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REVIEW OF SELECTED TECHNIQUES FOR CARDIOSIGNAL ANALYSIS

PREGLED ODABRANIH TEHNIKA ZA ANALIZU KARDIOSIGNALA

Ana Gavrovska[1,3], Milorad Paskaš[2], Irini Reljin[1], Dubravka Jevtić[2], Dragi Dujković[1], Branimir Reljin[1]

Correspondence to:

dipl.ing. Ana Gavrovska,
Faculty of Electrical Engineering,
University of Belgrade, Bulevar Kralja Aleksandra 73, 11120 Belgrade, Serbia,

E-mail: anaga777@gmail.com

[1]Faculty of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11120 Belgrade, Serbia
[2]Innovation Center of the Faculty of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11120 Belgrade, Serbia
[3]PhD stipendiary of the Ministry of Science and Technological Development, Republic of Serbia

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Key words
Cardiosignals, phonocardiogram, ultrasound image, echocardiogram, strain, signal and image processing techniques, review.

Abstract

The paper considers several techniques for cardiosignal analysis. We made a selection to present the importance of noticeable targeting in electrocardiograms (ECG), phonocardiograms (PCG), ultrasound (US) imaging and other cardiosignals. In this paper we discussed the existing problems in cardiosignal and parameter selection, pre-processing possibilities and automatic processing problems, pointing out several valuable techniques, from time-frequency PCG representation processing, wavelet pre-processing, myocard movements quantification to neural network based US image despeckling and phonocardiogram segmentation improvement. The final goal is improving early diagnosis of cardiovascular system dysfunctions applying different well-known techniques of signal and image processing by circumvention of existing ones in order to progress and profit. As cardiovascular diseases represent the leading cause of premature death, this field has numerous challenges facing in the future.

1. INTRODUCTION

Cardiovascular diseases still represent the leading cause of premature death. Besides being the major health concern, their further research has to be conducted having the important economic perspective in mind. Well-known, nonstandard, both new and forgotten techniques should be investigated leading to improved diagnosis and treatment. These possible improvements are expected to be future grand challenges confronted with the lack of understanding [1]. In this paper we focused on our views of some possible challenges by making a short review of some techniques and applying them on selected cardiosignals, where [1-3] only further indicate this topic's relevance.

One of the main challenges is identification of abnormal cardiovascular variability, patterns and other pathological indications more visible and accurate. Variety of interacting linear and nonlinear subsystems in the cardiovascular system conveys important information of underlying physiology [3]. Signal and image processing techniques, as well as mathematical models, allow better understanding of the valuable information for targeting possible cardiovascular dysfunctions and over the years a lot of research has been done in these areas. Nevertheless, most of the work is still in front of us. Full exploration of the whole heart (e.g. instead of focusing on the left ventricle), standard and advanced signal and image processing, different techniques and approaches of multidimensional cardiosignal analysis [4] are required for dysfunction localization and assisting physicians before, during and after interventions, while avoiding complex tools and parameter set-ups.

In this paper we briefly discuss the existing problems in cardiosignal processing and feature extraction (parameter selection) (Section 2.). A review of selected techniques and discussion of the obtained results are given in Section 3. Section 4. is dedicated to conclusions.

2. SELECTION OF CARDIOSIGNALS AND TECHNIQUES

Selecting the cardiosignal to be analyzed represent one important task. Different approaches of cardiovascular system monitoring are available in [4-5]. Electrophysiological pathologies are one of the most investigated for a long time. Electrocardiograms - ECGs (as well as some other onedimensional (1D) signals like heart rate variability, etc.) are often used as an additional information and/or reference. Their detailed examination over the years as a standard cardiosignal enables testing under controlled conditions and gathering the past knowledge and adding the new one, as ECG represents the most common quasiperiodic cardiosignal.

