# Diagnostic Quality-Derived Patient-Oriented Optimization of ECG Interpretation

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**Summary.** The paper discusses various aspects of diagnostic quality estimate in an adaptive ECG interpretation system. Since the ECG interpreting software adapts to the patient status and diagnostics goal variations, the commonly used term of data quality must be revised. We propose backgrounds and demonstrate the use of a multidimensional quality hyperspace depending on the assumed system adaptability. The emerging need of appropriate reference database and standardized description of human experts behavior is also addressed here. The subset of proposed quality estimators is used as adaptivity criteria in a prototype of wireless monitoring system for cardiology. The paper concludes with guidelines for testing the processing performance and with a comparison of rigid and adaptive software features.

## 1 Introduction

Quality control is the aspect of principal importance in every automated support of diagnoses. Since the end-user is not able to fully supervise the behavior of the software and the automatic system should allow him to pay more attention to the patient, professional organizations like cardiology societies implement strict certification procedures for medical electronic equipment [4]. In the domain of automated ECG interpretation software testing, worldwide standard databases with reference signals and data are used to measure whether the values issued by the software under test fall within the tolerance margin around the corresponding reference value (gold standard) [3]. The research towards adaptive distributed ECG interpretation networks revealed unprecedented advantages. Such networks shows high flexibility of interpretation task sharing, eliminating the unnecessary computation and data flow, finally they adapt to the variable status of the patient and diagnostic goals [2]. Until today, there was no standard to test these new features beyond the parameters common to the rigid software. Our proposal aims to fill this gap and to implement a multidimensional hyperspace of quality. Since the target system under test is adaptive and time plays crucial role in life-critical cardiac events, the quality estimation has to support dynamic behavior of the system and include transient description parameters. Unfortunately, medical guidelines and testing standards (e.g. AHA, IEC) describe only stable pathologies and provide reference records stationary in medical sense. This is sufficient for off-line interpretation systems attempting each part of the signal with the same assumption and thus guaranteeing high repeatability of results. Human experts, however, behave differently taking into account not only a limited section of cardiac electrical image, but also much wider context of history including extra-cardiac events. Staying in touch with their patients, human experts often witness emergencies of pathological events and modify their further diagnostic goal. Design of a remote adaptive interpretation system that is expected to simulate the presence of doctor, must consider new criteria of adaptivity and assessment of diagnostic quality present in the everyday clinical life, but not formally covered by current standards. These criteria should refer to the present patient status and cover:

- specific area of interest for further diagnosis (the optimal hierarchy of diagnostic parameters),
- expected data variability and resulting minimum update frequency of each parameter,
- tolerance of each parameter value,
- possible subsequent diagnoses (patient status) ordered by the likelihood of occurrence,
- reference records containing example transient signals.

## 2 Materials and Methods

### 2.1 Adaptive ECG interpretation system overview

The developed wireless adaptive ECG monitoring system consists of a star-shaped network managed by a stationary central server receiving medical data and controlling several remote wearable recording devices (fig. 1). The bi-directional GPRS link is used as data carrier, however the long-distance connections use the Internet infrastructure. Wearable recorders are manufactured as low-cost general-purpose instruments for vital signs acquisition. The recorder consists of a battery-operated computer integrated with signal digitizer, communication module and user interface. The hardware design provides wide range of control and re-programmability by the software.

The software consists of a rigid mandatory background and optional overlay modules that can be reconfigured in course of seamless operation. The background contains basic common modules: data acquisition and wireless communication services as well as fundamental user interface procedures. The overlay includes a repository of interpretation and report-formatting procedures programmed as diagnosis-oriented dynamic libraries. The upload and linking or release and deletion of each particular library is performed by the supervising server in any convenient time with respect to other linked libraries

