Electrocardiogram (EKG) Data Acquisition and Wireless Transmission

PATRICK O. BOBBIE
CHAUDARY ZEESHAN ARIF
HEMA CHAUDHARI
SAGAR PUJARI

Southern Polytechnic State University
School of Computing and Software Engineering
1100 S. Marietta Parkway, Marietta, GA 30060, USA
[pbobbie,spujari]@spsu.edu, [zeeshanarif,hemahesh]@hotmail.com

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: 1) The device would make the acquisition of EKG signal data prolific, easy to obtain, and effective. The packaged device would also be useful to heart patients with needs for home based monitoring. 2) The device would be useful in hospital premises to efficiently monitor EKG without compromising patient mobility due to wires. Also, it would facilitate central monitoring of cardiac patients from a nurses' station, significantly reducing the frequency of visits to check the respective monitors in each room.

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

1 Introduction[1,2] and Related Work

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, the result of the action potentials responsible for the mechanical events within the heart is the generation of 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].

An accurate indication of the frontal projection of the cardiac vector can be provided by three leads/electrodes, one connected at each of the three vertices of the *Einthoven triangle* [2]. Generally, as many as twelve leads are used to monitor cardiac signals. The most prevalent and significant among these is Lead II for diagnosing rhythm problems. Signals from Lead II measure the variations in potential between the right arm and the left leg, with the electrode of the left arm acting as the ground. A typical signal output, or waveform, of Lead II is depicted in Fig.1.

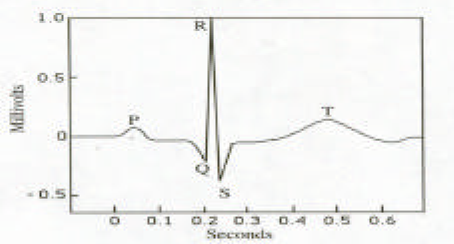

Fig. 1 A Typical Lead II Wave

---

[1] This work was supported by a grant from U.S. National Science Foundation, grant # EIA-0219547

[2] This work was supported in part by a grant from U.S. National Institute of Health, grant # NIH/RCMI G-1203020

1.2 Related Work

The development of EKG acquisition hardware has impacted the progression of research in electrophysiology. The goal of the work reported in this paper was to build a system to benefit and facilitate related telemedicine projects in our laboratory. The following subsections are synopsis of the noise-reduction techniques used in the construction of the signal acquisition hardware, a brief mention of the software we designed for signal analysis, visualization, and diagnosis of EKG-related health issues, and communication technologies we designed and developed for signal transmission.

1.2.1 Noise Reduction Techniques

The design of a notch filter is of critical importance in obtaining a high signal-to-noise ratio since the most significant noise signal is due to the harmonics of 60Hz AC mains interference. In most experiments the filter design is based on RC circuits. For our purpose, a 60Hz notch-filter, Texas Instruments UAF42, was used in the design of the signal acquisition hardware since the UAF42 has much better attenuation and sharp notch curve control than other technologies [3]. This has resulted in major noise reduction while amplifying the EKG signal.

1.2.2 Software Techniques

Generally, signal transmission through Bluetooth, or RF circuits, requires writing custom software drivers for signal reception. In the case of using IEEE 802.11b, Java stream-oriented socket API software was written for communication between the master node and the slave node. Having a TCP interface offers a reliable basis and mechanism for communication. The advantage for using standard interfaces includes ease of maintenance and enhancements to the capabilities of the software [4].

1.2.3 Telemedicine ECG – Telemetry with Bluetooth Technology

Looking for a choice between Bluetooth and IEEE 802.11 protocols, various indicators point the superiority of 802.11 over Bluetooth protocol. For e.g., experimental results have shown better performance for 802.11b as compared to Bluetooth. Also, the compatibility of 802.11b with existing LANs reduces the cost of extra hardware and the overhead of managing the Bluetooth network [5]. Therefore, the data acquisition unit, built in our laboratory, transmits EKG signals over IEEE 802.11, using stream-oriented TCP interface program.

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 include [3, 6]:

- 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

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 measurable 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.

