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Review article

Interpretive software conversion following changes of patient status and diagnostic goals

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This paper presents selected issues concerning the on-the-run conversion of ECG interpretive software following the changes of the patient status and diagnostic goals. The adaptation of diagnostic procedure, common in human action, but still absent in computerized processing, raises the necessity of including the additional medical knowledge in the feedback loop controlling the diagnostic process. Considering this knowledge in the form of complementary data attributes and the use of modern information processing and digital communication techniques opens up the opportunity to simulate a continuous presence of cardiology expert accompanying the patient in motion. At the same time, the software does not assume the exclusive correctness of the automated diagnosis and provides a human expert with verification tools at all stages of signal processing. The portable remote recorder was designed and prototyped in our laboratory allowing various approaches to automatic software adaptation to be tested.

Key words: *telemedicine, home care systems, healthcare technology interface, wireless technologies, ubiquitous cardiology, distributed computing, discrete optimization, agile software*

1. Introduction

Recent achievements in information technology allow easy digital data exchange in mobile networks. In metrological solutions, such networks typically consist of multiple data sensors and transducers distributed to each place where information is available and the data collector supervising the measurement process and integrating the data into a database. This topology was well adapted to telemedicine where the role of data collector is fulfilled by hospital or departmental information system and the patient-side recorders play the role of distributed sensors [1]–[3]. Recent advancements in microelectronics resulted in the development of portable and wearable computers accompanying the patient in motion, not only integrating the signals from various patient's sensors, but often also applied to preprocessing of gathered data. The distribution of preprocessing significantly reduces the transmitted data volume and thus is beneficial to the system operation costs.

All these general remarks specifically concern the telecardiology, recently used as a principal indicator of human wellness in home-care and mobile surveillance systems. Two approaches to the automatic ECG signal interpretation represented in today marketed systems assume either the transmission of raw signal to the interpretation center or the signal processing fully embedded in the remote device. Focusing on their drawbacks, the first method involves high cost of telecommunication service, while the quality and reliability of the second is limited as a result of the compromise between computational power and energy consumption.

This paper presents the alternative approach to the distributed electrocardiology and postulates that the interpretation process is performed as a distributed computing task shared between the remote recorder and the central server. Two aspects led us to this proposal of ECG interpretation process architecture:

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– the automatic interpretation process is driven by heuristic rules and factors; the performance testing uses a limited set of annotated cases and the software output for very irregular case is unpredictable, thus needs human supervision,

– the analysis of information flow for human signal interpretation shows that expert's approach is biased by the knowledge of the patient or the hypotheses that concern them; consequently, the use of standardized interpretive software results in unnecessary calculations and sub-optimal result.

In the framework of the research and development of auto-adaptive ECG interpretive software, we optimized three aspects of processing: the quality of the diagnostic parameters, the volume of data exchanged via wireless digital link and wearable recorder autonomy time.

This paper is organized as follows: Chapter 2 introduces quality-oriented attributes for cardiac data, Chapter 3 proposes the methods for static and dynamic optimization of interpretive software architecture, and Chapter 4 presents a future project of data-dependent non-uniform processing and reporting for cardiac data. The paper is closed with a discussion with references to detailed reports and testing results of particular elements of the system proposed.

2. Towards new attributes for medical data

Attributes used for technical specification of data reliability and variability, although widely used in metrology, rarely have their analogies in the world of quantitative medical data. Therefore, for providing a proper optimization background, we had first to propose and validate two attributes reflecting different approach doctors usually have to the data hierarchy and to the necessity for data update in the context of the patient status. Consequently, each diagnostic parameter value was complemented by two other variables:

– validity period, which represents, technically writing, maximum length of sampling interval resulting from the expected temporal variability of the parameter,

– priority, which represents medical relevance of the parameter in the context of present status of the patient, used to optimize the overall diagnostic quality estimate and allocation of resources.