Nowadays, analysis of vibro-acoustic heart signals [5] becomes more popular anticipating that the advanced image techniques can be avoided in many cases where their use is not required. This is referred as cardiosignal selection problem. Vibro-acoustic signals include PCGs (phonocardiograms, heart sounds), ACGs (apexcardiograms), CPs (carotid pulses) and other kinds of mechanocardiograms (MCGs) and describe mechanical functionality of the cardiovascular system. Characteristics of these signals largely depend on data acquisition conditions (e.g. sensor placement, recording conditions, patient's condition and position, etc.) and this is one of the main reasons why the cardiosignal analysis represents a challenging task. Auscultation plays an important role in establishing possible existence of hemodynamic anomalies. Digital records of heart sounds are acquired using digital stethoscopes providing better insight into cardiovascular system functionalities in order not only to hear, but to visualize the morphological characteristics of PCGs making early detection of possible abnormalities [6]. Reported incidence of heart murmurs detected in PCG in children of 77-95%, where less than 1% of this population has heart disease is one of the most common examples of need for reducing the number of unnecessarily expensive, complex equipment and techniques [7-9] and further PCG analyzing.

The advantage of ultrasound (US) imaging technique comparing to other diagnostic tools is in its non-invasive approach, mobility and accessibility [10]. On the other hand US images are corrupted by speckle noise degrading images and making physician's decision harder. In order to improve signal-to-noise ratio (SNR) there are many filters developed thus far. Filtering techniques are still developing and we will present later two denoising filters.

Quantification of cardiosignals toward automatic decision making is actual topic among researchers. Describing e.g. visual content in terms of quantitative values makes diagnosis easier. As some heart failures can be seen only in echocardiograms there is variety of techniques developed for echocardiogram inspection. Later there will be presented strain calculation for quantification of heart deformations during the heart cycle.

Correlation investigation between cardiosignals is very important in cardiosignal selection problem and generally feature extraction problem. By improving algorithm robustness and making the feature data collections it is believed that we can extract valuable information. When it comes to the difficulties of gathering all available parameters from physicians and/or data acquisition team and making complete data-sets from physicians, feature extraction presents a great challenge. The parameter selection can encounter numerous problems. One of these problems that is obvious is using incomplete data-sets.

Analyzing cardiosignals include numerous techniques, including 1D and 2D filtering, segmentation techniques, pattern recognition, suspicious events detection and classification, enhancement techniques, making mathematical models, using advanced tools such as neural networks, etc. The final list is beyond this paper. In the next section, we made a selection of some techniques that can improve the cardiosignal inspection and make some crucial changes in the records like in pre-processing phase.

3. A REVIEW OF SELECTED TECHNIQUES

Over the years there have been numerous techniques investigated for cardiosignal analysis. Research of different non-parametric and parametric, fixed mode and adaptive techniques should be conducted in order to acquire a low-cost, reliable module for assisting in making early and fast diagnosis. In this paper we have selected only few tech-

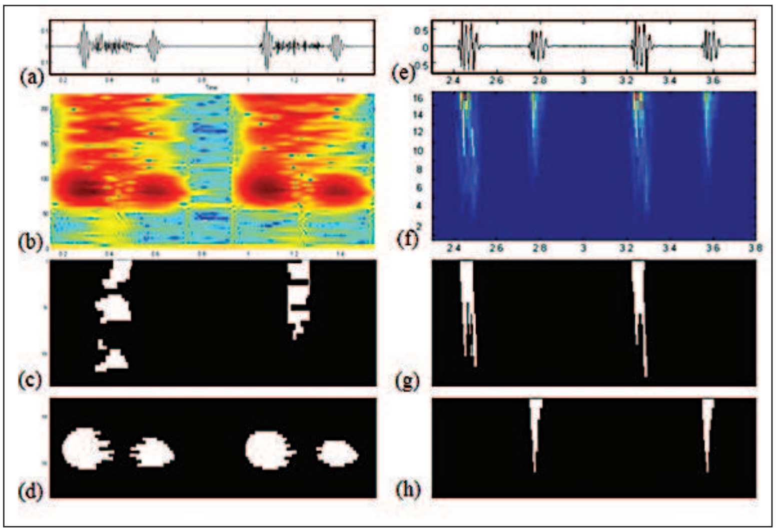

Fig.1. *Applying morphological operations for spectrogram and scalogram image: (a),(e)signals in time domain, (b)spectrogram of (a), (c)detected murmurs in spectrogram, (d)detected fundamental heart sounds in spectrogram, (f)scalogram of (e), (g)detected S1 splits in scalogram, (h)detected S2 sounds in scalogram.*