2.2 Noise Sources

There are four principal noise “pick up” or coupling mechanisms: 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. 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.

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.

2.3.2 EKG Right Leg Driver

EKG right leg driver is implemented to eliminate the common mode noise generated from the body. Fig.2. depicts the layout of the leads/electrodes on the arms and legs of patient and the overlay of the corresponding electrical signal propagation.

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.

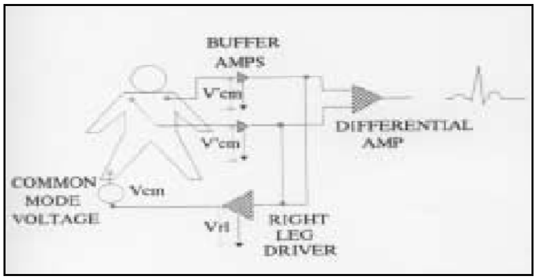

Fig. 2 Right Leg Driver Topology

2.3.3 Twisted Pair and Shielded Cables

The 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. Thus the twisting causes a cancellation of the noise signals.

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

3 Signal Acquisition Hardware Design and Construction

The circuitry for capturing EKG signals was built in our laboratory using traditional components and techniques. Fig.3 shows the actual breadboard circuit. The following sections elaborate on the details of the design and circuitry layout of each stage or component.

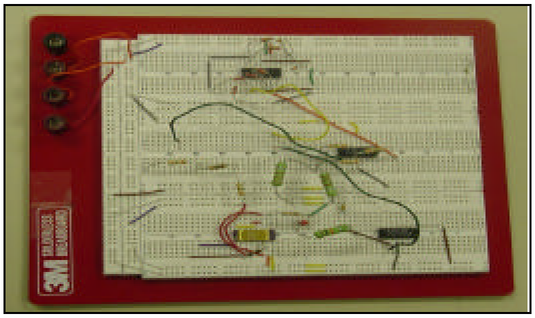

Fig. 3 Signal Acquisition Board - Developed In-House

3.1 Instrumentation Amplifier

The front-end for the signal acquisition system is an instrumentation amplifier. It has a very high common mode rejection ratio (CMRR) and high input impedance which is required for capturing EKG signals. 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 bio-electronics.

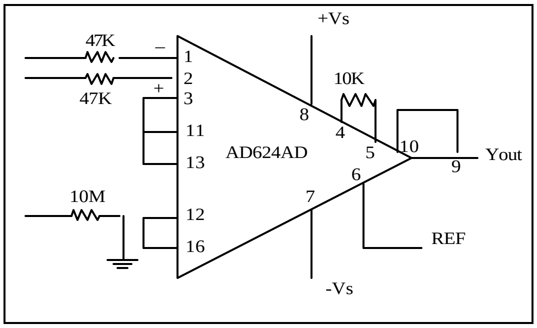

Fig. 4 AD624 Connection Diagram

Fig.4 shows the pin connections of the AD624 as integrated into the breadboard circuitry. A gain of 1000 was setup by connecting pins 3, 11 and 13.

3.2 Filters

The EKG signals were amplified by the instrumentation amplifier and fed into the noise filtering circuits in different stages.

3.2.1 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,

$$f_c = 1 / 2pRC \qquad (1)$$

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 [7].

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. Fig.5 shows the circuit diagram of the low pass filter used in the system. It is non-inverting and has a gain of unity.

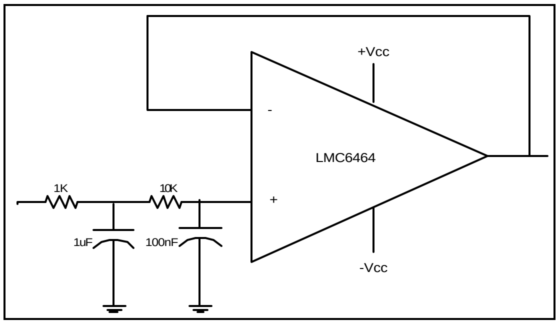

Fig. 5 Low Pass Filter

3.2.2 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. Fig. 6 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. Fig.7 shows the response plot for the circuit shown above where $f_o = 60$ Hz and $Q = 6$.

