AUTOMATIC DETECTION SYSTEM OF VENOUS AIR EMBOLISM EMPLOYING SIGNAL PROCESSING METHODS

R. Schlag[2], U. Korell[1], B. Siegmund[2], M. Pfeiffer[2], M.Pandit[2]

[1]Westpfalz Klinikum Kaiserslautern, 67653 Kaiserslautern
[2]Lehrstuhl für Regelungstechnik und Signaltheorie
Universität Kaiserslautern, 67653 Kaiserslautern

ABSTRACT

Methods of signal processing which have been developed and tested for the detection of venous embolism using ultrasound Doppler systems are presented. The detection scheme developed is based on a time-frequency characterization of the Doppler signals obtained with a suitable transducer placed on the cartoid vein. The developed scheme has been implemented and tested for the automatic signaling of an embolism which can occur in the course of a surgical operation.

1. INTRODUCTION

1.1 Occurrence of air embolism and survey of available detection methods

During surgery of the head performed on a patient in a sitting posture, there is an increased risk of the occurrence of an embolism caused by bubbles of air trapped in the vein. This is because the pressure difference between the point where air can enter and the heart can exceed 500 Pa. The cardiac function leads to sub-atmospheric pressure levels in the vein. Air absorbed in the form of small bubbles can diffuse into the right ventricle and accumulate there causing considerable decrease in the volume of blood pumped. Retransmitted into the pulmonary blood stream the air bubbles cause relocations of arterioles, sudden increase in flow resistance and a decrease in oxygen exchange. Such a pulmonary embolism could end in an acute failure of the right ventricle.

The most widely detection method employed consists in the use of an ultrasound Doppler (USD) transducer placed to the right of the breastbone between the third and the fifth intercostal space. The transducer output is fed into a loud speaker which emits an acoustic signal whose tone depends on the conditions of blood flow. Occluded air bubbles cause a characteristic swishing tone (mill wheel murmur) which the practiced anesthetist with a trained ear can easily make out.

An alternative method termed 'auscultation' consists in monitoring the heart-beat and translating it into an acoustic signal using a microphone. This method is however unreliable as it fails at high noise levels. A third method which consists in measuring the CO_2 content in the expired air is often considered to be too cumbersome [1][2][3].

Current standard practice employs a combination of an USD-transducer and auscultation. Also here, ultimately, the detection of the embolism is performed by the anesthetist by listening to the acoustic signal. This presents demands on the concentration of the anesthetist.

1.2 Objectives of the paper

In the paper a method is presented for the automatic detection and signaling of an embolism employing the USD-transducer signal. Thus, an alarm is automatically generated if an embolism occurs.

The USD-transducer signal is subjected to spectral analysis and the correlation between the spectral properties and the occurrence of the embolism is determined. Finally, this knowledge is used to detect the embolism.

2. ACQUISITION AND ANALYSIS OF SIGNAL-RUNS

2.1 Description of acquisition scheme

The analog output of an ECG-monitor which delivers an impulse train in synchronism with the systoles is recorded on one channel. The second channel stores the audio output of the processing unit of the USD-instrument sampled at 48 kilo samples per second in WAVE data format.

The signals recorded were obtained in legal animal experiments.

2.2 Analysis of signal-runs

After eliminating the power supply and other low pass disturbances, the vast amount of data collected was reduced by using a windowing and down sampling procedure.

Fig. 1 shows the USD-audio output for the cases of 'embolism' and 'no embolism'. These signals contain about 3000 samples/heart-beat.

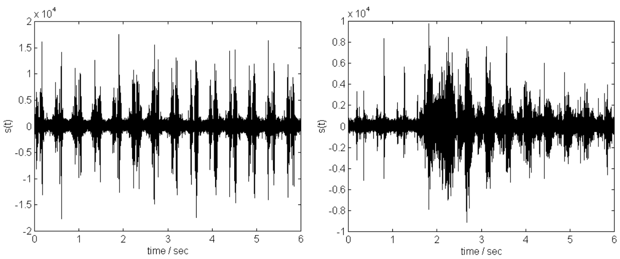

Figure 1. USD-signal-runs of normal heart-beats (left) and heart-beats containing air (right).

The spectrograms of the signals in Fig. 1 obtained by calculating the amplitudes of the harmonic components over a length of 256 samples (i.e. about a tenth of a heart-beat) of the signals for shifts of $n\cdot 128$, $n=1,2,...,$ are shown in Fig. 2. The calculation follows the following scheme of the coefficients $S_\nu^{(m)}$.

$$S_\nu^{(m)} = \sum_{n=0}^{N-1} s_{m-n} w_n e^{-j2\pi\nu n/N}$$

where s_n= original signal sample,

w_n= window function, here a Hanning-window,

m= 0,128,...,

N= 256.

