A Smartphone Based Telemedicine System for Recording Limited Lead Body Surface Potential Maps

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Abstract

In this paper we describe the development of a limited lead BSPM system which is based around a commercial 12-lead ECG acquisition unit and a smartphone. We repositioned the six precordial leads to allow for better information capture and hence more accurate reconstruction of BSPMs. The new lead positions were chosen using a data mining based lead selection algorithm. We developed two specific lead sets, one optimized for QRS monitoring and one optimized for ST segment monitoring. The 12-lead ECG device used is a commercially available system which is designed to capture the 12-lead ECG and transmit it via Bluetooth to a standard personal computer. The personal computer can then be used to store, display or print the recorded ECG. For our purpose we have replaced the personal computer with a Microsoft Windows Mobile based smartphone. To achieve this, software has been developed which allows the smartphone to capture the information from the 12-lead ECG device and store it on a removable solid state memory card. The software was developed using Visual Basic .NET and is designed to run on any device supporting the .NET Compact Framework. Further work is required to refine the developed software to support enhanced visualization and storage of the recorded data.

1. Introduction

One of the most widely used ECG recording formats is the 12-lead ECG. A 12-lead ECG is made up of six signals recorded from the limbs and six signals recorded from the precordium. Body surface potential maps (BSPMs) are also made up of six signals recorded form the limbs, however, a greater number of torso electrodes are also used. In some cases as many as 200 electrodes are used sampling information from the entire surface of the torso [1]. This increased spatial sampling has the potential to capture information that is not present on the regions of the body sampled by the 12-lead ECG. However, the large number of electrodes used makes BSPMs a cumbersome tool to use in routine clinical practice.

An approach that streamlines the process of BSPM acquisition is to record information from a reduced number of recording sites and estimate the information at sites that have not been recorded [2]. One of the first studies promoting this approach, often referred to as 'limited lead' BSPMs, recorded information from 32 sites and subsequently estimated information at a further 160 sites [3]. Predetermined transformation coefficients were used to make the estimation. More recently, a system which records information from just six torso sites has been reported [4,5]. This system uses transformation coefficients to estimate the information at a further 186 recording sites.

In all limited lead mapping systems the accuracy of the estimated information relies on two factors. Firstly, the recorded leads must be carefully chosen to capture information that most accurately estimates the remaining leads. Several strategies have been proposed for selecting leads for limited lead BSPMs [6-8]. Secondly, a suitable set of transformation coefficients, which allow estimation of the missing leads, must be determined. Statistical and deterministic methods have been proposed to derive these coefficients [9].

This article describes the development of a system which uses six chest leads and standard limb leads to record limited lead BSPMs.

2. Methods

The limited lead BSPM system developed in this study is based around a portable Bluetooth 12-lead ECG monitor and a smartphone. The monitor is designed to record information from the six precordial lead electrodes and four limb lead electrodes and produce the standard 12-lead ECG. In this study the positions of the precordial lead electrodes have been altered to allow accurate reconstruction of the BSPMs. The following Sections describe the choice of recording sites along with the technical development of the system.

Lead Selection

A lead selection algorithm was used to find the six recording sites on the torso that were most suitable for reconstructing BSPMs. The lead selection algorithm is based on a forward selection technique and finds the combination of recording sites that allow the most accurate estimation of BSPM patterns. Description of the algorithm is beyond the scope of the current study. Its operation has been previously described in [8].

The algorithm was applied to a set of existing BSPMs. The BSPM recording process is described in [10]. The dataset consisted of 744 recordings taken from 229 normal subjects, 278 MI subjects and 237 subjects with LVH. Each BSPM recording consisted of 117 leads. A schematic of the 117 lead electrode array is illustrated in Figure 1. The six leads chosen by the selection algorithm were a subset of the 117 leads. The lead selection algorithm was applied to 559 of the BSPM recordings. The remaining 185 BSPMs were used for subsequent evaluation of the chosen leads.

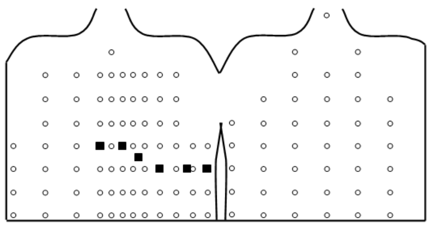


Figure 1. Electrode layout of BSPMs used during lead selection. Circles indicate positions of 117 leads. Shaded squares indicate positions of standard precordial leads.

