Electrocardiogram (EKG) Data Acquisition and Wireless Transmission

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Abstract
This paper presents a development platform of an EKG sensor, capable of transmitting EKG signals via wireless technology to a PC or set-top box. In the current version, 802.11b is used to demonstrate the working of the sensor. It is argued on two fronts that this development will make EKG data more: prolific, easy to obtain, and effective. The solution can be used to provide heart patients with home based monitoring facility or it can be used in hospital premises to efficiently monitor EKG without compromising patient mobility due to wires etc. Also, it can be used to centrally monitor the data in a nursing room type of facility instead of visiting each room and checking the respective monitors.

Key-Words:- EKG, wireless transmission, 802.11b, set-top box application.

1 Introduction

An EKG is a measurement of the electrical activity of the heart (cardiac) muscle as obtained from the surface of the skin. As the heart performs its function of pumping blood through the circulatory system, a result of the action potentials responsible for the mechanical events within the heart is a certain sequence of electrical events.

1.1 EKG Measurement

The electrical impulses within the heart act as a source of voltage, which generates a current flow in the torso and corresponding potentials on the skin. The potential distribution can be modeled as if the heart were a time-varying electric dipole.

If two leads are connected between two points on the body (forming a vector between them), electrical voltage observed between the two electrodes is given by the dot product of the two vectors [1].

Thus, to get a complete picture of the cardiac vector, multiple reference lead points and simultaneous measurements are required. An accurate indication of the frontal projection of the cardiac vector can be provided by three electrodes, one connected at each of the three vertices of the *Einthoven triangle*.

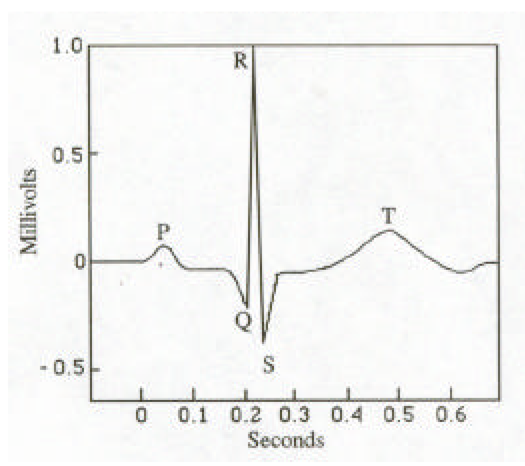

Figure 1-1 typical lead II wave

The 60 degree projection concept allows the connection points of the three electrodes to be the limbs [2]. A typical output of Lead II can be seen below in Figure 1-1. Lead II is defined as the lead between the right and left arms.

2 Sensor Design Considerations

The front end of an EKG sensor must be able to deal with the extremely weak nature of the signal it is measuring. Even the strongest EKG signal has a magnitude of less than 10mV, and furthermore the EKG signals have very low drive (very high output impedance). The requirements for a typical EKG sensor are as follows [3, 4]:

- Capability to sense low amplitude signals in the range of 0.05 – 10mV
- Very high input impedance, > 5 Mega-ohms
- Very low input leakage current, < 1 micro-Amp
- Flat frequency response of 0.05 – 150 Hz
- High Common Mode Rejection Ratio

In section 3, we discuss steps and measures/techniques we used to design the signal acquisition hardware we constructed.

2.1 Electrodes

Electrodes are used for sensing bio-electric potentials as caused by muscle and nerve cells. EKG electrodes are generally of the direct-contact type. They work as transducers converting ionic flow from the body through an electrolyte into electron current and consequentially an electric potential able to be measured by the front end of the EKG system. These transducers, known as bare-metal or recessed electrodes, generally consist of a metal such as silver or stainless steel, with a jelly electrolyte that contains chloride and other ions.

