Mobile Network-based Tele-electrocardiography: A Review

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ABSTRACT

Easy accessibility and affordability of the mobile phone network have made a mobile network-based tele-electrocardiography (ECG) a reality during the last 15 years. The instrument required for this purpose is very small compared to conventional ECG machines. It is lightweight, easy to carry and several folds lower in cost. Thus, it can be used in rural areas where there are no facilities available for managing cardiac emergencies. Many products are commercially available from domestic as well as international manufacturers. The technology has moved on from sequential 12 lead configurations to simultaneous 12 lead configurations; yet maintaining the overall size limited to credit card dimensions. Some of these have built-in interpretation algorithms (like Glasgow interpretation algorithm ECG), some offer cloud computing, whereas others are developing their algorithms for incorporating diagnostic features. All these technologies are reviewed in this paper for comparison.

Keywords: Android, Cloud computing, Rural healthcare, Tele-ECG, Wireless communication.


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INTRODUCTION

India has vast and varied topography with a dense population with more than 70% residing in rural areas, many of which are very remote. Commuting infrastructure is far from satisfactory in these areas. Reaching medical help within a crucial time becomes a challenge. Low doctor-to-patient ratio and lack of uninterrupted power supply in remote villages are formidable challenges. Therefore, telemedicine can have a big role in improving healthcare services in these places.

Rapid advances in telecommunication technology have made telemedicine feasible for diagnosis and treatment of patients who do not have access to advanced medical facilities. Initially, when satellite communication was not available conventional telephone lines were used for electrodagnostic signal transmission. It was possible to transfer images and data only after the advent of satellite communication. This resulted in the development of several centers in the country for the healthcare of patients. Seoncheol et al. reported that “Satellite communication link was 10–30 times faster than conventional terrestrial link.” However infrastructure required for satellite-based telemedicine is limited mostly to metropolitan areas in our country and therefore not feasible for remote rural areas.

Worldwide communication has become easier and much faster with the introduction of mobile cellular networks like global system for mobile (GSM) or third/fourth/fifth generation network (3G/4G/5G). Availability of mobile network in Indian villages, the familiarity of rural masses with mobile phones and the availability of mobile phones at an affordable cost has helped the development of telemedicine. Routine checkup, monitoring of patients at home, during traveling or at work has become possible via mobile phones.

Electrocardiogram (ECG) is an essential emergency diagnostic tool. Immediate diagnosis of acute myocardial Infarction by ECG can be lifesaving because once diagnosis is confirmed; treatment can be commenced within the golden hour. In ECG surface electrodes are used to sense electrical activity of the heart and graphically record the same. It was first introduced by Willem Einthoven in 1896 (his experiment shown in Fig. 1). ECG is recorded by placing 10 surface electrodes on the body from various spatial perspectives; commonly known as leads.

Rashid et al. conducted feasibility studies of transmission of biomedical signals through Bluetooth communication to mobile phone and subsequently to the cellular network. That is when the concept of tele-ECG was born. Since then many research and development organizations and several manufacturers of medical instruments have been developing battery-operated, portable and low-cost mobile network-based ECG machines. Their functions and capabilities are reviewed in this paper.
Figs 1A and B: Original arrangement used by Einthoven are shown in A to record ECG signal. The electrodes, show in B in form of saline tanks; (B) ECG recording by string galvanometer (courtesy: W. Einthoven)⁵