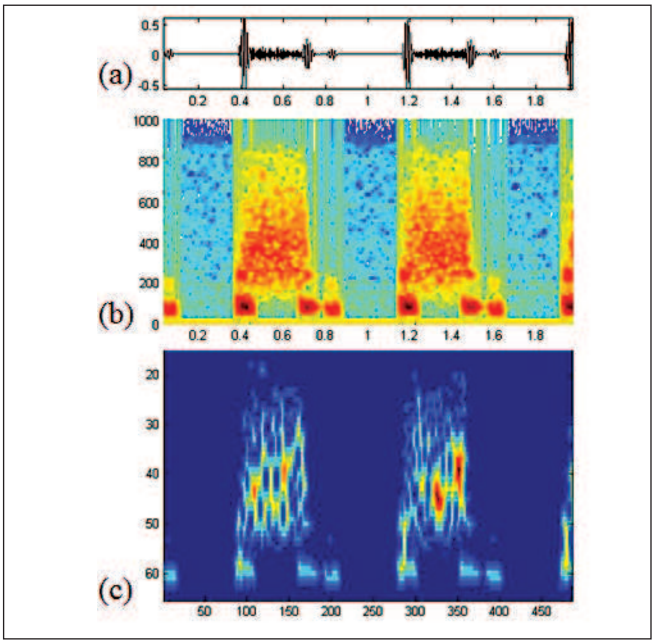

Fig.2. *PCG example: (a) time domain, (b) spectrogram image, (c) Euclidian distance based image.*

niques that can be used in such module. In 3.1. we consider PCG in joint time-frequency representation as 1D cardiosignal representative, where in 3.2. denoising and detecting relevant parts of the signal is considered. Ultrasound speckle filtering using CNN (Cellular Neural Network) and strain calculation are explained in Sections 3.3. and 3.4, respectively. Artificial neural networks in computer aided diagnosis are discussed in Section 3.5.

3.1. Phonocardiogram representation

Representation of cardiosignals is very important for physicians. Using the appropriate transformation, valuable signal characteristics become quite noticeable for easy event differentiation. Time, frequency and especially time-frequency domains are used for 1D cardiosignal representation in order to analyze morphological and other valuable information that can lead to instant preliminary conclusions about possible cardiac dysfunctions. Digital signal processing (DSP) research needs to be conducted in cooperation with physicians. Their knowledge is primarily based on their abilities (obtained during training process) to distinguish cardiac events, without exact information which parts of the signal representation are sufficient and which ones are redundant.

Considering visual morphological characteristics, PCGs human (physician's) visual system can be trained in order to target abnormalities. One of the most common trainings is auscultation. Even though, the reported primary care physician's accuracy rate in the auscultation is 20-40% and 80% for the cardiology experts [11]. Automatic detection technique applied on visual representation of cardiac events should enhance not only the detection process, but even the viewer's training process. The goal is to point out to some relevant parts of the signal representation and not to replace the physician's role.

Short-Time Fourier Transformation (STFT) is often used for joint time-frequency (JTF) representation purposes. Phonocardiograms are famous for their STFT spectrogram representations and physicians often use them as an additional tool for their analyzing in real-time and non-real-time applications. It is reasonable to use such representation because the cardiosignals represent non-stationary signals. Applying morphological operations on phonocardiogram 2D (3D) representation, problem of cardiac event distinguishing can be partially solved [12]. This is quite important with the murmurs that represent abnormal heart sounds like extra noise that blood makes flowing through the heart. Shape of the murmurs in spectrograms is valuable information for making preliminary decisions. Fig.1.(a)-(d) shows using several thresholds for spectrogram image, as well as morphological pre-processing resulted in distinguishing fundamental heart sounds (S1 and S2) and detected murmurs for aortic stenosis case.