On the skin side of the electrode interface, conduction is from the drift of ions as the electrical charges spread throughout the body. On the metal side of the electrode, conduction results from metal ions dissolving or solidifying to maintain a chemical equilibrium using this or a similar chemical reaction:

Ag ? Ag+ + e-

The result is a voltage drop across the electrode-electrolyte interface that varies depending on the electrical activity on the skin. The voltage between two electrodes is then the difference in the two half-cell potentials. Figure 2-1 depicts the electrode structure with charge distribution on the metal surface with respect to skin. Also, shown in the figure 2-1 is the conduction mechanism of the conducting gel i.e. AgCl.

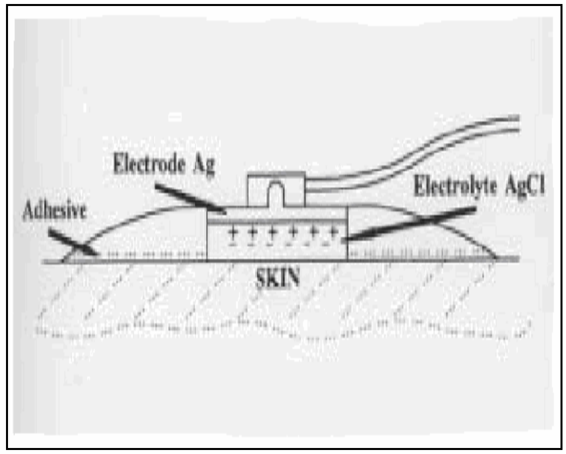

Figure 2-1 Recessed Electrode Structure [4]

2.2 Noise Sources

There are four principal noise "pick up" or coupling mechanisms for noise –conductive, capacitive, inductive, and radiative.

2.2.1 AC Mains Interference

The 60 Hz mains power-line frequency and its components are the most common source of interference in a biomedical signal. AC interference is coupled into the system from power-line and devices using AC power such as lamps. The coupling mechanism can be either capacitive or magnetic, but the capacitive mechanism is the more prevalent. The 60 Hz noise is common to all points on the patient, but the 60 Hz noise is additive to the EKG signal and is in the order of tens of volts.

2.2.2 Biological Noise Sources

When an electrode comes in contact with skin, a potential difference of up to ±300mV appears, known as the baseline wander. This can be made worse by poor connection of electrodes, perspiration or the movement of electrodes due to respiration. Any movement that causes muscle utilization generates noise that interferes with EKG signal. This is specially the case when limb leads are used. The best EKG signal is obtained when the patient is at rest and relaxed. Also, skin preparation to remove any nonconductive substance is important in obtaining a strong EKG signal.

2.3 Noise Reduction

2.3.1 Signal Filtering

The presence of noise gives rise to the need for signal filtering. Noise can be removed through the use of analogue circuitry or digital signal processing. Due to the weak nature of EKG signal and the noise affecting it requires that a range of filters be implemented.

2.3.2 EKG Right Leg Driver

EKG right leg driver is implemented to eliminate the common mode noise generated from the body. The system is shown in figure 2-2.

The two signals entering the differential amplifier are summed, inverted and amplified in the right leg driver before being fed back to an electrode attached to the right leg. The other electrodes pick up this signal and hence the noise is cancelled.

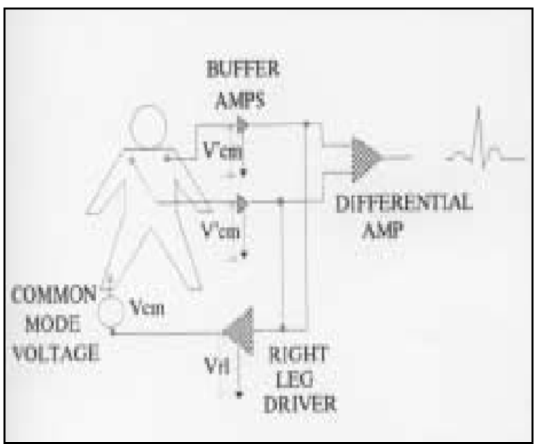

Figure 2-2 Right Leg Driver Topology

2.3.3 Twisted Pair and Shielded Cables

Use of twisted pair or shielded cable is recommended in obtaining a noise free signal. Due to the geometry of twisted pair wires and electromagnetism, the noise signals are induced with equal magnitudes, but in opposite polarity. This causes a cancellation of the noise signals.