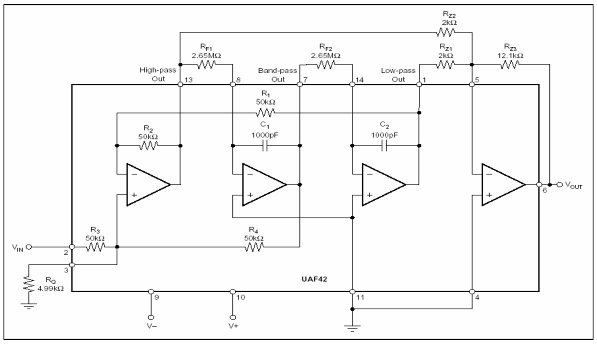

Fig. 6 UAF42 Realized As A 60Hz Notch Filter

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

$$f = A_{LP} / A_{HP} \bullet R_{Z2} / R_{Z1} \bullet f_o \qquad (2)$$

In equation (2), 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 $f = f_o$.

A 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.

3.3 Signal Amplification and DC Biasing Through Summing Amplifier

After amplification and filtering, signals are digitized by an analogue-to-digital converter (ADC). The ADC requires the sampled values to fall "completely" within the positive voltage range. The summing amplifier ensures the containment in positive range, and its topology is shown in Fig.7.

The DC voltage, which is added to signal-values, 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 is transposed up by half of the supply voltage.

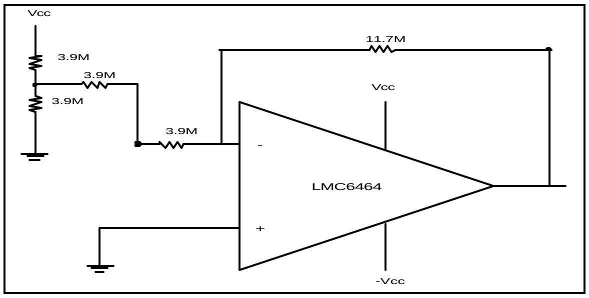

Fig. 7 Summing Amplifier

4 Digitization and Wireless Transmission Methodology

The process of digitization and wireless transmission is controlled through the embedded software on the ADuC831 and IPµ8930 boards, respectively. The on-board software defines a protocol which synchronizes the acquisition, digitization and transmission cycles of the EKG signal among various modules.

4.1 Analogue-To-Digital Conversion

Analogue Devices ADuC831 data acquisition system was used to manage the digitization of the EKG signal and subsequently store it for transmission. The ADuC831 has a built-in 12-bit ADC which was 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}. The supply voltage, V_{REF}, is set to 9V in the system.

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

The system has a sampling frequency of 400Hz which satisfies the Nyquist's criteria. Typically, in a telemetric system, the sampling frequency is much lower than 400Hz, thus, making the system acceptable.

4.2 Data Buffering

The transmission of data on the wireless IP network through IPu8930 has many latency issues due to the request/response architecture of Ipsil Control Protocol (ICP). The client has to request data by sending a header packet to IPu8930. Moreover, IPu8930 sends only 32-bytes of data in a single response packet. Therefore, many samples are lost while the packets are being transmitted on the network. This results in severe distortion when recreating the original signal. Thus, it is of vital importance 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 10 seconds. The ADC output was stored in the buffer locations using pointer arithmetic. Once the buffer was full, the bit stream was ready for transmission. To avoid over-writing the buffered data, the ADC was halted while the transmission took place for the buffered data. Once the transmission was complete, the ADC started conversion again, and the process continued as long as the system remained powered on.

The digitization of the analog input was done at a rate of 400samples/sec. Each sample was a 12-bit data occupying 2 bytes of space. 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, therefore, 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 selected 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.

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

4.3.2 The Host PC Communication

The host PC communicates with the IPµ8930™ via Java networking API and follows the ICP specification 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.

