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Abstract booklet of the Ph.D. Doctoral Thesis

New Methods for Computer Aided Analysis and Integration of Vital Signals into a Standardised Diagnostic System

by

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Budapest, April 2002.

Contents

Introduction

Processing of long-term recorded vital signals is an important application field of computer aided medical diagnostics, addressing problems of both medical informatics and signal processing. The evaluation of long-term and multi-channel signal records requires computer aided analysis, since a human expert could hardly manage and process the huge amount of measurement data.

This Ph.D. thesis addresses two major research areas: medical informatics and computer aided diagnostics.

The first chapter of the thesis introduces an open architecture patient monitoring system which was developed at my participation in the framework of an international research project. The main novelty of the presented patient monitoring system that it integrates the monitoring of various vital signals using standardised hardware/software components.

The next chapters of my thesis present new signal processing methods for the computer aided on-line analysis of three various kinds of long-term recorded vital signals:

I. single-channel hybrid ECG segmentation,
II. detection of episodes and type of apnea in the respiration signals,
III. determination of fetal heart rate using phonoacoustic recording.

Although the development of these new signal processing methods was connected to the open architecture patient monitoring system, they can also be applied as stand-alone clinical solutions.

The last chapter of my thesis presents the current applications of the achieved results and gives a summary of the presented work.

Research objectives

All of my Ph.D. theses address new signal processing methods for the computer aided analysis of long-term recorded vital signals. The developed methods are capable of more efficient and robust on-line signal processing than other existing and known solutions.

I. Single-channel hybrid ECG segmentation

The long-term variability of ECG segments carries an important diagnostic information. Due to practical considerations the long-term ECG recordings are usually taken by using only one or two signal channels. Current single-channel segmentation methods cannot properly handle different beat types and noisy signal sections, and they can only segment the clear normal sinus rhythms precisely enough.

The goal of my research work was to develop a novel single-channel ECG segmentation technique, which can handle various beat types and noisy signals more robustly. The presented system provides the real-time morphological segmentation during single-channel ECG recording. The objectives of the developed new ECG segmentation method are:

- complete (P-QRS-T) morphological segmentation of single-channel long-term ECG records,
- on-line segmentation (beat-to-beat, with maximum one beat delay),
- robust classification of various ECG beat types,
- using *a priori* morphological information at the segmentation,
- robustness against various noise,
- modular and scalable system structure.

II. Detection and classification of episodes of apnea

One of the most essential task at the monitoring of respiration signals is the tracking of breathing dynamics. The present clinical methods provide apnea (lack of breathing) detection with over 80-90% precision. The success rate of hypopnea (reduced breathing) detection and the determination of apnea type is far not as efficient. Another problem is that the most successful methods use off-line signal processing, which is not viable in many clinical applications (eg. patient or infant monitoring). The presented new neural-network-based on-line apnea/hypopnea detection systems apply the time windowed processing of the respiration time series. Another method provides the efficient detection of airway obstruction which is based on the analysis of the phase difference between the abdominal and thoracic excursion signals. The connection of the two systems allows the determination of the apnea type (obstructive vs. central episodes). The objectives of the presented new apnea/hypopnea detection and classification methods are:

- high precision, robust, on-line detection of episodes of apnea and hypopnea using only the respiration signals,
- classification of episodes of apnea and hypopnea (central vs. obstructive episodes),
- processing of respiration signals independently of patient-specific characteristic.

III. Determination of fetal heart rate by phonocardiography

The fetal health status can be monitored by the long-term measurement of the fetal heart rate (FHR) variability. Although frequent FHR measurement would be recommendable, the cost of the clinically most widely used active ultrasound technology is so high that it is not available for home care use. The possible solution for such applications could be the use of the fully non-invasive and cost-efficient passive phonocardiographic measurement. The processing of phonocardiographic records requires sophisticated signal analysis due to the low acoustic energy emitted by the fetal heart and the numerous disturbance.

The presented measurement system and new signal processing methods (two-channel recording, wavelet-based denoising, beat localisation using correlation, rule-based beat selection) provide the long-term determination of FHR at a precision which is comparable to ultrasound CTG technology. The key features of the proposed novel signal processing are:

- fully non-invasive, passive phonoacoustic measurement method (the measurement device can be used in the field of home care, too),
- determination of fetal heart rate at a precision and robustness which is comparable to regular ultrasound CTG,
- graphical presentation of FHR for diagnostic purposes,
- real-time computation.