**FIRST GENERATION TELE-ECG (SEQUENTIAL LEADS)**

Bhabha Atomic Research Center (BARC) was probably the first to develop a low cost, battery operated handheld tele-ECG unit (shown in step 2 in Figure 2) which has a bluetooth interface with a cellular phone.⁶,⁷ It comprises a hand-held tele-ECG unit which is connected via bluetooth to a mobile phone. The unit is capable of sequentially acquiring ECG data from all the 12 leads connected to a patient. The data, in turn, is transferred to a mobile phone or a laptop using a Bluetooth interface. The tele-ECG unit can be activated, operated and controlled by either of them. Using a mobile phone or laptop the operator can acquire and view signals from different leads. The data can be saved in the mobile phone in files. It can be transferred to other mobiles. The data can be transferred from a laptop over the internet. The file format used for storing acquired data is png/bmp. To get an expert opinion, the ECG data can be sent to an expert of choice through the GPRS network. The six steps followed for tele-ECG with the help of this unit are illustrated in Figure 2, for the purpose of administering emergency treatment to the patient in the golden hour. It has been providing cardiac care to the rural population. The report generated can also be shared through local area network (LAN) for integration with the hospital management system (HMS). This paperless procedure has proved advantageous over the hardcopy, which gets faded with time and also is at risk of being lost. This product has been clinically validated by Medical Institutes of national importance and has been commercialized. It has been successfully used for testing the heart condition of defense personnel, who are deployed at high altitude and other uncongenial locations.

Fig. 2: Model of mobile network-based tele ECG
SanketLife, a match-box size ECG machine, was next among the domestic developments. It is very economical, portable and one which does not use patient cable. It is Bluetooth enabled 12-lead ECG monitor which not only monitors heart but also gives alert for heart attack. It provides cloud storage along with heart rate variability to monitor daily, weekly or monthly trends. It has been clinically validated, and accuracy is claimed to be 98%.

The leads are captured sequentially by placing the metallic exposed part of the device at a specific position as guided in the user manual. The industry has a panel of cardiologists to review not only ECG reports generated by SanketLife but also any other ECG report through SanketLife application. SanketLife has many models to suit the user’s choice.

Brucal et al. have also described a portable ECG device, which can be interfaced with smartphones. The device has 9V CMOS batteries and leads ports to connect lead cables. The signal acquired from electrodes is processed through the instrumentation amplifier, band-pass filter, non-inverting amplifier, and pulse amplitude modulator. The signal is transferred to smartphone through the audio jack. Further processing is done in the android application in the smartphone. The processed signal could be sent to the doctors through the internet. The signal can be saved to Google drive (cloud) and in “0.3 gp” format. On similar lines, Jadhav et al. have developed a smartphone-based ECG monitoring system. There is no external power supply needed as a power requirement is taken care from a mobile phone via the audio jack. They have interfaced the signal with PC as well as a mobile phone through the audio jack. The waveform is displayed using windows sound-card oscilloscope application on PC and using the android application on mobile phone. ECG was successfully displayed on PC application whereas it was corrupted on mobile.

Walker and Muhlestein have reviewed some of the globally manufactured products (USA, Italy and Singapore) using mobile network based Tele-ECG technology (Kardia, ECG Check, D-Heart, QardioCore, EPI Mini and iHealth Rhythm). They are more or less similar to the BARC and Sanket models in hardware but possess enhanced software compatibility with i-phone, Blackberry, etc. Bansal and Joshi have reviewed the performance of some of these models with respect to their diagnostic accuracy and utility stating their pros and cons.

Over a period of time, an up-gradation for simultaneous recording of 12 leads has become necessary, which necessitated higher power consumption and an increase in size. Having 12 identical channels (preamplifier and main amplifier) using conventional electronic devices and crossover noise as a consequence of limited size has resulted in a paradigm shift from analog instrumentation to digital instrumentation. This has given rise to the second generation of Tele-ECG.

SECOND GENERATION (SIMULTANEOUS 12 LEADS)

The Tele-ECG technology developed by BARC has been upgraded to 12 channel simultaneous ECG recording. A VLSI (very large scale integration) chip of Texas Instrument USA ADS 1298 was used for the technology up-gradation. It provides 8 channels of identical differential amplifiers for amplification of bio-electric signals such as ECG, EMG (electromyograph), EEG (electroencephalograph), etc. The inherent noise in the linear design could be eliminated by the use of VLSI technology since most of the signal processing is done in the digital domain. Also, the use of ADS 1298 results in compact design reducing hardware requirement. The 12 lead tele-ECG unit, developed by BARC, uses microcontroller MSP430FG4618 which consumes less power. The Bluetooth module used is RN42.