The details of the investigations of expected bandwidth for each diagnostic parameter in the context of patient status and in relation to other parameters are presented in [4]. Even among the basic diagnostic parameters in cardiology, a significant difference in variability was observed in the study. In physiological norm, the heart rate (HR) should be related to a beat-to-beat rate (i.e. up to 4 Hz), while the QT dispersion (QTD) needs a single update per a 5-minute interval (0.0033 Hz). It is sufficient to report the heart rate once for 30 s in the case of normal sinus rhythm. In the case of atrial and junctional rhythm, the HR should be reported every 10 s, while in the case of ventricular rhythm – every 3 seconds.

The priority of diagnostic parameters was derived as a result of the research [5] of human expert preferences for particular diagnostic results correlated with the actual patient disease. We applied a custom-built software recording the expert interaction with the computer while he is gathering together all necessary diagnostic statements into a final report. The module works behind the standard ECG interpretation software and records 1730 human-verified examinations in 11 cardiologist offices. The statistical processing of these records yields justified parameter hierarchies for 12 most common heart diseases and approximate preferences for other 17. The utility of the diagnostic outcome hierarchy is expected in both:

– prioritized non-uniform transmission in wireless monitoring networks,

– disease-oriented assessment of quality of manual and automated ECG interpretation.

3. Aspects of ECG processing optimization

Two different approaches, i.e. static and dynamic, are proposed for the optimization of the processing in ECG interpretive software. The static approach is based on statistic studies of procedure usage and data flow and results in a general-purpose diagnostic algorithm, in selected aspects showing improvement achieved without alteration of processing methods or algorithms. The dynamic approach aims at real time optimization of the interpretive software on the run made towards personalized diagnosis tailored for a specified disease and personal features. Both approaches are presented in following sections.

3.1. Rearrangement of static software architecture

Static optimization relies on the rearrangement of the software architecture aimed at minimizing error propagation and the reduction of data volume at the early processing stage. Despite applying very thoroughly the testing procedures, any software engineer is not able to foresee all possible signal recording conditions combined with all possible heart diseases. In a typical processing chain, subsequent procedures use results of the previous ones, thus misinterpretations and inaccuracies may compensate or cumulate [6]. Unfortunately, the error-cumulative scenario is much more probable, because in terms of statistics, the correct and accurate result is a singularity in a cloud of all possible outcomes.

Each interpretive subroutine transforms the data fed to its inputs into results at its outputs. Since the whole interpretation process proceeds from a collection of signal samples (sometimes of diverse nature) to the final diagnostic outcome, from a statistical viewpoint it is a sort of data reduction tasks. For each specialized subroutine the information stream reduction ratio can be quantitatively measured by comparing the expected throughput of the outputs with the inputs.

The effective data reduction at the beginning of the process, postulated by the wearable recorders implementation, can be achieved with use of the following methods:

– putting the most reduction-effective procedures in front of the processing chain,

– putting the most frequently used procedures in front of the processing chain.

The particular challenge is the consolidation of all functions having access to the raw signal at their inputs. Unfortunately, the meaning of many signal-derived parameters depends on advanced calculations in long processing chains.

Since the data processing chain has to follow a specified order providing first the general information (e.g. a heart beat was detected) and then more precise details (e.g. morphology type or waves length), the rearrangement of software architecture is constrained by the logical flow of ECG diagnostic procedure. Within these constraints the reduction-effective and frequently used procedures were first identified experimentally [7] in order to favour more frequent, more accurate and more reduction-effective functions in access to the data streams. A typical data flow diagram for the basic ECG interpretation process contains many references to the raw signal. In order to allow the access to the unprocessed data representation exclusively for subroutines of high peak throughput and high frequency of use, we applied a concept of databuses. These inter-procedure information channels are sorted by the value of expected throughput. Each data flow was assigned to a throughput level combining statistical parameters of the data:

– average data stream when used,

– frequency of use (depending on data refresh rate),

– probability of use (depending on the frequency of related disease occurrence).

Consequently, several such procedures may be redesigned towards the use of a common very reliable data interface. The only exceptions were wave measurement and axis determination procedures, highly dependent on the previous computation results, that have occasional connection to a buffer cashing a copy of raw signal dependent on the position of detection points.

