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Diagnosis of aortic valve stenosis by correlation analysis of wavelet filtered heart sounds

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Abstract - Traditional auscultation performed by general practitioners (GP) remains problematic and often gives significant results only in a late stage of the heart valve disease. Valve stenoses and insufficiencies are nowadays diagnosed with accurate but expensive ultrasonic devices. This study is aimed to develop a new heart sound analysis method for diagnosing aortic valve stenoses (AVS) based on a wavelet and correlation technique approach.

Heart sounds recorded from 81 patients (43 AVS patients, 11 healthy controls - REF and 27 patients with other valve diseases - OVD) with an electronic stethoscope were wavelet filtered and envelopes were calculated. Three correlations on the basis of these envelopes were performed: (1) within AVS, (2) within mixed group AVS+REF and (3) within mixed group AVS+OVD leading to the mean correlation coefficients rAvS, rAVS/REF and rAVS/OVD•

The results show that rAvs is significantly higher than rAvs1REF and rAvs1ovo ($p<0.01$). These differences in sound patterns between the groups show that the introduced method provides an automatic diagnostics of AVS.

We developed a new method of heart sound classification that seems to be suited for diagnosing valve diseases and application in a low cost and easy to use system for GPs.

Keywords - correlation, digital signal processing, electronic stethoscope, heart sound, phonocardiography, wavelet decomposition

I. INTRODUCTION

Auscultation was for a long time the only method to detect diseases of the heart valves. At first a diagnosis was perfonned only by ear, later on mechanical recordings of heart sounds with plotters were applied for diagnosing pathological changes. With the establishment of the echocardiography the application of the unwieldy, difficult to operate and sensitive phonocardiography devices became less important. With miniaturization of electronic systems it is now possible to develop mobile devices for auscultation and to store heart sounds digitally. Most of these common available devices or software solutions do not perform a diagnosis, they only display the signals and the frequency spectra.

Classification of heart sounds of different valve diseases is very complex [1]. Auscultation requires experience and a quiet environment. Rarely only one single valve is diseased, often two or more valves are affected and may either be insufficient and/or stenotic. This makes the diagnosis more difficult.

In 1952 Maass and Weber [2] improved the mechanical registration of heart sound curves with plotters. They developed standards for filtering and amplifying separate frequency ranges with the result of a more accurate differentiation between low-frequency heart tones and mid- and high-frequency murmurs. Nowadays electronic stethoscopes with built-in filters make auscultation more comfortable. Tones and murmurs are easier to separate, but low murmurs are still covered by background sounds and may be under the threshold of audibility. In these cases the human ear is not capable to identify them.

With the introduction of the ultrasonic imaging valve diagnostics became much more accurate. This is a powerful technique but needs great experience and is rather expensive. Therefore, these devices are normally not used by general practitioners (GP).

The aim of this study was to develop an easy to use method for an early detection of aortic valve stenosis (AVS) that should be applicable fore GPs.

II. METHODOLOGY

We recorded heart sounds from 81 patients. The diagnoses of all valve diseases were confirmed by an experienced cardiologist via echocardiography. Heart sounds of 15 seconds duration were measured successively on 7 different auscultation areas (Fig. I).

As measuring device an electronic stethoscope combined with an one lead ECG amplifier were applied. The signals were digitized via a soundcard with 44100 Hz sampling frequency and 16 bit resolution and stored together with patient data in a database.

RR-interval (from synchronous ECG) related sound segments with a low signal-to-noise ratio were excluded from the analysis. Heart sound signals were decomposed into 20 frequency scales using wavelet analysis. This scales were extracted for every single heart cycle. Furthermore, an envelope with standardized length was calculated for each period. With these envelopes a representative pattern for every patient was calculated and used for correlation analyses to find specific differences between the groups.

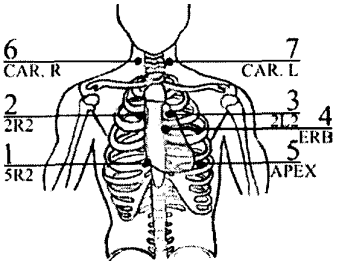


Figure 1: Auscultation areas I to 7.

Table 2: Definition of the degree of AVS in accordance to standards of echocardiography (3, 4). Abbreviations: ava - aortic valve area in cm^2, ppg - peak pressure gradient in *mmHg*, mpg - mean pressure gradient in *mmHg*, fv - flow velocity in *m/s*.

para-meter	AVS none	mild	moderate	severe
ava	> 2.0	2.0 – 1.2	1.2 – 0.75	< 0.75
ppg		< 35	35 – 65	> 65
mpg		< 25	25 – 50	> 50
fv		< 3.0	3.0 – 4.0	> 4.0

A. *Patients*

Three groups of patients were enrolled. The first group contains all patients who suffered from AVS (including mild, moderate and severe AVS, as shown in Tab. I), but partly suffer also from other valve stenoses and/or insufficiencies. The definition of the degree of AVS was made in accordance to standards of echocardiography [3, 4), as shown in Tab. 2. The patients of the second group (OVD) suffered from any other valve disease but not from AVS. The third group (REF) represents healthy subjects as controls.