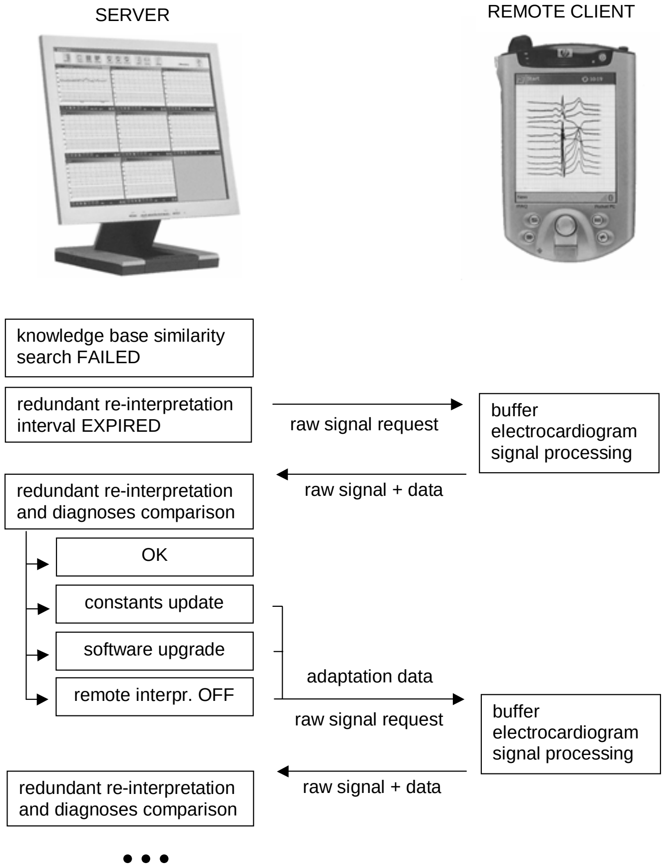


**Fig. 1.** The architecture of remote ECG recorder interpretation optimized for the data flow and processing error propagation

and to the available computational power. This approach personalizes the remote recorder to the patient-specific signal features and gives an unprecedented flexibility required for a pertinent real-time reaction for unexpected events. Most common and frequent cardiac episodes are interpreted by the wearable device software and the result fit in a cost-acceptable data stream. The occurrence of any difficult or unresolved event is reported as a short strip of raw signal for the interpretation by the server software automatically, or even in very rare cases with the assistance of a human expert. The prototype follows human relations-based organization of ECG monitoring particularly in two aspects:

- processing adaptability,
- reporting adaptability.

In both domains the adaptability is dependent on the past diagnostic result, monitoring goals and patient-specific features.

### 2.2 Concept of multidimensional quality estimate

While the conventional rigid software has to be evaluated in the domain of result accuracy only, the adaptive software may be assessed in the multidimensional hyperspace including:

- asymptotic accuracy,
- adaptation delay,
- convergence (adaptation correctness).

Asymptotic accuracy is the absolute value of diagnostic error when the transient-evoked software adaptation is completed. Assuming no other transient is present in the subsequent signal it may be expressed as:

$$Q = \lim_{t \to \infty} |v(t) - v_0| \tag{1}$$

where $v(t)$ is subsequent diagnostic outcome and $v_0$ is the absolute correct value. Adaptation delay is defined as the time period from the transient occurrence $t_0$ to the moment $t_D$ when the diagnostic outcome altered by the interpreting software modification starts falling into a given tolerance margin $\varepsilon$ around its final value.

$$D = t_D - t_0 : \forall t > t_D \; v(t) \in (v(\infty) - \varepsilon, v(\infty) + \varepsilon) \tag{2}$$

The convergence represents the correctness of decisions made by the management procedure about the interpretation processing chain. Taking the analogy from the theory of control, the software adaptation plays the role of a feedback correcting the diagnoses made automatically. If the software modification decisions are correct, the outcome altered by the interpreting software modification approaches to the true value, the modification request signal is removed in consequence of decreasing error and the system is stable. Incorrect decisions lead to the growth of diagnostic outcome error and imply even stronger request for modification. The outcome value may stabilize on an incorrect value or swing the measurement range in response to subsequent modification attempts. In such case the system is unstable and the diagnostic outcome does not converge to the true value.

### 2.3 Concept of weighted accuracy estimate

There is no general estimate of diagnostic quality and in the system composed of several procedures responsible for each parameter, the quality estimates need to correspond to the procedures selected for modification. Usually in the ECG interpretation chain there is a complex dependence of the diagnostic parameters and interpreting procedures (fig. 2). Each final outcome is influenced by several procedures and each procedure usually affects multiple parameters. The range of influence depends on the interpretation stage at which the procedure is applied. The quality of early processing stages affects all diagnostic parameters and the influence range gets narrower at subsequent stages. Each kind of diagnostic procedure is attributed by a static list of influenced diagnostic parameters.

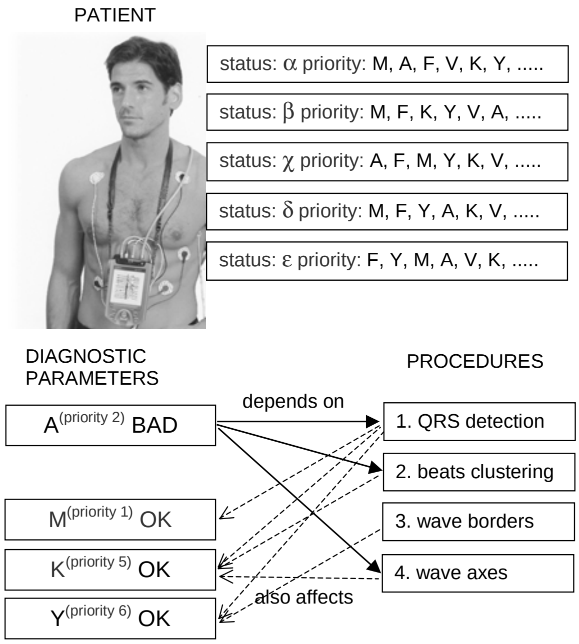


**Fig. 2.** The illustration of reciprocal dependencies of diagnostic parameters and interpretation procedures. Accordingly to the patient status, the parameters priority influences the final decision on remote software management. A bad parameter A triggers the replacement of only the procedures '2. beats clustering' and '4. wave axes' affecting parameters of lower priority K and Y)

