Faculty of Engineering

Department of Electrical and Electronic Engineering

MEDICAL APPLICATIONS OF ELECTRONICS AND ROBOTICS

Graduation Project
EE - 400

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First I would like to thank Asst. Prof. Dr Kadri Buruncuk for his support and Supervision, and for giving me the chance to accomplish this thesis as it is now.

For my parents, I dedicate it with all the love.

ABSTRACT

This thesis is mainly concerned by medical electronics, starting with the theory of medical instrumentation and design, and then to biopotential theories. It is important to stop in basics of physiology and their relation with medical instruments.

Implementation of some biological and medical knowledge was necessary to go through the applications later.

Electrocardiograph is a typical application of these theories. Some robotics applications are also included, as an example of the wide range applications of biomedical engineering.

The last chapter gives a general idea about hazards of electricity to humans and the safety precautions suggested for protection by electrical engineering solutions.

Some applications from hospitals are also discussed. Circuit theory, basic electronics and other electrical engineering theories explain most of the topics in the thesis.

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INTRODUCTION

There are many definitions of bioengineering. Other labels, such as medical engineering, biomechanics, bioelectronics, etc... each clearly refer only to a part of the subject. Bioengineering is taken to be the application of the concept and methods of the physical sciences and mathematics in an engineering approach to problems in the life science. Most often bioengineering is the application of these sciences and mathematics to the design and analysis of in animated, manufactured objects and structure. Bioengineering maybe viewed as he application of these disciplines to the study of living structure and organisms. The intent of such studies is to understand the physical process and engineering aspects of performance under both normal and abnormal conditions, and to design, develop and use diagnostic or artificial devices meant to measure, improve, safeguard or replace life functions. I hope the subjects I selected will satisfy readers, not to cover the whole material but to give a good introduction to medical electronics.

1. MEDICAL INSTRUMENTATION

1.1 What Is A Medical Instrument?

There are many different types of medical instruments. The ones on which we concentrate in this thesis are those that monitor and analyze physiological signals from a patient. Figure 1.1 shows a block diagram that characterizes such instruments. Sensors measure the patient's physiological signals and produce electrical signals (generally time-varying voltages) that are analogs of the actual signals.

A set of electrodes may be used to sense a potential difference on the body surface such as an ECG or BEG. Sensors of different types are available to transduce into voltages such variables as body core temperature and arterial blood pressure. The electrical signals produced by the sensors interface to a processor, which is responsible for processing and analysis of the signals. The processor block typically includes a microprocessor for performing the necessary tasks. Many instruments have the ability to display, record, or distribute through a network either the raw signal captured by the processor or the results of its analysis. In some instruments, the processor performs a control function. Based on the results of signal analysis, the processor might instruct a controller to do direct therapeutic intervention on a patient [closed loop control] or it may signal a person that there is a problem that requires possible human intervention [open loop control].

Let us consider two types of medical instrumentation and see how they fit this block diagram. The first is an intensive care unit (ICU) system, a large set of instrumentation that monitors a number of patient's stimultaneously. The second is a cardiac pacemaker so small that it must fit inside the patient.

In the case of the ICU, there are normally several sensors connected to each patient receiving intensive care, and the processor (actually usually more than one processor) monitors and analyzes all of them. If the processor discovers an abnormality, it alerts the medical staff, usually with audible alarms. A display permits the staff to see raw data such as the ECG signals for each patient and also data obtained from the analysis such as numerical readouts of heart rate and blood pressure. The network connects the bedside portion of the instrumentation to a central console in the ICU.

1.2 Iterative Definition Of Medicine

Data collection is the starting point in health care. The clinician asks the patient questions about medical history, records the ECG, and does blood tests and other tests in order to define the patient's problem. Of course medical instruments help in some aspects of this data collection process and even do some preprocessing of the data. Ultimately, the clinician analyzes the data collected and decides what is the basis of the patient's problem. This decision or diagnosis leads the clinician to prescribe a therapy. Once the therapy is administered to the patient, the process continues around the closed loop with more data collection and analysis until the patient's problem is gone.

The function of the medical instrument of Figure 1.1 thus appears to be a model of the medical care system itself.

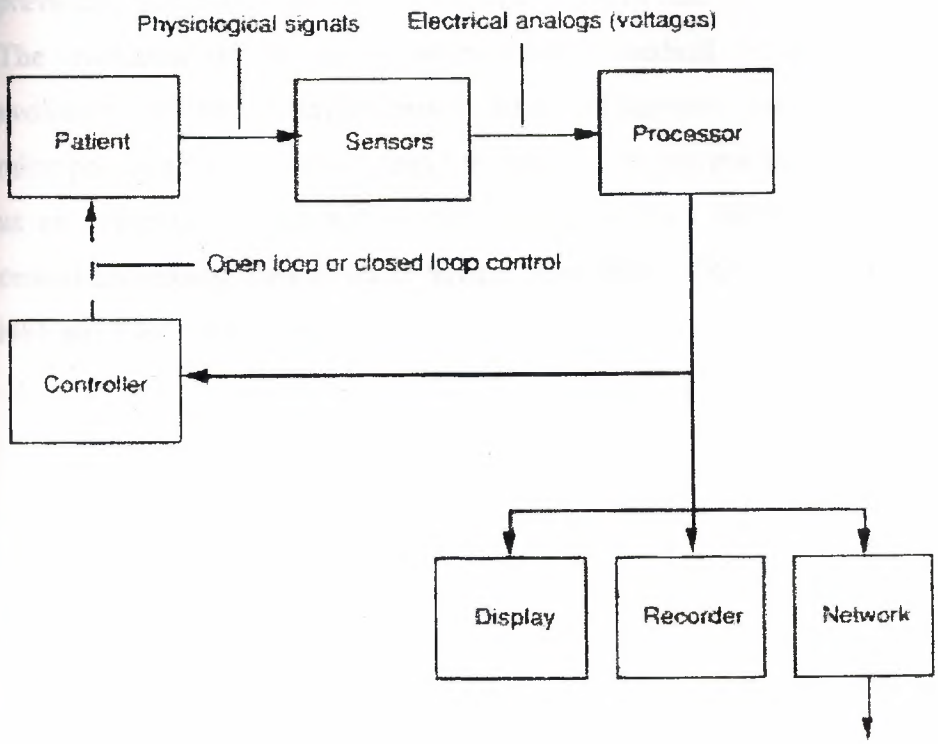

Figure 1.1 basic elements of medical instrumentation system

1.3 Evolution Of Microprocessor-Based Systems

In the last decade, the microcomputer has made a significant impact on the design of biomedical instrumentation. The natural evolution of the microcomputer-based instrument is toward more intelligent devices. More and more computing power and memory are being squeezed into smaller and smaller spaces. The commercialization of laptop PCs with significant computing power has accelerated the technology of the battery-powered, patient-worn portable instrument. Such an instrument can be truly a *personal* computer looking for problems specific to a given patient during the patient's daily routines. The ubiquitous PC itself evolved from minicomputers that were developed for the biomedical instrumentation laboratory, and the PC has become a powerful tool in biomedical computing applications. As we look to the future, we see the possibility of developing instruments to address problems that could not be previously approached because of considerations of size, cost, or power consumption.

The evolution of the microcomputer-based medical instrument has followed the evolution of the microprocessor itself (Tompkins and Webster, 1981). The microprocessor is now more than 20 years old. It has evolved from modest beginnings as an integrated circuit with 2,000 transistors (Intel 4004) in 1971 to the powerful central processing units of today having more than 1, OOO, OOO transistors (e.g., Intel i486 and Motorola 68040).

