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Design and evaluation of a wireless decision-support system for heart rate variability study in haemodialysis follow-up procedures

José García[a,*], *Jesús D. Trigo*[a], *Álvaro Alesanco*[a], *Pedro Serrano*[b], *Javier Mateo*[a], *Robert S.H. Istepanian*[c]

[a] *Communications Technologies Group (GTC), Aragón Institute of Engineering Research (I3A), University of Zaragoza, María de Luna 1, 50018 Zaragoza, Spain*

[b] *Department of Cardiology, University Hospital Lozano Blesa, Zaragoza, Spain*

[c] *Mobile Information and Network Technologies Centre, Faculty of Computing, Information Systems and Mathematics, Kingston University, London KT1 2EE, UK*

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ABSTRACT

In this paper a new wireless decision-support system for haemodialysis patients using heart rate variability (HRV) is presented. The telemedicine system provides connectivity to three participant sites: the general practitioner or nurse at the point of care in the dialysis unit, the remote information and processing server and the cardiologist. At the clinical point of care, the nurse acquires the electrocardiogram (ECG) by using a tailored mobile telecardiology system as well as other relevant physiological information during the clinical procedure, and sends it to the information server. The received information is stored in a secure file server, linked to the patient database and the ECG signal is automatically analyzed by using advanced signal processing tools in the processing server, where a complete clinical results report is generated. The cardiologist can then be linked by means of a web browser to the information server to analyze these results for further clinical diagnosis support. The system has been applied to study HRV in patients undergoing haemodialysis. The clinical report consisted of trends for time- and frequency-domain HRV indexes and other supplementary information automatically calculated, which show the response of the electrical activity of the heart to the dialysis process and that can be helpful for the follow-up of these patients. The telecardiology framework has been successfully evaluated both by the patients and the hospital personnel showing a high compliance with the system. The design and implementation of the telecardiology system have followed the most recent advances in web technologies, biomedical information and storage standards and signal processing techniques. The presented system can be used as a telemedicine tool for clinical diagnosis support and could also be used in other clinical settings.

* *Corresponding author*. Tel.: +34 976761962; fax: +34 976762111.
E-mail address: jogarmo@unizar.es (J. García).

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1. Introduction

Mobile health (m-Health) is an emerging area of telemedicine in which the recent development in mobile networks and telemedicine applications converge. This convergence of information and telecommunication infrastructures around telemedicine and mobile telecare systems is fostering a diversity of cost effective and efficient mobile applications. A comprehensive review of wireless telemedicine applications and the most recent advances on m-Health systems are presented elsewhere [1–3].

It is also well known that heart rate variability (HRV) is a measure of variations in the heart rate, which has been widely studied in cardiac diagnosis. The HRV is determined by analyzing the time series of beat-to-beat intervals from electrocardiogram (ECG). Different measures of heart rate variability have been proposed, which can be roughly subdivided into time- and frequency-domain [4]. HRV has been regarded as an indicator of the activity of autonomic regulation of circulatory function, and alteration (mostly reduction) of HRV has been reported to be associated with various pathologic conditions like hypertension, hemorrhagic shock, etc. HRV has been also considered as a predictor of mortality after an acute myocardial infarction.

Previous work pointed out the relationship between dialysis and heart rate variability (HRV), which may have prognostic value in haemodialysis patients identifying an increased risk for sudden death [5,6]. The low frequency–high frequency ratio has been found to be the most influential HRV determinant of death and could help to identify patients at risk in one of these studies [7]. These works used a reduced set of HRV indices, some analyzing only time indices [6] and others considering frequency indices [5,7]. These preliminary findings make it reasonable to promote further studies about the relation between dialysis and HRV.

Computer-based analysis of the ECG and HRV studies has been used during the last decades with significant success. Recently, innovative signal processing techniques have been developed by means of joint efforts of engineers and physicians, resulting in powerful tools used for ECG-based clinical decision support [4]. On this research field our group has experience in the proposal of new indices which can extract more information or present a faster response than others conventionally derived from the ECG signal [8–10]. The new signal processing techniques developed by different research groups around the world are sometimes available to medical users through Internet servers where the processing tools can be downloaded to be further compiled in the client and applied in an off-line mode to the acquired ECGs [11,12]. And more recently ECG signal processing servers have been used in an on-line mode by means of a connection from a web browser, thus providing support remotely to the diagnosis and without need of software packages installation in the local computers [13,14]. These telemedicine processing servers can be very appropriate in this context since the medical user only needs to use a web browser, and specifically in the area of dialysis due to a common session usually takes more than 4 h thus making it not possible to manually analyze the recorded ECG signals.