Also, the introduction of shield or ground braid in the cable can be used to isolate the signal leads from radio frequency interference and electromagnetic interference.

3 Signal Acquisition Hardware Design

The circuitry for capturing an EKG signal, in a largely traditional manner, was built. Figure 3-1 shows the actual breadboard circuit developed during the research at SPSU research facility. The following sections elaborate on the details of the design and circuitry layout of each stage or component.

3.1 Electrodes and Electrode Placement

Disposable self-adhesive electrodes were used in the experiments. Also, AgCl conducting gel was used for stronger signal capture.

As a general principle, the closer the electrodes are to the heart, the stronger the signal that will be obtained. In our lead II formation, electrodes were placed on the right arm and left leg with right leg acting as the ground for the body.

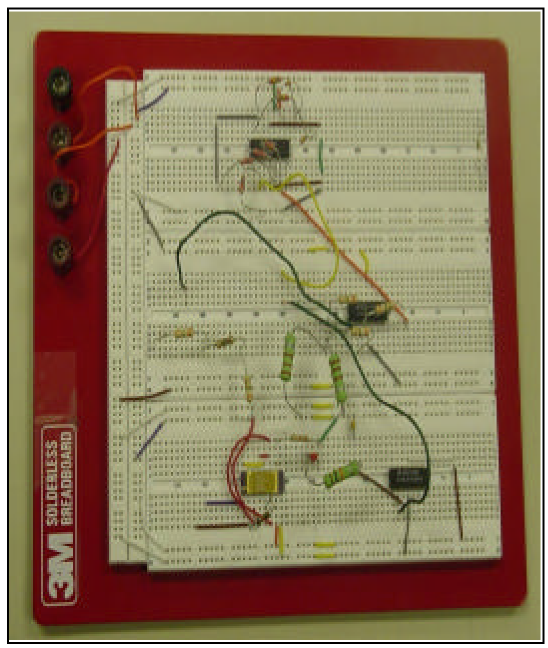

Figure 3-1 Breadboard circuitry developed in research lab at SPSU

3.2 Instrumentation Amplifier

The front-end for the signal acquisition system is an instrumentation amplifier. It has very high common mode rejection ratio (CMRR) and high input impedance which is a must for EKG type signal capture. The Analogue Devices AD624 was chosen for implementation in the system.

The AD624 is a high precision, low noise, instrumentation amplifier designed primarily for use with low level transducers, including bio-electronics, strain gauges and pressure transducers. An outstanding combination of low noise, high gain accuracy, low gain temperature coefficient and high linearity make the AD624 ideal for use in high resolution data acquisition systems.

The AD624 does not need any external components for pre-trimmed gains of 1, 100, 200, 500 and 1000. It has a CMRR of over 110dB at gains above 500. Figure 3-2 shows the pin connections of the AD624 as integrated into the breadboard circuitry. A gain of 1000 has been setup by connecting pins 3, 11 and 13.

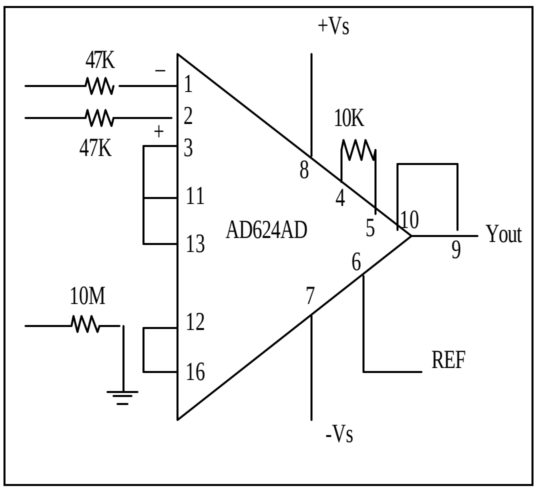

Figure 3-2 AD624 Connection Diagram

3.3 Filters

The EKG signal amplified by the instrumentation amplifier was fed into the noise filtering circuits in different stages.

