Validation of Automatic ECG Processing Management in Adaptive Distributed Surveillance System

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Summary. This paper presents the problem of diagnostic parameters quality control in the adaptive ECG interpretation system. The quality estimation is used for seamless adaptation of processing being a part of the optimization feedback. Therefore, quality control procedures - unlike in conventional systems - are embedded in the software. The proposed methodology is based on two principal concepts: diagnostic results priority depending on the patient status and the data convergence used as description of the adaptive system response to a transient in patient status. The paper includes an example of testing a surveillance network prototype with use of proposed parameters, demonstrating their high usability.

1 Introduction

Automated distributed diagnostic systems due to their wide spread and direct impact to the life quality are currently considered as very interesting and fast growing branch of telemedicine. Wearable recorders of today, although using the latest technology, functionally follow the bedside interpretive electrocardiograph [4] [3] concept formulated over 30 years ago [5]. Without the cooperative adaptation of the elements, surveillance networks are rather simulating a group of independent cardiologists using rigid interpretation procedures. Our approach, proposed in a series of papers [1] [9] [2] as the alternative, yields unprecedented personalization or diagnosis-oriented processing and thus better simulates the seamless presence of a cardiologist. The remote recorder, thanks to the reprogrammability, continuously adapts the ECG signal interpretation process to several prioritized criteria of medical and technical nature. The process is designed as distributed and performed partially by separated thread on the supervising server (network node) and partially by the agile software of the remote recorder. Important novelty is also the use of digital wireless link in a bi-directional mode for patient and device status reporting but also for management and control of the remote software, requests for adaptation of report contents and data priority and reloading of software libraries as necessary.

Such adaptive systems are expected to create new opportunities for the automated ECG processing, making the interpretation closer to the human way of reasoning and using some experimentally derived rules of cardiologists behavior. Until today they bring rather scientific challenges, revealing new unexploited areas present in clinical practice but not covered by the standards, recommendations or guidelines [8]. Comparing to conventional solutions, adaptive systems are much more complex and, in particular their correct behavior is not defined in a unique way.

This paper revises the notion of diagnostic data quality and quality monitoring in adaptive automated ECG interpretation systems. Comparing to the rigid interpretation systems, the quality is not only a performance factor [6], but also an important continuous measure of system compliance and error signal for the feedback modifying the interpretation software. Therefore seamless estimation of diagnostic data quality is an integral part of the system and determines its behavior. The proposed quality assessment system is based on the idea of prioritized convergence presented in this paper together with first results of tests performed on a developed prototype software using a modifiable subroutines in chain of distributed ECG interpretation process.

2 Materials and Methods

2.1 Overview of automatic software management

Since the optimal patient description depends on his status, variable priority factors are attributed to particular medical data and consequently to the branches of the interpretation process (fig. 1). Data priority implies also variable expectance about the accuracy and reliability of particular parameters. Unfortunately, calculation of all data with maximum precision may not be technically feasible in a battery-operated wearable recorder, moreover transmission of non-relevant data rises the costs of wireless communication channel. The proposed software management uses sorted repositories of procedures for principal ECG interpretation steps. Each task-oriented repository contains functions of various algorithms (i.e. originating from various inventors), different complexity, resources requirements and performance, but easy to substitute each other thanks to a standardized interface. The repository sorting is based on the correlation of the computation complexity and the result accuracy, commonly observed in software engineering. The management of interpretation process considers the patient-dependent requirements, current quality estimate and technical conditions, and continuously seeks for best available accuracy to complexity ratio yielding the expected quality of diagnostic result (fig. 2). The processing setup is revised each time the accuracy expectations are not met or with variations of patient status (i.e. changes of diagnostic

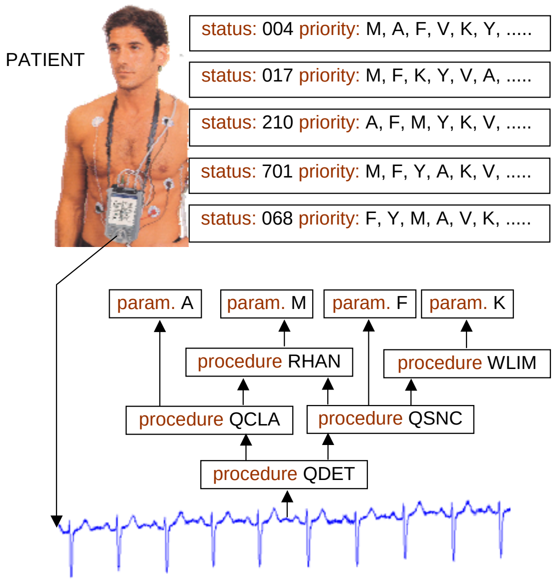

Fig. 1. Patient status-dependent priority of results from particular processing branches of ECG interpretation

goal) and technical environment changes (e.g. transmission conditions). The feedback configuration data is sent via wireless channel to the remote recorder in order to replace and re-link particular procedure or procedures chain by their upgraded or downgraded alternative versions.