The aim of this work was to design and implement a wireless decision-support system in the area of telecardiology follow-up procedures and to evaluate it during the study of HRV changes in patients undergoing haemodialysis. The design and implementation of the proposed framework have been carried out following the most innovative web technologies, ECG storage standards and HRV signal processing techniques, and the system has been evaluated from both patients and clinicians perspectives. The paper is organized as follows: first, the telemedicine system is presented, and how it was used in the HRV follow-up. Then, the evaluation of the system by different users along the study is shown. Finally, the main conclusions of this work are presented.

2. Wireless HRV telemedicine system

The telemedicine system consists of three operational subsystems (see Fig. 1). This include the general practitioner or nurse at the point of care who acquires the ECG signal during the clinical procedure; the remote information server where the ECGs are received, processed and stored; the cardiology specialist who analyzes the results to provide a diagnosis.

2.1. *Wireless ECG acquisition system*

The ECG signal is acquired using a small portable signal recording unit (gMOBIlab by gTEC, Graz, Austria). The mobile biosignal amplifier provides a two-channel ECG recorder, each channel sampled with 1024 Hz and 16 bits per sample. The biosignal amplifier is connected to a personal digital assistant (PDA) equipped with a wireless local area network (WLAN) card and 640×480 pixels screen resolution. Different software applications have been developed and installed on the PDA. ECGs can be recorded and stored following the SCP_ECG standard directly on the PDA. An ECG viewer was developed to visualize the signals on the PDA during acquisition or after recording (see Fig. 2). Additionally the PDA includes a mobile web client in order to provide access to the information server to send the signals and to introduce relevant patient data or events during recording (see a sample of the mobile web client screen as shown in Fig. 2). The data collected at the point of care can be securely sent either through a wireless connection to the information server using the WLAN in the hospital or through a third generation (3G) mobile network in case when there was no access to the wireless hospital network at the point of care. If a 3G network is used, then the ECG will be automatically sent after applying ECG compression techniques installed in the PDA (that guarantee the clinical quality of the received signals) to optimize the available bandwidth (much smaller than in a WLAN) and transmission efficiency [15].

2.2. *Information server*

The acquired clinical data is received by the information server, which consists of several modules including the web server (based on Apache Tomcat), the patient database (developed in MySQL), the processing server (based on Matlab) and the file server. The server is located inside the hospital net-

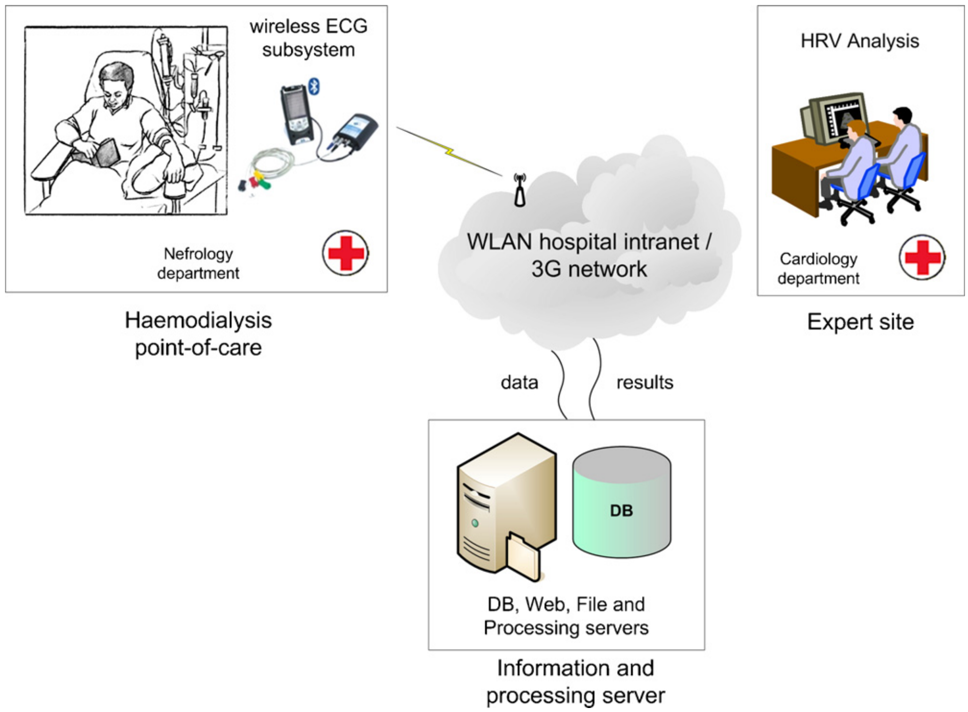

Fig. 1 – HRV-based wireless telecardiology system.

work. The web server was designed using the most advanced web technologies including Struts that enables to separate the application logic from the presentation and the processing of petitions, which is very useful in the design of large and scalable projects. Besides, it facilitates the personalization of the connections and thus it permits secure access from web browsers both at the point of care (using a PDA to send the collected information, see Fig. 2) and in the cardiology expert site (PC to access to the results, see Fig. 3). The information transmitted is stored on the file server and linked to the patient database, which is a standardized database designed jointly with the cardiology department. The corresponding entity-relationship (ER) diagram is shown in Fig. 4. The main entities of the database (physician, patient, assistance, test) and their relation (is_responsible_of, undergoes, does, includes) are shown, as well as the main attributes of each entity. This summarized ER diagram illustrates the specific part of the database dedicated to dialysis, and these fields have been integrated in a larger and more complete cardiology database. A sample of the specific information included in the database that is needed in a HRV analysis during dialysis assistance can be seen in Table 1. This table shows the expanded attributes of the entity assistance.