ECG potentials sensed from the body using the 10 surface electrodes (RL, LL, RA, LA, V1, V2, V3, V4, V5, V6) are connected to the VLSI ADS 1298 through protection circuit. While leads I, II and V1 to V6 are directly amplified by ADS1298, leads III, aVR, aVL, and aVF are derived from leads I and II. For example, Lead III is (Lead II−Lead I); aVR is (−(Lead I + Lead II))/2 and so on. In addition, ADS1298 derives lead-fail detection internally. Wilson center terminal is derived internally by three integrated amplifiers. The right leg drive is derived from the combination of input channels. Also, the problem of electrode potential, an inherent limitation of electrodiagnostic instruments, is taken care of in the digital domain with the help of 24-bit sigma-delta analog to digital converter.

The output of ADS1298 is read by the microcontroller through a serial peripheral interface (SPI). From mobile or PC, data and commands are transferred through a Bluetooth module, interfaced with the microcontroller as shown in Figure 3, with the help of embedded firmware described below. ECG recording is initiated and guided through laptop/desktop or mobile phone. All the required operations like display of ECG data, saving and transmitting data, saving of patient’s information can be done from laptop/desktop or mobile. After start command, ADC data is read and transferred repeatedly through bluetooth module to laptop/desktop or mobile. The sampling interval is 2 milliseconds. The unit checks for start/stop which may come from mobile phone or desktop via bluetooth. The initial data is acquired in the calibration mode. The on-screen indication is provided.
for battery charge level. Bluetooth devices in the vicinity are checked by the application software on mobile. After discovering and selecting “ECG12CH”, Bluetooth link is established between mobile and ECG device. After successful connectivity, the user interface screen appears. Menu option provides facility to enter information like name, age, gender, etc. This can be saved for generating a report. Click on start button initiates acquisition in auto mode. The signal from various leads is displayed on the screen. It can display all 12 leads simultaneously. Different menu options like test and ECG mode, filtering, etc. are also available. An option to generate an ECG report in .png format is provided. It contains patient information like name, age, sex along with the date. The report is stored in the internal memory of mobile which can be used for sending MMS, or it can be sent through email. The report can be sent to expert through WhatsApp or any other file sharing application. Automatic shutdown after 5–10 minutes (adjustable) of non-usage limits battery consumption. This unit can also be used to study Heart Rate Variability (HRV) and performs statistical analysis for the purpose of stress monitoring. Postgraduate Institute of Medical Education and Research, Chandigarh; Medical Division, BARC and Father Muller Medical College Mangalore have tested and validated this instrument.

Graph 1 shows ECG obtained from the conventional machine and that by tele-ECG unit at medical division BARC. Leads I, II, III, aVR, aVL, aVF, and V1 to V6 are shown in the figure in familiar conventional format. It has been confirmed through a comparative study that the ECG machine from BARC is at par with that of the commercial ECG machine. There is no significant loss of information. The conventional ECG and digital tele-ECG have the same morphology in all the 12 leads as is evident from the figure. No qualitative loss in ECG received at the experts’ end has been reported. The technology has been transferred to more than 10 entrepreneurs for commercial production. Many models are available in the market.  

Graphs 4A and B: 12 Channel ECG recorded from a conventional ECG machine (top) and BARC’s tele-ECG machine (bottom). As seen the bio-potentials recorded by tele-ECG have the same morphology as that of conventional ECG in all the 12 leads. Amplitudes recorded with tele-ECG appear to be little higher than the conventional ECG and may call for fine tuning in the device gain.
Similar technology is also available from two other well-known brands in healthcare, namely BPL (BPL Cardioline Touch ECG) and Phillips (Efficia ECG100). Table 1 compares the features of these units with BARC developed tele-ECG.

