THE APPLICATION OF COMPOUND EMERGENCY INDICATOR AS A SOFTWARE ALTERNATIVE FOR THE PATIENT BUTTON IN LONG-TERM CARDIAC MONITORS

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Searching for the economy and opportunities for applications of the human experience yielded a development of a request-driven ECG interpretation method. It assumed that the processing of the acquired ECG is triggered by the expiry of data validity period or by the emergency detector continuously supervising the basic parameters of the signal. This paper focuses on the correct choice of the emergency detector procedure covering a wide range of diseases but not requiring much computational power in the patient-side wearable system. After the investigation of the numerical complexity for initial stages of ECG processing and of the representation of most common diseases in basic cardiac parameters, we propose the use of a compound rhythm- and contour-based index as the emergency indicator. The computation is simple enough to be performed in a limited-resources environment (e.g. cell phone) without considerably influencing its autonomy time.

INTRODUCTION

The development of a theoretical background and the experimental determination of validity time values for particular diagnostic parameters of the ECG led to the implementation of the on-demand interpretation of records. This mode shows its particular advantages in cardiac monitoring networks. The avoidance of unnecessary data processing and transmission leads to a considerable reduction of power consumption and to the extension of autonomic operating time. The additional benefit comes from the management of the datastream transmitted to the supervising center through the wireless digital link [1].

In the on-demand processing scheme, the signal interpretation in the remote recorder is initiated by the expiry of previous data validity or by the alert from the emergency detector. This idea mimics the natural relation between the patient and his doctor. It assumes the scheduling of examinations in the medically justified time intervals (periodic examinations) or as a result of deterioration of the patient's status subjectively perceived as pain or fear. The validity time is determined for particular ECG diagnostic parameters on the basis of current values being components of the medical description of the patient. In this context, with regard to the diagnostic relevance of parameters, the surveillance system automatically builds a hierarchical list of values required to be calculated with their temporal attributes determining next time points of the required update.

In case the medical description of the patient is correct and his or her real status gets worse suddenly, relatively long validity time specified for particular diagnostic parameters cause the loss of monitoring continuity. This scenario, very probable in the cardiac monitoring, requires the prompt update of the patient description in the system even if the validity intervals - based on the previous values of diagnostic parameters - are not yet expiring. This functionality is supported by the patient's (event) button in traditional long-term (Holter) recorders and in looping event recorders it is additionally used for triggering the acquisition and interpretation of the signal strip [2]. The use of the patient button depends on subjective feelings (pain or fear), often having the origin independent of the recorded pathology. On the other hand, some life-critical events may happen without clear symptoms and thus will be missed in the event set. Although the implementation of the patient button and its functionality is required by the international standards [3], in author's opinion it should not be left as the unique option for initiating of the data acquisition and interpretation. Therefore, we postulate to embed the emergency detector in the recorder software. Its role is to detect the patient's status

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deterioration and triggering of the acquisition and interpretation of a signal strip. Setting the long validity time for diagnostic parameters would no longer prevent the immediate adaptation of the monitoring system to the sudden changes of the patient's status.

The proposed solution consists in a continuous limited-range signal interpretation, as necessary for the detection of the emergency. The functionality of the detector mimics the patient's feelings of pain and is oriented to spot the abnormality. Unlike the pain, the automatic detection and recording of events is the objective and reproducible process, and therefore is more reliable than the patient button. Additionally, the detector does not require any interaction from the monitored person.

The emergency detector consists of the selected subset of the ECG interpretation subroutines. The selection is based on the compromise between two contradictory criteria:

- support of a wide range of pathologies causing the alert,
- low computational complexity, the use of only the initial steps of ECG interpretation process helps avoiding the error propagation and improves the detection reliability.

For initial stages of the on-demand ECG interpretation testing, the emergency detector was based on the absolute value of successive RR interval differences [4]. It was proposed as a result of studies on the medical standards and consulted with the cardiologists. In course of further research it was necessary to optimize the ratio of the detection quality to the computational complexity which is the main subject of this paper.