One of the problems with STFT is to acquire satisfying both time and frequency resolution. Wavelet transformation (WT) solves this problem by letting different window dimensions. Such representation is called scalogram. Scalogram representation using CWT (Continuous Wavelet Transformation) is presented in Fig.1.(f). Morphological image operations seem to be successful even in the cases of detecting splits in the heart sounds [13], like in normal PCG from Fig.1.(e)-(h). Determination of morphologically valuable segments in JTF representations are of great importance

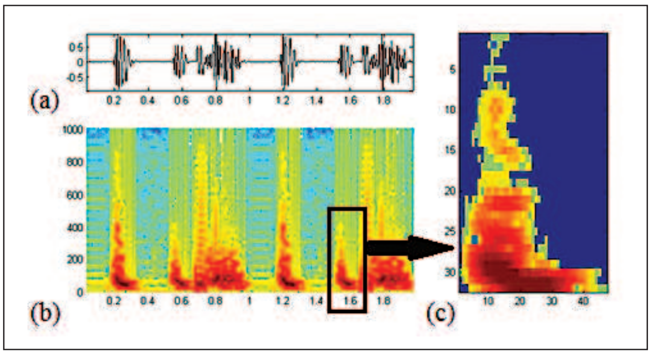

Fig.3. *PCG example: (a) in time domain, (b) spectrogram image, (c) color and Euclidian distance based extraction of S2 sound.*

and it is necessary to identify different cases of cardiac events, as well as to make the comparison of available JTF methods.

Morphological operations are not the only solution. In the cases where the physician is not sure which component belongs to which cardiac event, its energy and Euclidian distance may help distinguishing cardiac events in JTF representation [14]. In Fig.2. mumur content is more visible when applying Euclidian distance transformation.

In the example of PCG spectrogram, color and Euclidian distance based algorithm may help extracting whole cardiac events as in Fig.3.

There are some indications [14] that this can contribute more thorough familiarization with the cardiac events in 1D cardiosignals like PCGs.

3.2. Pre-processing of 1D cardiosignals

Pre-processing of quasiperiodic cardiosignals has always been a burning issue. Noise nature ignorance and different cardiosignal nature take all the credit for this. ECG beside