CLOUD COMPUTING IN TELE-ECG

Mobile cloud computing is the next level of advancement in tele-ECG. There is huge storage and computations requirement in the processing of ECG data. Adaptation of the mobile cloud computing approach resolves the difficulties mentioned above. The cloud computing model as described by Venkatesana et al. is shown in Figure 4.

ECG sensors and mobile devices are wirelessly connected to the cloud. The cloud storage space is used to store a large volume of data. Complex mathematical computations are carried out in a virtual machine for cloud computing. Hseih and Hsu have described cloud computing based 12 lead tele-ECG. According to them, “The cloud computing-based ECG teleconsultation service expands the traditional 12 lead ECG application onto the collaboration of clinician at different locations or among hospitals.”

Cloud Computing is the Method of Choice for the Following Reasons

It reduces the burden of heavy storage in individual devices like ECG machine, mobile phone, laptops or desktops. The patient data is securely preserved on the cloud even if there is a problem in the device.

Upgradation of software application can be achieved without much hassle through cloud computing; upgrading on device basis is a tedious process as the vendor has to call back the machines from the users and upgrade them.

If the application is cloud-based, it can be used by other manufacturers through mutual agreement. Any user can view analyzed ECG reports irrespective of the specific model of the machine used.

Cloud computing has been very helpful in huge data analytics as healthcare industries can share data to build a more comprehensive database which can be used for medical research.

CONCLUSION

Recent developments of the mobile-based tele-ECG system are reviewed. These technologies aim at easy, Table 1: Features of BARC, BPL and Philips technologies

<table>
<thead>
<tr>
<th>Feature</th>
<th>BARC Technology</th>
<th>BPL</th>
<th>Philips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size/weight</td>
<td>Credit card size, Small (3.5”x2.5”x1.0”) and light weight (100 grams)</td>
<td>Extremely small, light-weight (&lt;90 grams)</td>
<td>Palm size, small (&lt;300 grams)</td>
</tr>
<tr>
<td>Battery life</td>
<td>Li-ion rechargeable battery, records &gt;100 ECG’s on single recharge</td>
<td>Not Specified</td>
<td>Li-ion rechargeable battery, 4 hours of non-stop usage</td>
</tr>
<tr>
<td>Simultaneous no. of Leads</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Storage</td>
<td>ECG report stored for future reference in .TXT, .DAT and PDF</td>
<td>The data can be stored in PDF and SCP formats</td>
<td>Stores ECG in PDF format. Large storage capacity (1000 ECGs per 1GB) on the device.</td>
</tr>
<tr>
<td>Interfaced with/ display on Connectivity</td>
<td>PC (Windows) Smartphone (Android) Unit-Mobile→PC→Bluetooth Mobile-Mobile→MMS/ Apps/ internet/ Bluetooth Mobile-PC→Internet/Bluetooth</td>
<td>PC (Windows) Smartphone (Android) Unit-Mobile→PC→Bluetooth Mobile-Mobile→MMS/ Apps/ internet/ Bluetooth Mobile-PC→Internet/Bluetooth</td>
<td>Smartphone (Android) Unit-Mobile→Wi-Fi Mobile-Mobile→MMS/ Apps/ Wi-Fi/ internet</td>
</tr>
<tr>
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<td>Lead map, lead fail, and noise level indicators.</td>
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<td>Glasgow ECG interpretation algorithm built in the unit</td>
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<tr>
<td>Cost</td>
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affordable and faster consultations available to the remote rural population as well as to people living in towns and cities for diagnosing life-threatening cardiac emergencies within the golden hour. Though first generation technology does not record all the 12 leads simultaneously, it still has relevance due to its low cost and cloud computing-based ECG analysis. Advancement to second generation simultaneous 12 lead recording gives an edge to this technology in terms of greater diagnostic accuracy. All the machines can be integrated with Hospital Management Systems. Another new dimension to this technology is cloud computing which resolves the problem of storage and processing of massive amounts of data generated.

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