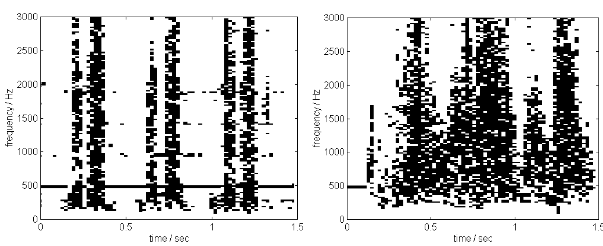

Figure 2. Spectrograms of a normal signal (left) and a signal with an occurring air embolism (right). In both cases we can see three heart-beats.

3. DESCRIPTION OF PROPOSED PROCEDURE FOR DETECTING AIR EMBOLISM

3.1 Spectral analysis

An examination of the spectrograms revealed that the low frequency components in the second quarter of a heart-beat succeeding the systole are considerably larger in the case of 'embolism' than in the case of 'no embolism'.

Thus, to detect emboli ρ_k of the k-th systole is compared with a threshold determined by experiment.

$$\rho_k = \frac{\sum_{m=N_p/4}^{N_p/2} \sum_{\nu=100}^{1000} S_\nu^{(k\cdot N_p - m)}}{\sum_{m=N_p/4}^{N_p/2} \sum_{\nu=100}^{1000} S_{ref\,\nu}^{(m)}}$$

where N_p= pulse period.

$S_{ref\,\nu}^{(m)}$ are the amplitudes in the spectrogram for a reference signal which is obtained with a trial run before the operation. Fig. 3 shows ρ_k as a function of time. Note that the embolism was induced in the period 1.5...5.5 seconds. The increase in ρ is noticeable.

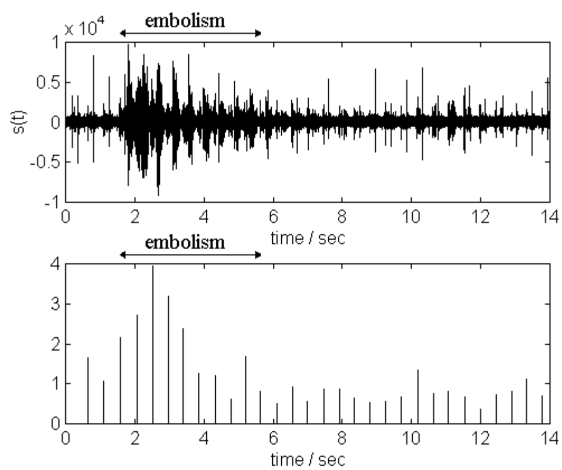

Figure 3. Spectral analysis of an USD-signal.

3.2 Variance analysis

An alternative method of detecting the change in the USD-audio signal characteristic caused by embolism is to consider the energy of the signal in the sample interval $N_{p/4...}N_{p/2}$. This corresponds to 3.1 however where the summation of the square of the amplitudes is carried over all the frequencies, i.e. here the variance

$$\sigma_k^2 = \frac{1}{N_p/4}\left[\sum_{m=N_p/4}^{N_p/2} s_n^2 - \left(\sum_{m=N_p/4}^{N_p/2} s_n\right)^2\right]$$

over the critical interval $k{\cdot}N_p{+}N_p/4...k{\cdot}N_p{+}N_p/2$ is considered. Fig. 4 shows the result in behavior of σ_k as a function of time.

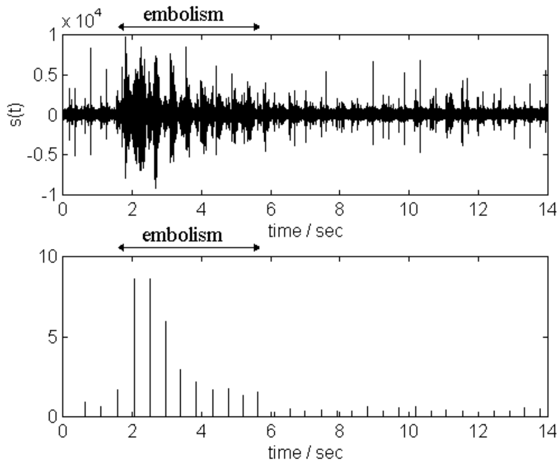

Figure 4. Variance analysis of an USD-signal.

3.3 Autoregressive parameters

A further method which was tried is based on the description of the signal as an autoregressive (AR) process using the AR coefficients to characterize the signal [4]. Extensive tests with the signal ensemble led to the choice of the order 4 and the fact that the coefficients a_1 and a_2 are influenced by the embolism. Fig. 5 shows the distribution of a_1 and a_2.

