The Use of Selected Diagnostic Parameters as a Feedback Modifying the ECG Interpretation

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Abstract

The paper presents the principles and prototype implementation of adaptive wireless monitoring system using medical parameters as a feedback modifying the ECG interpretation process. The paper focuses on the decision-making procedures such as: optimization of patient description, resources availability prediction and assessment of diagnosis reliability. Human expert preferences as well as the data reliability factors were revised for the purpose of this implementation.

The prototype limited-scale implementation was tested with use of 2751 one hour 12-leads ECG records. In that total, 857 signals were combined of a physiological and pathological parts representing one of 14 diseases most frequently observed in out-hospital patients. In 80,2% of the cases, the remotely modified software yielded results in the priority similar to the reference observed from the experts' survey.

1. Introduction

The adaptivity of ECG processing and transmission controlled by the medical contents of the signal offers many opportunities for diagnosis customization in a distributed patient surveillance network. This idea good approach the procedure used by human experts leading the diagnostic process iteratively to the most probable conclusion, avoiding unnecessary computation and uneven data [1-3]. The adaptive recorder connected to a life-surveillance network simulates well the constant presence of medical staff without limiting the patient usual life style including world-range mobility.

The challenging problem of determining the critical diagnostic parameters and their impact to the modifying feedback is presented in this paper. As far, from the automatic analysis viewpoint the only important parameters were thee correctness of diagnostic parameters and computation time. Currently, the use of a medical outcome in adaptation of the interpretation chain, several new factors should be estimated, quantified and considered in course of the decisive process:

– the medical severity of the case,
– the interpretation reliability,
– the remote resources availability etc.

The aim of the feedback modifying the ECG interpretation is a multi-criteria optimization of the patient description available at the center. The principal considerations are:

– the set of parameters optimally describing the patient status for the fastest and most accurate diagnosis
– the extent of feasibility of the optimal processing in the available hardware resources
– the influence of the processing adaptivity to the report consistency.

The automatic remote correction of interpretation software considers disease-dependent priority of delivered diagnostic parameters and provides protective measures against consequences of wrong adaptation decisions. The software modifying feedback provides automatic evaluation procedures aiming at the continuous assessment of the diagnosis quality. The remote interpretation result just affected by the adjustment of the software is compared to a redundant interpretation performed by the server on the same signal strip. The adjustment was confirmed as appropriate in case of convergence of these results.

Since the adaptive ECG processing issues demand-dependent variable data stream, a flexible data transmission format must be used in wireless reporting. The reporting of optimization consists in delivering the most important data in the shortest possible time and is based on the following factors:

– mandatory report content,
– data-specific update frequency,
– optimal data priority.

All principal aspects: decision making and validation, modification of interpretation process and flexible reporting format has to be considered together in prototyping an implementation of adaptive wireless ECG surveillance network [4, 5]. This paper is particularly focused on the decision-making and validation procedures. Our approach uses the term of "feedback" as the analogy to the classical control theory justified by the use of bi-directional transmission channel.

2. Methods

The automatic adaptation of remote ECG interpretation is a function *f* minimizing three prioritized variables:

$$y(m,k) = f(\delta,\varepsilon,\gamma) \quad (1)$$

where: δ is the distance of expected and achieved diagnostic goals, ε is the distance of required and achieved diagnostic reliability, γ is the use of resources (wireless channel, computation costs, power supply etc.) and the output y defines the modification parameters quality m and quantity k. In practice, some outputs are difficult to quantify and some others has only binary states. In our implementation, we assume each ECG interpreting procedure:

- is driven by a limited vector of control coefficients also called "constants"
- exists in multiple variants of simultaneously ascending output reliability and computational resources requirements.

The set of available specific disorder-dedicated procedures and their mutations expands a two-dimensional space of function values (fig. 1).

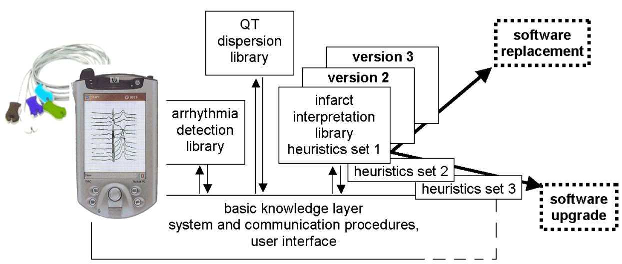

Figure 1. Two dimensional space of modification for remote recorder interpretation software.