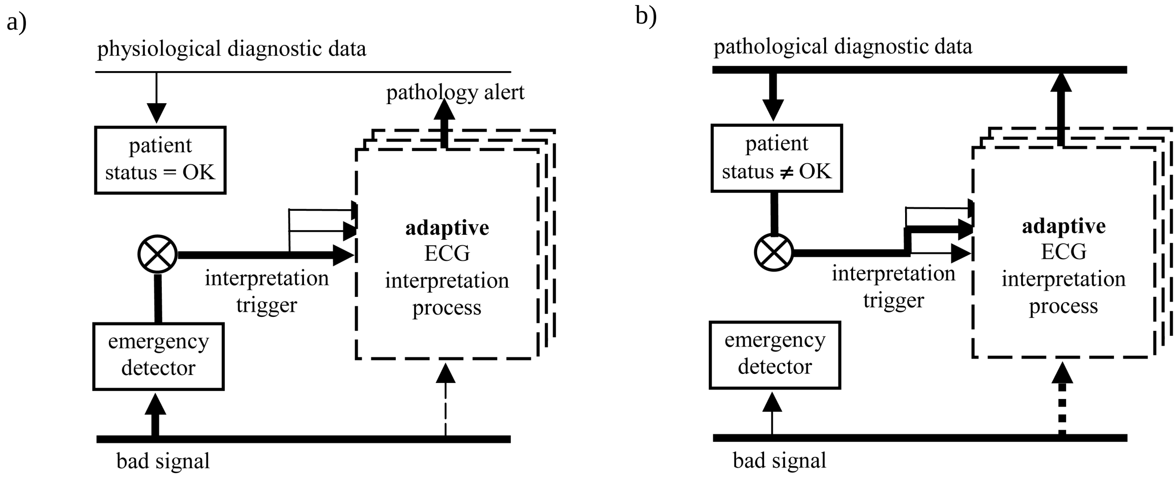

Fig.1. Detection of the emergency; (a) diagnostic parameters validity time are long based on the previous set of diagnostic results; the emergency detector captures the change of patient's status and initiates the interpretation of current signal; (b) the values of diagnostic parameters represent the pathology and shorten the corresponding validity time what results in a more frequent interpretation of the signal.

METHODS

A. Estimation of the complexity for a diagnostic procedure

Common complexity estimators may be used for the assessment of computing power necessary to perform the detection of emergency [5]. In real applications, the ECG interpretation uses various algorithms and often particular processing stages are difficult to be distinguished. The investigation of algorithms is additionally burden by the protection of manufacturer's intellectual property. The procedures are usually not available in the source code (e.g. C/C++, Delphi etc.) that could be easily analyzed, instead the user gets target platform-oriented precompiled libraries. Although the majority of manufacturers were not interested in disclosing of their code for the scientific purpose, general conclusions drawn from certain available procedures are interesting from the viewpoint of the software design.

The efficiency of diagnostic procedures highly depends on the use of resources determined individually for each target platform and on the input signal and the probability of diseases occurrence. For this reason, alternatively to the use of theoretical complexity estimators calculated from the code analysis, we designed a prototype detector application. In order to limit the range of considered mobile platforms (cell phones, SmartPhone, PDA computers, etc.), we selected a well documented development kit of the PXA-270 processor [6] (fig. 2), already applied in a wide range of PDA computers of various brands (Asus P-565, Sharp Zaurus, Motorola A780, Acer n50, Compaq iPaq 3900). Microprocessor PXA-27X with updated XScale core is the Marvell's implementation of fifth generation ARM architecture (codenamed *Bulverde*). It supports one of the selectable clock frequency: 312, 416, 520 i 624MHz. It is an integrated *System-on-Chip* with no internal memory designed to mobile applications of high dynamics and low power requirements, thanks to a very high ratio of the computing power to the energy consumption reaching 4.625 MIPs/mW.

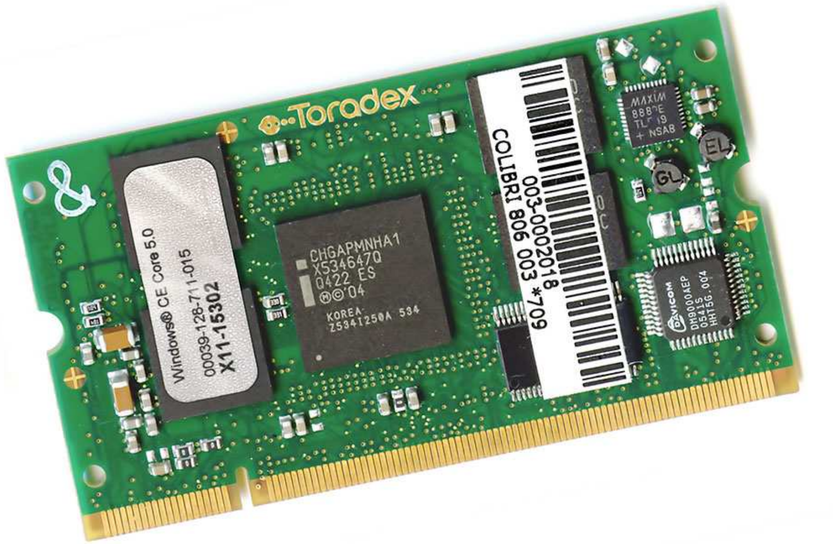

Fig. 2. The development kit of the PXA-270 microprocessor (real size: 67.6 x 36.7 x 5.2 mm)