1.4 Alternative operational modes

Direct-Indirect Modes

Often the desire& measurand can be interfaced directly to a transducer because the measurand is readily accessible or acceptable invasive procedures are available. When the desired measurand is not accessible, then we can use either another measurand that bears a known relation to the desired one or some form of energy or material that interacts with the desired measurand to generate a new measurand that *is* accessible. Examples are cardiac output (volume of blood pumped per minute by the heart), determined from measurements of respiration and blood gas, or dye dilution; morphology of internal organs, determined from x-ray shadows; and pulmonary volumes, determined from variations in thoracic electrical impedance.

Sampling And Continuous Modes

Some measurand—such as body temperature and ion concentrations—change so slowly that they may be sampled infrequently. Other quantities—such as the electrocardiogram and respiratory gas flow—often require continuous monitoring. The frequency content of the measurand, the objective of the measurement, the condition of the patient, and the potential liability of the physician all influence temporal aspects of the acquisition of medical data. Many unused data are often collected.

Generating and Modulating Transducers.

Generating transducers produce their signal output from energy taken from the measurand, while modulating transducers receive their energy from an external source and provide their output by varying this external energy according to the measurand. For example, a photovoltaic cell is a generating transducer because it provides an output voltage related to its illumination, without any additional external energy source. However, a photoconductive cell is a modulating transducer, since to measure its change in resistance with illumination, one must apply external energy to the transducer.

Analog and Digital Modes

Signals that carry measurement information are either analog, meaning continuous and able to take on any value, or digital, meaning discrete and able to take on only a finite number different values. Most currently available transducers operate in the analog mode, although some inherently digital measuring devices have recently been developed. Increased use of digital signal processing has required concurrent use of analog-to-digital and digital-to-analog converters to interface computers with analog transducers and analog display devices. Researchers have developed indirect digital transducers that use analog primary sensing elements and digital variable-conversion elements (optical shaft encoders). Also quasi-digital transducers, such as quartz -crystal thermometers, give outputs with variable frequency, pulse rate, or pulse duration that are easily converted to digital signals.

Advantages of the digital mode of operation are greater accuracy, repeatability, reliability, and immunity to noise. Also periodic calibration is usually not required. Digital numerical displays are replacing many analog meter movements because of their greater accuracy and readability. Many clinicians, however, prefer analog displays when they are determining whether a physiological variable is within certain limits or when they are looking at a parameter that can quickly change, such as beat-to-beat heart rate. In the latter case, digital displays often change numbers so quickly that they are very difficult and annoying to observe.

Real-Time and Delayed-Time Modes

Of course transducers must acquire signals in real time as the signals actually occur. The output of the measurement system may not display the result immediately, however, since some types of signal processing, such as averaging and transformations, need considerable input before any results can be produced. Often such short delays are acceptable unless urgent feedback and control tasks depend on the output.

Deflection and Null Modes

For instruments that operate in the deflection mode, the output signal produces an effect that is opposed by a spring or similar device so that a displacement proportional to the quantity measured can be displayed. For example, the torque produced by current flowing through a D'Arsonval meter movement is opposed by a spring so that displacement of the needle is proportional to input current.

Instruments operating in the null mode utilize a detector of imbalance between the unknown quantity and a known calibrated opposing quantity. The output is read as the value of the opposing quantity for a balanced detector at maximum sensitivity. The Null-type device is generally more accurate because the unknown is compared directly with a standard and the detector of imbalance can have high sensitivity because only a small'range near zero need be covered. The null detector does not have to be calibrated, since it is used only to detect the presence or absence of a signal. The major disadvantage of null methods is the typically poor dynamic response, even when automatic balancing devices are used.

1.5 Medical Measurement Constraints

The medical instrumentation is designed to measure various medical and physiological parameters. The principal measurement and frequency ranges for each parameter are major factors that affect the design of all the instrument components. Most of the parameter measurement ranges are quite low compared with nonmedical parameters in most industries. Note for example that most voltages are in the microvolt range and that pressures are low (about 100 mm Hg = 1.93 psi = 13.3 kPa). Also note that all the signals are in the audio frequency range or below and that many signals consist of dc and very low frequencies. These general properties of medical parameters limit the practical choices available to designers for all aspects of instrument design.

Many crucial variables in living systems are inaccessible because the proper measurand —transducer interface cannot be achieved. Unlike many complex physical systems, a biological system is of such a nature that it is not possible to turn it off and remove parts of it during the measurement procedure. Even if interference from other

physiological systems can be avoided, the physical size of many transducers prohibits the formation of a proper interface. Either such inaccessible variables must be measured indirectly as just described, or corrections must be applied to data that are affected by the measurement process. The cardiac output is an important measurement that is obviously quite inaccessible.

Variables measured from the human body or from animals are seldom deterministic. Most measured quantities vary with time, even when all controllable factors are fixed. Many medical measurements vary Widely among normal patients, even when conditions are similar. This inherent variability has been documented at the molecular and organ levels, and even for the whole body. There are many internal anatomical variations that accompany the obvious external differences between patients. Large tolerances on physiological measurements are partly the result of interactions between many physiological systems. Many feedback loops exist between physiological systems and many of the interrelations are poorly understood. It is seldom feasible to control or neutralize the effects of these other systems on the measured variable. The most common method of coping with this variability is to assume empirical statistical and probabilistic distribution functions. Single measurements are then compared with these norms.

Nearly all biomedical measurements depend either on some form of energy being applied to the living tissue or on some energy being applied as an incidental consequence of transducer operation. X-ray and ultrasonic imaging techniques and electromagnetic or Doppler ultrasonic blood flow meters all depend on externally applied energy interacting with living tissue. Safe levels of these various types of energy are difficult to establish because many mechanisms of interaction are not well understood. The heating of tissue is one effect that must be Joined, because even reversible physiological damages can affect measurements. Damage to tissue at the molecular level has been demonstrated in some instances at surprisingly low energy levels.

Operation of instruments in the medical environment imposes important additional constraints. Equipment must be reliable, simple to operate, and capable of withstanding physical abuse and exposure to corrosive chemicals. Electronic equipment must be designed to minimize electric -shock hazards .The safety of patients and medical personnel must be considered in all phases of design and testing of instruments.

1.6 Classifications Of Biomedical Instruments

The study of biomedical instruments can be approached from at least four viewpoints. Techniques of biomedical measurement can be grouped according to the quantity that is transduced, such as pressure, flow, or temperature. One advantage of this classification is that different methods for measuring any quantity can be compared readily.

A second classification scheme uses the principle of transduction, such as resistive, inductive, capacitive, ultrasonic, or electrochemica]. Different applications of each principle can be used to strengthen understanding of each concept; also new applications may be more apparent.

Measurement techniques can be studied separately for each physiological system, such as the cardiovascular, pulmonary, nervous, or endocrine systems. This approach isolates all the important measurements for specialists who need to know only about a specific area, but it results in considerable overlap of principles of transduction.

Finally, biomedical instruments can be classified according to the clinical medicine specialties, such as pediatrics, obstetrics, cardiology, or radiology. This approach is valuable for medical personnel who are interested in specialized instruments. Certain measurements—such as blood pressure—are important to many different medical specialties.

1.7 Interfering And Modifying Inputs

A typical electrocardiographic recording system, shown in Figure 1.2, is used as an example to illustrate that the desired input is the electrocardiographic voltage **Vecg** that appears between the two electrodes. One interfering input is 60-Hz noise voltage induced in the shaded loop by ac magnetic fields. The desired and the interfering voltages are in series and both components appear in the output. Also capacitively coupled displacement current flowing through the electrodes and the body to ground causes an interfering voltage to appear between the two electrodes.