The selection process was conducted twice to yield the six recording sites on the torso that most accurately estimated the BSPMs during the QRS complex and the six recording sites on the torso that most accurately estimated the BSPMs during the STT. For the sake of practicality the selection process was constrained to only choose recording sites on the anterior of the torso. In a further bid to promote practicality and to allow consistent placement of recording electrodes a clinical physiologist reviewed the positions of the recording sites chosen by the selection algorithm and, where possible, suggested slight amendments in favor of good anatomical landmarks.

After the leads were selected using the 559 BSPMs their performance in reconstructing the remaining 185 BSPMs was evaluated. RMS voltage error (RMSE) was used to compare each reconstructed BSPM frame with the actual, recorded, BSPM frame. This resulted in an RMSE value for each individual BSPM frame. The median RMSE was then calculated for each of the 185 subjects. An overall measure of RMSE was determined by calculating the median across all 185 subjects. Correlation coefficient was also used to assess performance. This measure was used to determine the reconstruction accuracy of each individual lead (as opposed to each BSPM frame). This resulted in 117 correlation coefficient values across all subjects. As a performance benchmark BSPMs were reconstructed from the standard 12-lead ECG and compared using the above metrics.

Telemedicine system

The telemedicine system is based around the BT12 12-lead ECG monitor commercially available from Corscience GmbH [11] along with a TYTN II smartphone developed by HTC Corporation [12].

The BT12 monitor is illustrated in Figure 2. This device consists of a unit measuring approximately 6mm x 24mm x 25mm. This unit houses the necessary circuitry for recording and transmission of the ECG, two AA batteries and an LCD display. Attached to this unit are ten cables that facilitate the recording of channels II, III, V1, V2, V3, V4, V5, V6 of the 12-lead ECG. These cables can be attached to standard ECG electrodes. The BT12 monitor is capable of sampling at a rate of up to 500 Hz. Sampled data are not stored on the device but rather are transmitted to a PC workstation via Bluetooth. The PC workstation requires additional software to communicate with the BT12 monitor. In the current study custom software, 'smartphoneECG', was developed to enable the BT12 device to communicate with the smartphone.

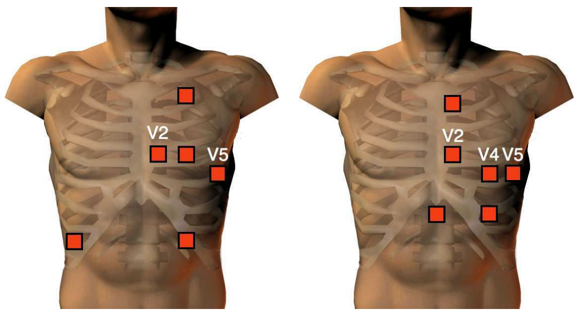
Figure 2. BT12 12-lead ECG recorder [11].

The TYTN II has standard smartphone features that include a large display/touchscreen (71 mm), full QWERTY keyboard, microSD memory slot, Bluetooth and Wi-Fi. It uses Microsoft Windows Mobile 6.1 Professional operating system and supports the .NET Compact Framework 2.0 [13]. The smartphoneECG software was developed using the Visual Basic .net 2008 programming language. The .NET Compact Framework's serialport class was used to allow access to a virtual serial port on the TYTN II smartphone. This virtual serial port was created using the serial port profile of the TYTN II's Bluetooth interface, with which the BT12 device had been paired.

3. Results

Lead Selection

The positions of the top six recording sites, optimized for the QRS and the STT, are illustrated in Figure 3. It can be seen that, for both the QRS and STT, most of the chosen leads are on the left side of the anterior torso. This is with the exception of the QRS leads where one lead is located on the right anterior side. In both lead systems a number of standard precordial leads were selected. i.e. for the QRS leads V2 and V5 were retained, and, for the STT leads, V2, V4, and V5 were retained.



(a) (b)

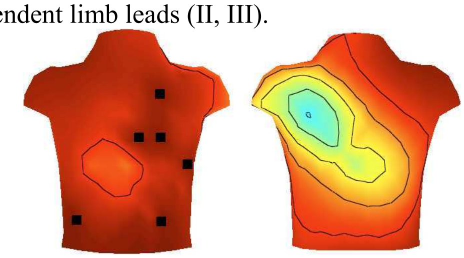
Figure 3. Positions of selected recording sites for reconstruction of BSPMs during (a) QRS, (b) STT. In both cases selected leads which occupy the same positions of standard precordial leads have been highlighted.