3.3.1 Low Pass Filter

The first stage was a low-pass filter designed at the cut-off frequency of 150Hz. The low-pass filter was implemented as cascaded RC, or passive filters. At high frequencies, the op-amp, whose output is limited to its slew rate or maximum frequency of output, may not be able to cope with the high frequency of the signal. For this reason, the low pass filter was implemented as cascaded RC filters before isolating the filter from the rest of the circuit by a voltage follower. The cut-off frequency was calculated by the equation,

$$f_c = 1 / 2pRC$$

At the cut-off frequency of the first filter, the attenuation is determined as 20dB/decade ($f_c \times 10$). At the cut-off frequency of the second filter, the attenuation is set at 40dB/decade thereafter. Typically, if the two cut-off frequencies are equal, then the slope is 40dB/decade from the common cut-off frequency [5].

The second stage of the amplifier presents a load to the first stage, for this reason the second stage's impedance must be higher than that of the first stage. Figure 3-3 shows the circuit diagram of the low pass filter used in the system. It is non-inverting and has a gain of unity.

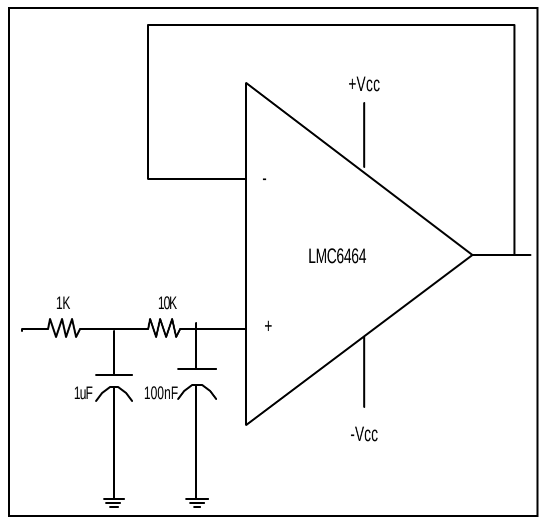

Figure 3-3 Low Pass Filter

3.3.2 Notch Filter

A Notch filter was implemented using Burr-Brown's Universal Active Filter (UAF42). The UAF42 is a monolithic, time-continuous, 2nd-order active filter building block for complex and simple filter designs. It uses the classical state-variable analog architecture with a summing amplifier plus two integrators. This topology offers low sensitivity of filter design parameters f_o (natural frequency) and Q to external component variations along with simultaneous high-pass, low-pass and band-pass outputs. An auxiliary high performance operational amplifier is also provided which can be used for buffering, gain, real pole circuits, or for summing the high-pass and low-pass outputs to create a band reject (notch) filter.

A notch filter is easily realized with the UAF42 and six external resistors. Figure 3-4 shows the

UAF42 configured into a 60 Hz notch filter. The auxiliary operational amplifier is used to sum both the high-pass and low-pass outputs. At $f = f_{NOTCH}$, both of these outputs times their respective gain at the summing circuit are equal in magnitude but 180º out of phase. Hence, the output goes to zero. Figure 3-5 shows the response plot for the circuit shown above where f_o = 60 Hz and Q = 6.

