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Modeling of ECG Interpretation Methods Sharing Based on Human Experts Relations

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Abstract— **The introduction of distributed ECG interpretation is currently limited by the computational capacity of a battery-operated wearable recorder. The relations between human experts in cardiology are generalized in this paper and considered as a pattern of co-operation between computerized interpretation centers. Studying the cardiologist's practice we found out that during the years the range of family doctors skills, their adaptations to the patient-specific needs and their communication with the regional experts were optimized. Extrapolation of this approach to the artificial networks assumes that only selected and commutable basic interpretation routines are implemented in a remote recorder limiting its costs, increasing the autonomy time and adaptability. While most of cases are resolved on local level, the complicated but not very frequent events are reported directly to the interpretive center, for automated or human-assisted interpretation. Such architecture, derived from natural task sharing, is believed to fulfill all the diagnostic requirements with minimum involvement of complicated equipment and at minimum costs of data transmission.**

I. Introduction

The ubiquitous monitoring of vital signs is currently believed the most safe and convenient solution for elderly people independent life [1]. Certainly, wearable recorders and modern digital telecommunication services simulates well the continuous assistance of medical experts, therefore most of supervised patients return to their everyday activity instead of filling the hospitals. Although many physiological parameters represent the patient status, the most important one is often the electrocardiogram. The principal reason is the acuteness of cardiovascular diseases [2], but the other is the longstanding experience and well-established standards of ECG signal interpretation. This process, currently fully automated, consists of various signal processing, pattern recognition and decisive procedures.

The computational complexity of ECG interpretation is the main constraint of real-time software implementation in battery-operated wearable devices. Frequently, the interpretation procedures are simplified and the diagnosis reliability is reduced for the difficult and unusual records. Moreover, in rare devices only the raw signal is available for off-line verification in case of doubts or false alerts [3].

The other widespread solution is the continuous ECG telemetry assuming the entire interpretive signal processing to be performed at the other end of the link. The algorithm complexity no longer limits the performance, additionally the real expert's assistance is feasible for extremely difficult records. Unfortunately the important drawback of the centralized interpretation is the cost of telecommunication service. Since the recorder is not equipped with autonomic interpretive software, the continuous high-throughput connection with the server is a vital condition of its operation [4] [5] [6].

As an alternative to the monitoring system architectures presented above, we propose considering the ECG interpretation as a distributed computing task. The signal processing is partially performed by the remote recorder as far as the limitation of resources does not affect the diagnosis reliability. The data transmission is necessary in most cases, for the tiny data stream of results only, and occasionally for the whole unresolved records of which the interpretation is completed by the server software. Main novelty of this approach is the adaptive task sharing between the patient-side and the central devices. From the user viewpoint, the recorder software can be adjusted to the patient status, current diagnostic goals and transmission channel availability. The supervising server is not only receiving medical data at diverse processing stages (from raw signals to a full diagnostic outcome), but also is sending processing parameters or software libraries over the worldwide range bi-directional GPRS link.

The principle of the network operation is conceptually based on the following generalized rules of human relations often observed in cardiology:

– general practitioners interpret a wide range of easy records on they own, in case of doubts they ask experts for the interpretation,
– cardiology experts interpret more specialized, but also more difficult records, they often report their findings to general practitioners,
– repeating problems stimulate the growth of the general practitioners' knowledge supported by the experts findings and advice, consequently general practitioners are getting more specialized,
– the expert knowledge is based on the experience in the meaning of records successfully interpreted in the past; since patients look for the best diagnosis available, the

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growth of expertise increases the probability of future encountering of similar records.

Authors believe that during the history of medicine the interpersonal relations were created optimally. Now, in the era of artificial intelligence a significant improvement of diagnosis quality may be achieved by reproducing these relations in the network of co-operating computers [7].

II. Materials and Methods

Several problems of different nature had to be investigated before putting the proposed monitoring system idea into the practice. In following chapters we focus on main technical issues and present final solutions applied in the prototype.

A. The architecture of interpretive network

The star-shaped network is managed by a stationary central server receiving medical data and controlling several remote wearable recording devices (fig. 1). As data carrier the worldwide range bi-directional GPRS link is used, however the long-distance connections use the Internet in the background. In aspect of network architecture, three principles are specific for the adaptive interpretation:

– each remote recorder is serviced by a separate independent software thread running on the server,
– although running on a different platform, the server interpretation software is able to continue the ECG processing from the point where it was abandoned by the remote recorder,
– the server controls remote recorders in aspect of the available computation power and current interpretation abilities and manages the process of remote adaptation.

The adaptation of the ECG monitoring network size to the clients fluctuation may be achieved by the star scalability or by the multiplication of the basic structure.