An example of a modifying input is the orientation of the patient cables. If the plane of the cables is parallel to the ac magnetic field, magnetic interference is zero. If the plane of the cables is perpendicular to the ac magnetic field, magnetic interference is maximum. Time-dependent changes in electrode impedance are an example of a modifying input.

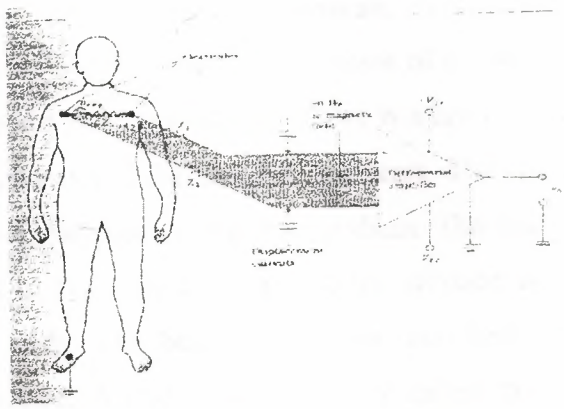

Figure1.2 interfering and modifying inputs.

2.ORIGIN OF POTENTIAL:

2.1 the Anatomy Of The Heart

The heart is a muscle, about the size of your fist that is encased in a sac called the pericardium. The pericardium helps to keep the heart in position and protects it from getting hurt. The pericardium and the heart are separated by a layer of lubricating fluid, which allows the heart to pump freely inside the walls of the chest. The heart is made up of three layers of muscle, the endocardium, myocardium and epicardium. The myocardium makes up about seventy five percent of the heart tissue. The epicardium is a thin lining that covers the myocardium. There is a layer called the endocardium that is between the myocardium and the inside of the heart. The endocardium acts as the inner covering of the heart and protects the myocardium. The heart functions as a pump that circulates nourishment and oxygen to, and carbon dioxide and waste away from, tissues and organs of the body. The heart is separated into four different chambers through which blood is pumped. A thick wall of muscle called the septum, which divides the heart into two halves, separates the heart. Each half is then separated into an upper and lower chamber by valves. The upper chambers are called the atria and are the inputs to the heart. The lower chambers are called the ventricles and are the outputs of the heart. [1] The valves that separate the upper and lower chambers are called the atrioventriclular valves. The valve that separates the right atrium from the right ventricle is called the tricuspid valve and the valve that separates the left atrium from the left ventricle is called the mitral valve. A different set of valves controls the flow of blood from each ventricle to the main arteries. The valve that separates the right ventricle from the pulmonary artery, the artery that carries blood to the lungs, is called the pulmonary valve. The aortic valve is the valve that separates the left ventricle from the aorta, the main artery that carries blood to the rest of the body's organs and tissues.

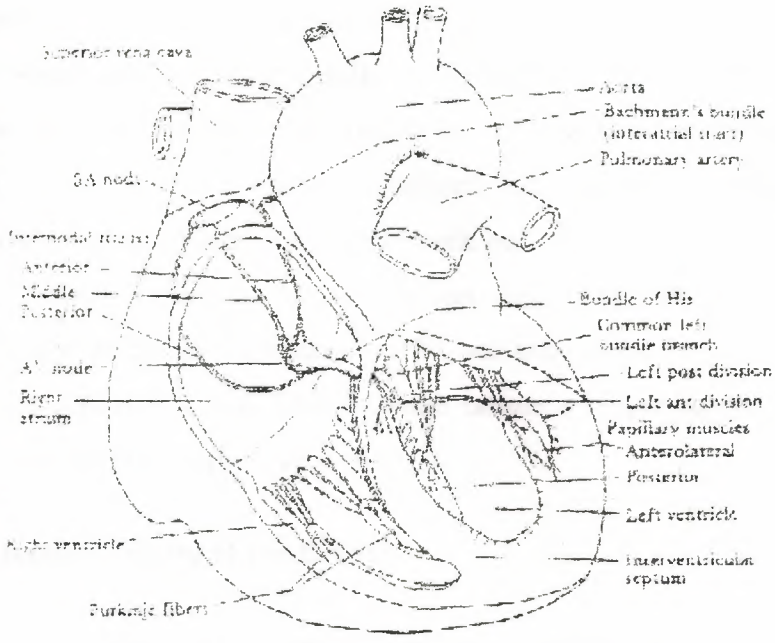

Figure 2.1 human heart diagram

2.2Electrical Potential Of A Cardiac Cell

The cardiac system is a closed-loop hydraulic system that is constantly contracting and relaxing, pumping blood throughout the body. The cell wall of cardiac cells is a semipermeable membrane that allows the passage of some ions while restricting others. The cell membranes, at rest, tend to be more permeable to some ions than others. The movement of ions across a membrane changes the concentration of ions within and outside the cells, which results in an action potential. This action potential of the cell results in a depolarizing and depolarizing of the cell itself. [2] In a cardiac cell the action potential is caused by the movement of sodium and potassium at different rates. A phenomenon in a cardiac cell called the sodium-potassium pump moves sodium outside the cell and potassium inside. This results in a difference of ion

concentration, which in turn results in an electrical potential. [1] At rest the concentration of positive sodium ions outside the cell is higher than the concentration of sodium inside the cell, which results in the electrical potential. This electrical potential is negative with respect to the outside resulting in a resting potential of a negative seventy to ninety millivolts. When the cell is stimulated the sodium ions rush into the cell forcing potassium out which results in the action potential. This action potential results in the inside of the cell being twenty to forty millivolts more positive than the outside and the cell is said to have depolarized. [2] The cell is repolarized when the sodium-potassium pump pumps the sodium back out of the cell and the potassium back into the cell, which resets the cell so, it can depolarize again. An ionic electrical conduction is started by the depolarization of one cell, which in turn triggers the next cell causing an action potential. This situation causes a triggering of cells in a cascade effect making all the cells depolarize.

Electroconduction System of the Heart

The electroconduction system of the heart is a complicated system of the body that begins in the right atrium at the sinoatrial (SA) node. The SA node, a small bundle of cells located on the back wall of the right atrium, serves as a pacemaker for the heart. The SA node fires, by self-excitation, an electrical impulse that is spread across the right atrium and to the left atrium by the Bachman's bundle so that both atria can contract at the same time. [1] The contraction of the atria forces blood from the atria to the ventricles through their respective valves. The impulse that is started at the SA node then travels to the atrioventricular (AV) node. The AV node acts as a delay line to slow down the action potential along the internal electroconduction system. This is done so that all of the blood from the atria can be emptied into the ventricles before the ventricles contract. [1] The action potential then travels from the AV node to the Purkinje fibers. The Purkinje fibers are arranged in two bundles, one bundle branching to the muscle in the right ventricle and the other branching to the muscles in the left ventricles. The action potential moves through these fibers very rapidly and spreads throughout the ventricles at two to four meters per second. This causes the ventricles to pump fast and hard. This forces the blood through their respective valves out to the body at an extremely fast rate. The contraction of the ventricles is known as systole. The relaxation of the ventricles is known as diastole. [2] The electroconduction of the heart

starting at the SA node and traveling through the AV node to the Purkinje fibers creates a mass electrical signal that can be detected by placing electrodes on a patient's chest or extremities. This electrical signal can be mechanically plotted and the resultant plot is called an electrocardiogram (ECG). The letters on the ECG represent different functions that occur in the heart. The P-wave indicates atrial contraction. Ventricular contraction is represented by the QRS complex, and the T-wave indicates ventricular repolarization.