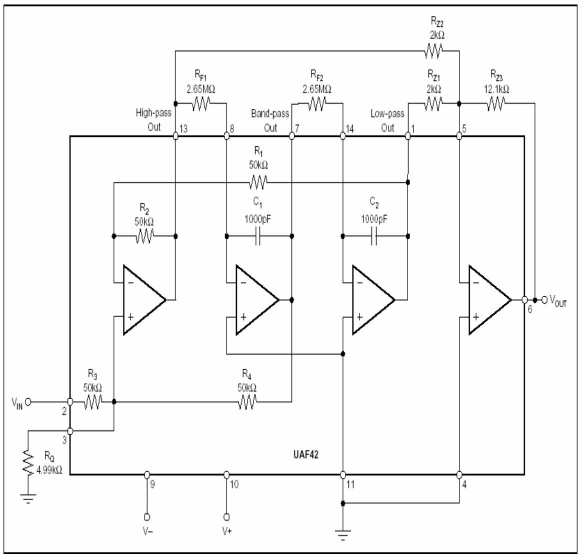

Figure 3-4 UAF42 realized as a 60Hz notch filter

The notch frequency for the notch filter is set by the following calculations:

$$f = A_{LP} / A_{HP} \bullet R_{Z2} / R_{Z1} \bullet f_o, \text{ where}$$

A_{LP} = Low pass output and
A_{HP} = High pass output.
Typically, A_{LP} / A_{HP} = 1 and R_{Z2} / R_{Z1} = 1, which means $f = f_o$.

Notch filter plays an important role in getting rid of the AC mains signal interference through the human body. If successfully implemented, it passes clean EKG signal at its output.

3.4 Signal Amplification and DC Biasing Through Summing Amplifier

After amplification and filtering, the data is ready to be digitized by the analogue-to-digital converter (ADC). The ADC requires the signal for sampling to be contained completely in the positive voltage domain. The summing amplifier is used to achieve this and its topology is shown in Figure 3-5.

The DC voltage that the signal is added to is supplied by the voltage divider circuit made with two 3.9MΩ resistors. The other resistors set the gain of the amplifier to one, and they don't influence the voltage division. In this way the output of the summing amplifier is the EKG signal transposed up by half of the supply voltage.

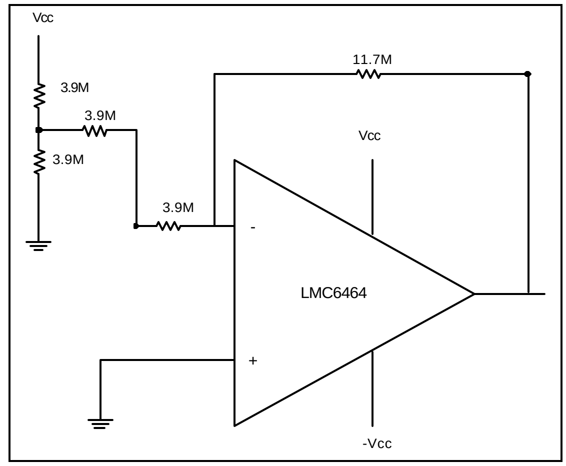

Figure 3-5 Summing Amplifier

4 Digitization and Wireless Transmission Methodology

The process of digitization and wireless transmission takes place at both hardware and embedded software level. The ADC and the wireless module follow a defined protocol through the on-board software.

4.1 Analogue-To-Digital Conversion

Analogue Devices ADuC831 data acquisition system is used to manage the digitization of the EKG signal and subsequently stored for transmission. The ADuC831 built-in 12-bit ADC is used for digitization.

The ADC has 8 channels and is configurable via 3-register (ADCCON1, ADCCON2 and ADCCON3) Special Function Register (SFR) interface. The analog input voltage range is from 0V to V_{REF} which is set to be 9V in the prototype system.

Once configured through ADCCON1-3 SFRs, the ADC converts the analog input and provides a 12-bit result into ADCDATAH/L SFRs.

Due to latency issues involved in wireless transmission on IP network (using 802.11b), the sampling rate has to be fairly low when compared to clinical system, which samples at 1 kHz. In a telemetric system, the sampling frequency is typically much lower than 400Hz, making the system acceptable. This is more than the Nyquist's criteria for sampling rate. The data resolution has not been compromised so as to create an accurate signal out of the sampled data.

