Web-based architecture for ECG interpretation service providing automated and manual diagnostics

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Abstract: The ECG interpretation process is currently fully automated and consists of various signal processing, pattern recognition and decisive procedures. The worldwide unified interpretation guidelines are differentially implemented by software manufacturers. Moreover, the most sophisticated algorithms are rarely used, since the corresponding medical cases are relatively infrequent. Our work focuses on designing all the advanced ECG interpretation routines as distributed web services. The key idea is to extend the interoperability by multiple method-specialized complementary interpretation services. The proposed architecture service concentrates the specialized processing tasks and, apart from the medical advantages, is a reasonable method preserving the inventor's intellectual property rights.

Keywords: automatic ECG interpretation, distributed computing, e-health, decision support

1. Introduction

The computerized ECG interpretation is currently a clinical standard in the range of basic diagnostic procedures. Unfortunately for software manufacturers, the most sophisticated interpretation algorithms meet only a limited demand, thus the research expenditures are hardly returned. In the clinical practice the specialized functions increasing the price of advanced equipment are rarely justified, because the corresponding medical cases are relatively infrequent. Moreover, some methods recently introduced are fully or partially patented causing the development of custom solutions by concurrent companies. Consequently, instead of interoperability, new constraints are created for standardization of the interpretation procedure.

Our proposal is motivated by the studies on human relations between cardiologists and has a procedure-use statistics as a background. Following the human network of specialization in cardiology we found interesting that the common universal skills reach a certain level, from which upward only a very particular domain is practiced and reaches the maximum. In a national scale, every cardiologist is able to interpret a certain range of most common cases, while in infrequent diseases the regional or national specialists usually have to be involved. Such organization limits the costs that had to be borne to educate every doctor in the whole range of cardiology, without affecting the medical service quality provided by a fast access to the appropriate specialist. The specialists are then treating the pre-selected cases matching their interest, what is a positive feedback for their further education and skills. The principles above, we take as particularly useful, as they are verified since many years in everyday practice .

The stand-alone interpretive software was conceived as a model of the cardiologist's reasoning. In a similar way, the distributed healthcare network may be modeled with some constraints in a computer network [1]. The general-purpose patient-side recorders play the role of basic-skilled cardiologist, and report every unusual case as unresolved to the specialized center. The centers play the role of regional or national specialists and are realized as Unix-based multitask and multi-user servers scaled to the estimated demand for particular interpretation task. We make no assumption on the centers number, in particular, each heart disease may be supported by several physical interpretation nodes using independent interpretation methods and located in different parts of the World [2]. The interpretation of difficult diseases needs the transmission of considerable amount of data over the network, however this affects the overall performance only slightly due to the rare occurrence of these cases.

Some advantages of commercial nature are worth to be mentioned in context of the web-based ECG interpretation services:

- the recorder is marketed as a low-cost general-purpose device, the potential ability of specialized interpretation does not increase its price and the client pays for the actual count of such interpretation performed as necessary.
- the inventor of specialized interpretation method may be rewarded for the service in an extent proportional to the service usability and quality.
- the inventor's intellectual property rights are well protected, since the distribution of software source code or executable files is no longer required.
- the interpretation method is widely standardized and does not depend on recorder manufacturer or physical location of the patient.

Another advantage of our proposal is no necessity of changes in bedside interpretive ECG recorders being in use today. The only modification consists in extending the connectivity, used only for electronic patient record, by a procedure co-operating with multiple method-specialized remote interpretation services. The service could be organized independently and managed by the inventor of a particular diagnostic method or other standard high-quality computing provider.