The final architecture of ECG interpretation software optimized for reliability and early reduction of data stream (figure 1) contains three raw signal access points:

– common interface for signal quality estimation, baseline estimation and pacemaker detection procedures,

– heartbeat detection filtered input,

– wave measurement and axis determination filtered off-line buffer (provided also for ST measurement and P-averaging not considered here).

The group of functions accessing the raw signal issue a complete description of a heartbeat (bus 2), which is not the diagnostic outcome, but contains all the meta-data necessary for further processing and thus the raw signal is no longer necessary. These data appear occasionally, once per heartbeat, but even for heart rate as high as 180 bps, the data stream is 8.2 times lower than for a 12-lead 500 sps raw signal.

In tests with use of two standard ECG databases, i.e. MIT-BIH [8] and CSE [9] recommended for testing the software performance and the standard interpretive software, two factors were assessed separately for the original and the databuses-based architectures:

– average reduction of data rate at the subsequent processing stages,

– average inaccuracy δ and error probability ε for selected diagnostic parameters.

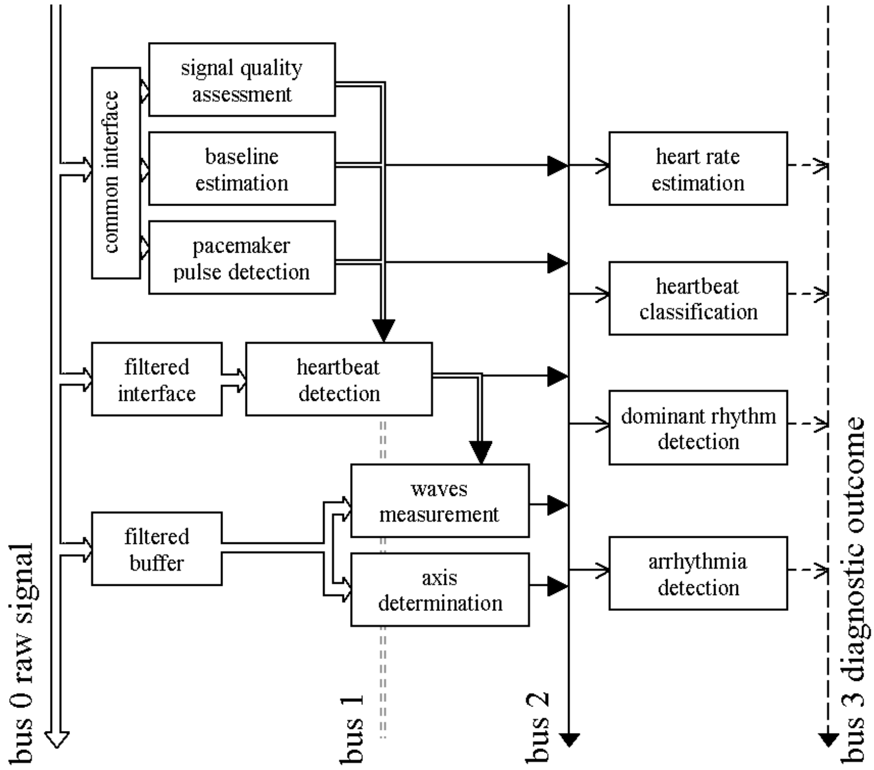

Fig. 1. Final architecture of ECG interpretation software optimized for reliability and early data stream reduction

Due to architecture optimization, the processing stages could not be set in a similar way for the original and for the modified software. Therefore, with regard to the identical testing conditions, we used the processing time as an estimation of the interpretation progress. At the first control point (20% of total execution time) the measured volumes of the remaining data were 78% and 47%, respectively, thus the data reduction gain was 31%. At the second control point, the gain was also considerable (23%) showing effective allocation of data reducing procedures in front of processing channel.

The improvement of data reliability was most spectacular for wave measurement (the drop of δ from 5.1% to 3.3% and ε from 7.5% to 5.3%) and axis determination. Less prominent, but also considerable improvement was achieved for pacemaker pulse detection, heartbeat detection and heartbeat classification [7].