Table I: Patients. Subgroups: I - only AVS, 2 - AVS plus a further valve disease.

group	subgroup	num-ber	mean age	gender f	m
all AVS		43	64±14	21	22
	1	8	66±10	3	5
	2	35	63±15	18	17
mild AVS		19	63±14	8	11
	▌	4	67±10	2	2
	2	15	62±15	6	9
moderate AVS		19	66±14	11	8
	1	3	71±8	▌	2
	2	16	65±15	10	6
severe AVS		5	58±15	2	3
	▌	▌	51	0	▌
	2	4	59±16	2	2
OVD		27	66±13	18	9
REF		11	60±24	7	4

B. *Multiresolution Wavelet Analysis*

There are various methods of digital signal processing available to analyze heart sounds. Comparisons between Fourier, short time Fourier and wavelet transform showed that wavelet transform are most apted to analyse heart sounds [5, 6) and to seperate background noises from biosignals [7).

Filtering a signal with wavelet technique has two main advantages: a high time/frequency resolution and the applicability for the analysis of non-stationary signals. The applied multiresolution wavelet analysis with subband coding decomposes a signal into octave containing frequency ranges and halves the resolution with every step down [8, 9).

The selected filter (Daubechies wavelets of order 14) splits the frequency range of the input sequence $f = 0 \text{ to } 7r$ in two parts from $flow = 0 \text{ to } 7r/2$ and $f\,high = 7r/2 \text{ to } 7r$ and requires the same sampling frequency for all data. The output of the lowpass filter is used for calculating the next stage. Signals were divided into 20 scales (10 levels· 2 sublevels).

C. *Calculation of envelopes*

After filtering, envelopes were calculated for each scale. The mean values m of subsequent segments (of length N) were calculated using the absolute values of all samples ck of the filtered signal with the length $tmax$· The desired envelope size n was 40 samples and it has to be considered that N depends on the scale level of the filtered signal and $trnax$·

$$m(n) = \frac{1}{N} \sum_{t=nN}^{(n+1)N-1} |c_k(t)| \Big|_{n=0 \text{ to } 39} \qquad (1)$$

D. *Correlation*

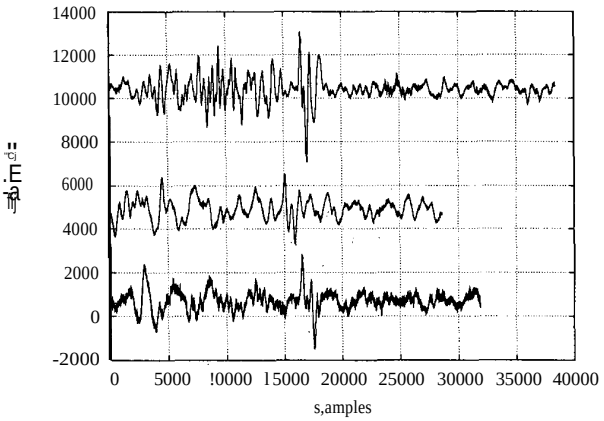
The similarity of two envelopes Xn and Yn was proved by the correlation coefficient K [10):

$$K = \frac{S(x_n y_n) - \frac{1}{N} S(x_n) S(y_n)}{\sqrt{\left[S(x_n^2) - \frac{1}{N}(S(x_n))^2\right]\left[S(y_n^2) - \frac{1}{N}(S(y_n))^2\right]}} \qquad (2)$$

where the sum of an envelope is defined as:

$$S(m_n) = \sum_{n=1}^{N} m_n \qquad (3)$$

To obtain a heart rate independent correlation and to avoid interrupted heart tones and murmurs all envelopes were arranged virtually in a cyclic manner (the first and last sample of the envelope were linked).



Figurl! 2: Heart sound signals recorded at the ausculatation area 7 of a patient with severe aortic.valve stenosis (top), a healthy subject (centre) and a patient' with mild mitral and mild tricuspid valve insufficiency (bottom, signal is two times amplified). The different length of these sound sample's are caused by different heart period lengths. For visualization purposes an offset was added to the upper curves.

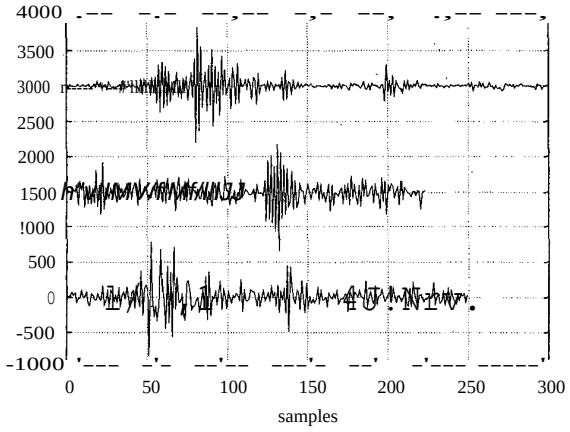


Figure 3: Wavelet filtered signals (scale from 172 to 345 Hz) of the signals from Fig. 2. For visualization purposes an offset was added to the upper curves.