2.3 Problems Occurring In The Heart.

The heart is a system that has to be exact in all of its functions from start to finish for each beat to beat successfully. If a problem occurs, severe or minor, it can cause death for the patient. Physicians can look at a simple ECG reading and can tell if the patient is having any problems that can either be fatal or could lead to something fatal. Some heart problems that plague humans around the world are arrhythmias. Arrhythmias are abnormal beats that can be detected on the ECG. [3] Two of the arrhythmias that people with heart problems encounter are tachycardia and bradycardia. [3] Tachycardia is a problem in which the heart beats at a rate faster than the normal human heart rate. Treatment for tachycardia consists of cardioversion or the delivery of a broad depolarizing shock to a restricted region of the heart. Rapid bursts of pacemaker impulses timed and placed at the proper time can often stop the tachycardia. [1] Bradycardia is a problem in which the heart beats at a rate slower than the normal human heart rate. An implanted pacemaker can restore the lower heart rate to a more physiological value that will improve cardiovascular function. Fibrillation is another major problem that affects the heart. [3] Fibrillation is the uncontrolled beating of different parts of the heart. Ventricular fibrillation is a fatal arrhythmia of the heart in which the victim will die in minutes if it is not corrected. Atrial fibrillation is a less serious arrhythmia because the ventricles are still pumping. However it can lead to problems if it is not corrected. Heart block is another problem caused by the interruption of the internal electroconduction system of the heart. [2] These are a few heart problems that people encounter that can be conquered with help from pacemakers, defibrillators, and modern technology.

2.4 Pacemaker Technology

Pacemaker technology has expanded immensely over the last three decades. Each phase of development has been associated with clinical improvements each step of progress has led to smaller, more reliable devices with greater programmability. [24] The longevity of devices has been advanced with better generator technology and battery design. The first devices used asynchronous pacing which had a significant effect in reducing the mortality of surgically induced complete heart block. [24] Ventricular demand pacemakers overcame the problem of asynchronous competitive pacing, but at the same time patients exposed to pacemaker syndrome. Atrioventricular sequential pacing restored atrioventricular synchrony, resulting in hemodynamic improvement, but like the other improvements it caused the phenomenon of pacemaker-mediated tachycardia.

Alternative dual chamber modes and algorithms have brought solutions to these and other problems. [24] Adaptive-rate devices have been of benefit to patients with chronotropic incompetence and are now incorporating increasing variety of biosensors. Such devices offer improved survival and quality of life, but at the cost of increased complexity. Amazingly, the expense of the pacemaker has not increased much over the years. Cost still remains the major limitation to the use of such readily available and advantageous technology. [24] Nearly all of the problems that pacing has presented over the years have been overcome, but the increasing complexity of pacemaker technology is now a major limitation to its proper use.

In future generations, developments in the field of microprocessor technology will lead to greater flexibility in the self-adjustment of rate, output, and the overall sensitivity of pacemakers. [24] The continued innovation of programmability and telemetry will increase the diagnostic capabilities of pacemakers. Systems are being developed which can facilitate storing of patient details and which can diagnose rhythm disturbances using sophisticated algorithms. Sensors will be combined with electrogram analysis to differentiate between physiological and pathological alterations in hemodynamics in such a way that appropriate adjustments can be initiated. [24] Pacemaker technology that is self-adjusting will evolve that can differentiate arrhythmias and initiate the appropriate pacing modality. Progress in battery technology

will reduce generator size further without effects on longevity. [24] Generator microprocessors will permit more flexible programming of algorithms that will satisfy the patient's changing requirements.

Future applications of implantable pacemakers need to be able to interact in a patient's body with internal defibrillators. Large amounts of energy that pass through the pacing electrode may cause damage at the electrode - myocardium interface. [7] This damage can temporarily or permanently alter the pacing and sensing thresholds of the pacemaker. A pacemaker may be reprogrammed or experience a change in the sensing or pacing thresholds after a shock from a defibrillator. [7] In future generations, it is important that the pacemaker be able to protect itself from excessive energy and shocks caused by a defibrillator.

Benefits of Pacemaker Technology

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2.5 Defibrillators

What is a Defibrillator

Defibrillators are devices that are used to apply a strong electrical shock to the heart. The shock changes ventricular fibrillation to an organized ventricular rhythm or changes a very rapid and ineffective cardiac rhythm to a slower, more effective rhythm. This device helps treat cardiac disorders, which include ventricular fibrillation, ventricular tachycardia, atrial fibrillation, and atrial flutter. The idea of fibrillation started around 1888 when Mac William, a clinician, noted that ventricular fibrillation might be the cause of sudden death. It was 1899 when Provost and Patella stumbled upon the concept of electrical defibrillation on animals. [10] Many scientists in the early nineteenth century studied and experimented with the idea of how to reduce tachyarrhythmias using electrical defibrillation.

The First Ideas

In 1947 Claude Beck, a Cleveland surgeon, first defibrillated a human heart [11]. He had tried six other patients and was not successful, but on his seventh attempt, the patient lived. In 1954, Kouwenhoven and Milnor defibrillated a dog through a closed chest with a capacitor-discharged defibrillator. [11] Zoll, a cardiologist, worked on human hearts instead of animals. He worked with Kouwenhoven's ideas, and Zoll's results led to the first external defibrillation of the human heart.

The First Internal Defibrillator (ICD)

The father of the implantable defibrillator is widely recognized to be Dr. Micheal Mirowski. Dr. Mirowski began the initial work on the ICD in the late 1960s after Dr. Harry Heller died as a result of ventricular arrythmia. He was frustrated by the absence of an implantable device which could have aborted cardiac arrhythmias. As a result, Dr. Miroski developed a small compact defibrillator which could be implanted in a human and could provide continuous monitoring and appropriate electrical shock therapy when necessary.[10]

How Does the Internal Defibrillator Work?

Each Internal Cardiac Defibrillator (ICD) is designed to automatically detect episodes of bradycardia, ventricular tachycardia (VT), fast ventricular tachycardia (FVT), and ventricular fibrillation (VF). When an arrhythmia is detected, the device will deliver the programmed pacing, cardioversion, or defibrillation therapy. The device has two independently programmable tachyarrhythmia detection procedures, one for VT and a second for VF. The detection of FVT can be programmed via either VT or VF detection. Generally up to four therapies can be independently programmed for each arrhythmia type (VT, FVT, and VF). The device generally has two electrodes. One bipolar electrode system serves for both defibrillation and sensing the cardiac electrical waveform. [10] This lead system uses an intravascular catheter positioned in the superior vena cava near the right atrial junction with the cathode having the form of a flexible rectangular patch placed over the left ventricular apex. The other bipolar electrode system, which serves for rate detection and R-wave synchronization during pulse delivery, consists of either a right ventricle endocardium catheter or two intramural electrodes. [11]

3. ELECTROCARDIOGRAPHY

One of the main techniques for diagnosing heart disease is based on the electrocardiogram (ECG). The electrocardiograph or ECG machine permits deduction of many electrical and mechanical defects of the heart by measuring ECGs, which are potentials measured on the body surface. With an ECG machine, you can determine the heart rate and other cardiac parameters.