We consider diagnostic subroutines as black-boxes and do not attempt to modify the interpretive algorithms nor their mathematical foundations. The improvement is achieved by shortening the processing chains and by reducing the dependence of subsequent functions input data and the results of previous processing stages. Such approach no longer favours the cumulative error propagation.

3.2. Dynamic optimization of software functionality

Every manufactured interpretive electrocardiograph of today has embedded a static “general purpose” software designed and tested for an average patient [10]–[14]. Demographic data are only determining normal–abnormal borderline values for each individual examined. In mobile devices, this approach leads to severe limitations resulting from hardware compromises such as weight, size, and autonomy time. The diagnosis quality is usually affected in result of the uniform approach in the presence of these limitations. Therefore telemedical solutions are the first area of applications in proposed adaptive software that modifies device functionality according to the current needs of the patient. Besides the patient and the doctor, this approach is also very attractive for the manufacturer, since wearable recorders may be mass-produced as general-purpose electronic equipment, while the personalization and target functionality are achieved with the software during the first minutes of use. The auto-adaptive diagnostic process was designed and prototyped to perform analogically to the physician who selects the diagnostic equipment upon necessity and availability and decides what kind

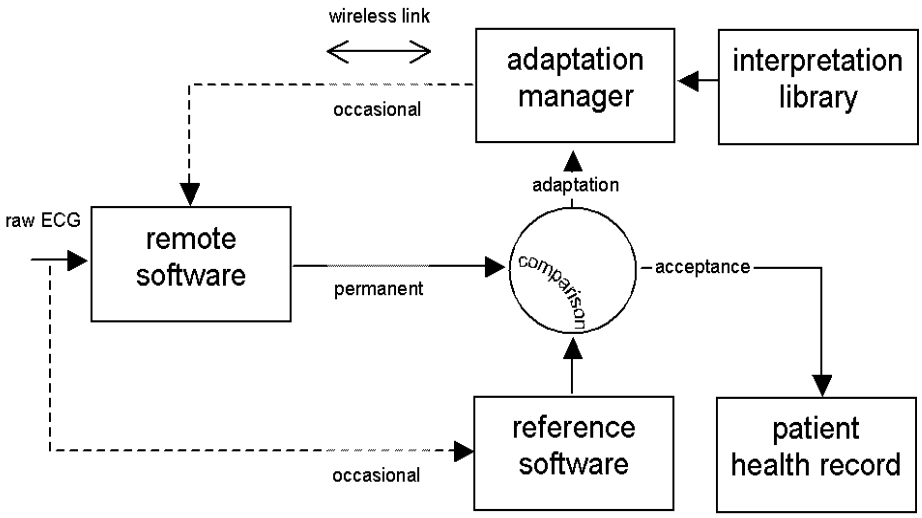

Fig. 2. General scheme of auto-adaptive system for ubiquitous cardiology

of data make the diagnosis precise and complete [15]. The remote ECG interpretation is dynamically adjusted to be 'optimal' in the sense of the best available reliability of diagnostic outcome. The optimization loopback (figure 2) includes: remote interpretation procedures, quality estimation routine and adaptation manager.

The error function represents differences between remotely calculated diagnostic parameters and their reference values occasionally computed from the same strip of raw signal by the central server. The adaptation manager sends a multidimensional modification vector which is applied by the remote OS to improve the ECG interpretation process. In result of few successive iterations, the adapted remote process is expected to issue diagnostic parameters converging to their references and consequently the error value achieves its temporal minimum.

The optimized signal interpretation process may become suboptimal in the presence of two factors external to the loopback:

– changes of the patient status imply modification of the relevance ranking of diagnostic parameters errors;

– changes of resources availability (battery, memory, connection, etc.) may result in the worst quality of issued diagnostic parameters.

In given time points, dependent on the patient status, the quality estimation routine requires a strip of raw electrocardiogram and performs the independent calculations of reference diagnostic parameters in virtually unlimited environment of the server. If the returned difference value exceeds a given threshold, information about non-compliant data (error vector) is sent to the modification vector generator.