Research results

Thesis group I

1. A new on-line computer aided ECG segmentation system was developed which carries out the complete morphological segmentation of single-channel long-term ECG signal records. The developed system provides more efficient segmentation than any other currently known single-channel segmentation methods. The input signal of the system is the single-channel ECG signal. The output signals of the system are the type of the actually segmented beat (N, PVC, or APC), and the segmentation details of the individual ECG beats (length, height, area of the ECG waves, and length of the relevant characteristic times). The block diagram of the developed hybrid segmentation is depicted in Fig. I-1:

   The noise is removed from the *e* ECG signal by using a wavelet-based method resulting the *f* signal, in which the R-peaks are located. The separation of the individual ECG beats are realised by a new adaptive beat isolation method. The classification of the isolated beat's type is carried out by a feed-forward artificial neural network. The segmentation of the beats is based on morphological segmentation units which were activated after beat type classification. The segmentation units use the linearly approximated image (*d*, *m*) of the isolated *b* ECG beat.

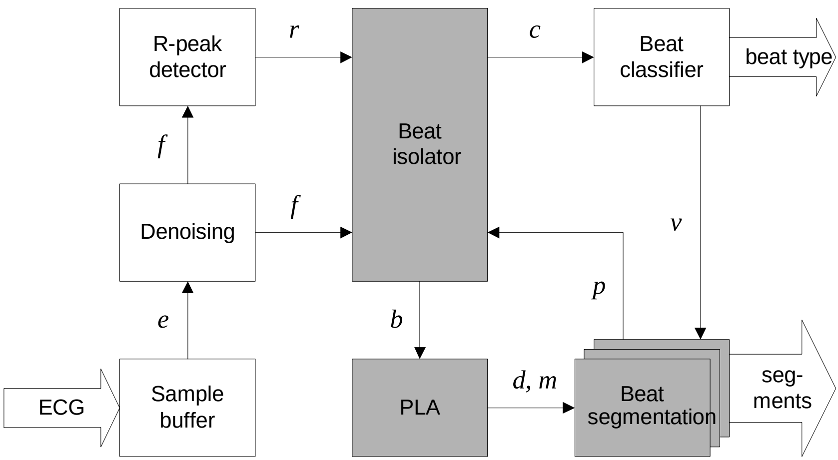

Fig. I-1: The block diagram of the hybrid ECG segmentation

2. Several new signal processing methods were developed for the efficient operation of the hybrid ECG segmentation system presented under paragraph 1 (see the gray boxes of Fig. I-1):

- A new adaptive beat isolation algorithm was developed which isolates those *b* sample points of the denoised ECG signal which belong to an ECG beat. The algorithm also computes a beat image consisting of *c* constant number of samples which is used at the beat classification. The adaptivity of the isolation is ensured by considering the *p* end position of the last isolated beat.

- A PLA (*Piecewise Linear Approximation*) algorithm was developed, which provides the linear approximation of the *b* isolated beat (*d* - section length vector, *m* - section slope vector). The PLA algorithm is the modified version of a method used in another ECG processing system (*Vullings et al.*). The following modifications were done in order to reach the goals:
  a. A minimal step size l_{min} = 10 [ms] must be applied at increasing of the individual *l* linear pieces in order to ensure adequate convergence speed.
  b. The error limit ε_{max} must be equal to the maximum of the *j* number of individual linear approximation errors (and not the total approximation error). This ensures better approximation performance.

- Three new morphological segmentation algorithms were developed which carry out the segmentation of three basic beat types: N, PVC, and APC, respectively. The morphological segmentation is based on the linearly approximated beat image (*d*, *m*) and provides the determination of all relevant beat segment information: length, height and area of individual ECG waves, and the length of the most important characteristic time intervals.

  The rule-based segmentation methods were realised with finite state automatons. The conditions for the state transitions were determined the physiological and statistical analysis of a huge number of ECG beats using *a priori* morphological information.

Thesis group II

1. Several neural-network-based apnea/hypopnea detectors were developed for the on-line monitoring of respiration signals. The neural networks classified the time series of the respiration signals using a classification time window. As the result of the classification the normal breathing and the episodes of apnea and hypopnea could be distinguished.
   The feed-forward neural network with two hidden layers was the best performant amongst the examined network structures (feed-forward, Elman, ANFIS) for the classification of respiration time series.
   The optimal length of the classification time window was empirically determined (16 seconds). The narrowing of the window would result in instable classification, the widening of the window would harden the network training and reduce the classification performance.