3.1 Basic Electrocardiography

There are three basic techniques used in clinical electrocardiography. The most familiar is the standard clinical electrocardiogram. This is the test done in a physician's office in which 12 different potential differences called ECG leads are recorded from the body surface of a resting patient. A second approach uses another set of body surface potentials as inputs to a three-dimensional vector model of cardiac excitation. This produces a graphical view of the excitation of the heart called the vectorcardiogram (VCG). Finally, for long-term monitoring in the intensive care unit or on ambulatory patients, one or two ECG leads are monitored or recorded to look for life-threatening disturbances in the rhythm of the heartbeat. This approach is called arrhythmia analysis. Thus, the three basic techniques used in electrocardiography are:

1. Standard clinical ECG (12 leads)
2. VCG (3 orthogonal leads)
3. Monitoring ECG (1 or 2 leads)

The basic objective of electrocardiograph can be seen By looking at electrical signals recorded only on the body surface, a completely noninvasive procedure, cardiologists attempt to determine the functional state of the heart. Although the ECG is an electrical signal, changes in the mechanical state of the heart lead to changes in how the electrical excitation spreads over the surface of the heart, thereby changing the body surface ECG. The study of cardiology is based on the recording of the ECGs of thousands of patients

over many years and observing the relationships between various waveforms in the signal and different abnormalities. Thus clinical electrocardiography is largely empirical, based mostly on experiential knowledge. A cardiologist learns the meanings of the various parts of the ECG signal from experts who have learned from other experts.

3.2 Electrodes

As time went on, metallic electrodes were developed to electrically connect to the body. An electrolyte, usually composed of salt solution in a gel, forms the electrical interface between the metal electrode and the skin. In the body, movement of ions produces currents whereas in a wire, currents are due to the movement of electrons. Electrode systems do the conversion of ionic currents to electron currents.

Conductive metals such as nickel-plated brass are used as ECG electrodes but they have a problem. The two electrodes necessary to acquire an ECG together with the electrolyte and the salt-filled torso act like a battery. A dc-offset potential occurs across the electrodes that may be as large or larger than the peak ECG signal. A charge double layer (positive and negative ions separated by a distance) occurs in the electrolyte. Movement of the electrode such as that caused by motion of the patient disturbs this double layer and changes the dc offset. Since this offset potential is amplified about 1, OOO times along with the ECG, small changes give rise to large baseline shifts in the output signal. An electrode that behaves in this way is called a polarizable electrode and is only useful for resting patients.

3.3 The Standard Limb Leads

Figure 3.1 shows how we can view the potential differences between the limbs as ideal voltage sources since we make each voltage measurement using an instrumentation amplifier with very high input impedance. It is clear that these three voltages form a closed measurement loop. From Kirchhoff's voltage law, the sum of the voltages around a loop equals zero. Thus

$$II-I-III=0$$

We can rewrite this equation to express any one of these leads in terms of two leads.

$$II=I+III$$

$$I=II-III$$

$$III=II-I$$

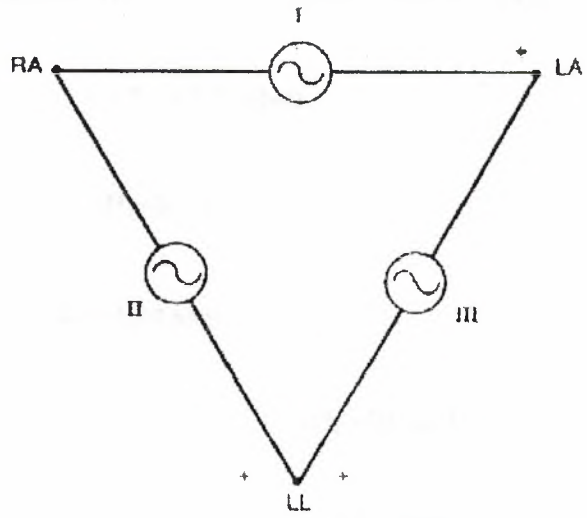

Figure 3.1 leads I, II, III are the potential differences between the limbs and LA Is the right and left arms AND LL is the left leg.

It is thus clear that one of these voltages is completely redundant; measure any two and compute the third. In fact, that is exactly what most. Machines do. Most machines measure leads I and II and compute lead might ask why we even bother with computing lead III; it is redundant so new information not contained in leads I and II. For the answer to this quest need to go back to Figure (3.1) And recall that cardiologists learned the relation between diseases and ECGs by looking at a standard set of leads and red appearance of each to different abnormalities. Since these three leads were in the beginning, the appearance of each of them is important to the cardiologists.

3.4 The augmented limb leads

The early instrumentation had inadequate gain to produce large enough EC for all subjects, so the scheme in Figure 3.1 Was devised to produce large amplitude signals, the left arm signal (augmented limb lead aVL, Iis Measured using the average of the potentials on the other two limbs as a reference, we can analyze this configuration using standard circuit theory, from the bottom left loop:

$$I * r + I * r - II = 0$$

$$I * r = II / 2$$

From the bottom right loop

$$-I * r + III + aVL = 0$$

Or

$$aVL = I * r - III$$

Combining eqs gives

$$aVL = II/2 - III = (II - 2 * III)/2$$

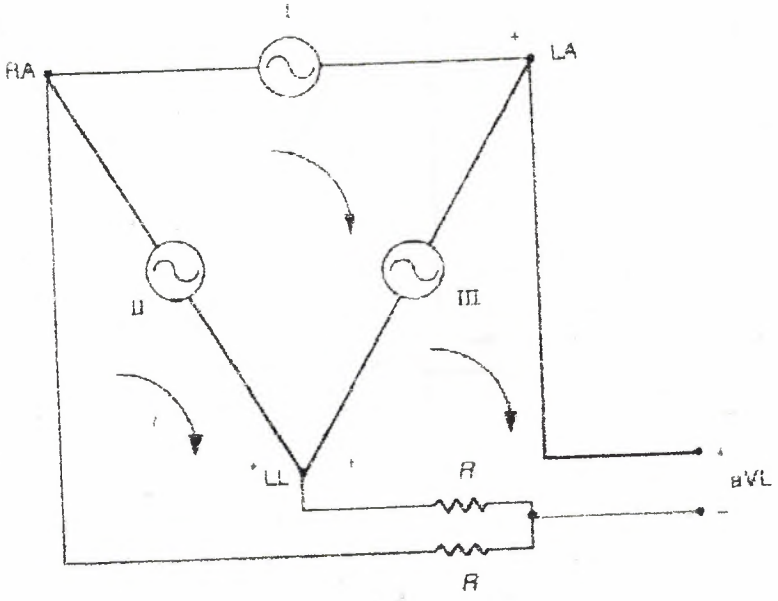

Figure 3.2 measuring the augmented limb lead Avl.

From the top center loop:

$$II=III+I$$

Substituting gives:

