ECG Processing Algorithms for Portable Monitoring Units
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Citation

Abstract
This paper presents DSP algorithms running on a portable unit (COMPASS, co-operating mobile patient assistance and surveillance system) for automatic on-line monitoring and analysis of the ECG, used as a pilot study of a wider, advanced project we are involved in. According to the largely recognised trend toward the achievement of a tight physician to patient cooperation, this project has been conceived both to alleviate physician from false alarm calls and to allow the educated patient to report accurately his symptoms. Such a piece of equipment should perform accurate analysis of on-line signals and generate dependable alarms. In particular the scope of this study is to design and develop low computational cost algorithms for portable bio signals and data processing units (intelligent holter, loop recorders, event/alarm recorders). This paper summarises previous findings, introduces a reliable non linear QRS detection operator, a simple and effective combinatorial-sequential network for ectopic beats and episodes onset (ischemia) detection and classification.

INTRODUCTION
Deep and extended changes are going to characterise, along common directions, health systems organisation in Europe, North America, and some of the countries of Pacific area as well [1]. One of these will be the managed care approach that has some implications on the extended role of the practitioners. Moreover evidence based medicine will stimulate a more objective attitude in symptoms evaluation, possibly through personal instrumentation encouraging patient to physician cooperation.

Development of devices for personal monitoring has also gained a new momentum because of various factors, like: availability of resources, demand of home care providers, increased senior population, increased costs of in-hospital assistance, international trend according to evidence based medicine. Such monitoring devices should fulfill quite new requirements as far as reliability and dependability. In particular we focus our studies on ECG signal monitoring, in fact especially for cardiac patients, a portable and reliable system plays a pivotal role in order to generate alarms when a heart attack is detected and to provide useful diagnostic parameters extracted by ECG during the daily life of ambulatory patients [2]. In this paper we'll introduce an algorithms set for portable units, based on a high performance and low computational cost quadratic operator, for arrhythmia and gradual onset episodes (ischemia) detection.

METHODS
Biological signal processing is usually developed through an appropriate DSP algorithms cascade (Fig. 1). The main stage consists in a signal segmentation, such as to include characteristic wave shapes to be detected.

Figure 1

Figure 1: Algorithms cascade

Wave shapes detection generally is based on enhancing slope variations respect to a level of reference (base line). For instance the element to be identified in the case of ECG are the wave shapes of the QRS complex.
Such a detection is traditionally done with digital filter design techniques, both in time and frequency domain [4].

It's often advisable to precede the derivative stage with a band-conditioning filter or with one that generically reduces the energy of the noise through smoothing tasks.

In this study, involved in carrying out a realization of a portable instrument, it is essential to guarantee efficient and effective performances of algorithms [4].

Being the process of detection of the QRS wave shapes the most important one of the analysis chain, therefore involved in the elaboration of every signal sample, it's an important task to estimate if a single operator is sufficient for an effective detection.

QRS DETECTION

In this paper we propose a high performance QRS detector by exploiting the curve-length concept [5]. Fig. 2 shows how the lengths L1 and L2 are able to characterize the shape of the curves, given a certain time interval DT.

Figure 2

Figure 2: The curve length concept

This principle can be applied to detect the wave -fronts that characterizes the beginning and the end of an episode.

Applying Pythagoras theorem in the discrete time domain we can approximate the arc- length relative to the i-th sample with the chord length, obtaining:

\[ L = \sum_{i=0}^{n-1} l_i = \sum_{i=0}^{n-1} \sqrt{T x^2 + (y_i - y_{i-1})^2} \]

L is the total estimated length of the episode, T is the sampling interval, yi –yi-1 represents the i-th increment and n is a rough estimate of the duration of the episode (or waveform) to be detected: in our case n is an estimate of QRS duration.

We can also write L as:

Figure 4

\[ L = Tx \sum_{i=0}^{n-1} \sqrt{1 + \left( \frac{y_i - y_{i-1}}{Tx} \right)^2} = Tx \sum_{i=0}^{n-1} \sqrt{1 + \left( \frac{Dy}{Tx} \right)^2} \]

Now, being T a constant and approximating the hypotenuse of successive triangles with their height we obtain:

Figure 5

\[ U1 = L \approx \sum_{i=0}^{n-1} Dy \]

During experimentation we found that taking the square of this quantity bring us a better discriminator capacity. So we can define a new operator, called U2, as:

Figure 6

\[ U2 = \sum_{i=0}^{n-1} Dy^2 \]

Finally, centering the computational window on the i-th sample, and calling w=n/2 we obtain a recursive low computational cost form easily programmable also using assembly languages for DSPs processors, usually used in portable systems:
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Figure 7

\[ U_{3,i} = U_{3,i-1} - (y_{i-w} - y_{i-w})^2 + (y_{i+w} - y_{i-w})^2 \]

In Fig. 3, 4, 5 we can observe the operator responses applying ECG signals as inputs. Data records are provided by European ST-T database [6].