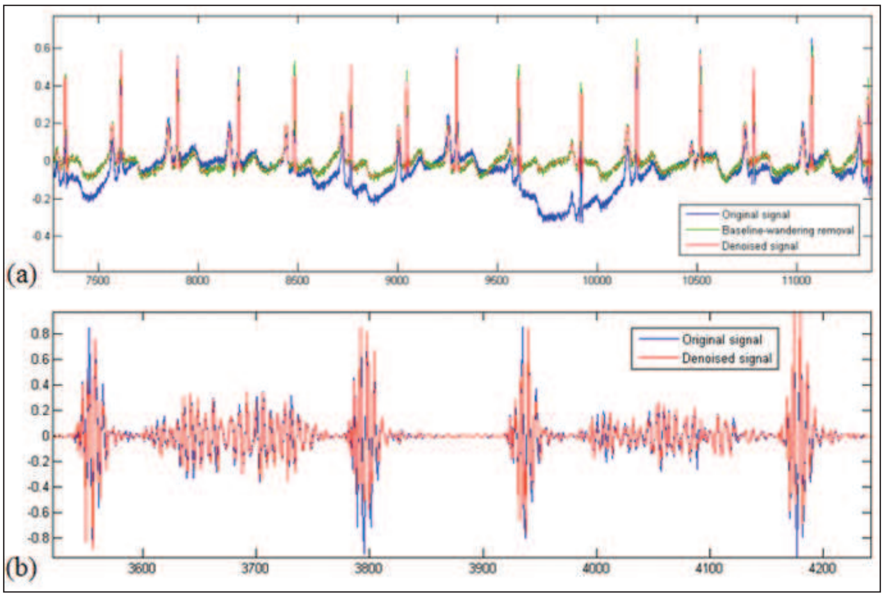

***Fig.4**. Examples of DWT denoising for (a) ECG and (b) PCG.*

baseline wander (BW) noise, EMG (electromyographic) noise, 50/60Hz power line interference, may have ambient and other unforeseen caused noises, like noise caused by loose positioned electrodes. Vibro-acoustic signals have different manifestations of noise. Ambient noise may cause many difficulties in analyzing PCG. Noise can be caused by skin and sensors contact, as well as noise caused by other physiological systems. Morphological characteristics of the signal dependable on patient's stress condition and position worsen the ability to precisely detect noise characteristics.

Noise classification and model making is not an easy task, considering the variety of the noises that can occur in signal. Three types of noise based on how they change over time can occur: stationary (without big or fast changes in spectrum over time), quasi-stationary (with relatively constant noise in spectrum over time) and non-stationary (with big or fast changes in spectrum over time, as well as with sudden, unpredictable occurrence and disappearance). Uncertainty in making records is inevitable due to the presence of random and systematic errors and their combinations.

Standard using of filters has numerous problems such as nonlinear phase characteristics, delay, segment attenuation and other difficulties. Using Fast Fourier Transformation (FFT), frequency components are chosen to be removed, attenuated or amplified and the results can be satisfying. Nevertheless, in the cases of non-stationary noises, noise-cancellation techniques with multichannel recording with different stakes of useful and redundant components are expected to give good results.

As explained, denoising is often done in some transformation domain, by changing appropriate coefficients, and then applying the inverse transform like in discrete WT (DWT) case [15]. In DWT, after signal is decomposed to chosen level, selection of coefficients must be made with appropriate thresholding and the reconstructed signal should present the result released from non-relevant noise. In Fig.4.(a) an example of DWT denoising applied on ECG for baseline wandering removal and high-frequency denoising is presented. DWT is also an accurate tool for denoising PCG (Fig.4.(b)).

Wavelet tools allow overcoming common problems and giving better results than standard filters (median, Butterworth, Kaiser) in most cases. They are advantageous in avoiding delay and obtaining better SNR (Signal-to-Noise Ratio), where the selection of wavelet types, decomposition level, coefficients selection and thresholding are crucial. In [16] statistics of used decomposition level is presented for ECG denoising purpose. We have tested techniques such like double density wavelet transformations [17] and full-wavelet transformations [15], where obtained results were slightly better on account of algorithm complexity and time-consumption. Applying adaptive filters must be tolerant on some conditions changing. This tolerance needs to be investigated further.

Technique selection depends on the signal's length even if it is window-based. If we want to make our system to "learn" the parameters, we should take into account the length of the cardiosignal. The results of pre-processed first several quasi-periods only will not be satisfying even if the technique works fine, and this is quite important in the cases where only 3-5 heartbeats of PCG are recorded [18]. However, adaptation time is not a problem with long-length cardiosignals recorded.

3.3. Ultrasound image filtering

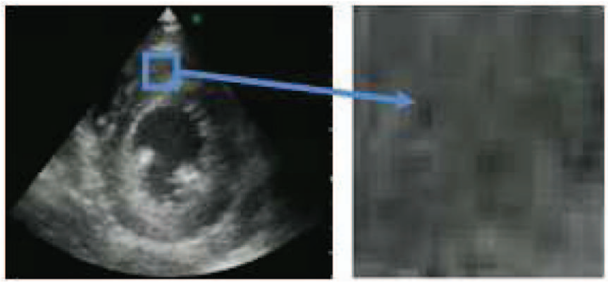

Fig.5. *Encircled homogeneous region (left) in echocardiogram and enlarged region (right) with speckle pattern typical in ultrasound images.*