$$aVL=(III+I-2*III)/\ 2=(I-II)/\ 2$$

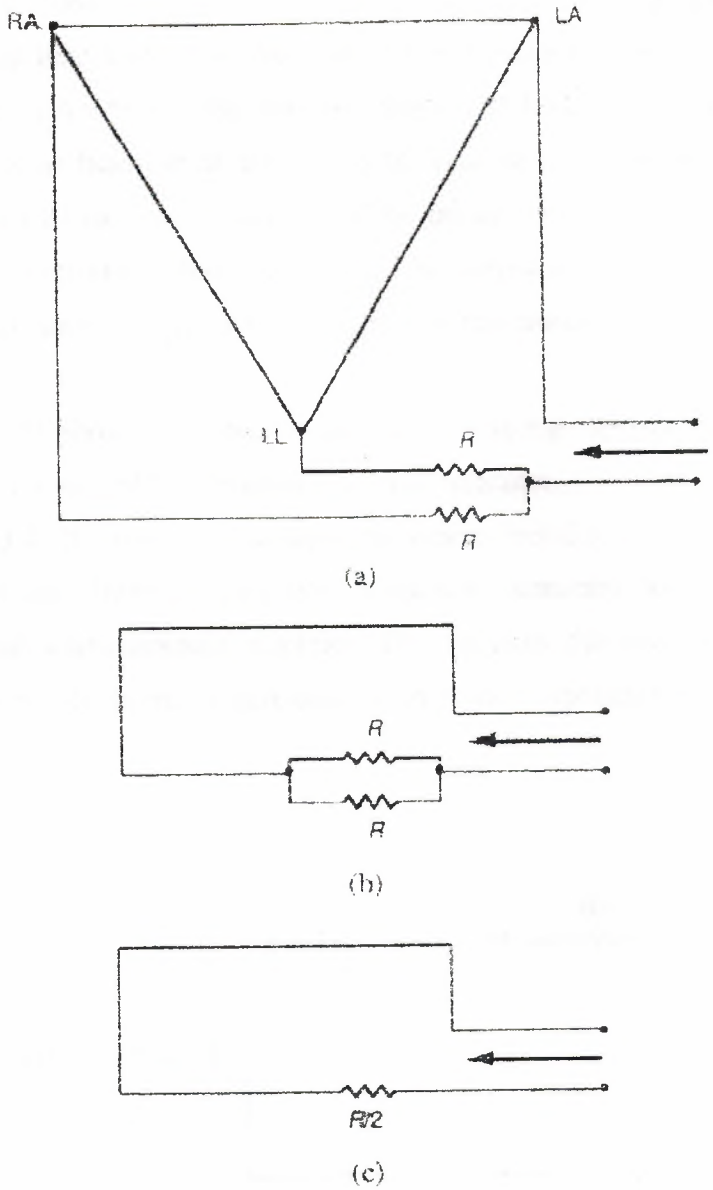

Figure 3.3 determination of the thevenin resistance for the aVL

This is the Th6venin equivalent voltage for the augmented lead aVL as an average of Iwo of the frontal limb leads. It is clear that aVL is a redundant lead since it can be expressed in terms of two other leads. The other two augmented leads, aVR and aVF, similarly can both be expressed as functions of leads I and Ill. Thus here we find an additional three leads, all of which can be calculated from two of the frontal leads and thus are all redundant with no new real information. However due to the empirical nature of electro cardiology, the physician nonetheless still needs to see the appearance of these leads to facilitate the diagnosis.

Figure (3.3) Shows how shorting out the ideal voltage sources and looking back from the output terminals find the Th6venin equivalent resistance.

Figure (3.4) Illustrates that a recording system includes an additional resistor of a value equal to the Th6venin equivalent resistance connected to the positive input of the differential instrumentation amplifier. This balances the resistance at each input of the amplifier in order to ensure an optimal common mode rejection ratio (CMRR).

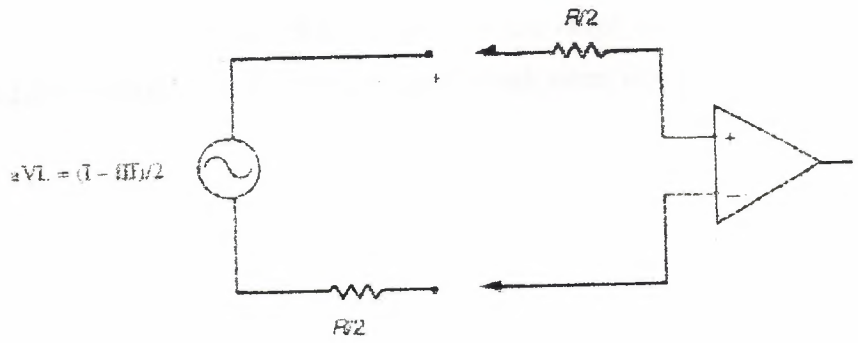

Figure (3.4) practical device for recording aVL.

3.5 ECG Signal Characteristics

Figure (3.5) shows three bandwidths used for different applications in electrocar diography (Tompkins and Webster, 1981). The clinical bandwidth used recording the standard 12-lead EGG is 0.05—100 Hz. For monitoring application such as for intensive care patients and for ambulatory patients, the bandwidth is striated to 0.5—50 Hz. In these environments, rhythm disturbances are principally of interest rather than subtle morphological changes in waveforms. Thus the restricted bandwidth attenuates the higher frequency n caused by muscle contractions (electromyographic or EMG noise) and the lo frequency noise caused by motion of the electrodes (baseline changes). An ii bandwidth used for heart rate meters (card jotachometers) maximizes the signal noise ratio for detecting the QRS complex. Such a filter passes the frequencies' the QRS complex while rejecting noise including non-QRS waves in such as the P and T waves. This filter helps to detect the QRS complexes but torts the ECG so much that the appearance of the filtered signal is not clinically ceptable. One other application not shown extends the bandwidth up to 500 1-1 order to measure late potentials. These are small higher-frequency in the ECG following the QRS complex.

The peak amplitude of an ECG signal is in the range of I mV, so an ECG typically has a gain of about 1,000 in order to bring the peak signal into a r. of about lV.

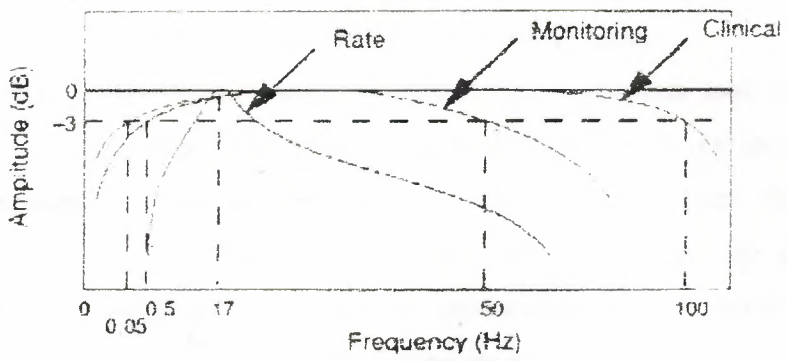

Figure (3.5) bandwidths used in electrocardiography.

3.6 Ecg Interpretation

This section covers the techniques for analysis and interpretation of the 12-leadECG. Then it discusses ST-level analysis that is used in cardiac stress test systems. Finally, there is a summary of the hardware and software design of a portable ECGarrhythmia monitor.

Computer interpretation of the 12-lead ECG uses algorithms to determine whether a patient is normal or abnormal. It also provides written description of any abnormalities discovered.

Historical review of ECG interpretation by computer

ECG interpretation techniques were initially developed and used on mainframe computers in the early 1960s (Pordy et al., 1968). In those days, mainframe computers centrally located in computing centers performed the ECG analysis and interpretation. The ECGs were transmitted to the computer from remote hospital sites using a specially designed ECG acquisition cart that could be rolled to the patient's bedside. The cart had three ECG amplifiers; so three leads were acquired simultaneously and transmitted over the voice-grade telephone network using a three-channel

analog FM modem. The interpretation program running in the mainframe computer consisted of several hundred thousand lines of FORTRAN code.

As technology evolved, minicomputers located within hospitals took over the role of the remote mainframes. The ECG acquisition carts began to include embedded microprocessors in order to facilitate ECG capture. Also, since the interpretation algorithms had increased failure rates if the ECG was noisy, the microprocessors increased the signal-to-noise ratio by performing digital signal preprocessing algorithms to remove baseline drift and to attenuate power line interference.

Ultimately the ECG interpretation programs were incorporated within the bedside carts themselves, so that the complete process of acquisition, processing, and interpretation could be done at the patient's bedside without transmitting any data to a remote computer. This technology has now evolved into stand-alone micro. Processor-based interpretive ECG machines that can be battery powered and small enough to fit in a briefcase.