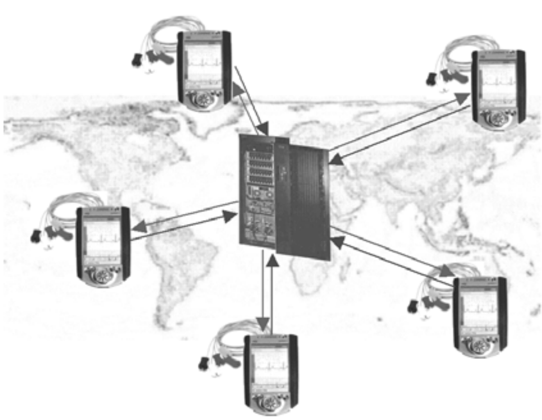

Fig. 1. The star-shaped architecture of adaptive ECG monitoring network

B. Features of interpretive wearable recorder

Wearable recorders are manufactured as low-cost general-purpose vital signs acquisition devices. From a technical viewpoint the recorder consists of a battery-operated computer and three principal peripherals: the signal digitizer, the communication module and the user interface. The hardware design assumes maximum of control and re-programmability by the software. The software is designed in two layers: a mandatory background and an optional overlay. The background contains basic common modules: data acquisition and wireless communication services as well as fundamental user interface procedures. The flexible overlay includes all 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 and the available computational power. This approach not only personalizes the remote recorder to the patient-specific signal features, but also gives an unprecedented flexibility required for a pertinent real-time reaction for unexpected events.

Following the relations between cardiologists, most common and frequent episodes are interpreted by the wearable device software and then issue 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 node software automatically, or even in very rare cases with the assistance of human expert (fig. 2). Two aspects of adaptability are particularly fitting in the human relations-based model of ECG monitoring network:

– processing adaptability,
– reporting adaptability.

Both of them are justified by the past diagnostic result, monitoring goals and patient-specific features.

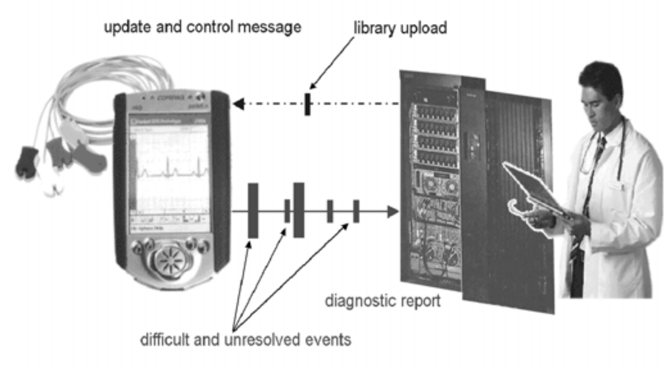

Fig. 2 Details on client-server information interchange

C. Processing adaptability

With the ECG processing adaptability the user is provided with the functionality of a patient-dedicated or task-dedicated device, although he or she uses a mass-produced recorder. Moreover, the recorder use or operation may be remotely altered in a wide range of functions as necessary for the optimal diagnosis [8]. The adaptability is achieved in two ways:

- by updating the processing parameters vector,
- by uploading and linking of complementary libraries of interpretation subroutines.

The processing parameters vector is applied immediately when received and alters the interpretive subroutines. This method is provided for adjustment of the interpretation process key properties to the patient-specific signal features. Consequently, alerts may be generated more appropriately and may not include persistent pathologies (e.g. atrial fibrillation).

The complementary libraries of interpretation subroutines are linked to the main processing chain in order to change the recorder's operation. Since the commutation may affect the signal processing already in progress, it is performed only at the edges of reporting epochs. New libraries complement the recorders interpretation ability and orient it towards a detailed investigation of specific disease. Therefore, this tool is useful for critical events or when the diagnostic goals change. Several constraints must be observed by the upload manager subroutine running on the server, because of the remote recorder's total computation power is limited and many procedures base on the results of others.

D. *Reporting adaptability*

Since the re-programmable overlay contains also report-formatting procedures [9], three diagnostic report aspects are subject of adjustment:

- report content,
- data priority,
- reporting interval time.

The data communication format contains mandatory data description fields and optional data containers of variable size. This solution increases the report flexibility and allows future extensions for various data types (e.g. patient communications, patient positioning coordinates etc.).

Other crucial issue is data priority in the report. The report of abnormal finding is a potential emergency message carrier and must be delivered as soon as possible. The overall network transmission delay is expected not to excess the time typical for bedside ECG recorders (2s). The report of normal finding may include supplementary data and larger delay is tolerable without affecting the diagnosis consistency.

The reporting interval is set by the central server accordingly to the patient status severity. The reporting is as rare as safe in case of a physiological record and the interval is shortened as abnormalities are detected. In emergency the continuous reporting may be programmed as well. The patient is provided with an event button and occasionally can also trigger a report. A short strip of signal directly preceding the event is available for the analysis and reporting from a circular memory buffer.

E. *Supervision and control of adaptability*

Two supervisory processes are necessary for optimal information management and task sharing. One of them aiming at diagnosis quality assessment is implemented as a part of each interpretive function running on the remote recorder. Each diagnostic result issued by the remote recorder is verified and the supervisory process decides what was reliably interpreted by the recorder and what is too difficult and needs further analysis by the server.