Once the ECGs arrive to the server, they are automatically processed using the advanced signal processing techniques available in the processing server and, then, a result report is generated. Several connections were set up between the different modules of the system as shown in Fig. 5. The con-

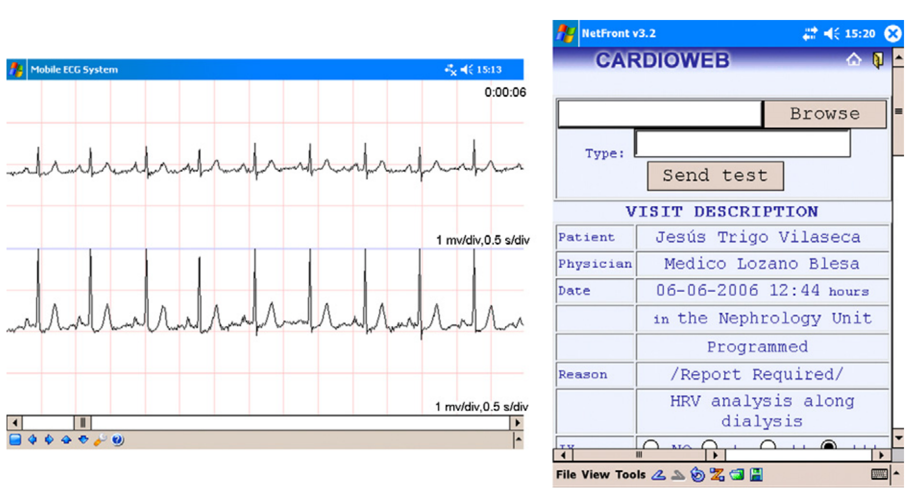

Fig. 2 – Sample of ECG signals viewer and web access to the database (PDA-based platform).

Fig. 3 – Sample of system's web database (access from a PC-based platform).

nection between Java (web server) and Matlab (processing server) has been established by means of Matlab server pages (MSP) [16] which enables the development of technical web pages using extended HTML tags. Java shares some data with Matlab extracted from the database (e.g. patient information), whilst the whole core intelligence for signal processing is programmed in Matlab. When the processing procedure ends up, the database is updated with the results generated by Matlab. To achieve this goal a Matlab interface to MySQL server [17] has been used, which makes it possible for the modification of database fields in a Matlab environment. Integrated with Struts, two useful frameworks have been installed: Dimensions and Tiles. Dimensions are a framework which enables to build Struts applications whose aspect is modified accord-

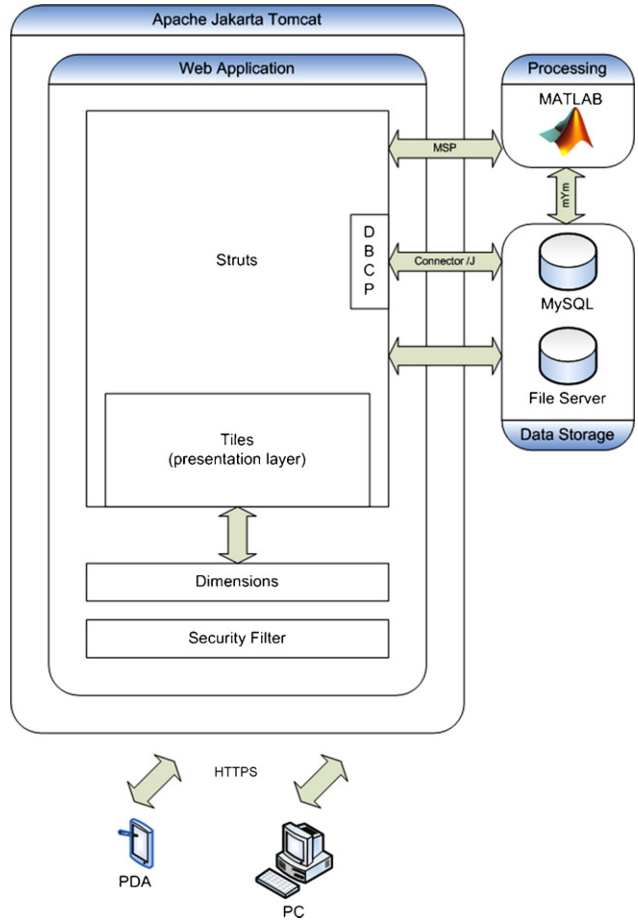

Fig. 5 – Software/database structure of the system.