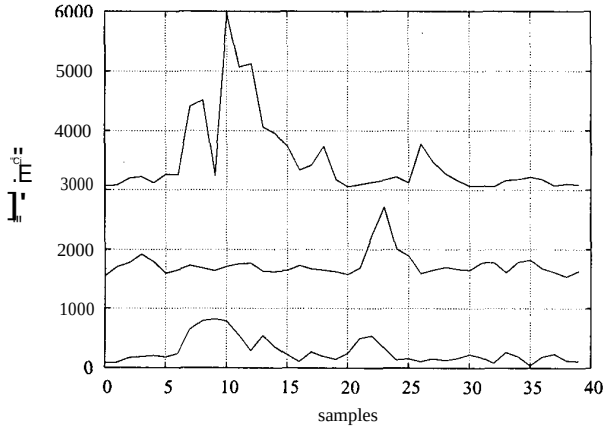


Figure 4: Envelopes with standardized length of the filtered signals from Fig. 3. For visualization purposes an offset was added to the upper curves.

For further analysis, the maximum value $K(t)$ of the cyclic correlation was used as quantity for similarity of two envelopes. All correlations were calculated within one scale and one auscultation area. The representative pattern for one patient was defined as the pattern with the highest mean correlation coefficient in comparison to all other patterns of the patient. Then every representative pattern of each patient is correlated with every representative pattern of each other patient. Mean values and standard deviations of these correlation coefficients were calculated for every group. The mean value of the correlation coefficient of the AVS group decribes the similarity within this group, but the mean values of the mixed groups describe how one group differs from the other one on an average.

For statistical analysis a Mann-Whitney U-test was applied to find whether the proposed method could distinguish between aortic valve diseases and healthy subjects and other valve diseased patients.

III. RESULTS

From the 7 investigated auscultation areas especially positions 1, 2, 6 and 7 revealed considerable differences between AVS and AVS/REF as well as AVS and AVS/OVD (Fig. 5). Using the 20 calculated scales most significant results were received in the scale from 172 to 345 Hz (level 6, sublevel 1). As shown in Tab. 3, the mean correlation coefficient (auscultation area 7, scale 172-345 Hz) within the AVS group was significantly ($p < 0.01$) higher than those between AVS and AVS/REF (rAvSIREF) as well as between AVS and AVS/OVD (rAVS/Ovo).

Table 3: Mean correlation coefficient r, standard deviation a and probability p for the tests AVS vs. AVS/OVD and AVS vs. AVS/REF (auscultation area 7, scale 172-345 Hz).

group	r	a	p
AVS	0.71	0.13	
AVS/OVD	0.57	0.14	< 0.01
AVS/REF	0.60	0.12	< 0.01

IV. DISCUSSION

The presented method has the ability to differentiate between heart sounds of AVS and healthy subjects as well as between AVS and patients with other valve diseases. Further on, this study confirms that optimal results were received in the auscultation areas that are generally used for diagnosing AVS. Interestingly auscultation area 7 reveals the highest significant differences between AVS and AVS/REF and also between AVS and AVS/OVD.

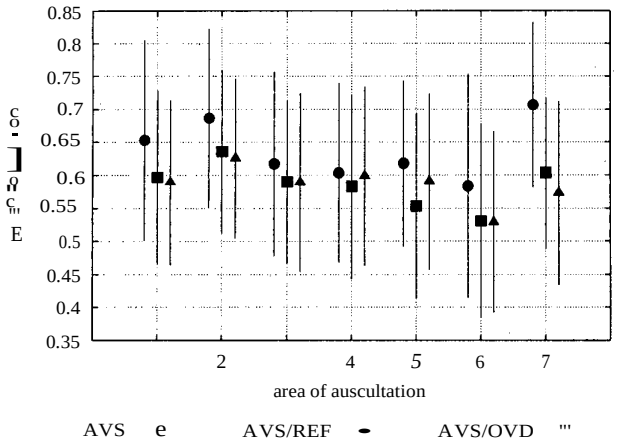


Figure S: Mean correlation coefficient *r* for all groups (scale 172-345 Hz).

To validate these first results the number of patients has to be increased. Several studies are in progress to collect more data and to evaluate the clinical value of the system for a detailed diagnosis of the most common valve diseases. Further studies have to be performed to analyse the influences of (1) contact pressure of the electronic stethoscope, (2) heart anatomy, (3) tissue between heart and surface especially on the power spectrum analysis.

V. CONCLUSION

We developed a wavelet and correlation based method which is applicable for an automatic diagnostics of aortic valve stenoses. This new method of heart sound classification seems to be suited for diagnosing valve diseases and application in a low cost and easy to use system for GPs.

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