2. Three different methods were developed for the preprocessing of the input signals of the neural-network-based classifier defined in paragraph 1 (see Fig. II-1):
   a. adaptive normalisation of the original respiration time series (nasal airflow, thoracic and/or abdominal excursions) using the signal conditions in the last time window,
   b. derivation of an instantaneous respiration amplitude and time interval signal from the adaptively normalised respiration signals with a new algorithm,
   c. determination of the dominant base frequency and the spectral energy of the adaptively normalised respiration signals, in each time window, using short time Fourier-transformation.

   It was pointed out that input signals derived according to point *b* were the most appropriate for on-line neural-network-based classification. The overall classification precision was over 90%. It can be shown that the instantaneous respiration amplitude and time interval signals represent the breathing dynamics in way, which is appropriate for high precision apnea/ hypopnea detection, but does not contain the patient and measurement-specific signal detail.

   The input signals derived with the method of point *c* could be efficiently used only to distinguish normal breathing and episodes of apnea.

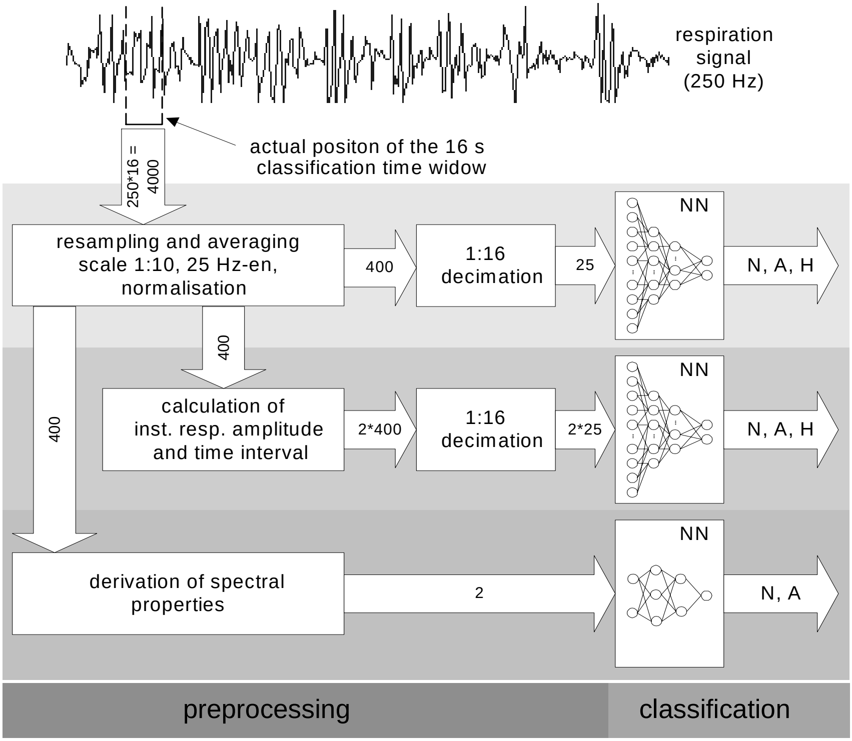

Fig. II-1: Three different neural-network-based apnea/hypopnea detectors
(N - normal breathing, H - hypopnea, A - apnea)

3. The phase relation of the abdominal and thoracic respiration movement was defined. A new rule-based phase detector was developed for the analysis of the phase relation between the thoracic and abdominal excursions. The phase detector can more efficiently detect increases in the airway resistance (i.e. obstruction) than any other existing and known methods.
   The obstruction detector together with the neural-network-based apnea/ hypopnea detector of paragraphs 1 and 2b provides the classification central and obstructive episodes of apnea and hypopnea (difference-diagnostics Fig. II-2).