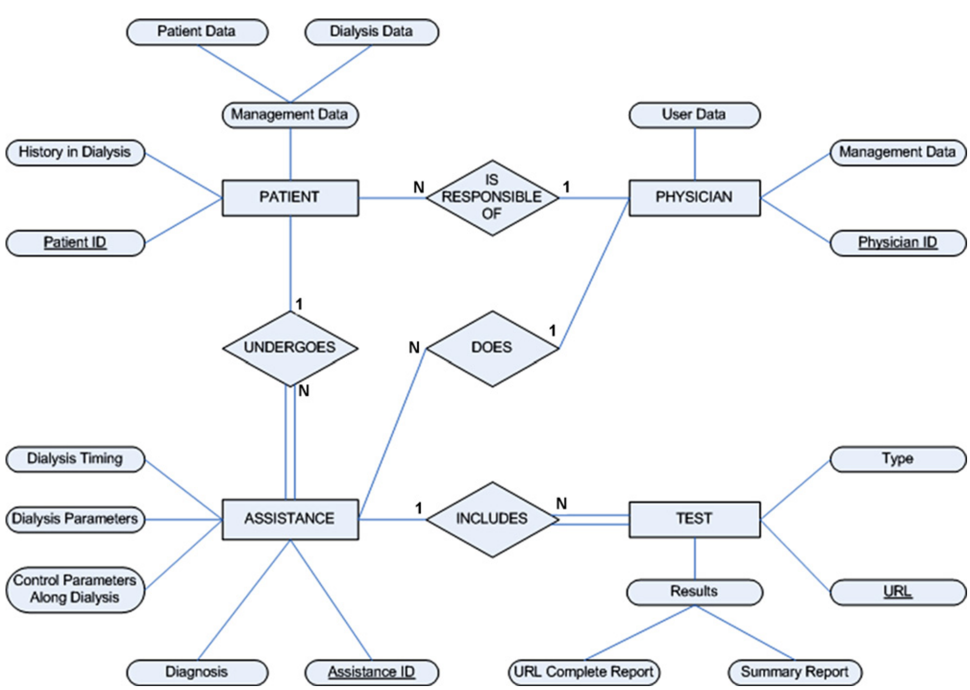

Fig. 4 – Summarized database entity-relationship (ER) diagram.

Table 1 – Dialysis assistance data

Time data	Date of accomplishment Time of registration start/finish Time of dialysis start/finish	
Fixed parameters	Flow (cm^3/min) U.F. (ml/h) C.U.F. (ml/h) Dialyzer Heparin	
Variable parameters along dialysis	Start, each hour and end	°C Beats per minute Ta
	Pre- and post-dialysis	Weight Control variables
Diagnosis and incidences	Dizziness Incidences Treatment	

ing to different criteria but without modifying the business logic. In summary, Dimensions acts as a decider, evaluating what type of client has connected, such as type of user (normal, administrator, etc.), type of device (PC, PDA, etc.) and serving the appropriate pages in consequence. On the other hand, Tiles is a presentation technology used to build pages from smaller JSP pages. It reduces the amount of source code necessary to be written because of the intelligent re-use of the repeated elements and moreover it can take advantage of the framework Dimensions, so as to serve different pages according to the user/device connected.

The processing server comprises signal processing and analysis techniques that include from basic tools such as e.g. beat detection to more complexes like the estimation of HRV frequency-based indices used for clinical decision support. The first step is once the ECG file has been received in the server is the application of a basic pre-processing of the signal. It includes ECG baseline wandering removal, QRS complex detection and identification and rejection of abnormal beats. A cubic spline interpolation is applied to fill the estimated potential gaps between beats location. The QRS fiducial points are further used to estimate the RR intervals and other HRV time-based indices: mean heart rate (mHR), standard deviation of the normal-to-normal (NN) QRS intervals (SDNN), root mean square of successive NN differences (RMSSD), percentage of intervals larger than 50 ms respect to the total (pNN50). For the HRV frequency-based indices, the power spectral density (PSD) of HRV is estimated from the linearly detrended and interpolated heart timing signal resampled at 2 Hz, reducing the effect of ectopic beats [9]. HRV frequency-based indices are defined as the spectral power in the following frequency bands: very low frequency (VLF, 0–0.04 Hz), low frequency (LF, 0.04–0.15 Hz) and high frequency (HF, 0.15–0.4 Hz). Finally, the processing server generates a summary results report (stored directly on the database) based on graphics and trends which is available for a quick consultation of the cardiologist (an example of a summary results report is shown in Fig. 6), and a complete results report with more detailed information of the analysis, which is stored in the file server together with the recorded ECG and linked to the patients' database.