4.2 Data Buffering

The transmission of data on the wireless IP network has many latency issues. Therefore, many samples are lost while the packets are being transmitted on the network. This results in severe distortion when recreating the original signal. It becomes very critical to design the system in a way that samples are not lost while the data is being transmitted on the network. Thus, a data buffering strategy was designed to overcome this limitation.

A buffer space was introduced in the system to hold data for 5 seconds (at least in order to show sufficient sections of the waveform for analysis). The ADC results are stored in the buffer locations using pointer arithmetic. Once the buffer is full, it is ready for transmission. A signal is sent to the transmission module to start transmission. To avoid over-writing the buffered data, the ADC is halted while the transmission takes place for the 5-second buffered data. Once the transmission is complete, the ADC starts conversion again and this process continues as long as the system stays powered on.

The digitization of the analog input takes place at a rate of 400samples/sec. Each sample is 12-bit which takes 2 bytes of space for storage. The ADuC831 has 4kB of EEPROM space for data storage which is built on-chip. The tests for storage of data on this space didn't produce accurate results due to slow access speed of the ROM (380µs for writing 4 bytes as a page). Many samples were lost and accurate signal could not be reproduced.

The ADuC831 provides for external memory interfacing up to 16MB. A high-speed non-volatile SRAM was tested. The results produced by external RAM interfacing were much better and more accurate than the EEPROM. Therefore the external RAM was used in our prototype system instead of the internal EEPROM.

4.3 Wireless Transmission Module

At the heart of the wireless transmission module is the IPµ8930™ chipset by Ipsil® Inc. The IPµ8930™ combines a TCP/IP controller, HTTP-compliant web server, micro-controller peripheral, 10BaseT Ethernet controller into a single, small (3.3cm x 3.4cm) daughterboard.

4.3.1 Microcontroller Peripheral

The microcontroller peripheral in IPµ8930™ is actually a serial port connection which can be configured to act as a Serial-to-Ethernet bridge using IP tunneling or a microcontroller unit (MCU) interface. In our prototype system, ADuC831 was connected to IPµ8930™ using MCU interface configuration.

Once the digitized data is accumulated for a certain time interval (10 sec in current version of the system) in the SRAM, it is ready to be transmitted over the network. This data is transferred to the IPµ8930™ using the MCU interface. A special format of bits arranged in a packet to be transferred needs to be observed since IPµ8930™ follows a proprietary MCU interface protocol. Therefore, the data is divided into packets of 32 bytes each because it is the maximum that can be sent to IPµ8930™ in one write operation. The ADuC831 performs the serial port transfer using an interrupt mechanism, and performs the pointer arithmetic to transfer the buffer locations onto the IPµ8930™. Once the data is transferred, it is ready for network transmission.

4.3.2 PC Communication

The PC communicates with the IPµ8930™ via Java networking API and follows the Ipsil Control Protocol (ICP) for read/write operations. ICP packets are very similar to MCU interface packets and follow the pattern of sending header bits followed by the data divided into packets of 32-bytes each.

ICP allows for both TCP and UDP connections. TCP/IP sockets were used in the system for reliable communication. Once the socket connection is established, it remains alive as long as the physical network connection is present. Therefore, it reduces the overhead of opening the socket connection for each transfer.

4.3.3 Transmission Protocol

Wireless transmission takes place using 802.11b protocol at the lower level. The application level protocol was developed to allow for flawless communication among various chipsets involved in the system including the PC software.

When the ADC conversion cycles produce data for the 10-second period, the ADC is halted to avoid any over-writing of the buffered data. The serial port is activated on the ADuC831 to transfer the data onto the IPµ8930™. Once the data, which is divided into 32-byte packets to follow the IPµ8930™ MCU interface protocol, is fully transferred, the ADuC831 sets one of the ports (Port 2 in current setup) of the IPµ8930™ general purpose I/O ports.