As an implementation example, throughout this paper we present principal technical problems encountered during the design and development of the example QT-Dispersion service and discuss the alternative solutions. QT-Dispersion, derived from inter-lead comparison of QT interval duration in several leads of standard ECG is one of the most significant predictive factors of repolarization abnormalities (fig. 1). The extensive research originated from the early 80-ties [3] [4] shows that the heterogeneity of refractoriness in myocardial tissue contributes to increased vulnerability to ventricular tachyarrhythmias. Increased QT-Dispersion is associated with cardiac death in nonischemic patients, with ventricular fibrillation and sustained tachycardia and other severe heart failures. This parameter is also used to identify high-risk patients awaiting heart transplantation.

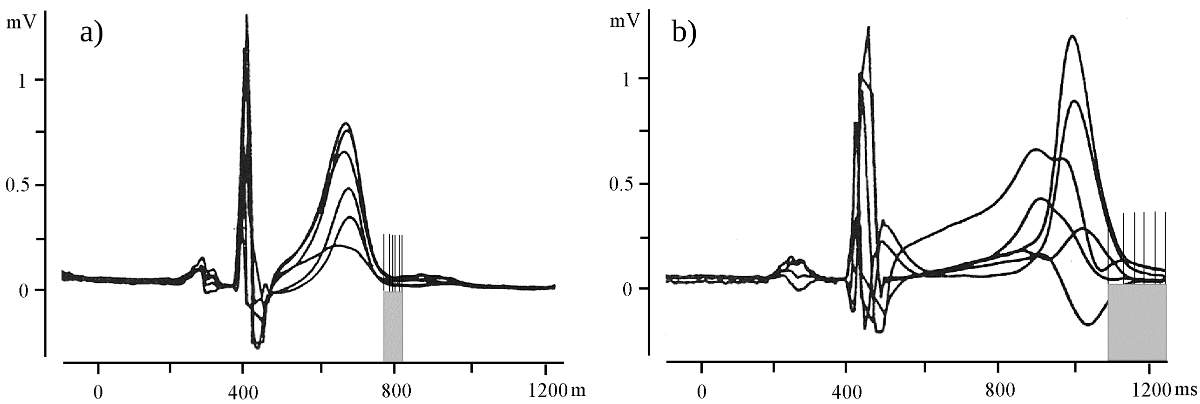

Figure 1. Precordial leads representation of an example heartbeat a) normal, b) high QT-Dispersion (Long QT Syndrome)

2. MATERIALS AND METHODS

Main technical issues concerned during the design and development of QT-Dispersion service are presented in this chapter. Only the signal processing algorithm is processing-specific, while all other issues are common for any ECG interpretation routine designed as a web service.

2.1 The computation algorithm

The studies of QT-Dispersion algorithm in various manufacturers [5] [6] [7] reveal that the AHA guidelines are implemented in different way and the software returns significantly diverse results from the same test signal. The most problematic issue is the correct delimitation of T-end point for each ECG lead independently. As sources of differences we found:

- various approximation techniques to be responsible for the differences.
- Difference in the statistics used for outliers suppression, that excludes leads differing too much from the mean value as too difficult to be analysed.

Consequently, the results are not reproducible from one machine to another, and the serial comparison or follow-up are manufacturer-dependent.

As recommended in the literature [8], our algorithm uses a second order approximation of T-wave maximum and a maximum slope approximation of T-wave end (fig 2). The approximation techniques allow a sampling frequency-independent processing for a wide range of acquired signals.