2.3. *The cardiology specialist site*

In the expert site, the cardiologist is automatically informed via email of the clinical results. Specific web pages including the dialysis patients' fields described before and connected to the database were implemented for this purpose. A sample of these dialysis web pages are shown in Fig. 3. Thus, the specialist can access to the results produced by the processing tools and visually check in his computer and/or in his PDA for the complete ECG signals (using the corresponding ECG viewers designed for the PC and PDA platforms, respectively). The PC-based viewer is similar to the presented for the PDA but with enhanced options. With the results provided by the processing server the specialist has additional information which can be helpful in the clinical decision, to stratify patients at risk, for research purposes or during follow-up studies.

3. HRV follow-up during haemodialysis

The wireless telecardiology system has been successfully applied and evaluated in preliminary clinical trials to study HRV for patients undergoing haemodialysis in the University Hospital "Lozano Blesa" of Zaragoza (Spain). A total of 31 patients (12 females) were asked to participate in the study. One of them rejected to be included and six patients were discarded. Only permanent pacemaker carrier patients and patients with auricular fibrillation or auricular flutter, i.e., those who were not at sinusal rhythm during the complete ECG registration were excluded. Patients with diabetes or isquemic cardiopathy were not excluded but considered so as to find potential relations with the results of ECG processing. Finally, 24 patients were recruited for the project. The data of the population are summarized in Table 2. The protocol to study HRV during dialysis has been followed during 2 months in this preliminary study. Two general practitioners were in charge of the dialysis and one cardiologist was responsible for the HRV follow-up procedure. The ECG was recorded from 10 min prior to dialysis until 10 min after it is in order to compare indexes during and out of the dialysis process. The average ECG acquisition time was 4 h 19 min ± 11 min and the average ECG file size was 60.7 MB. The WLAN of the hospital was used to transfer ECG files in store-and-forward mode from the dialysis unit to the information server.

The clinical setup of the system at the point of care is shown in Fig. 7. It shows the ECG acquisition in the dialysis unit during a common session. The ECG portable device and

Table 2 – Patients group

Number of patients (female)	24 (10 f)
Age (mean ± S.D., median [range])	62 ± 13.86, 65 [30–81] years
Time on dialysis (mean ± S.D., median [range])	35.44 ± 35.94, 14.5 [4–108] months
Diabetic	3 (0 f)
Isquemic cardiopathy	4 (1 f)