2.2 The data convergence for estimation the quality

Random redundant signal re-interpretation is proposed as a tool for occasional monitoring of remote interpretation reliability. This procedure uses bi-directional transmission and begins with the raw signal request issued by the supervising server. The remote recorder does the interpretation independently and besides the diagnostic result returns the raw electrocardiogram as well. The raw signal strip is interpreted by the server software in conditions of unlimited resources availability and thus the results are used as reference in comparison to those received form the remote interpretation. Any difference δ_i is statistically processed and compared to the tolerance thresholds ϵ_i with consideration of current data priority w_i (1).

$$Q = \sum_i |\delta_i| \cdot w_i \qquad (1)$$

where: $\delta_i = d_{i,k} - d_{i,ref}$, d is the diagnostic value of the parameter i and k is the modification attempt number

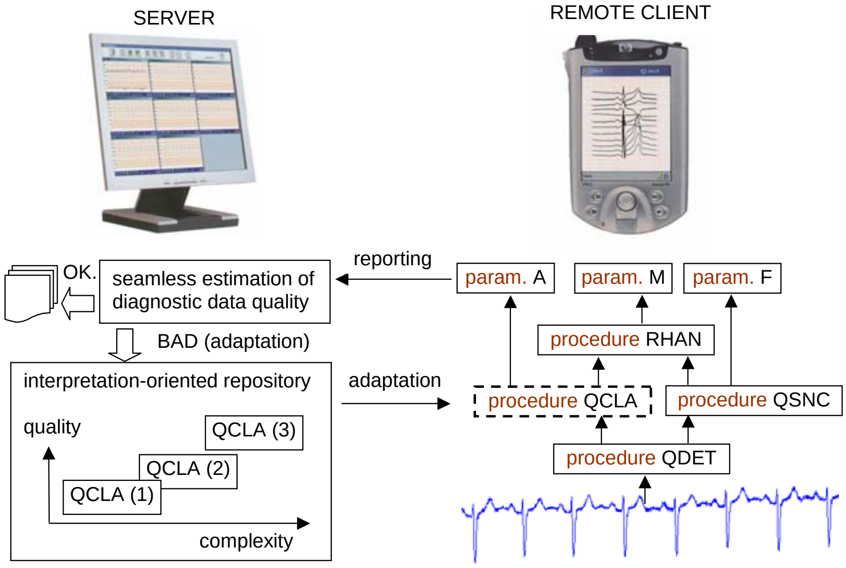

Fig. 2. The seamless estimation of diagnostic data quality in the remote recorder software adaptation feedback

Every outstanding value is a background for modification of the remote recorder interpretation software. Since the raw ECG is buffered in the remote recorder, the suspicious signal strip is interpreted again and the results are sent to the server are compared to the reference. The convergence represents the correctness of decisions made by the management procedure about the remote interpretation procedures. The software adaptation plays the role of a discrete feedback correcting the automatically made diagnoses and consequently the convergence of diagnostic results C is required for the stability of the adaptive interpretation system.

$$C = \lim_{k \to \infty} |d_{i,k} - d_{i,ref}| \tag{2}$$

If the software modification decisions are correct, the outcome altered by few attempts of interpreting software modification k approaches to the true value $d_{i,ref}$. The modification request request R is removed as soon as the outcome value $d_{i,k}$ falls into a given tolerance margin ϵ_i around its true value $d_{i,ref}$, and $|d_{i,\infty} - d_{i,ref}| < \epsilon_i$ indicates that the system is stable.

Incorrect decisions lead to the growth of diagnostic outcome error δ_i and imply even stronger request for modification R. The outcome value $d_{i,k}$ may stabilize on an incorrect value $d_{i,\infty}$, where $|d_{i,\infty} - d_{i,ref}| > \epsilon_i$ or swing the measurement range in response to subsequent trials (3).

$$\lim_{k \to \infty} |d_{i,k+1} - d_{i,k}| > 0 \tag{3}$$

In such case the system is unstable and the diagnostic outcome i does not converge to the true value $d_{i,ref}$(fig. 3).