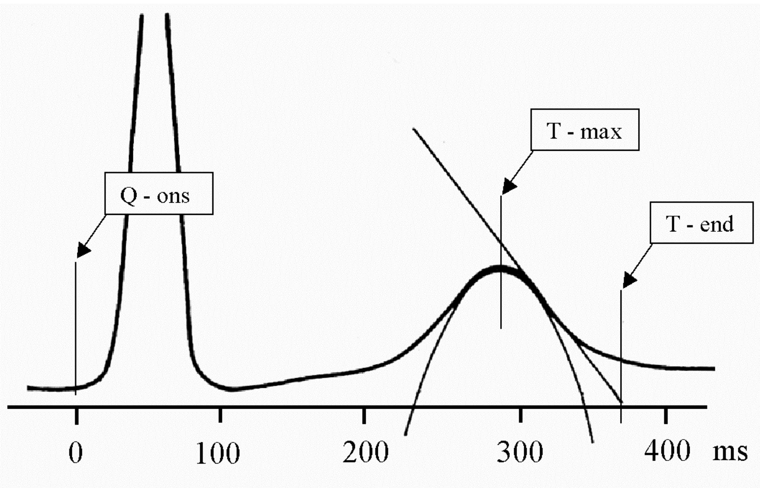

Figure 2. Details on T-wave maximum and T-end point measurement.

2.2 Signal quality verification

The purpose of signal quality verification is the correct estimation of diagnostic outcome reliability. In case of weak amplitude, noisy signals, spikes in the T-end area or baseline wander, the analysis may finish with incorrect results. The signal is analysed but not filtered in any way before the diagnostic processing starts. Suspicious input signals are identified, and a warning message is issued together with the diagnostic outcome. In case the result does not satisfy the recipient, a client-side filtered version or simply another, distortion-free signal section may be resubmitted for interpretation. The signal quality is estimated by computation of several parameters as the slope of power spectrum decay, the percentage of monotonic sections, the number of isolated signal accelerations and decelerations etc.

2.3 Multithreading and human assistance

The diagnostic subroutines of service software were designed to be launched as multiple asynchronous remotely controlled threads (fig. 3) assigned by the system to the corresponding clients in the log-in order. The clients have regular user privileges with access limited to their thread and their parent directory. Two ways of supervision are designed for the service: server administration and medical expert assistance. The help from a qualified cardiologist is crucial at this point, because not only resolves current conflicts or misinterpretation, but also gathers and qualifies information on errors. Consequently, these remarks are considered as a background for future versions of interpretive software.

There are several aspects of human assistance at the specialized interpretation server:

- supervising the adequacy of basic cases interpretation performed remotely,
- controlling and correcting the task assignment,
- supervising and improvement the specialized interpretation procedure,
- using the knowledge base and extracardiac information,
- authorization of the output diagnosis.

Improvement of automated diagnosis quality will reduce the supervisory tasks expected from the human expert increasing his/her efficiency and limiting his/her duties to the manual interpretation of very rare cases currently not supported by the software.

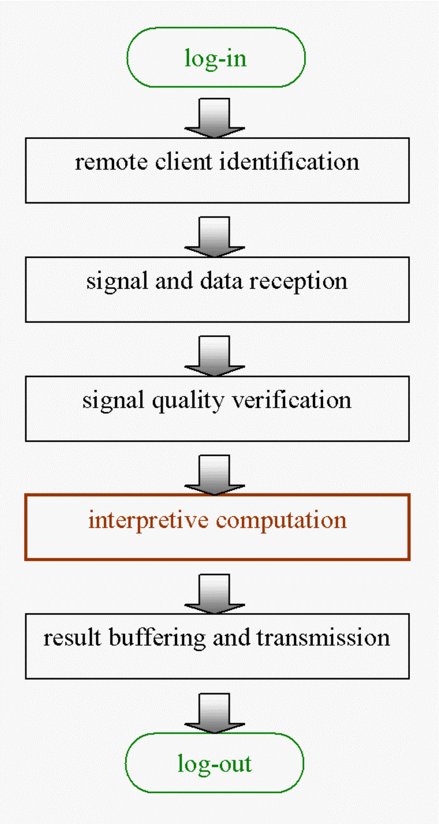

Figure 3. Interpretation request processing chain

2.4 Remote access and client identification

The general-purpose ECG recorder provides the acquired signal over the network, requests the interpretation service and accepts the diagnostic outcome. Although the service in its experimental stage is accessed by a closed group of remote clients, recognized by their IP addresses, for the future expansion the remote client identification procedure was implemented. The purpose of this procedure is twofold:

- assignment of the diagnostic outcome to the proper client request,
- identification of the service subscriber status and prevention from unauthorized or multiple task request.