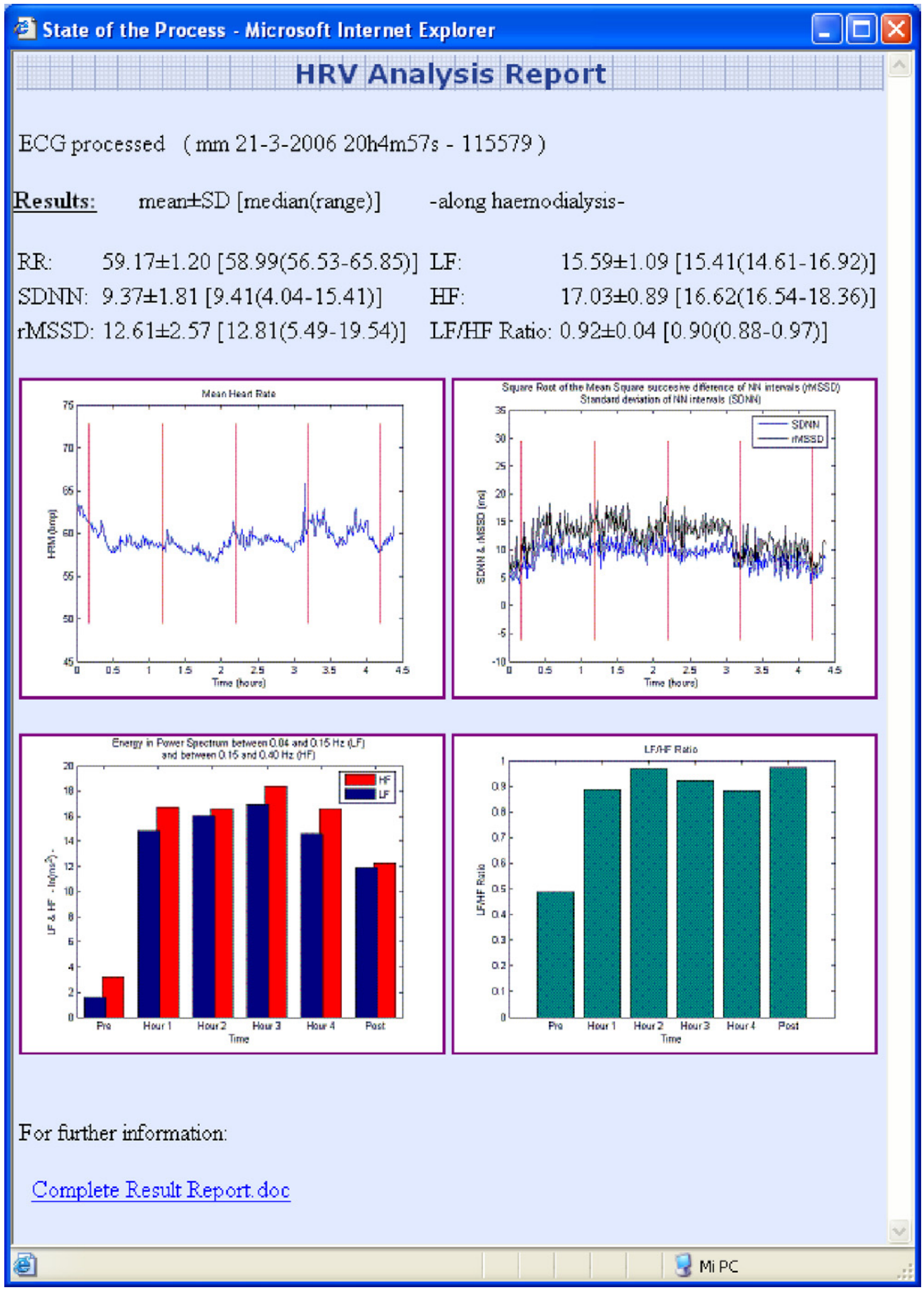

Fig. 6 – Example of HRV results in the summary report.

the PDA are placed on the tray. The nurse in charge of the dialysis unit was responsible of placing the ECG electrodes and of the correct use of the system. The evaluation of the usability of the telecardiology system by the personnel and the patients is presented later on this paper.

The most relevant HRV indices were automatically calculated including [8]:

- Time-domain HRV indices: number of normal beats (NN), number of ectopic beats (NE), mHR, SDNN, rMSSD and pNN50.
- Frequency-domain HRV indices: PSD of HRV on the different bands LF, HF and their ratio.

The system provides the cardiologist with HRV results in different formats as presented in Fig. 6. As it is shown time and frequency HRV indices are included in these summary reports, showing variations along the complete dialysis process. Average values for the different indices before and during dialysis are also presented. A link to the complete results file can be also found on this page. The complete report is stored in the file server and available in case the cardiologist needs to use more information than the included in the summary

Fig. 7 – Wireless telemedicine setup in the haemodialysis unit (the mobile ECG acquisition device and PDA are on the tray).

report. Moreover, statistical tools are included on the server to produce statistics from the study group. Therefore, the cardiologist has at his disposal a complete set of available tools to use in the follow-up procedure (ECG viewers, trends obtained from the processing tools, statistics, etc.).

The HRV indices estimated in the study group showed different pattern of changes during the dialysis sessions. An estimation of the changes induced in the different HRV indices by dialysis was automatically calculated for each patient at every interval of the dialysis session related to the period of control (pre-dialysis period). The formula used to estimate the changes was

$$C = \frac{|V_i - V_0|}{V_0}$$

being V_0 the parameter of reference (the mean of the corresponding HRV index values during control period) and V_i the mean of the HRV index values at each hour of the dialysis session and the post-dialysis period. This estimation relates each HRV index value with the control period and provides a normalized factor. Most of these indices did not reflect significant variations during the dialysis process. For example, the variations of the mean of HRM (mHR) during haemodialysis compared to pre- and post-dialysis periods were non-significant, as can be seen in Fig. 8, where the largest values did not exceed the 0.25 threshold. Main changes, when observed, were found along the first interval of the session. From the preliminary results 4 out of the 24 patients (17%) showed changes that could be considered as clinically significant respect to the control period. The most relevant changes were found on the following indices: SDNN, rMSSD, LF and HF. For instance, as it is shown in Fig. 9, changes above a threshold of 1 in the normalized factor of rMSSD can be observed in 4 out of the 24 patients, which means that the rMSSD HRV index became twice the control period value. These HRV changes may permit to stratify patients at risk by selecting those who present significant variations in order to be closely followed by doctors.

4. Evaluation of the telemedicine system

The first step when evaluating projects or technologies consist on precise formulation of the objectives that this evaluation pursues [18]. Normally, two grand objectives are defined: general and specific. General objective describes the main, generic or widest purpose of evaluation (such as assessing a telemedicine project implementation) and specific one, which describes the particular aims that intend to be achieved with the evaluation (e.g. determine whether or not the designed tool is useful for clinical decision). Patients were asked only about general issues meanwhile clinicians about both types.