2.1. Quantifying diagnostic goals

While the fastest and most accurate diagnosis chain is implied by the cardiology standards, the expected diagnostic goal for 14 most frequent diseases was estimated by the experiment. From a commercial ECG interpretation software manufacturer we obtained a customized release with the default selections of final report contents menu replace by a random proposal. Using this software for 6 months, 87 doctors were faced against randomly pre-selected all possible report items and prompted to include or exclude items to/from the report contents each time the interpretation is completed (53192 cases). This willing action was recorded with the diagnostic outcome and after statistic processing yields a prioritized list of diagnostic parameters representing doctors' preferences in most common diseases.

2.2. Estimation of diagnostic reliability

The estimation of diagnosis reliability was implemented as two complementary procedures (fig. 2):

- *Knowledge base similarity search* is performed for every data packet received. The central server accesses the database for verification of the consistency of the received data by comparing it to the most similar database record and estimating the trends of diagnostic parameters from changes observed in similar records. The database search is optimized through data priority by disease history, sex and fundamental ongoing findings (e.g. heart rate or rhythm type). As far as the packet contains 'expected' data, the remote diagnostic results are considered reliable.
- *Redundant signal re-interpretation* triggers the raw signal request and the received signal is redundantly interpreted by the server software thread aiming at the comparison of local results to those received form the remote interpretation.

Any difference or suspicious case is carefully analyzed, statistically processed and compared to the tolerance thresholds. Outstanding values generate an output y, which ends with modification of the remote recorder interpretation software.

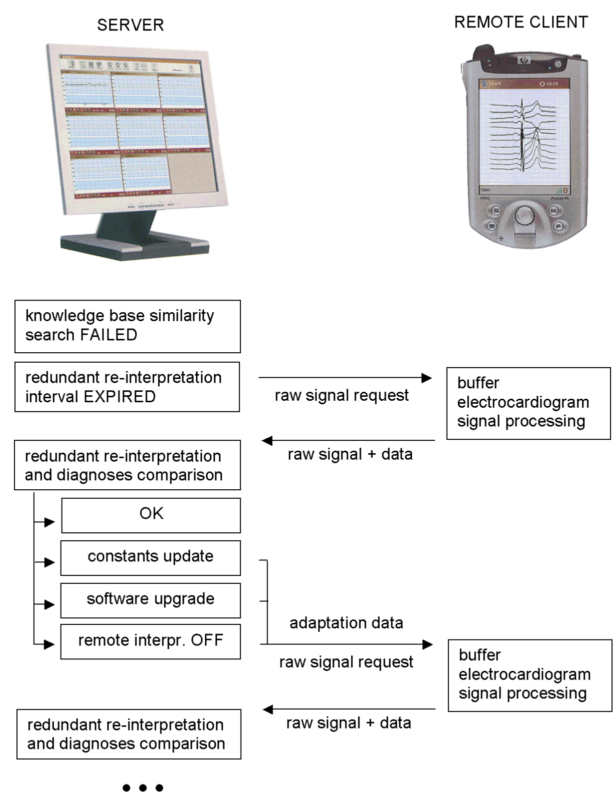

Figure 2. Data exchange for estimation of remote diagnostic reliability.

2.3. Verification of convergence

The software modification is not finalized until the remote interpretation fulfills the expected standards or central interpretation is performed instead. Each software modification implies the diagnostic results convergence test verifying whether the results issued by the modified remote procedure are improved or degraded. Once the results fall into the tolerance margin a stop condition for the modification loop is fulfilled.

The convergence of diagnostic results is required for the stability of the adaptive interpretation system. The central interpretation is here considered as a reference because of unlimited resources availability, access to distributed databases and optional intervention of human expert upon necessity.

2.4. Adaptation constraints

The automatic adaptation of remote ECG interpretation is constrained by available resources, in particular the wireless channel throughput and computational environment (CPU, memory usage etc.). Therefore the resources availability is continuously reported and compared to the estimated new requirements resulting from the software adaptation. The adaptation output is inhibited when the remote diagnostic procedures are at risk to violate the system memory allocation rules or processing time restrictions.

Since results of various interpretation procedures, or their mutations, are compared in respect of the same signal strip, the important constraint on the adaptivity comes from the length of the remote ECG buffer. The remote recorder acquires the patient signal in real time, and thus is not designed to accumulate it unprocessed in the memory. The adaptation process causes the diagnostic outcome delay that may by life-critical in some circumstances. In order to minimize the discontinuity risk we admit up to 5 consecutive steps of interpretation software adaptation.

3. Results

The behavior of automatically adjustable software was investigated in a limited-scale network prototype. The database contained 2751 one-hour 12-leads ECG records reproduced by a multi-channel programmable generator. The remote recorder was based on a PDA-class handheld computer with ADC module (12 channels, 12 bits, 500 sps) and bi-directional GPRS connection. The stationary server was a PC-class desktop computer with a static IP address and 100Mb Internet access running Linux OS.