The system makes its decision about the software modification with regard to all diagnostic parameters that may be concerned. The list of influenced diagnostic parameters is hierarchically scanned in order to detect any conflict of interest between simultaneously affected data. This hierarchy is, however, variable depending on patient status. Following the dependence of the diagnostic parameters medical relevance on the patient status, we propose the use of the same list of relevance factors to weight the contribution of particular parameters error to the general estimate of diagnostic quality.

### 2.4 Providing the uniform data

Non-uniform asynchronous updating of particular diagnostic parameters is an intrinsic advantage of adaptive interpretation systems, however direct comparison of their outcome to the reference values is not possible. The patient status has to be estimated from the irregular series of data issued by the adaptive system under test at each data point when the reference results are available. The diagnostic outcome of the adaptive interpretation being non-uniformly sampled time series $Nj(n, v(n))$ was first uniformized with use of the cubic spline interpolation [1] given by a continuous function:

$$S_i\,(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3 \qquad (3)$$

The interpolation yielded the uniform representation of each parameter by sampling the $Si(x)$ at the time points $m$ corresponding to the results of the fixed software:

$$N'_j(m) = \sum_m S_i\,(x) \cdot \delta\,(x - mT) \qquad (4)$$

$x \in [x_i,\ x_{i+1}]$, $i \in \{0,\ 1,....n\text{-}1\}$ best fitted to the series $N_j$. The values estimated at regularly distributed time points were finally compared to the reference. The assessment of data conformance has to consider three quality factors: tested data accuracy at their individual sampling points, interpolation error and reference data accuracy.

## 3 Results

The behavior of limited-scale network prototype of an ECG monitoring system with auto-adaptive software was investigated with use of the proposed tools. The remote recorder was based on a PDA-class handheld computer with ADC module (8 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 of artificially joined physiological ECG and a signal representing one of 14 pathologies under question. The main goal of the test was the assessment of the software adaptation correctness. The remote software update process is initiated if remote-issued diagnostic results differ from the server-calculated reference by more than a threshold defined accordingly to the diagnosis priority in four categories: 2% for QRS detection and heart rate, 5% for wave limits detection and ST-segment assessment for ischemia, 10% for morphology classification and 20% for remaining parameters. In case the result after a single software modification step is still out of the given tolerance margin, the decision about next update is made upon the new value is closer to the reference, and allow up to four consecutive update steps.

**Table 1.** Results of remote diagnostic results convergence test after the consecutive steps of interpretation software modification

| calculation constants update steps | converging % | non-converging % |
|---|---|---|
| first | 63.1 | 36.9 |
| second | 74.5 | 25.5 |
| third | 79.1 | 20.9 |
| fourth | 80.7 | 19.3 |

In technical aspect, the correctness of software upgrade and replacement is expressed by the percentage of incorrect adaptation attempts. As such were considered resources overestimation, leading to allocation violation, and underestimation, resulting in suspending of the software upgrade when the upgrade was feasible (tab. 2). In medical aspect, the correctness of interpretive software upgrade and replacement is expressed by the percentage of adaptation attempts leading to diagnostic parameters converging to the reference values (tab. 3). The overall distance in the diagnostic parameters hyperspace is expressed by the values of diagnostic parameters errors weighted by diagnosis priority.

**Table 2.** Technical correctness of software upgrade and replacement

| action | upgrade possible | upgrade impossible |
|---|---|---|
| software upgrade | 647 (75,5%) | 27 (3,1%) |
| library replacement | 62 (7,3%) | 121 (14,1%) |

**Table 3.** Medical correctness of software adaptation

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

The quality tests demonstrated for this particular system the technical correctness of 768 (89,6%) of adaptation attempts, 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 (medical correctness). In 63,1% of cases the modification completed in a single iteration of 4,4 s average duration. The total of 89 (10,4%) adaptation attempts 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.

## 4 Conclusions

Presented method offers estimations of various new features emerging due to the ECG processing adaptivity. Several concepts presented in the paper (multidimensional quality estimate, weighted accuracy estimate) reveal high complexity of the problem and some area not covered by the medical procedures and recommendations. These topics were presented for discussion on a cardiologist's forum. 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.

## 5 Acknowledgment

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