4.1. *Evaluation of the wireless telecardiology system by the patients*

Before their participation, all the patients involved in the study were informed on the project and signed a written informed consent. After their participation they were asked to

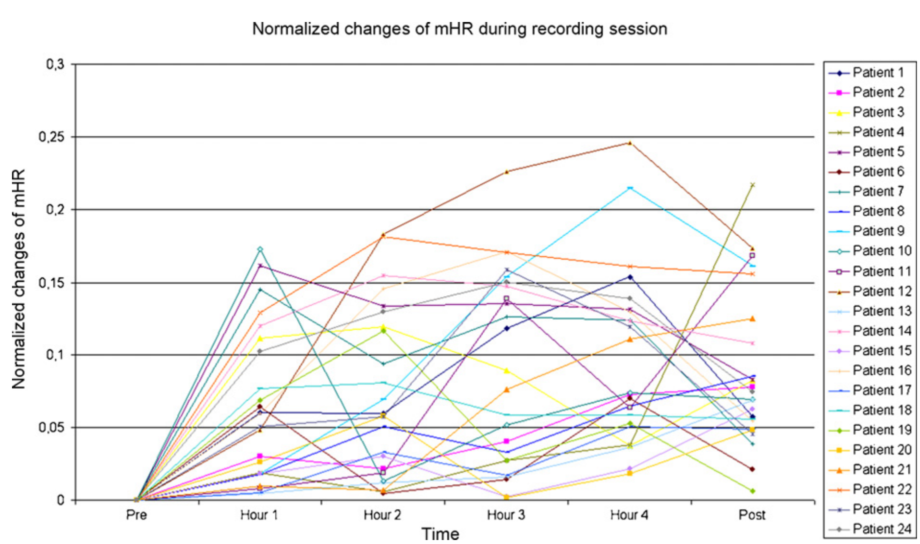

Fig. 8 – Normalized changes of mHR during dialysis session.

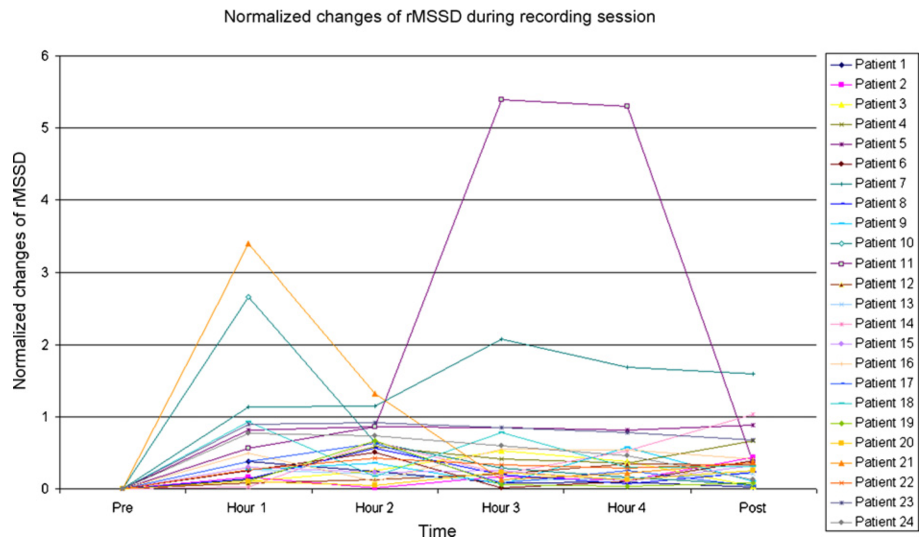

Fig. 9 – Normalized changes of rMSSD during dialysis session.

fulfill a short questionnaire to obtain their general evaluation and acceptability of the system (see Table 3). The questions were related to the clarity of information given about the project, comfort during session and improvement in the attention by using this system. Table 3 shows a summary of the patient evaluation indicating that more than 90% of them answered positively to the cardiology system. Among those who disapproved the system, the sensations were from indifference to unwillingness, showing a skeptical or reluctant attitude.

4.2. *Evaluation of the telemedicine system by the clinicians*

The telemedicine system was also evaluated by the cardiologist and the nurses involved in this study and they were also requested to complete a questionnaire. Four main issues of the system were analyzed: general evaluation, technical quality, impact over the personnel and impact over the patients (see Table 4). A subjective opinion of the system use including general comments about the experience was also required. Two nurses were involved in the study and fulfilled the questionnaire in complete agreement (time and percentage values are expressed as average between both). The hospital personnel valued positively the system, emphasizing its technical quality and usability. They accepted the necessary changes without complaints, observed and assessed the reactions of the patients undergoing the HRV analysis. The cardiologist also highlighted the possibilities of such kind of telemedicine systems for use in other follow-up studies and research activities such as e.g. to analyze the effects of different treatments on the HRV or over the ECG waveforms, etc.