Specialized expert system is applied in management of the interpretation subroutines and generates modification data vector for the remote recorder. It works with a knowledge base consisting of task-oriented libraries corresponding to all replaceable blocks of the interpretive software. Subroutines collected in each library fulfil the same interpretive task, but are designed with different prerequisites for resource requirements and result quality. Their data communication gateways are standardized in order to ease commutation in the course of interpretive software optimization in the run. Each subroutine is attributed by quality coefficient, resources requirements and external dependency tree in order to facilitate the expert system decisions. For the purpose of fine tuning, interpretation subroutines provide external access with modification rights to few parameters having read-only status within the subroutine, used as factors or thresholds and considered as calculation constants. The expert system proposes variants for possible modifications of the remote ECG interpretive software on the background of two principal arguments: diagnostic data error and resource availability. When only fine tuning is required or when lack of available resources makes the procedure commutation impossible, the expert system adjusts calculation parameters to the currently working subroutine. Otherwise an alternative subroutine is selected in the knowledge base according to quality coefficient and with respect to resource requirements and sent to the remote device. Thanks to identical gateways it is relinked in place of the precedent one while the remote ECG interpretive software is running.

In the case the selected subroutine requires more resources than available, the relevance ranking of diagnostic parameters is pursued in order to determine a procedure yielding a result of low significance. If such procedure is detected, the expert system removes it completely or commutes for its simpler version in order to release more resources for new subroutine of high relevance. Otherwise the generator only modifies calculation parameters, since this can be done without requirements of extra resources.

The generator's output is restricted to a set of calculation parameters with limited range of variability or to a subroutine selected from the knowledge space as more appropriate. In any of these cases, the control over the interpreting software is discrete and nonlinear. The effect of software modification can only be predicted roughly. Additional difficulty is caused by mutual relationships between the quality of diagnostic parameters resulting from their possible common origin in the interpretation tree. If the incompatibility of received diagnostic parameters and locally calculated references is detected, the external dependency tree is pursued in order to determine the procedure most affecting the erroneous data, being the target of software modification.

The ECG interpreting software is the control object represented by the quality of calculated parameters. On the other hand, it is designed to run in the wearable patient-side recorder, thus strict rules for computational complexity and management of resources have to be observed in the course of design and prototyping. This software consists of basic procedures, including signal acquisition and buffering, user interfacing, wireless communication and control over the interpretation infrastructure. The ECG interpretive procedures are linked dynamically with their communication gateways to that backbone. Once a particular subroutine is linked, the program control is passed to it and before the exit results are returned to the basic layer. All internal variables are dynamically declared within procedures and the memory is released upon exit. Absent procedures are passed over, the memory allocation remains unchanged and corresponding results are missing in the report. Usually, due to mutual dependence of several procedures, the modification vector generator simultaneously loads and activates all such components. The unlinking or replacement of the subroutine is suspended while the processing control (e.g. stack pointers, etc.) remains within its executable code.

For the simulation of rapid patient status changes not represented in reference databases, ECG test signals with various pathologies and transients were artificially combined from custom-recorded signals. Among the total of 2751 one hour 12-leads ECG records, 857 records (31.2%) required the adaptation of ECG interpretive software [16]. For 86 records (3.1%) no appropriate procedure was found in the knowledge base, and the signal was interpreted by the server software. Correct were 768 (89.6%) software adaptation attempts, while the remaining 10.4% failed due to incorrect management of available resources. Data consistency was restored in a single iteration of remote software adaptation in 63.1% of cases. In other 19.3% of cases, the results were still not converging after four iterations. The adaptation delay was measured with the use of a real wireless GPRS connection (Plus GSM). The average value was 4.3 s, but the longest single iteration lasted 6.0 s and the longest adaptation 17.1 s in the case of four iterations.

4. Non-uniform cardiac processing and reporting

The idea of patient status-dependent processing of the ECG signal, and consequently adaptive reporting on diagnostic features, was extended to the concept of request-driven interpretation based on individual data validity periods [4]. While maintaining the required data quality, it considers two issues crucial for wearable devices with a wireless connection: maximized autonomy and minimized transmission channel costs.