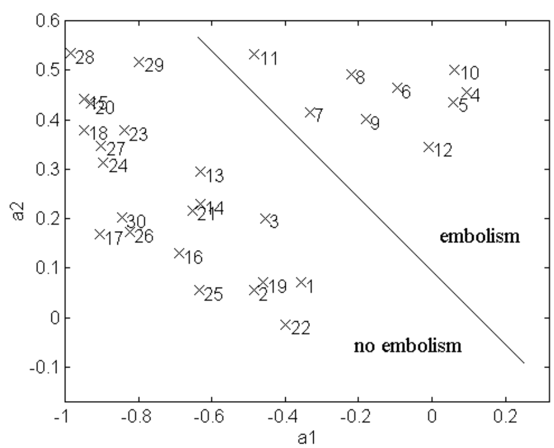

Figure 5. Autoregressive parameters of a fourth order model.

For the classification it is necessary to locate the position of a_1 and a_2. This is brought about by the computation of Mahalanobis distances d_m which represent the distance and therewith the affiliation to the classes ‘no embolism’ and ‘embolism’.

The specification of these classes is realized by the means of the computation of statistical characteristics such as mean value, standard deviation and covariance which are the conditions for computing the Mahalanobis distances.

$$d_m = \sqrt{(a_1 - \mu_1, a_2 - \mu_2) \cdot \Lambda \cdot \begin{pmatrix} a_1 - \mu_1 \\ a_2 - \mu_2 \end{pmatrix}}$$

$$\Lambda = C_{a_1 a_2}^{-1}(a_1, a_2) = \left(\mathrm{E}\left\{ \begin{pmatrix} a_1^2 & a_1 a_2 \\ a_2 a_1 & a_2^2 \end{pmatrix} \right\} \right)^{-1}$$

where a_1, a_2 = pair of parameters
C = covariance matrix

4. TEST RESULTS

4.1 The overall detection system

The automatic detection system of venous air embolism is composed of the three methods of extracting characteristics which have to be classified. The outputs of the classification algorithms are the input signals of a decision instance. This unit releases an alarm when at least two characteristics appointed to the class ‘embolism’ appear. Fig. 6 shows the basic instances of the system.

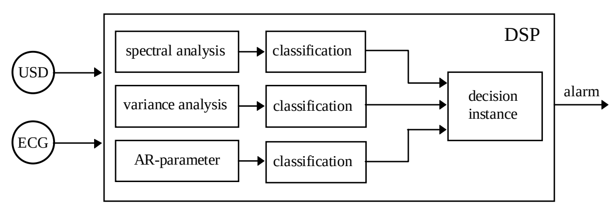

Figure 6. The detection system.

The prerequisite for a successful detection of air embolism is a learning phase. During that phase the system is adjusted at the specific parameters of each patient. These parameters yield the basis for computing the reference values which are necessary for the classification of the characteristics. So the thresholds for the spectral and variance analysis are computed as well as the specification of the classes ‘no embolism’ and ‘embolism’ is executed.

4.2 Sensitivity and specifity of tests

First let us define our detection system as a diagnostic test. The sensitivity of such a test is defined as the number of positive test results referring to the whole number of sick persons [5]. In our case it is the measure of suitability of the test to extract entirely the heart periods containing air. In several attempts the system achieved a sensitivity of approximately 93%, i.e. 93 out of 100 heart periods containing air were classified in the right way. The base of computation is the number of heart periods instead of the number of occurring air emboli. In the second case we would have a sensitivity of 100%.

The specifity of a diagnostic test is the number of negative test results referring to the whole number of healthy persons. So it is the measure of suitability of the test to register only the normal heart periods. A large number of wrong positive results reduce the specifity. The detection system achieved a value of 89%, i.e. 89 out of 100 normal heart periods are classified correctly.

5. CONCLUSIONS

Signal acquisition and processing methods have been proposed, implemented and tested for detecting air emboli in the course of operations. The processing methods are based on evaluating the spectral properties of the ultrasound Doppler signal. The majority logic scheme employed enhances the correctness of detection. Satisfactory results have been obtained with field data. Currently a DSP-based system is being developed for use in an operating theater.

6. REFERENCES

[1] Auer T., Ennemoser O., Ambach W., and Huber C. *Frequency Analysis of Sounds for the Identification of Air Emboli*. Biomedizinische Technik, 3/1994.

[2] Couture P., Boudreault D., Derouin M., Allard M., Lepage Y.,Girard D., and Blaise G. *Venous Carbon Dioxide Embolism in Pigs: An Evaluation of End-Tidal Carbon Dioxide, Transesophageal Echocardiography, Pulmonary Artery Pressure, and Precordial Auscultation as Monitoring Modalities*. Anesth Analg, 1994;79:867-73.

[3] Lui P.-W., Lin Y.-M., Chan F., Tsou M.-Y., Wang S., Lam F., and Poon P. *Spectral Characteristics of embolic Heart Sounds detected by precordial Doppler Ultrasound during venous Air Embolism in Dogs*. British Journal of Anaesthesia, 1993;71:689-695.

[4] Schukat-Talamazzini E. *Automatische Spracherkennung*. Vieweg Verlag. Braunschweig. 1995.

[5] Zöfel P. *Statistik in der Praxis*. Gustav Fischer Verlag, Stuttgart. 1992.