Table 3 – Evaluation by the patients

Question	Yes	No
Clarity of provided project information	24	0
Did you feel comfortable during sessions?	22	2
Do you consider you are better attended?	21	3

5. Discussion

With respect to transmission issues, long duration ECGs did not constitute a problem since the system operated in this scenario in store-and-forward mode and moreover it made

Table 4 – Evaluation by the clinicians

General evaluation	Yes	No
Opportunity of the project to specific needs	√	
It is easy to use?	√	
It is intuitive?	√	
Would you use the system in future?	√	
Technical quality		
Technical characteristics present enough quality to permit diagnosis, treatment, etc.?	√	
Technical problems in the system?	√	
Frequency of failures	5%	
Impact over the personnel		
Need of organizational changes to introduce the telecardiology system in the dialysis routine?	√	
Were these changes well accepted?	√	
Additional time due to the use of the telecardiology system during dialysis	25 ± 7 min	
Impact over the patients		
Reaction of the patient to the use of the system	Calmness	
Could be associated with the use of the system any differences regarding patient satisfaction, anxiety, care, acceptation, etc.?		√
Were patients worried about attention responsibility, data confidentiality, etc.?		√

use of the hospital WLAN. As it was noted before, in a real-time operation or in scenarios using, e.g. a 2.5G/3G mobile network between the point of care and the information server, the PDA incorporates real-time ECG compression techniques which are automatically applied before transmission to optimize the bandwidth use and cost. The transmission of ECG signals and other clinical information was done applying security protocols, and the use in this study of the securized hospital intranet further reduced the risk of external attacks.

One of the main advantages of using a processing server of biomedical signals in a remote way is that the cardiology experts can obtain from the telemedicine system standard and new indices automatically estimated along the complete sessions. Some of these new indices and methods included in the presented processing server have been recently developed in our group, such as e.g. the PSD estimation of the HRV by means of the heart timing signal, which permits to derive the HRV frequency-based indices in a more precise way and more robust to the presence of ectopic beats than using other methods in the literature [9]. The cardiologists become users of the system but do not need to be specialist on signal processing techniques. The computerized processing tools permit to analyze the long ECG signals involved otherwise it would not be possible. The experts have also the possibility to visually check any excerpt of the ECG signals recorded during the complete procedure to detect cardiac events.

Since the general system has been designed as a wireless m-Health framework, several advantages appear as opposed to the traditional systems, such as wide range coverage or quick diagnosis support. Although the wireless system is not strictly needed in the particular case of HRV analysis, it nevertheless facilitates the clinical procedure. In other clinical settings, on where this framework could be applied, the wireless connectivity becomes more useful as it would happen for example in rural environments, where the offered 2.5G/3G mobile connectivity could be very practical. The fact of using a wireless system also increases the usability and acceptability of the doctors and nurses.

Regarding the specific application of the system in the analysis of HRV in haemodialysis follow-up procedures, preliminary results have shown different patterns of HRV changes during dialysis and some of these variations could be considered as clinically significant by the cardiology specialist. The identification of relevant HRV changes have permitted to select patients (around 17% in this study) that should be closer followed-up by the cardiology expert, that would have been missed without the use of the telemedicine system.

The evaluation results of the telemedicine system by both the patients and the clinicians indicated a very good acceptance of the telemedicine decision-support system in this preliminary study. The patients answered that they felt comfortable with the use of the ECG acquisition procedure and better attended when being monitored during dialysis. From the nurses and cardiologist point of view, the system can be very helpful for clinical diagnosis support and subsequently to provide a better attention to the patients. The 5% failure indicated in the questionnaire of clinicians was due to the lack of battery power either in the PDA or the ECG acquirer (because of forgetting to charge the devices) or connectivity problems (e.g. too much distance to the wireless access point, server temporarily not available, etc.). Besides, the use of the wireless acquisition system by the nurses required an extra time added to the dialysis sessions, which was reduced after a few days of recording once they became familiar with the use of the system.

6. Conclusions

A new wireless telecardiology system for heart rate variability analysis in haemodialysis follow-up procedures has been presented. The system comprises of three main subsystems: the general practitioner who acquires the ECG signal in the dialysis unit, the remote information server where the ECGs are received and processed, and the cardiology specialist who analyzes the results in the follow-up procedure.

The proposed telemedicine system permits specialists to explore aspects of the cardiovascular system difficult to study without the support of information technologies considering that very long ECG signals are recorded during a dialysis session. The telemedicine system has been designed using the most recent web technologies, ECG storage standards and signal processing techniques, and has been successfully applied for HRV follow-up procedures, but it may be also useful for other varied studies in the area of cardiology.

Acknowledgments

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