4.3.3 Transmission Protocol

Wireless transmission of digitized signals was accomplished 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 produced data for the 10-second period, the ADC was halted to avoid any over-writing of the buffered data. The serial port was activated on the ADuC831 to transfer the data onto the IPµ8930™. Once the data, which was divided into 32-byte packets to follow the IPµ8930™ MCU interface protocol, was fully transferred, the ADuC831 reset one of the ports (Port 2 in current setup) of the IPµ8930™ general purpose I/O ports.

The PC side software continuously polled to check if the Port 2 of the IPµ8930™ was set. When the port was set, it started reading data using ICP from the IPµ8930™. In the meantime, the ADuC831 continuously polled to check if the Port 2 of the IPµ8930™ was reset. When the PC software finished reading data, it resets the Port 2 to signal end of data transfer. ADuC831, upon detection of ‘reset’, started the ADC cycle again and the process continues.

5 Results

5.1 Electrodes and Electrode Placement

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 left arm acting as the ground for the body.

5.2 Signal Display

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

The successful implementation of the EKG signal acquisition hardware is evidenced in the overall results where a clean stream of EKG signals was obtained and displayed on the PC as shown in Fig.8.

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

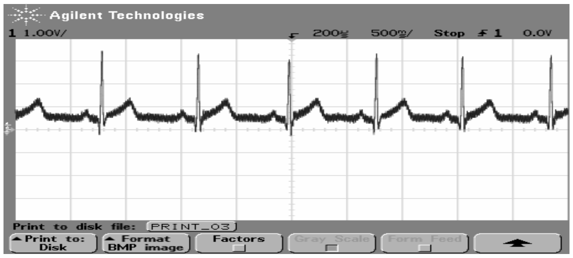

Fig. 8 Captured EKG Signal (Lead II)

5.3 Post Signal Analysis

The data acquired through the circuitry was passed through several stages of signal analysis and various sections of the EKG are identified.

5.4 Tachycardia Diagnosis

Once the sections of the waveform have been identified, the signal data was analyzed using an algorithm we developed to detect the symptoms of Tachycardia such as wide or narrow QRS complexes and obscured P wave.

6 Conclusion

Work is currently ongoing for improving aspects of the system in both hardware and software. In the following, we summarize some of the current activities.

6.1 EKG Signal Acquisition from Individually Measured Electrode Potentials

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

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 signals. This is due to the voltages generated by muscle movement in the body and results in baseline wander of the EKG signal [8, 9]. 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 would allow the higher frequency EKG signal to pass through while the low frequency noise is 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. The development of functions that check the EKG waveform for abnormalities and alert the nurse/doctor or the patient is 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.

References

[1] BE304 Laboratory Notes, Michigan Technological University www.biomed.mtu.edu.au/osoykan/classes/be304/week3/week3.htm

[2] Bronzio, J. D., The Biomedical Engineering Handbook, IEEE Press, 2000, pp 73-1 - 73-5.

[3] Lu, M., The Design and Construction of an ECG Telemetry System, M.S. Thesis, University of Queensland, 1994.

[4] Bobbie, P. O., Chaudhari, H., and Arif, C.-Z., "Homecare Telemedicine: Analysis and Diagnosis of Tachycardia Condition in an M8051 Microcontroller," 2nd IEEE-EMBS International Summer School and Symposium on Medical Devices and Biosensors (ISSS-MDBS), Hong Kong, China, June 23- July 03, 2004 (appearing).

[5] S. Khoor, J. Nieberl, K. Fugedi, E. Kail, Telemedicine ECG – Telemetry with Bluetooth Technology, Computers in Cardiology 2001, 28:585-588.

[6] Khorovets, A., "What is An Electrocardiogram?" The Internet Journal of Health, Volume 1 Number 2, 2000.

[7] Ayang-ang, C. K. B., Sison, L. G., "Electrocardiograph Pre-Filtering, QRS Detection, and Palm Display Programming for Biomedical Applications," ECE Conference, University of St. Tomas, Manila, 2001.

[8] Schamroth, C., An Introduction to Electro Cardiography, Blackwell Sci. Publishing, 7th edition, 2001.

[9] Timothy K., Knilans, T.-C., Chou, L. S. R. , Electrocardiography in Clinical Practice Adult and Pediatric, W B Saunders; 4th edition, 1996.