Client identification procedure provides a substantial tool for the service usage statistics and is expandable for the future client management. In case of subscription would be made payable, this solution may be considered at a first approach to the service's financial support. The subscribers have to pay for the number of interpretation tasks requested over a given period and not for the potential ability of analysis embedded in their recorders.

At the testing stage, we had to consider the human access as well and as we found it useful in some circumstances (e.g. for medical researchers), the human clients support is kept in the final version of the service. The server interface is able to perform the requested computation on the uploaded user data and to return the result without disclosure of the software code. The service can be manually launched and controlled by the client via limited set of parameters. Any modern graphic-based web browser is suitable as user interface if only supports user file transfer, the selection of options and the results presentation. The transfer of computation results as a file is also under consideration, making support for text interface-based terminals.

3. RESULTS

The prototype of the service was build with use of a Linux-based web server. For the human access, a standard website is developed in order to upload signal, launch the processing thread and present the diagnostic outcome. For the machine access an automatic login and identification procedure is provided, and a returning message contains the diagnostic outcome in binary format. The service test was initially made using human access, since the machine access required manufacturer's approval for modification of an existing ECG machine by adding communication interface, proper data upload and task request format support. Except for two real ECG machines, the remaining clients were emulated during the test with use of independent PC machines. The other advantage of client simulation was the alternative local implementation of the diagnostic subroutines made on the PCs in parallel, allowing easy measurement of delay caused by remote operation.

3.1 Experimental devices setup

The wired connection tests were performed on the prototype QT-Dispersion service with static IP address and 100Mbps direct Internet connection. A maximum of 10 clients performed their computation tasks simultaneously. This number was limited only by the available IP reserve. The remote computation was nearly as fast as its local counterpart, the systematic delay measured for the remote processing was 130ms ± 53ms and was found not significant for the diagnostic performance.

A similar test was repeated for the node server connected to the web out of the institution area and domain. The packet routing procedure and consecutive mediation of internet nodes influences the processing delay, in particular for the first connection (1639ms ± 280 ms). Subsequent connections from the same machine are performed much faster (170ms ± 67ms).
The test of wireless client-server connection was performed within the institution address domain for one wireless-connected client, while the others use a regular cable connection. The separated client used a 802.11g LAN PC Card set for the maximum data transfer of 11Mbps. Here again, the time necessary to establish the connection was very significant (up to 5s), and the subsequent tasks were processed faster (210ms ± 97ms).

3.2 Results and observations

The delay was measured by the client computer as a difference of completion time between the remote and local task performed on the same signal section. Table 1 summarizes all the mean values and standard deviations of delay caused by the remote operation of QT-Dispersion interpretation.

Table 1. Statistics of the QT-Dispersion interpretation delay (remote processing vs. local processing).

Connection method	average delay [ms]	standard deviation [ms]
100Mbps Ethernet connection within the same address domain	130	53
100Mbps Ethernet connection different address domains (first look-up)	1639	280
100Mbps Ethernet connection different address domains (subsequent connection)	170	67
802.11g LAN PC Card 11Mbps infrastructure mode (first look-up)	4105	880
802.11g LAN PC Card 11Mbps infrastructure mode (subsequent connection)	210	97

Three sources of the delay were identified during the analysis of remote task:

- remote service connection and file transfer,
- client recognition, data verification and result buffering,
- interpretive computation in a multitasking environment.

The contributions of a particular component depend on the service scale, internet connection quality, computation power etc. Because of high specialization, the service scale and the server resources may be adjusted accordingly to the medical demand.

