Content-Adaptive Signal and Data in Pervasive Cardiac Monitoring

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Abstract

Although the pervasive monitoring of patients at cardiac risk is widely recognized as a valuable tool, the content-dependent signal and data adaptability is rarely considered. Consequently the autonomy of wearable recorders is affected by the unnecessary computation and the wireless data carrier is wasted by the unwanted information. The thorough analysis of human ECG interpretation process and detailed studies of diagnostic procedures reveal that the adaptation of the perceptual strategy to the ECG content is an intuitive and common practice of cardiology experts. Considering human interpretation-derived directions we re-arranged a typical machine interpretation software to simulate the human reasoning. Several aspects of data are adjusted accordingly to the automatic rough estimate of the record contents: the interpretation process flow, the result priority, report content and frequency and the local sampling frequency of the ECG included.

1. Introduction

Remote heart diagnostic and surveillance of elderly people are currently widely spread thanks to the use of wearable computers [1] [2]. A long-term acquisition performed in sparsely populated area is a typical application for home-care ECG recorders. Two different approaches to the automatic signal interpretation assumes raw signal transmission or remote signal processing. First solution involves high cost of telecommunication service, while the other offers limited quality and reliability as a result of the compromise between computational power and energy consumption.

Our alternative approach postulates the interpretation process to be performed as a distributed computing task. From the user's viewpoint, main novelty consists in flexible adaptability of interpreting device software to the patient status, current diagnostic goals and transmission channel availability. The star-shaped network is managed by a central server node collecting medical data at diverse processing stages (from raw ECG signal to a full diagnostic outcome) and includes several remote wearable recording devices communicating over the bi-directional GPRS link of worldwide range.

The distributed computing means the processing is initiated in the remote device immediately after signal capture and continued as far as necessary and possible. The patient-specific adaptation of the remote interpretation procedure is achieved with use of specialized subroutines uploaded from the supervising node [3]. Technical limitations of the remote device are compensated by a complementary interpretation thread running on the server, distilling any ambiguous or unresolved records. The adaptation is locally controlled by the remote device procedure and additionally supervised by the monitoring server software with an optional human assistance in critical cases.

The adaptability of the distributed interpretation process involves the continuous and dynamic control of the task share and the data flow. Consequently, the signal and medical data reported by the remote recorder depend on many medical and technical circumstances including:

- diagnostic goal,
- current status of the subject,
- interpretation performance and reliability,
- environmental dependencies, etc.

The main aspects of dynamic update of recorders capability are discussed in [3] and the studies on structural rearrangement of the interpretive software targeted to a wearable device are presented in [4]. The proposed architecture considers estimated reliability and error propagation factors oriented towards the improvement of remote interpretation quality and data stream optimisation. The present paper highlights the concept and main details on the proposed adaptive report format.

The principle of task sharing is conceptually based on the generalized rules of human relations often observed in cardiology. Reproducing interpersonal relations, optimally created during the history of medicine, in a network of co-operating computers has a significant impact to the diagnosis quality. Following such relations, most common and frequent episodes are interpreted by the recorder 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 to be interpreted by the node software automatically, or even, in very rare cases, with the assistance of a human expert.

2. Methods

One of the consequences of interpretation programmability is the multitude of output signal formats ranging from raw electrocardiogram to the sparse data (e.g. heart rate). The modifiable transmission protocol is very useful for optimization of wireless channel use aiming at keeping the monitoring costs at the commonly acceptable level. As a general rule we propose the transmission of basic interpretation results for all monitoring time and more detailed reports for short time intervals. Occurrence or suspicion of any event, result in a more detailed report including up to the corresponding strip of raw signal. This approach was conceived as a result of cardiologist's behavior analysis, but it can be remotely programmed upon request.

The adaptability of the remote monitor goes far beyond the functional or economic aspects. Four issues were considered in a framework of content-adaptive signal and data format project:

- reporting frequency,
- report contents and data priority in a report,
- signal sampling variability,
- supervising of adaptability, including negotiation rules for the exchange of processing abilities for the report volume and reliability.