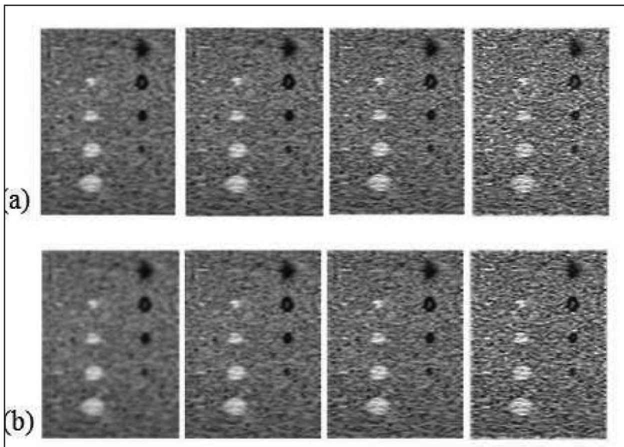

Fig.6. *Results of filter (a) F1 and (b) F2 implementation for different values of parameter α(α is growing from left to right).*

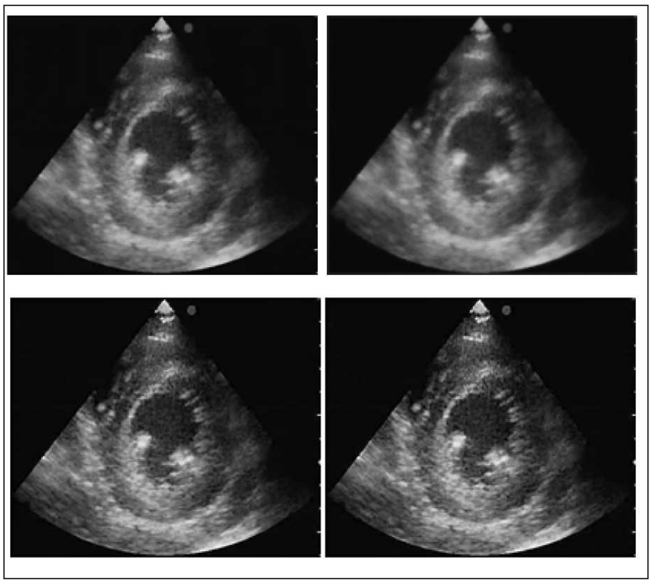

Fig.7. *Echocardiogram (upper, leftmost) and filtered replicas for different values of parameter α.*

Ultrasound images provide numerous information on tissue that should be extracted from the image. Acoustic waves produced by transducer are transmitted in the human body where they will be reflected, refracted and diffused in the tissue. The tissue structure can be modeled by two types of scatterers: structural and diffuse scatterers [19]. Structural scatterers are uniformly distributed in the tissue and they correspond to real anatomical features (signal in terms of signal processing). Ultrasound waves when reflected from such objects do not change the phase angle. Diffuse scatterers are micro structures in the tissue which are even or less of ultrasound wavelength and they are distributed in the tissue randomly. As opposed to structural scatterers, diffuse scatterers cause diffusion, i.e. amplitude and phase of such scattered wave will be random. Furthermore, two closely spaced (distance less than ultrasound wavelength) diffuse scatteres produce interference. There are two types of interference: constructive and destructive, and this is called speckles. It is illustrated in the Fig.5. Speckle pattern is seen as combination of bright (interference maxima) and dark spots (interference minima).

Speckles are immanent in ultrasound images and degrade it (represent noise in terms of signal processing). Due to speckles, regions in the ultrasound image supposed to be homogenous have speckle-like-pattern (texture). This should be suppressed and it is done using number of filters, as described further in the text. However, as diffuse scatterers (the cause of speckles in the ultrasound image) are within the tissue they will move together with it. Thus it is possible to track tissue movements only by tracking the speckles in the image. Therefore speckles can be observed either as a degrading factor in ultrasound images (noise) or like acoustical markers for tracking tissue movements.

