLİ, E. D., GÜLER, İ.,(2004): 'Spectral broadening of ophthalmic arterial Doppler signals using STFT and wavelet transform', *Computers in Biology and Medicine,* **34,** pp. 345–354.

[13] ATIKSON, P., (1982): 'Doppler Ultrasound and its use in clinical measuremen', Prentice-Hall, USA.

[14] ARENSON, J.W., (1982): 'Real-time two-dimensional blood flow imaging using a Doppler ultrasound array', McGraw-Hill.

[15] JAE, S. L., OPPENHEİM, A., (1988): 'Advanced Topics in Signal Processing', Prentice Hall, New Jersey, pp. 298-300.

[16] KALUZYNSKİ, K., (1989): 'Order selection in Doppler blood flow signal spectral analysis using autoregressive modeling', *Medical&biological Engineering & Computing,* **27,** pp. 89-92.

[17] GÜLER, İ., KARA, S., GÜLER, N.F., KIYMIK, M.K., (1996): 'Application of autoregressive and fast Fourier transform spectral analysis to tricuspid and mitral valve stenosis', *Comput Methods Programs Biomed.* **49**, pp. 29-36.

[18] GÜLER, N. F., KIYMIK, M. K. AND GÜLER, İ., (1995):'Comparison of FFT and AR based Sonogram outputs of 20 MHz Pulsed Doppler Data in Real Time', *Comput Biol. Med,* **25**, No.4, pp. 383-391.