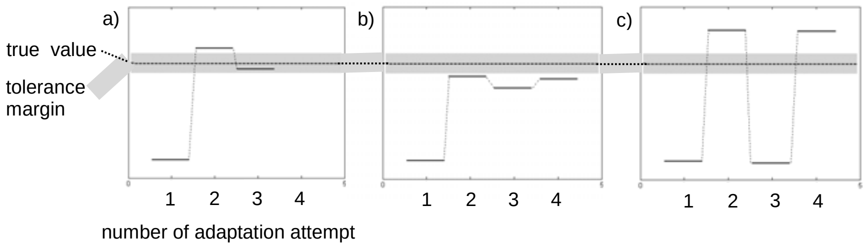

Fig. 3. Examples of possible system adaptation a) converging and stable, adaptation ends in 2 iterations; b) stable but not converging - the data error still results in adaptation request; c) not stable and not converging

2.3 Data priority-dependent software management

The overall estimate of diagnostic quality has to follow the variability of patient status and the data relevance. A straightforward approach assuming that quality estimates directly correspond to modified procedures is here impractical. The dependence between diagnostic parameters and interpreting procedures is much more complex (fig. 4). Each final outcome is calculated by a chain of several procedures affecting its quality. Conversely, each procedure, particularly at early processing stages, affects several diagnostic parameters. These relations, implied by the software architecture were compiled to a static list appended to each repository attributes and considered by the software management subroutine. In case the modification request R is issued by the particular parameter-oriented quality estimator, the list is hierarchically scanned in order to detect any conflict of interest between simultaneously affected data. This hierarchy depends on current patient status and approves the modification only in case of procedures contributing to parameters of lower priority.

3 Examples of use and results

The behavior of single client-server pair being a limited-scale ECG monitoring network prototype with auto-adaptive software was investigated with use of the proposed tools. The remote recorder was based on a PDA-class handheld computer with Bluetooth-connected ECG acquisition module (Aspekt 500 by Aspel, 8 channels, 12 bits, 500 sps) and bi-directional GPRS connection. The stationary server was a PC-class desktop computer with a static

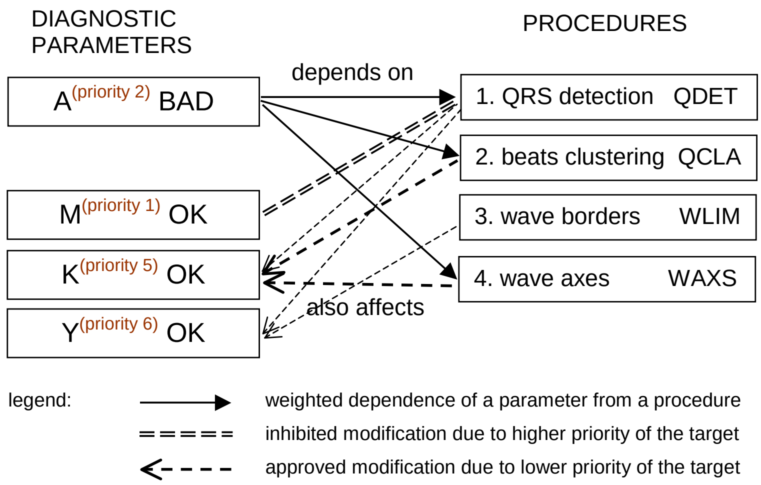

Fig. 4. Example of dependence between diagnostic parameters and interpreting procedures influencing other outcomes of various priority

IP address and 100Mb Internet access running Linux-Apache-MySQL-PHP (LAMP) package. The database contained 857 signals composed of physiological ECG and 14 most frequent pathology representations joined artificially [7] [10]. The standard goal of such test is the assessment of the software adaptation correctness, but in our case main attention was paid to the usability of newly proposed quality estimation tools. Triggering error threshold for remote software modification was set accordingly to the diagnosis priority in four categories: 2% for QRS detection and heart rate, 5% for wave limits detection and ST-segment, 10% for morphology classification and 20% for other parameters. The overall distance Q in the diagnostic parameters hyperspace is expressed by the values of diagnostic parameters errors weighted by the priority of particular data (1). The correctness of software modification is ex-

Table 1. Cumulative percentage of remote diagnostic results convergence test after 1-4 consecutive steps of interpretation software modification

step no.	converging	non-converging
1	63,1	36,9
2	74,5	25,5
3	79,1	20,9
4	80,7	19,3

pressed in technical aspect by the percentage of incorrect adaptation attempts

(89 cases, 10,4%). As such were considered resources overestimation, leading to allocation violation (27 cases, 3,1%), and underestimation, resulting in suspending of the software upgrade when the upgrade was feasible (62 cases, 7,3%). In medical aspect, the correctness of interpretive software modification is expressed by the percentage of adaptation attempts leading to diagnostic parameters converging to the reference values (740 cases, 96,4%). In 28 cases (3,6%), however, diagnostic results quality was inferior in result of software modification.

4 Conclusions

Presented method offers estimation of various new features emerging due to the ECG processing adaptivity. Two principal concepts presented in the paper (data convergence, priority-dependent software management) reveal high complexity of the auto-adaptive software as well as areas not fully covered by current medical recommendations. Principal elements of proposed quality estimation method was used for assessment of a prototype cardiac monitoring network. In this application our method contributed to final adjustment of the system properties in particular automatic decision making about further processing and reporting in a remote recorder.

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