The reporting frequency is independently controlled by the server and by each of co-operating remote recorders. In typical cases, all reports are issued with the frequency computed remotely from the diagnostic data. Since the reporting interval value is included in the report, missing reports are easily detected by the server and recovered by a supplementary report request. For difficult signals, similar solution supports the report of unexpected cases. Since the remote recorder cannot interpret the signal, the complementary processing thread running on the server issues both: the interpretation and the report interval imposed to the remote device.

The continuous reporting is supervised by the server only, because in real time the remote recorder issues only basic diagnostic parameters (e.g. heart rate) accompanied by the raw signal, so the main interpretation is performed by the server thread. Figure 1 summarizes all modes of reporting frequency control.

From the signal-theory viewpoint, the frequency of patient status capture should fulfill the Shannon rule. The temporal variability significantly differs for particular diagnostic parameters and occurrence of critical values increases the variation expectancy. Thus the maximum time interval to the next measure point should be determined individually considering the past and present values for each parameter. Irregularly sampled data streams may be interpolated in case the mid-point samples need to be estimated.

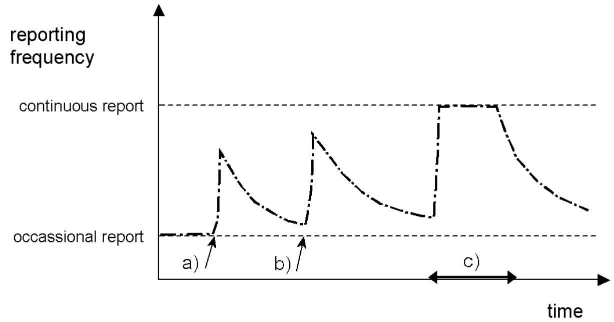

Fig. 1. Examples of reporting frequency control a) and b) – pathological ECG interpreted remotely, c) – unexpected event causing raw signal transmission and server-side interpretation.

During the ECG interpretation process, medical information is represented in various data forms: signals, diagnostic parameters and meta-data. The distributed architecture of interpretive software with adaptive task sharing involves the transmission of data at various processing stage. Consequently, the data communication format contains mandatory data description fields and optional data containers of variable size (fig. 2). 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 the 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.

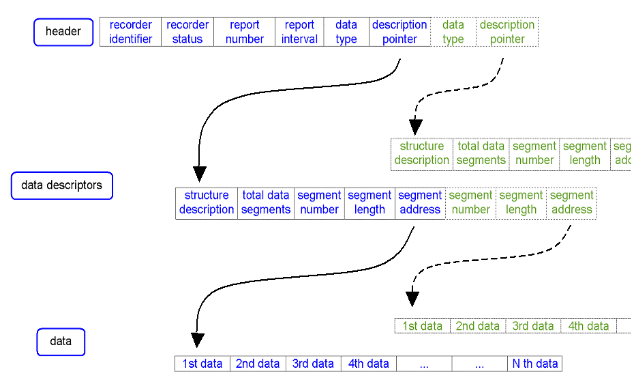

Figure 2. Data communication format; mandatory fields are bordered by the solid line, optional fields are bordered by the dashed line

The adaptive ECG signal sampling bases on the P, QRS and T-waves recognition, and is limited to the cases when the remote recorder recognizes the waves correctly, but fails in the further signal interpretation. The raw ECG signal is compressed before the transmission with use of the information on expected local bandwidth in particular sections representing the cardiac cycle. Thanks to the use of physiological background, the compression is expected to fully preserve the signal diagnostability, although the reconstructed data sequence is not bit-accurate (fig. 3) [5]. Technically writing, the signal is resampled to a non-uniform sequence with use of cubic splines. The time interval between samples and the cut-off frequency of the anti-aliasing filter strictly follow the local bandwidth of each section detected in the ECG.