Figure 8

Figure 3: U3 output, normal beats

Figure 9

Figure 4: U3 output, base line shifts

Figure 10

Figure 5: U3 output, PVC (left) and ischemic attack (right)

A procedure producing similar results was published by Pan-Tompkins [7] and consists of a cascade of four filters: a bandpass, a differentiator, squaring operation, and finally a moving window integrator.

DOUBLE THRESHOLD ALGORITHM

After the ECG signal has been filtered by the U3 quadratic operator, the normalised (0...1) output signal is compared first with an opportune primary threshold in order to detect the QRS complexes and then with a variable secondary threshold used to detect QRS following episodes (premature beats, T wave and ST changes) captured by the particular form of U3 output signal (Fig. 3, 4, 5).

The study of the annotated ECG database European ST-T [6], that we have carried out to validate the operator, has underlined that the values of the primary threshold maximizing the performances of the detection algorithm vary in the range 0.5..0.6. The secondary threshold is dynamically moved, controlled by the system logic, in order to recover missed beats or to detect gradual onset events (ST, T changes).

CONTROL LOGIC

Each time a primary event is detected, RRa interval is calculated and compared with the mean RR (calculated on the last 10 s buffer). The procedure is:

If

the system has probably missed a beat.

In this case a time window (“A” window), starting after

Figure 11

[RRa - 2RR] < [RRa - RR]

and ending at the beginning of the following beat is analyzed with the secondary threshold that, assuming values decreasing to zero, looks for a cross point with U3. If no beat is detected a flag, called MB, is set, meaning that a missed beat (pause of length RRa) has been detected, otherwise the RR series (RRa value) is corrected adding the new beat. This procedure is also useful in presence of some particular forms of PVC (Fig. 6) that are not detected with the primary th. while usually the ectopic QRS shows large U3 wave shapes (Fig.5) allowing reliable detection.
The secondary threshold is also used to monitor the time window ("B" window)

Figure 13

Figure 6: U3 output in presence of critical PVC episodes

The secondary threshold is also used to monitor the time window ("B" window)

Figure 14

\[ QT_a = 0.39 \sqrt{RR} + 0.04 \]

seconds following the current beat, looking for secondary peaks of U3. Compatible events with those peaks are:

ST-T changes: The onset of ischemic ST-T changes is detectable using the secondary threshold (Fig. 7). When looking into this time window the secondary th. is initially set to 0.05 (experimental best value).

Figure 15

Figure 7: Secondary th. and ischemic episodes

When a secondary event is detected the algorithm looks back, decreasing the th. value, into the buffered U3 data (20 s) measuring the Max. values of the secondary peaks. If the procedure finds a positive trend a flag, called STT, is set and the algorithm proceeds measuring the following U3 secondary peaks in order to find the end of the episode. When no more secondary peaks are detected the flag STT is reset.

Abnormal T waves: Some patients presents an ECG signal characterized by an abnormal T wave shape. U3 operator enhances this feature (Fig. 8) and the secondary th. is used to detect each wave. When secondary peaks with the same amplitude are detected in each beat, a flag TS is set to inform the system of this signal feature.

Figure 16

Figure 8: Abnormal T wave shape.

ALARM NETWORK

The following schematic (Fig. 9) represents, using a sequential-combinatorial logic net architecture, the alarms management module of the applicative software. Each time a QRS is detected a clock pulse is generated.

Figure 17

Figure 9: Logic control network

The inputs are derived parameters obtained by previously presented numerical algorithms. The sequential module acts like a counter switching the outputs (N,PVC,DP,TP,TAC flags) on when arrhythmia episodes are detected. Those signals represent strobe lines for the following alarm enabling combinatory net (see Tab. 1). The binary variables obtained as output from this second stage represent an example of a real time data set taking part in defining a dynamic context [9] for patient monitoring.
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RESULTS

System performances are strictly related with the main U3 algorithms performances, so a wide validation has been performed in order to test the quadratic operator. The signal database, ST-T European Database \([1]\), used as test set, was provided by Physionet \([8]\) and consists of 90 annotated excerpts of ambulatory ECG recordings from 79 subjects. The subjects were 70 men aged 30 to 84, and 8 women aged 55 to 71. Myocardial ischemia was diagnosed or suspected for each subject. Each record is two hours in duration and contains two signals, each sampled at 250 samples per second with 12-bit resolution over a nominal 20 mvolt input range. The sample values were rescaled after digitisation with reference to calibration signals in the original analogue recordings, in order to obtain a uniform scale of 200 ADC units per millivolt for all signals. Two cardiologists worked independently to annotate each record beat-by-beat and for changes in ST segment and T-wave morphology, rhythm, and signal quality. ST segment and T-wave changes were identified in both leads (using predefined criteria which were applied uniformly in all cases), and their onsets, extrema, and ends were annotated. Records also contain arrhythmia annotated episodes.

In order to test the algorithm performances, each record has been filtered with U3 and then, varying the primary th. from 0.1 to 1.0 (step 0.1), the revealed beats have been compared with the annotations. For each record, sensibility and P+ have been calculated for different values of the th. We also calculated ROC curves for each record. The obtained best th. value was 0.4 (Min Max), giving mean sensibility and P+ values of 0.998 and 0.999 over the entire database.

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