The PC side software continuously polls to check if the Port 2 of the IPµ8930™ is set. When the port is set, it starts reading data using ICP from the IPµ8930™. In the meantime, the ADuC831 continuously polls to check if the Port 2 of the IPµ8930™ is reset. When the PC software finishes reading data, it resets the Port 2 to signal end of data transfer. ADuC831, upon detection of 'reset', starts the ADC cycle again and the process continues.

5 Results

5.1 Signal Display

Successful implementation of the hardware necessary to obtain an EKG signal is evidenced in the overall results where a clean EKG signal is obtained and displayed on the PC as shown in figure 5-1.

A Java library for charting and plotting called JFreeChart has been used in the display module. It is freely downloadable under GNU Lesser General Public License.

6 Conclusion

It is evident that a lot of work and improvements in all facets of the system are required before the ultimate goal of a miniaturized, complete wireless EKG system can be reached. Some of the more important improvements are discussed here.

6.1 EKG Signal Acquisition from Individually Measured Electrode Potentials

The instrumentation amplifier has very high CMRR. The noise that is common to both electrodes attached to the body has much greater amplitude as compared to the actual EKG signal. It is the instrumentation amplifier that rejects the common noise having high CMRR and only amplifies the actual EKG signal. If the EKG signal becomes common to both electrodes, it is also rejected due to the high CMRR of the instrumentation amplifier, thus, resulting in either no or a very weak output of the instrumentation amplifier.

Further investigation is needed into a type of material which has conductivity properties as the electrode. However, such material should fail to pick up the EKG signals but detect or carry the coupled noise signals. This will make noise common to both electrodes while the EKG will be conducted by only one of them.

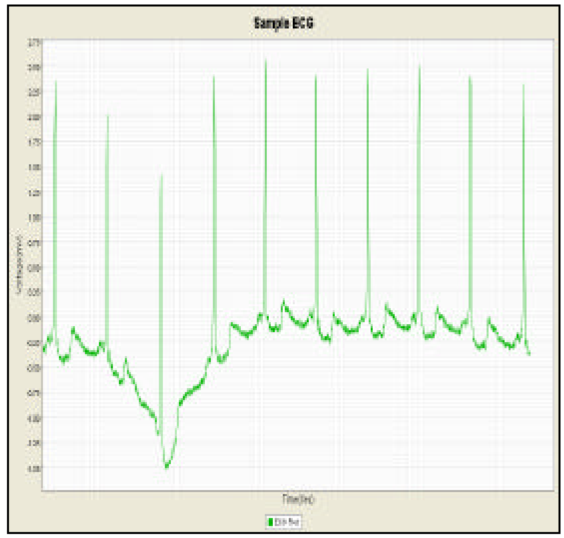

Figure 6-1 EKG displayed by the PC software

6.2 Signal Compression

The use of signal compression, once the EKG signal is digitized, further improves the system's performance. Compression also reduces the memory footprint of the stored EKG data and also reduce the network traffic while transmission. However, special algorithms could be used in order to avoid any loss of resolution while compressing and decompressing.

6.3 Baseline Wander Reduction

The patient movement results in muscle contractions that can distort the EKG signal. This is due to the voltages generated by muscle movement in the body and results in baseline wander of the EKG signal [6, 7]. This kind of noise is of very low frequency and can be overcome using a well-designed high pass filter of 0.02-2 Hz. This allows the higher frequency EKG signal to pass through while the low frequency noise will be attenuated.

6.4 PC Software

Much functionality could be added to the PC program, although several performance-rich algorithms are already implemented at the moment. Functions that check the EKG waveform for abnormalities and alert the nurse/doctor or the patient are one area of potential future improvement (A base system in this area has been developed in a separate research effort). Also, to provide home-based patient care, software can be transformed into OSGi bundles as part of a set-top box technology, which resides on the patient's premises. Such a system can continuously monitor the EKG and set an alarm through the WAN connections to the nursing station if it detects anything abnormal.

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