The early ECG carts had three built-in ECG amplifiers and transmitted $^{2.5}$-sec-ond epochs of three simultaneous channels. In order to acquire all 12 leads, they sequenced through four groups of three leads each, requiring 10 seconds to send a complete record. Thus, the four acquired three-lead sets represented four different time segments of the patient's cardiac activity. Since a 2.5-second interval only includes two or three heartbeats, the early algorithms had difficulty in deducing abnormalities

Called arrhythmias in which several heartbeats may be involved in rhythm disturbance.

Interpretation of the 12-lead ECG

ECG interpretation starts with feature extraction, which has two parts. The goals of this process are (1) waveform recognition to identify the waves in the ECG including the P and T waves and the QRS complex, and (2) measurement to quantify a set of amplitudes and time durations that is to be used to drive the

interpretation process. Since the computer cannot analyze the ECG waveform image directly like the human eye-brain system, we must provide a relevant set of numbers on which it can operate.

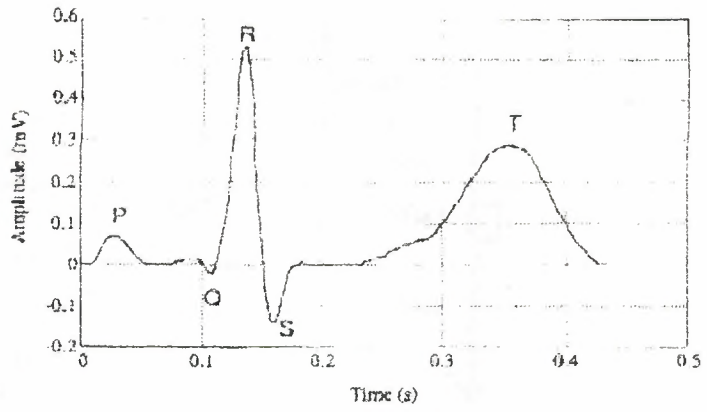

Figure (3.6) ECG for one normal heartbeat showing typical amplitudes and time durations for P, QRS, and T waves.

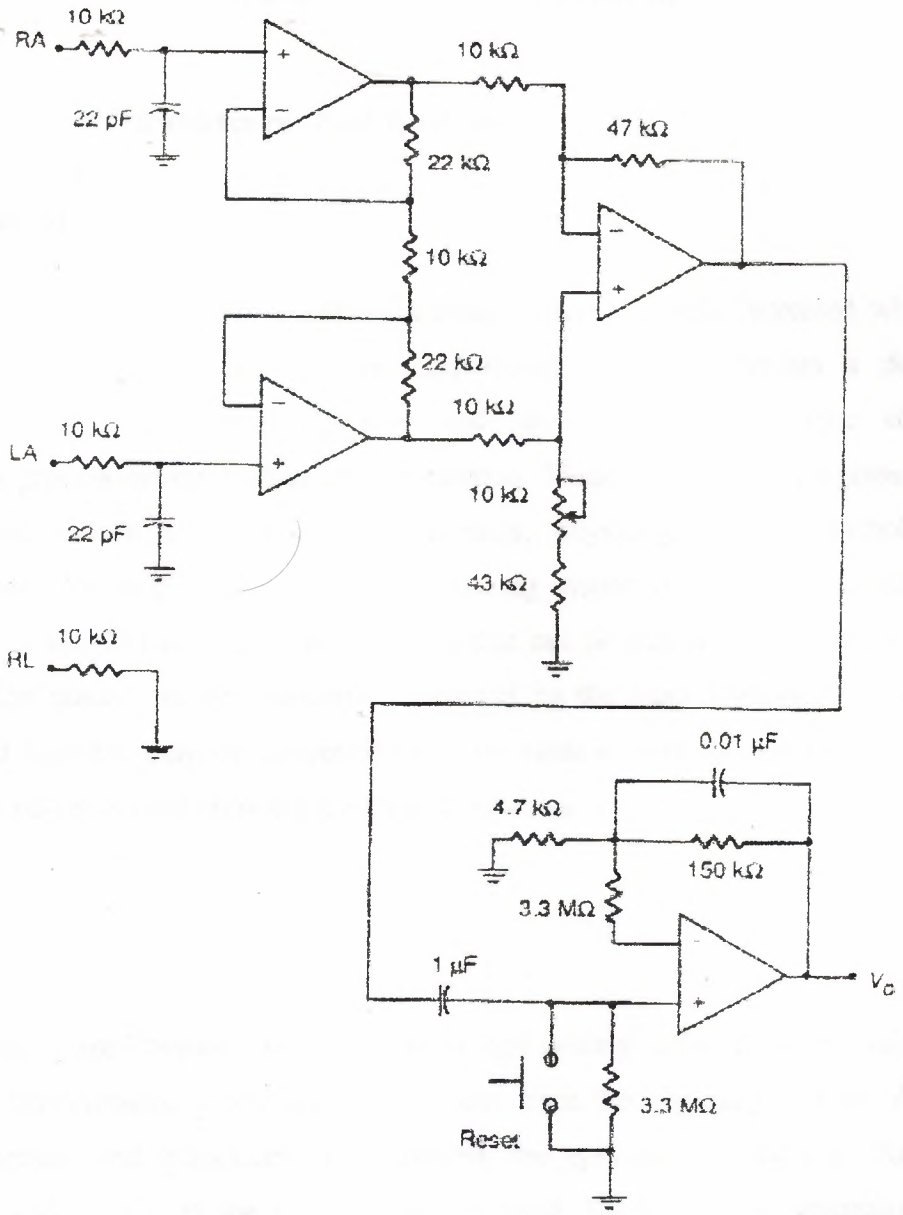

Figure (3.7) circuit diagram of ECG amplifier.

4. ROBOTICS APPLICATIONS

4.1 Sensors And Transducers: An Overview

Measurement systems

The amount of confidence in the results of a measurement is greatly increased when all factors influencing the measurement are fully understood. This requires a detailed knowledge of the measurement process and the possible interactions of the measurement process on the system being measured. These interactions can come from direct physical influences as well as biochemical, physiological, and psychological interactions with the measuring process. A measuring system is required to compare a quantity with a standard or to provide an output that can be related to the quantity being measured. The quantity to be measured is detected by the input transducer or sensor. The detected quantity may be converted to a mechanical form or electrical form of energy. For most biomedical purposes, the form is electrical.

Brief History

Because sensors and transducers are so broad and widely used, it is impossible to pinpoint the first invention. They have been around since the beginning of time. All life forms use sensors and transducers. For example, the eyes sense a stimulus from the environment and send it to the brain to be processed. Even a simple invention from many years ago such as the wind vane (tells which direction the wind is blowing) can be considered a sensor. It is only since the developments in microprocessor technology that digital transducers have become important and useful.

What are Sensors and Transducers

The words sensor and transducer are both used in referring to measurement systems. *Sensor* is derived from the word sentire meaning to perceive whereas transducer is from transducere meaning to lead across. To distinguish between the two, a sensor is a device that detects a change in a physical stimulus and turns it into a signal which can be

measured or recorded, and a transducer is a device that transfers power from one system to another in the same or in a different form. Normally, the sensor is just the sensing element itself and the transducer is the sensing element plus any associated circuitry. Sensors and transducers may sense either analog or digital signals. An analog signal is a continuous measurable quantity, and a digital signal is a quantity that is sampled at fixed intervals. A higher sampling rate increases the accuracy of measurement. Because the human body produces analog signals, analog-to-digital converters are required in measuring with digital sensors.