Main novelty of our method consists in non-uniform ECG processing triggered and defined by two sources:

– patient status,
– emergency detector.

These triggers launch a subset of remote interpretation subroutines necessary to provide the requested diagnostic parameters (figure 3). This approach helps to avoid unnecessary processing, thus the interpretation is relatively fast and additionally the outcome contains highly relevant data transmitted in smart packets.

In regular measuring systems, the acquisition of subsequent data point occurs at regular time intervals and unconditionally triggers the computation of all parameters. When variable data validity intervals are applied the calculation triggering occurs individually for each diagnostic procedure and its source is located at the end of the corresponding processing path. Since the path usually consists of serial connection of multiple procedures, each data request first verifies whether existing metadata are still usable (i.e. within their

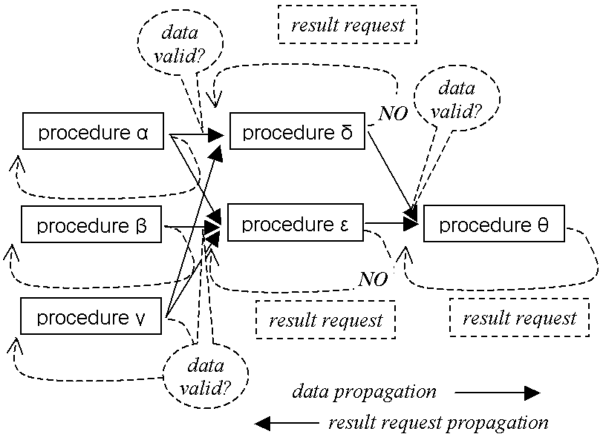

Fig. 3. Scheme of asynchronous computing in ECG interpretation

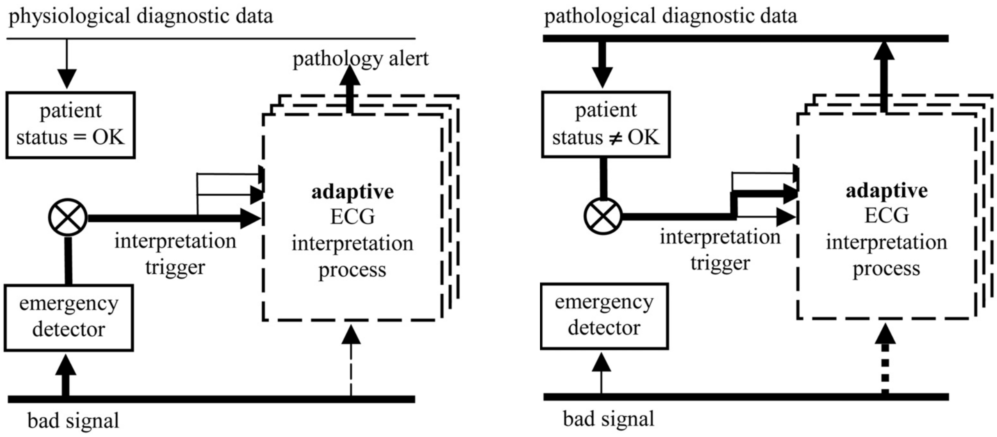

Fig. 4. Detection of sudden abnormality occurrence: (a) data validity periods are long corresponding to physiological data, emergency detector triggers interpretation which issues pathology alert; (b) pathological diagnostic data shortens data validity periods and triggers interpretation more frequently

validity period) before an attempt to compute them (figure 3). Frequently the validity period is longer for metadata than for the final data, thus only a fraction of the triggers achieves the beginning of the processing chain, avoiding the unnecessary processing of huge amount of raw data.

In the case of stable or improving patient conditions, each component of the diagnostic result has to be calculated and transmitted not earlier than its validity period expires. The interval length is individually set by a supplementary cross-reference procedure in the context of data variability and patient status represented by the parameter under consideration and other parameters as well. Therefore the datatype-specific validity periods were determined through detailed investigation of correlations between diagnostic parameters and multidimensional nonlinear regression describing their contribution to the data validity period [17].