Speckles are assumed to be multiplicative noise in the image. The first filters used for speckle suppression were taken from synthetic aperture radar (SAR) imagery: Lee, Kuan and Frost filters. Statistics of neighbor pixels (mean value and standard deviation) determine the filtered value of that pixel. The main drawback of adaptive filtering is smoothing the edges. There is the same filtering criteria both for pixels in homogenous regions and in regions with contrast (edges). To overcome this problem researchers turned to filters based on partial differential equations (PDE), such like speckle reducing anisotropic diffusion (SRAD) filter [20]. These filters forces smoothing in homogenous regions while suppresses smoothing of edges.

Here we represent two filters we developed using PDEs. Filters are realized using cellular neural network (CNN), where the feedback matrix controls speckle reduction while control matrix keeps edges sharp [21]. Both filters are optimized according to the same edge-preserving condition. Filter F1 uses heat diffusion template [22] for speckle reduction, while filter F2 uses Laplace PDE solver for the same reason. Parameter α multiplies control matrix and it takes values from the range (0,2).

From Fig.6. it can be seen how small values of parameter α favor smoothing and bigger values of that parameter preserve the edges in in vitro images (these images are obtained by filtering phantom image simulated by Field II program [23]). The proper value of α should be determined by inspection of physician. Fig.7. shows in vivo testing of filter F2.

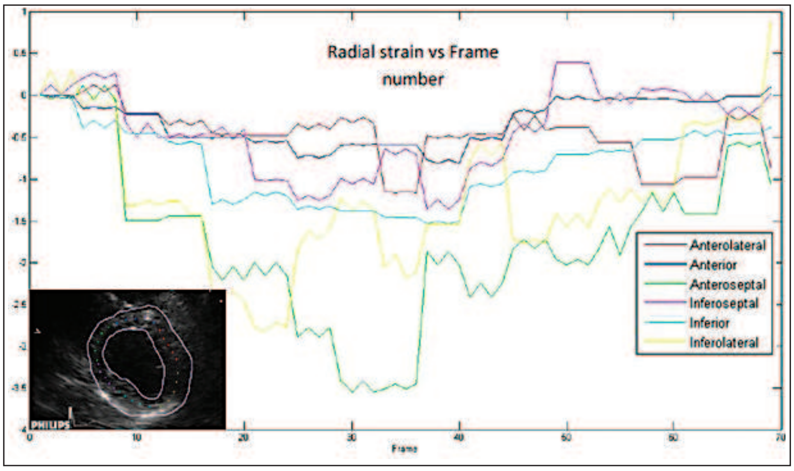

Fig.8. *Radial strain versus frame number.*

3.4. Strain calculation in echocardiograms

Strain calculation represents one step towards quantification of myocardial movements. It is defined as a deformation of the object relative to its original shape [24]. If we assume deformation of the heart, there are 17 segments [25] in the myocard that should be tracked in order to get the whole picture of heart deformation in one heart beat. Then, strain rate (SR) is calculated as a first derivative of strain. One approach in strain calculation is Doppler tissue imaging (DTI). From Doppler images SR is calculated as a spatial velocity gradient, while integration of SR gives strain values. However, DTI is angle (of transducer) dependent technique which means that motion vector must be parallel to the beam.

In order to exceed these constraints of DTI analysis there is speckle tracking technique. As it was mentioned earlier, speckles can be used as acoustical markers which move together with tissue. It is also shown the speckle pattern (fingerprint) in the ultrasound images. As it is stable pattern it can be tracked in ultrasound video from frame to frame. Sum of absolute differences (SAD) algorithm is widely used block-matching method used for speckle tracking because of its simplicity. SAD searches for speckle pattern (20x20 pixels window) in the next frame which is the most similar to the speckle pattern from the current frame. When the displacement is determined via SAD, strain and SR is computed for every frame.