When the two leadsets were tested on the existing BSPM dataset it was found that BSPMs during the QRS complexes could be reconstructed with a median RMSE of 46.3 microvolts. Likewise, BSPMs during the STT segments could be reconstructed with an RMSE of 20.9 microvolts. The 12-lead ECG was found to reconstruct BSMPs with a median RMSE of 53.0 microvolts and 23.3 microvolts during the QRS and STT respectively. The correlation coefficient values determined for each lead for each lead set and for the 12-lead ECG during each complex are illustrated in Figure 4. These plots allow the visualisation of where on the torso the reconstructed leads are least similar to the shape of the original signals.

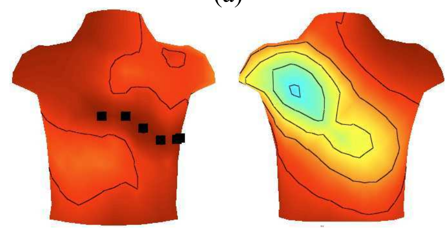
Telemedicine System

The user interface consisted of several screens. These supported configuration of the system, monitoring and recording. The configuration screen allows the user to set various default parameters for a recording, e.g. storage location, storage format, duration of recording and sampling frequency. The monitor screen, illustrated in Figure 5, allows the operator to look at the scalar trace on any individual lead. The recording screen allows the user to initiate and terminate a recording.

The software currently stores the recorded information as a CSV file on the phone's removable microSD memory card. The information can be stored as the eight sampled channels (II, III, V1, V2, V3, V4, V5, V6), or the software can be configured to use the inbuilt transformation coefficients to store the data as the reconstructed 117 channels alongside the two independent limb leads (II, III).



(a)



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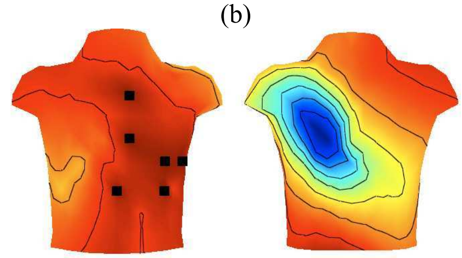
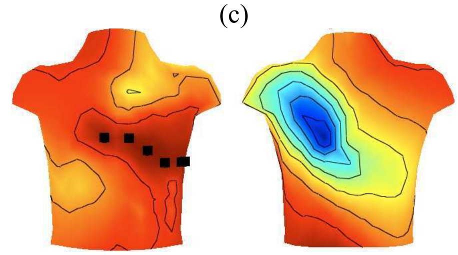


(c)



(d)

Figure 4. Plot of correlation coefficient between measured and reconstructed leads. Each plot shows how similar reconstructed leads on the anterior (left column) and posterior (right column) are to the original leads for (a) QRS complexes reconstructed from leads selected for the QRS, (b) QRS complexes reconstructed from the 12-lead ECG, (c) the STT reconstructed from leads chosen for STT, and (d) the STT reconstructed from the 12-lead ECG.

4. Discussion and conclusions

If the positions of the leads are considered it can be seen that there are similarities between leads chosen for reconstructing BSPMs during the QRS and during the

STT. Indeed, after preliminary investigation, results indicated that both lead sets performed comparably in the reconstruction of BSPMs from complexes that they were not designed for. These preliminary findings would indicate that it may not be necessary to provide the option of different lead systems for the two complexes.

The results presented here have shown that, based on RMSE, BSPM patterns can be more accurately reconstructed using the repositioned chest leads as opposed to the standard precordial leads. This is as one would expect. However, the distributions of correlation coefficient (Figure 4) indicate that although a greater number of leads are more accurately reconstructed on the anterior surface using the optimally chosen leads, the patterns of error on the posterior surface are similar to that observed when the 12-lead ECG is used for reconstruction. This would suggest that the leads selected in this study record no more posterior information than is available in the current 12-lead format.

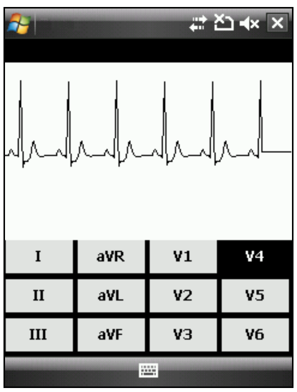


Figure 5. Monitor screen that allows user to view real time data for each sampled lead.

In terms of the actual recording apparatus the developed system has illustrated the capabilities of the Windows Mobile platform and the .NET Compact Framework for applications in medical device interfacing. Although other smartphone operating systems allow integration with external devices not all operating systems provide the functionality to allow integration of devices that use non-proprietary and custom protocols. Further work is required to refine the smartphoneECG application. Work is currently underway to develop standards for storing the recorded BSPM data and an elaborate interface for visualisation.

Acknowledgements

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