The database contained 857 signals composed in the first half of a physiological record and in the second half of signal representing one of 14 pathologies under question. The main goal of the test was the assessment of the software adaptation correctness, thus the software provided software provided selective disabling of the principal adaptivity features. The adaptation processes were roughly classified to two categories: *software upgrade* consisting in modifying of control coefficients vector and *software replacement* consisting in relinking dynamic libraries containing interpretive procedures.

3.1. Medical aspect of adaptation correctness

The correctness of interpretive software upgrade and replacement in medical aspect, is expressed by the contribution of adaptation attempts leading to diagnostic parameters approaching to the reference values (tab. 1). The overall diagnostic improvement is expressed by the diagnostic parameters error weighted by diagnosis priority.

Table 1. Medical correctness of software adaptation (only correct adaptation attempts are considered)

action	diagnosis improvement	diagnosis degradation
software upgrade	643 (99,4%)	4 (0,6%)
software replacement	97 (80,2%)	24 (19,8%)

3.2. Technical aspect of adaptation correctness

The technical correctness of software upgrade and replacement is expressed by the contribution of adaptation attempts leading to resources violation due to overestimation and attempts where the upgrade was possible but inhibited due to resources underestimation (tab. 2).

Table 2. Technical correctness of software upgrade and replacement

action	upgrade possible	upgrade impossible
upgrade performed	647 (75,5%)	27 (3,1%) resources overestimation
upgrade suspended or library replacement	62 (7,3%) resources underestimation	121 (14,1%)

3.3. Results of convergence test

Additional test were performed to investigate the convergence of diagnostic results computed by the remote monitor in consequence of software upgrade to the reference values computed from the same signal by the server. As a response to the remote software adaptation, the questioned ECG signal is re-interpreted from the memory buffer. This iterative process is expected to bring the remote-calculated diagnostic results closer to the central-calculated reference value, what we call here 'convergence' (tab. 3).

Table 3. Convergence of remote diagnostic results after the software upgrade

calculation constants update steps	cumulative percentage	
	converging	non-converging
first	63,1	36,9
second	74,5	25,5
third	79,1	20,9
fourth	80,7	19,3

A single iteration is sufficient in majority of cases to yield diagnostic results falling into the tolerance margin and to satisfy the stop condition of the modification loop. Otherwise, provided the new results are closer to the reference, next software upgrade is executed within the allowed steps limit.

4. Discussion and conclusions

The software adaptation and customization of a remote interpretive ECG recorder during the seamless monitoring made on a background of automated diagnosis verification and resources assessment is a complicated and responsible task. The interpretive software of a remote recorder is continuously adapted and personalized in course of fully automatic multi-criteria optimization process. This yields the unprecedented advantages of the surveillance system:

- auto-adaptivity of the remote interpretation to the diagnostic goals and patient status variability,
- improved reliability of diagnostic outcome as a result of systematic comparison to the reference,
- optimal use of the available resources in aspect of the diagnostic process without unnecessary computing or wireless channel overload.

As demonstrated in the tests, 768 (89,6%) of adaptation attempts were technically appropriate, among of them 643 (99,4%) software upgrades and 97 (80,2%) software replacements yielded diagnostic results similar to the reference observed from the experts' survey. In 63,1% of cases the modification completed in a single iteration of 4,4 s average duration. Among the 857 adaptation attempts, 89 (10,4 %) failed in result of incorrect estimation of resources availability. Resources overestimation resulting in the remote OS crash and thus monitoring discontinuity occurred in 27 (3,1%) cases.

The use of diagnostic results or their differences as arguments for adaptation of ECG interpretation procedures is interesting, but it needs further investigations to reveal any unexpected system behavior and to assess the possible medical risk.

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References

[1] Balasz G, Kozmann G, Vassanyi I. Intelligent Cardiac Telemonitoring System. Computers in Cardiology 2004;31:745−8.

[2] Oefinger M, Moody GB, Krieger M, Mark RG. System for Remote Multi-Channel Real-Time Monitoring of ECG via the Internet. Computers in Cardiology 2004;31:753−6.

[3] Fayn J, Ghedira C, Telisson D, Atoui H, Placide J, Simon-Chautemps L, Chevalier P, Rubel P. Towards New Integrated Information and Communication Infrastructures in E-Health. Examples from Cardiology. Computers in Cardiology 2003;30:113−6.

[4] Augustyniak P. Implementing the ECG Interpretation Procedure in a Distributed Wearable Computer Systems Folia Cardiologica 12(D), 2005.

[5] Augustyniak P. Content-Adaptive Signal and Data in Pervasive Cardiac Monitoring. Computers in Cardiology 2005;32:825-8.

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