Abovementioned tracking algorithm is conducted for all of 17 segments of the heart. Actually, in every segment there are several patches tracked and the final strain value of the segment is calculated as a mean. It is assumed as a spatial averaging. We also applied a time averaging by averaging strain values through time, i.e. as a mean of strain values from several previous frames. This procedure is done due to speckle out of plain motion.

Regarding local heart coordinate system [26], there are three axis: radial, longitudinal and circumferential axis. Fig.8. shows radial strain values for six segments corresponding to short axis view of pappilary muscle. Strain calculation starts at the end of diastole and therefore it has negative values during the whole heart cycle. In the first step of algorithm endocardium and epicardum should be traced manually while the rest of algorithm (segmentation and tracking) is automatic. Segmentation of short axis view of the heart is shown in Fig.8. and corresponding strains in the graph are coloured accordingly.

3.5. ANNs in computer aided diagnosis (CAD)

The neccessity of adaptive techniques do not rely only on the fact that there is a need to automatically set the algorithm parameters while analyzing cardiosignal inputs, but on the fact that system shoud „recognize" which segments of the signal are relevant. Artificial intelligence (AI) implementations may improve different processing phases, from heart sound detection and segmentation to murmur classification or replace available analytical mehods. AI should be included in computer aided diagnosis (CAD). Gavrovska et. al. [27] present an example of ANN (Artificial Neural Network) implementation for PCG segmentation of whole fundamental heart sounds (S1 and S2). Results of segmentation analytical methods may not be satisfactory and ANN may improve them, involving the „intelligence" part [14]. This can be important in the cases of adjacent cardiac events, to reduce eventual physician's uncertainty.

4. CONCLUSIONS

Signal and image processing modules (SIPMs) for cardiosignal analysis should include efficient, low-cost techniques. Some of them are presented in this paper. JTF representations like spectrograms and scalograms may improve representation of 1D cardiosignals, as well as well-known image processing techniques. We highlighted morphological operations and color-based segmentations as techniques that can contribute easier targeting. Wavelets are presented as almost essential tool for pre-processing. If they are used properly, they do not affect morphological characteristics that can be of great importance (e.g. murmur shape within PCGs). Pre-processing of PCG can be viewed in two ways: for auscultation purposes and visual representation. The pre-processed signal that has satisfactory visual representation may sound too artificially. Also, the pre-processed signal that can be satisfactory auscultated, may be too noisy in the visual representation. Two classes of pre-processing techniques need to be considered in this case. It is important to mention that the order of applying techniques can drastically affect the results (e.g. applying decimation on pre-processed 1D signal). US as an example of 2D cardiosignal processing was used in order to present filtering techniques and strain calculation possibility. ANNs and adaptive techniques take an important role in compute aided diagnosis (CAD). All these selected techniques and many more may change the way we have observed cardiosignals till now.

Apstrakt:

U ovom radu je razmatrano nekoliko tehnika za analizu kardiosignala. Napravili smo izbor kako bi prezentovali potrebu za jasnim pregledanjem elektrokardiograma (ECG), fonokardiograma (PCG), ultrazvučne (US) slike i ostalih kardiosignala. U ovom radu razmatrani su postojeći problemi u izboru kardiosignala i parametara, mogućnosti preprocesiranja i problema automatskog procesiranja, posebno obraćajući pažnju na nekoliko značajnih tehnika, od procesiranja vremensko-frekvencijske PCG reprezentacije, preprocesiranja pomoću talasne transformacije, kvantifikacije pokreta miokarda, do isticanja ivica na US slici i poboljšanju segmentacije fonokardiograma upotrebom neuralnih mreža. Konačan cilj je unapređivanje ranog dijagnostikovanja nefunkcionalnosti kardiovaskularnog sistema primenom različitih poznatih tehnika obrade signala i slike zaobilaženjem postojećih u cilju napretka i isplativosti. Kako kardiovaskularne bolesti predstavljaju vodeći uzrok prerane smrti, ovu oblast tek očekuju veliki izazovi u budućnosti.

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