B. Investigations of parameters variability in presence of diseases

Studies of recommendations and guidelines for ECG signal interpretation issued by the professional organizations of cardiologists (e.g. *American Heart Association* [7]) led to the conclusions on dependence of the variability of diagnostic parameter values and represented pathologies. Taking into account the variety of standards in use, we decided to experimentally investigate the archive ECG records and the variability of calculated parameters. The experiment was expected to yield the assessment of the relative difference of the parameters and their respective physiological values observed in presence of particular most common pathologies. Considering additionally the probability of occurrence for these pathologies, we can optimize the choice of diagnostic parameters being a basis of the emergency detector, for the achievement of maximum reliability. In the set of total N archive records captured in proportion to the natural occurrence of represented diseases, the average value of absolute difference between parameter values from “normal” e^n and “pathologic” e^a record (or two parts of the same record) from the particular patient was taken as the first approach to the *Variability Index* VI^e

$$VI^e = \frac{1}{N}\sum_{i=1}^{N}\left|e_i^n - e_i^a\right| \tag{1}$$

We aimed at finding the parameter e_1 attributed with the maximum value of VI and other parameters e_n representative to the pathology, but statistically independent from the previously selected. During the selection the values of variability index were weighted by the complement of absolute cross correlation value in order to favorite the mutually independent parameters:

$$\begin{gathered} e_1 = \max_e(VI^e) \\ \forall n : e_n \notin \{e_1, e_{n-1}\}\ e_n = \max_{e_k : k \notin \{e_1, e_{n-1}\}}(VI^e)\cdot \\ \cdot(1-\left|c_{n,n-1}\right|)\cdot(1-\left|c_{n,n-2}\right|)\cdot\cdots\cdot(1-\left|c_{n,1}\right|) \end{gathered} \tag{2}$$

C. Compound emergency index

The description of the emergency detector so far was simplified by the assumption of the statistical independency of particular diagnostic parameters. In a real ECG interpretation algorithm this assumption is not fulfilled. The recorded signal is the source of all diagnostic parameters and the procedures at the initial stages of processing influence several diagnostic parameters. On the other hand, the emergency detector based on a single diagnostic parameter was sensitive only in a limited range of pathologies, therefore we propose the *Emergency Index EI* as a compound parameter, calculated out of several selected meta-parameters $e_1...e_n$ available in the ECG interpretation process, despite of their mutual correlation..

$$EI = \sqrt{e_1^2 + e_2^2 + \ldots + e_n^2} \tag{3}$$

The appropriate choice of the component parameters is important in the aspect of uniform sensitivity of the detection in a wide range of cardiac pathologies with regard to their acuteness and minimal requirements for the computation power. First of these requisites raises the question of variability of ECG diagnostic parameters caused by the pathologies in context of their possible consequences and occurrence probability. The expected sensitivity in presence of the pathologies of various origin, suggests the selection of meta-parameters based on their minimum cross correlation.

The description of computation power requirements in portable systems applying advanced power management solutions, is much more practical with the use of direct power units (microwatts) than with the general polynomial-based estimate of the complexity. This description is also useful in the assessment of the contribution from the continuously running emergency detector algorithm to the total power consumption of the portable ECG recorder.

RESULTS

A. Estimation of the computation complexity

For all procedures of which we have available the source code, the computational complexity was assessed theoretically and expressed as the most probable count of machine cycles performed in the course of execution. This value was next multiplied by the nominal power requirement for a single machine cycle specified in the microprocessor application note what yields a first approach of the total power required for the execution of each ECG interpretation procedure. In cases we have available several implementation variants based on different algorithms, the average value of expected power consumption was calculated (tab. 1).

Tab.1. Computation complexity of ECG interpretation procedures (single-lead ECG signal of 10s length, sampling frequency 500Hz, average HR=78 bpm)

procedure purpose (in the execution order)	**implementation variants**	**theoretical complexity**	**expected power consumption [μW]**
detection of heart beats	4	785000	169.7297
izoline level detection	2	115000	24.86486
calculation of the heart rate	2	700	0.151351
classification of heart beats morphology	3	38760	8.380541
detection of wave borders	2	1320000	285.4054
detection of wave axes	1	168000	36.32432
determination of the dominant rhythm	2	208800	45.14595
arrhythmia detection	1	14760	3.191351
SUM		**2651020**	**573.1935**

B. Parameters variability in presence of diseases

This research was aimed at indicating the diagnostic parameters showing the highest variability in presence of change of the patient's status in a wide range of pathologies. In result of the investigations, presented in details in [8], twelve most frequent pathologies (normal sinus rhythm, sinus tachycardia, sinus bradycardia, possible AV block, ventricular escape beats, atrial fibrillation, AV conduction defect, infarct of any localization, atrial enlargement, ventricular hypertrophy, left and right bundle branch blocks) were found in 1730 studied records. These records were now investigated again in order to find the most "universal" diagnostic parameter e_1 and further independent diagnostic parameters $e_2...e_n$ of values varying in presence of pathologies in their possible widest range. The normalized results of parameters variation for selected 12 pathologies are displayed in table 2.