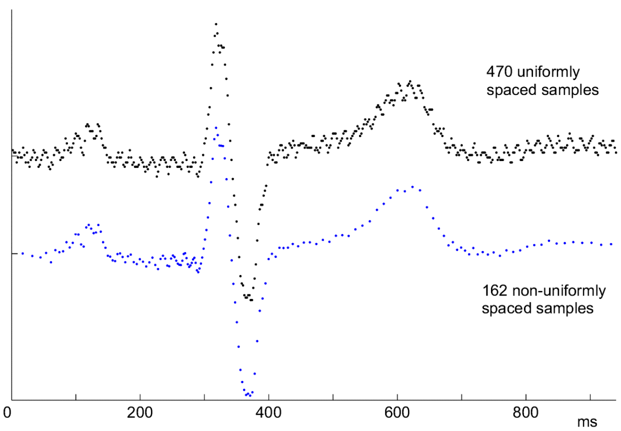

Figure 3. Comparing a heart beat in the regular and in the variable sampling rate signals

Three aspects of ECG reporting adaptability were implemented in a prototype client-server configuration using a PDA computer (Hewlett-Packard) running the WindowsCE operation system. The ECG conditioning and digitizing module is connected through the USB interface and performs the 12-lead standard acquisition (frequency: 500Hz, accuracy: 10bits). The transmission is based on an embedded mobile phone module with a GPRS connection to the internet. 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 specified remote recorder.

The interpretation software source code was written in C++ programming language. The interpretive software architecture must be re-designed for a complementary run on both platforms. The processing chain contains multiple exit and entry points at which the interpretation process may be transferred to the server.

3. Results

Except of soft customisation of the general-purpose low-cost device to the specific tasks in the particular patient status and diagnostic goal, the adaptability of the remote interpretive software has several measurable advantages over the fixed procedures being in use today. Two principal of them are:

- extending of the remote recorder autonomy achieved by avoiding all unnecessary computation and data transmission,
- reducing the costs of digital communication achieved by content-adaptive signal and data representation.

For the sake of concern with the information reliability and consistency, the data quality parameters and transmission delays were measured accordingly to the typical procedures [6].

All tests were performed on 58 artificial signals originating from looped normal CSE records with inserts of pathological CSE records. The inserts were made with regard to the corrected baseline points on each record. For the test integrity, signals of duration of 1-1.5 hour were reproduced by a multi-channel programmable generator conceived for the advanced tests of interpretive ECG recorders.

Comparing to the uniform regular reporting, our tests show data reduction ratio of 5.6 times in result of report content management. In some cases involving the raw signal transmission, additional data reduction of 3.1 times was achieved thanks to the non-uniform signal sampling. Furthermore, data reduction of 2.6 times is a result of irregular reporting with use of the prediction of diagnostic parameters variability.

By avoiding unnecessary computation and data transmission, the report content management also extends the remote recorder battery life in average by 65% comparing to the software of a standard architecture running on the same PDA.

All diagnostic data were reconstructed by the recipient using interpolation techniques and were found within the respective standard deviation accuracy limits. Regular report messages were delayed in the internet up to 20 s, while in case of abnormal finding message, the total delay falls below 1.3 s thanks to the priority attribute and a concise form.

4. Discussion and conclusions

Considering human interpretation-derived directions we re-arranged a typical machine interpretation software to simulate the human reasoning. Several aspects of the data are adjusted accordingly to the automatic rough estimate of the record contents: the interpretation process flow, the result priority, the report content and frequency and the local sampling frequency of the reported ECG strip.

The content-adaptive signal and data format has a considerable impact to the diagnostics quality due to the following features:

- the monitoring and auto-alerting parameters are adjustable to the patient-specific signal anytime during the recording,
- the reporting can follow any unexpected event and the interpretation is flexible enough to cover a variety of diagnostic goals changed or updated remotely.
- the reporting closely follows the medical practice of personal interactions optimized during the centuries of history of medicine

Additionally, the adaptive report may include audiovisual communication with the patient or his supervisors supporting the transmission of instructions necessary in case of technical troubles (e.g. electrode replacement), medical risk (e.g. physical overload), medication intake or remote modification of monitor's function.

The adaptive ECG formats may also be considered for other applications typical for the digital age:

- message optimisation and prioritising
- pre-selection of abnormalities – facilitating doctor's interpretation
- data fingerprinting – faster and more reliable management of databases

The most problematic issue is now the compatibility of the interpretive software designed for different platforms. The server-side thread optimisation is sacrificed to creating of multiple entry points where the interpretation could be taken up from the remote recorder. Consequently, the processing chain of server thread must follow the solution designed for its counterpart in a PDA.

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