4. DISCUSSION AND FINAL REMARKS

Our work aimed at implementing a typical well known diagnostic procedure as web-accessible service. We propose new technical solution for the implementation of any existing highly specialized procedures as well as of new algorithms that would appear in the future. The example service are designed and developed for QT-Dispersion interpretation, and the principle of this experiment was rather to face and solve all the range of technical issues, than to open a healthcare center. Other medical signal processing-based services, not limited to the cardiology, may follow our path. The advantages we found important and unprecedented are:

- high reliability of interpretation and protection of inventor's intellectual rights,
- worldwide standardization of procedures and interoperability,
- justified low cost at high scales of service.

The experimental part confirmed the hope for the practical usefulness of the service. Except for the first request, the task were performed by the remote service not noticeably longer than by the local subroutine. In case of multiple different interpretation tasks ordered from specialized services in parallel (fig. 4), the processing may be completed even faster than a sequential local analysis performed by an interpretive electrocardiograph with limited computation power.

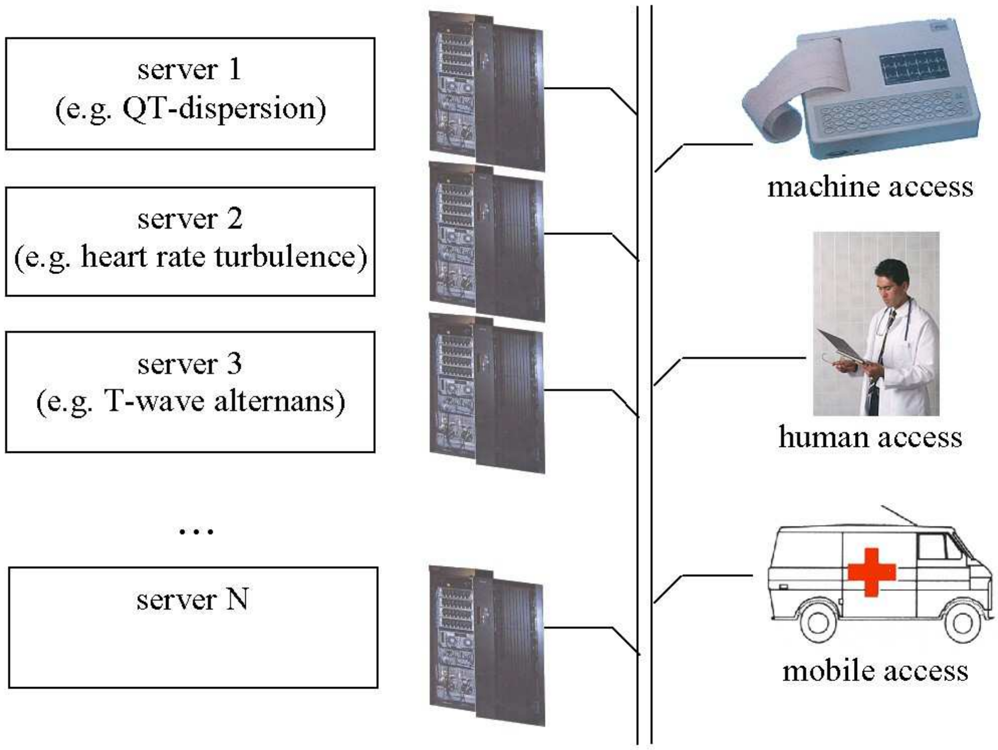

Figure 4. Worldwide accessibility of ECG specialized interpretive services.

For the further experiment we plan the use of a GPRS client connection that simulates better the conditions in a busy network of worldwide range. The 3G global telecommunication should definitely solve the problem of clients in motion (e.g. ambulance) or remote areas inhabitants without the wired access to the Internet.

The investigation of the web-based ECG interpretation services in the future is expected to precisely distinguish the interpretation tasks for the recorder and for the centre. Various aspects should be considered for the design of an ECG machines family for a web-based service. The most important are:

- interpretation feasibility in the constrained remote resources,
- manufacturing costs,
- frequency of disease occurrence,
- medical severity and urgency.

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