C. Optimal representation of the emergency

The results from table 2 were used to determining of ranges for the pathologies represented by a risen variation of particular diagnostic parameters. As it may be noticed from table 2, the variation of the heart rate is particularly high within the group of rhythm-related diseases, whereas the variation of the QRS contour is more important within the group of contour-related pathologies. Consequently, designing the emergency detector based on the diagnostic parameters specifically varying within such disjoint groups of pathologies, we expect to made it sensitive enough for all these pathologies.

For the purpose of the research, we assume that the positive emergency detection requires the value EI^e to be equal or greater than EI^n + std(EI^n), where EI^e is the value of emergency index (eqn. 3) for the pathology, EI^n is the value of emergency index for the physiological signal, and std() stands for the standard deviation. The probability of missing the emergency event in case of the use of simple emergency indicator and two variants of compound emergency indicators is displayed in table 3.

Tab. 2. Correlation of variation of ECG diagnostic parameters in presence of most probable pathologies.

pathology type	e_1 - variation of the heart rate	e_2 - variation of the QRS contour	e_3 - variation of the waves length
normal sinus rhythm	0.05	0.11	0.07
sinus tachycardia	0.67	0.12	0.22
sinus bradycardia	0.71	0.14	0.28
possible AV block	0.31	0.41	0.27
ventricular escape beats	0.44	0.81	0.31
atrial fibrillation	0.33	0.08	0.12
AV conduction defect	0.27	0.25	0.20
infarct (any localization)	0.20	0.37	0.37
atrial enlargement	0.12	0.27	0.28
ventricular hypertrophy	0.08	0.42	0.35
left bundle branch block	0.11	0.27	0.21
right bundle branch block	0.14	0.31	0.33

Tab. 3. Results of investigations for the optimal compound emergency indicator (single-lead ECG signal of 10s length, sampling frequency 500Hz, average HR=78 bpm)

parameters used	e_1	e_1 & e_2	e_1 & e_2 & e_3
true positive	17412	17550	17612
true negative	89076	89140	89204
false positive	1220	1098	989
false negative	890	810	793
sensitivity	0.951371	0.955882	0.956914
specificity	0.986489	0.987832	0.989035
positive predictive value	0.934521	0.94112	0.946831
theoretical computational complexity	900700	1107460	2427460
power required [μW]	194.7459	239.4508	524.8562

DISCUSSION

Interpretation of the results displayed in tab. 3. leads to the conclusion that the components of the optimal compound indicator are:

- heart rate variations (e_1) and
- QRS contour variations (e_2).

The additional considering of wavelength variations (e_3) is not recommended, because this does not significantly increase the detector reliability and requires much of the additional computation power, rising its total consumption to 524μW. Significant efficacy of the emergency detector composed of the heart rate variations and QRS contour variations is a result of a very low correlation between these parameters. Thanks to the mutual independence, these parameters cover almost disjoint ranges of pathologies (see tab. 2). This table also helps in explaining a low increase of the detector efficacy in result of additional use of wavelength variations (e_3). This parameter, requiring considerable computational power, does not significantly correlate with any of the 12 most frequent pathologies (maximum value of correlation is 0,37 for the myocardial infarction).

One of the most surprising result of the experiment carried out with the prototype recorder is the low electrical power required for the interpretation of a single lead 10s ECG record, hardly exceeding 0.5 mW. This is possible thanks to the application of a powerful microprocessor working at a low clock frequency. Unfortunately in a real recording system the required power is significantly higher due to the necessity of support of the operating system as well as powering the peripherals: memory, communication module and low-signal analogue circuitry.

Tests of the emergency detector software supporting the patient button, performed with use of artificial long term signals derived from the CSE database showed the sensitivity of 0.956 and the specificity of 0.988 while the power consumption raised due to the signal interpretation by only 0.24 mW. These results were confirmed in further tests using custom 24-hours annotated Holter recordings.

The performance of the recording or monitoring system no longer relies on subjective perception of pain or “something uncommon”, for the patient's button the reported sensitivity is of the order of 70% and the specificity hardly excesses 55%. In Holter systems, the reliability of event marks accompanying the record may be significantly improved thanks to the software support of patient button without limiting the recorder autonomy time. In the looping event recorders, the emergency alert may remotely change current medical procedure or trigger a rescue action. Similar technique is also useful in auto-adaptive ECG interpretation or distant on-demand recording for changes of the software architecture and functionality.

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