The second supervisory procedure is running on the server within each processing thread and manages the interpretive libraries for each co-operating remote recorder. This software analyses remote recorder errors, estimates the probability of events repetition and the available remote computational power in order to decide about an upload of a complementary interpretive library to the wearable device.

III. Results

The idea of human relation-based adaptive ECG monitoring network was prototyped in its main features. However, many new challenges for the cardiology open with the flexible interactive diagnostic link and many medical issues need the verification in diagnostic practice. The prototype uses a PDA computer (Hewlett-Packard) running the WindowsCE operation system selected for its programming facility and application-ready user interface. The ECG conditioning and digitizing module is connected through the USB interface and performs the 12-lead standard acquisition (frequency: 500Hz, accuracy: 10bits). The battery-operated module is certified to comply with national standards for patient safety and measurement accuracy by a manufacturer-independent internationally recognized laboratory. The transmission module is based on a S60 mobile phone (Siemens) connected through a Bluetooth interface. An alternative cable connection was also considered, but the wireless solution offers more flexibility for setting the distance of the GPRS transmitter from the biosignal acquisition module as necessary for interference-free operation.

The central server was a PC-standard computer connected to the Internet via 100Mbps Ethernet card. At the reported stage of experiment multithreading interpretation was not implemented, consequently the sever accessibility was limited to the single specified remote recorder.

The interpretation software source code was written in C++ programming language: beat detection, dominant rhythm recognition and the heart rate computation were the only interpretive subroutines included in the basic layer of the remote monitor software. All other procedures (e.g. arrhythmia detector, pacemaker assessment procedure, ST-segment and QT-segment analyses) were compiled as dynamically linked libraries (DLLs).

The interference immunity test was performed on five health volunteers in various life conditions (at rest, during physical exercise, during sleep) and the distant software reconfiguration was validated with use of an ECG simulator. All reconfiguration options were thoroughly tested with use of program tracing, dataflow measurement (fig. 3) and analysis of saved report contents (fig. 4).

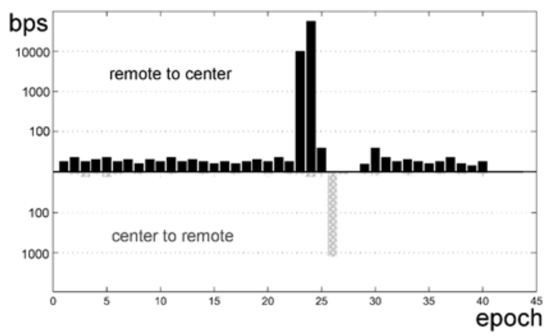

Fig. 3. The example client-server dataflow during the update of processing parameters vector

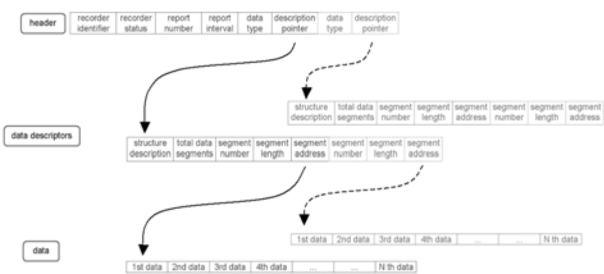

Fig. 4. The data communication format; mandatory fields are bordered by a solid line, optional fields are bordered by a dashed line

IV. Discussion and Final Remarks

The technology of distributed ECG interpretation is mastered in its principal points: distant recorder re-programmability, communication issues and network management. Focussing on technical problems required some medical aspects to be solved approximately. The example questions to answer in the further research are:

– the relationship of diagnostic result severity and the reporting frequency,
– the optimal diagnostic tests to be requested from the remote device in context of detected heart abnormality,
– the medical foundations for the remote update of interpretation library.

In the author's opinion, the main advantage of the human relations-based adaptive ECG monitoring network is the interactive adaptability achieved thanks to the use of bi-directional digital communication.

Certainly, some medical rules proposed as a result of our investigation of human experts relations and worldwide-approved standards need to be formalized as an algorithm. On the other hand, the flexibility of the diagnostic link not constrained by the time or distance is not fully realized and new application ideas will hopefully arise with the experience. The functional extensions include:

– acquisition and processing of other vital signs (e.g. breathing, pulsoxymetry, noninvasive blood pressure, electromyography),
– bi-directional messaging with the remote patient, automated or man-operated guidance on physical load, drugs intake, emergency control or pre-medical aid, etc.

Despite the limited implementation, the prototype testing confirmed the principal advantages of the distributed computing approach to the ECG interpretation. The remote device is able to interpret autonomously the custom-defined set of most frequent record types and only occasionally uses a high-bandwidth connection. In case of poor reliability of remote interpretation or any unexpected event, the report contains meta-data or the raw signal for unlimited automatic or human-assisted processing.

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