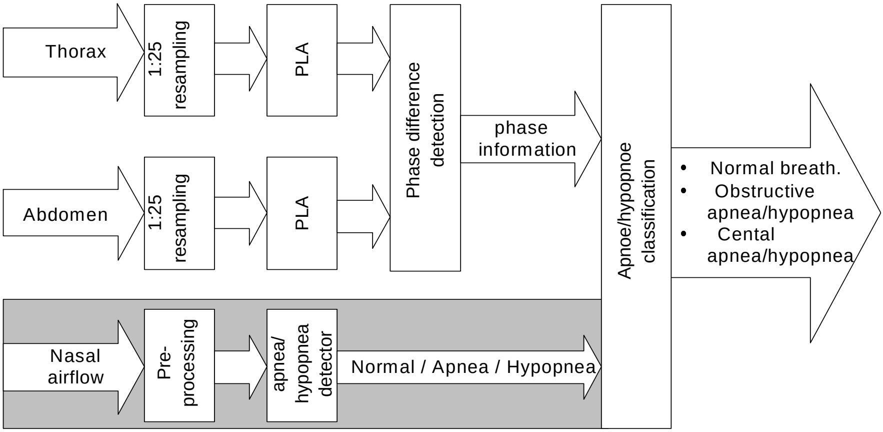

Fig. II-2: Block diagram of the developed apnea/hypopnea detector and classifier (the apnea/hypopnea detector of paragraphs 1 and 2.b is shown in a gray box)

Thesis group III

1. A new double-channel phonocardiograph was developed for the fully non-invasive, passive, acoustic determination of the fetal heart rate (FHR). The main novelty of the double-channel recording technique that it provides an additional signal channel (environment) in order to eliminate the external noise from the useful signal (fetal heart sound). The block diagram of the proposed measurement system is depicted in Fig. III-1.

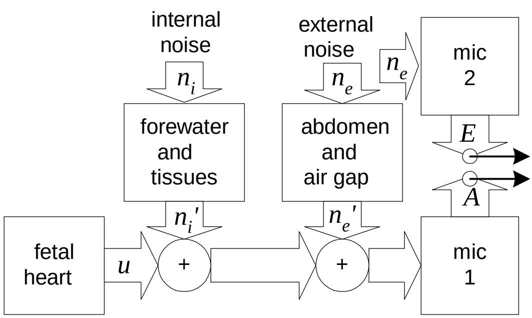

Fig. III-1: Block diagram of the double-channel phonocardiograph

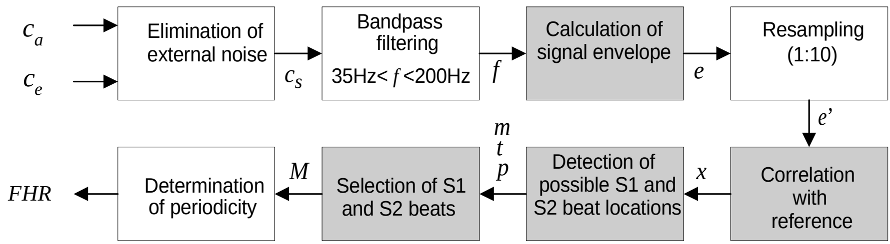

Fig. III-2: Block diagram of the developed new signal processing method for the phonoacoustic FHR detection

2. A new wavelet-based method was developed for the elimination of the external noise from the useful abdominal acoustic signal. It was pointed out, that an appropriate noise filtering can be achieved if both channels are decomposed using the 6th order Coiflet-2 as mother wavelet. The wavelet coefficients of the signal free of external noise were determined by an adaptive cross-channel thresholding technique. The signal free of external noise was reconstructed from the thresholded coefficients.

3. A new signal processing method was developed for the determination of the S1 (systolic) and S2 (diastolic) fetal heart beats using the prefiltered *f* acoustic signal. The method consists of the following main steps (see gray boxes of Fig. III-2):

   At first the *e* envelope of the *f* prefiltered signal is calculated. Afterwards the envelope signal is cross-correlated with the envelope of a reference fetal heart beat. The possible S1 and S2 heart beats correspond to the local maxima in the *x* cross-correlated signal. The local maxima were selected by using probability analysis.

   The real S1 and S2 beats were determined with a rule-based system (implemented by a finite state automaton) which is partly a modified version of the method proposed by *Kovács et al.* The main novelty of the method that it regards the physiological information on the time conditions and magnitudes of the S1 and S2 fetal heart beats, too.

4. A new algorithm was developed for the determination of the FHR periodicity. The noise which could not be filtered out cause that not all S1 and S2 beats can be detected. The essential of the proposed method that it uses a time window for the determination of the periodicity and it examines both the neighborhood relation and the time variability of the subsequent beats.
   According to the experiments, the requirements of real-time signal processing and stability can be met by selecting a 3 seconds-long time window.

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