In case the patient is getting worse, the system adapts data validity periods – estimated as relatively long – to sudden changes of patient's conditions. The emergency detector is a computationally simple procedure consisting of selected interpretation routines aimed at issuing an alert sign triggering the update of diagnostic parameters, before their validity period expires. This revises the patient status representation in the system and may result in the shortening of validity period for selected diagnostic parameters (figure 4).

Since no single diagnostic parameter is able to make the emergency detector equally sensitive in a wide range of diseases, we recently designed and prototyped a compound emergency indicator calculated from data available at early stages of ECG interpretation process. Our pursuit of a representation of possibly wide spectrum of heart diseases with considering their frequency and acuteness required the analysis of disease-dependent ECG parameters variability in the context of disease implications and occurrence probability. To cover a wide range of diseases with few simple parameters, we also considered their minimum correlation and calculation costs. The resulting emergency detector was proposed as the combination of heart rate and QRS contour variations. During tests performed with the use of MIT-BIH long term database the implementation of emergency detector running in the PXA-270 CPU 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.

Tests of the prototype of request-driven ECG interpretation required ECG test signals representing dynamic changes of various pathologies. Unfortunately, transient or sudden events are rarely represented in databases and we had to combine test signals artificially from several strips of original MIT-BIH [8] recordings. In order to compare the non-uniform diagnostic outcome of the adaptive system with the fixed software result used as reference, the non-uniformly sampled diagnostic time series was first made uniform with the use of the cubic spline interpolation [18]. Besides the compliance of diagnostic results with the tolerance margins specified in standards [19], new parameters were added to the global performance estimate reflecting the dynamic aspect of adaptation. The convergence error was represented by the usage of statistics weighted sum of relative error of 12 most frequently used diagnostic parameters. For the normal to atrial fibrillation transient the initial value of Q was 19.1% and dropped down to 2.4% in 6.7 seconds. For other types of transients the adaptive system yielded values converging to static software-calculated references within a tolerance margin of 4.7% in about 5 seconds. The only exception was the reaction to the sudden ST segment depression lasting 12.2 seconds for the reason of not have been detected as emergency.

The results of tests show also technical and economical advantages of request-driven ECG interpretation. Depending on the medical contents represented in the ECG signal, the processing time was reduced to 27–85% of its initial value and the transmitted data volume was reduced to 12–40%.

5. Discussion

The paper presents the directions of the development in automatic interpretation of the ECG in ubiquitous surveillance systems. Each of the mentioned solutions was thoroughly tested, and technical implementation aspects with detailed results are specified in the bibliography. All proposals have a common root based on the innovative assumption that diagnosis is a dynamic process and automatic signal interpretation is witnessing the pathologic changes. This implies the dependence of processing scheme and current diagnostic values on the patient's history and brings the computer interpretation closer to human reasoning. Despite lower reproducibility of results and consequently difficulties with program quality assessment, the behaviour of adaptive software simulates the human expert approach consisting in successive refinement of diagnosis achieved in a series of information acquisition and interpretation performed alternately.

Automatic adaptation of the telemetric cardiac recorder software has a considerable practical impact on all three participants of the surveillance process:

– the manufacturer releases general-purpose recorders with only a basic software layer embedded, cheap thanks to the mass-production,

– the patient after a short initial adaptation time owns a highly personalized recorder considering his proper (and not averaged) conditions of pathologies, promptly adapting to the changes of medical parameters and transmitting the optimized diagnostic report of minimum data volume,

– the cardiologist is provided with the diagnostic description of the patient optimal in the sense of diagnostic goal and complying with quality requirements; the adaptation of recorder's functionality is feasible in wide range of supported functions without the need of physical contact with the patient.

The development directions are compliant to the assumptions of technical environment adaptation to the human features, which is particularly important in medical applications. The adaptive system simulates well the seamless presence of a medical expert without limiting the patient mobility and privacy.

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