Classification of Sensors and Transducers

Sensors and transducers must be classified according to the physical property that they use (piezoelectric, photovoltaic, etc.) or according to the function that they perform (measurement of length, temperature, etc.). Since energy conversion is an essential characteristic of the sensing process, the various forms of energy should be considered. The following table lists the main forms of energy and their occurrence:

Type of energy	Occurrence
Radiant	radio waves, visible light, infrared
Gravitational	gravitational attraction
Mechanical	motion, displacement, forces
Thermal	kinetic energy of atoms and molecules
Electrical	electric fields, currents
Magnetic	magnetic fields
Molecular	binding energy in molecules
Atomic	forces between nucleus and electrons
Nuclear	binding energy between nuclei
Mass energy	energy given by E=mc^2

All of the above forms may be applied to biomedical measurements. For measurement purposes, six types of signals are important: radiant, mechanical, thermal, electrical, magnetic, and chemical. The signal is fed into an input transducer, which changes the form of energy, usually into electrical. A modifier, usually an amplifier, and an output transducer then convert the energy into a form to be displayed or recorded.

Three basic types of transducers are the self-generating, modulating, and modifying transducers. The self-generating type (thermocouples, piezoelectric, photovoltaic) does not require the application of external energy. Modulating transducers (photoconductive cells, thermistors, resistive displacement devices) do require a source of energy. For example, a thermocouple is self-generating, producing a change in resistance in response to a temperature difference, whereas a photoconductive cell is modulating because it requires energy. The modifying transducer (elastic beams, diaphragms) is characterized by the same form of energy at the input and output. The energy form on both sides of a modifier is electrical.

Why Do We Need Biomedical Sensors and Transducers?

The engineering profession has little room for improvement without measurements. An engineer must know the output of a measurand before he or she can manipulate it for a given purpose. Many years ago, people dealt with rulers and protractors to perfect geometry in structures. Today, advancements in technology have allowed measurements of complex systems that people previously thought were impossible. By the use of sensors and transducers, the properties of a system can be measured by observing the change in the properties of another. For example, the absorption of ultraviolet light in some chemical compounds can be measured by directing a given spectrum of light into a compound and measuring the amount of light transmitted on the other side with respect to its wavelength. The sensor provides this measurement, and the transducer converts it to an electrical signal that is representative of the measurement. From this signal, a computer can tell which wavelengths of light are absorbed and which are transmitted, also taking into account the reflected light. So why do we need these things? We do not need them for survival, but, for continuing improvement in technology, biosensors and transducers are a must. They allow us to measure useful entities such as the voltage across the heart, brain activity, and the presence of foreign compounds in the blood. From these measurements, physicians can prescribe treatments and detect abnormalities, and engineers can develop devices to correct abnormalities such as the pacemaker and defibrillator. Transducers and biosensors unveil the great curtain that masks the secrets of our bodily functions. For example, by measuring the

voltage across the heart, we have developed a graph of the voltage with respect to time, called the electrocardiogram (ECG) that is common for normal sinus heart rhythm in most people. Any change in the voltage pattern is representative of a problem such a ventricular fibrillation or heart flutters. The possibilities are limitless. Any abnormality that causes a change in a measurable property opens the pathway for new transducers and biosensors.

Examples of Modern Biomedical Sensors and Transducers

In Vivo Measurement of Dye Concentration Using an Evanescent Wave Optical Sensor. This sensor is designed for in vivo measurement of dye concentrations. Dye may be used for a number of purposes, usually to detect the presence of a chemical substance in the blood. This sensor, constructed with polished fibers, allows continuous monitoring of the florescent spectra between 380 and 650 nm. The dimensions of the sensor probe allow insertion into hypodermic needles for spectroscopic analysis of tissues and blood.

A Transcutaneous Blood Constituent Monitoring Method Using a Suction Effusion Fluid Collection Technique and an Ion-Sensitive Field-Effect Transistor Glucose Sensor: This sensor allows noninvasive, transcutaneous monitoring of low molecular weight substances in the blood without ordinary blood sampling. It has been effectively used to measure glucose levels in humans. Such a sensor opens the possibility of disease detection without the use of needles to withdraw blood.

Electrocatalytic Glucose Sensor:

This sensor is a flowthrough cell with three electrodes that can be integrated into a blood vessel. The measurement principle is based on the electrochemical oxidation of glucose at a membrane-covered noble-metal electrode. Noninvasive Measurement of Blood Glucose Concentrations by Analyzing Fourier Transform InfraRed Absorbance Spectra Through Oral Mucosa: This experiment involved the evaluation of whether Fourier transform infrared spectroscopy with an attenuated total reflection prism could be applied for noninvasive glucose measurement through oral mucosa. The results showed the same absorbance peak at 1033 cm^{-1} in glucose aqueous solution as in the absorbance spectra through mucous membrane. The noninvasive measurement of

glucose in blood could be useful for diabetes patients. Optical Oxygen Sensor Based on Phosphorescence Lifetime Quenching and Employing a Polymer Immobilised Metalloporphyrin Probe: Continuous monitoring of the respiratory gases (oxygen and carbon dioxide) is a common procedure in the medical field. It is used for the study of respiration, assistance in anesthesiology, and treatment and diagnosis of cardiopulmonary disorders. Such a sensor is useful in monitoring these gases. Simple, Noninvasive System for Measuring the Heart Rate of Avian Embryos and Hatchlings By Means of a Piezoelectric Film:

The minute movement of the incubated avian egg is produced by atrial and ventricular contractions as well as blood ejection to the aorta. To measure the heart rate of a newly hatched bird noninvasively, researchers used a flexible piezoelectric film that detected precordial movements of hatchlings comparable to their cardiac contractions. This is referred to as the apexcardiogram (ACG).

Laser Photoacoustic Determination of Physiological Glucose Concentrations in Human Whole Blood:

A spectroscopic technique, based on photoacoustic spectroscopy, is used to determine the glucose concentration in human whole blood. The device uses a carbon dioxide laser operating with microjoule pulse energies. The sensitivity of this system is comparable with existing commercial enzymebased diagnostic systems presently used in hospitals. [9]

Pulse Oximetry: Theoretical and Experimental Models:

The pulse oximeter is a noninvasive optical instrument that measures arterial oxygen saturation in a pulsatile vascular bed. The optical properties of blood are measured as a function of cuvette depth by transmission spectrophotometry using red and infrared light-emitting diodes as light sources.

Monitoring of Respiratory and Heart Rates Using a FibreOptic Sensor: Results from the use of a new fiberoptic probe to monitor respiratory and heart rates provide evidence that respiratory and heart rates can be monitored using the reflection mode of photoplethysmography (PPG). The patient can be monitored from different sites, and

the method is convenient. The probe is also X-ray transparent, insensitive to electromagnetic interference and may be made very light and small.

Fast Responding Automated Airway Temperature Probe:

The purpose of this project was to build a temperature-measuring system to be placed into the airways of airway diseased patients while they were exercising. The result was a device that could be used to monitor the thermal transients, which are seen in the airways of asthmatic patients as their airways rewarm following hyperpnea.

4.2 A Robot Test-Bed For Assistance And Assessment In Physical Therapy

This article describes an experimental test-bed that was developed to assist. And assess rehabilitation during physical and occupational therapy. A PUMA 260 robot was used for which a controller and interface software wasdeveloped in-house. The robot can operate in two modes: (i) passive and (ii) active. In the passive mode, the robot moves the subject's arm through specified paths. In the active mode, a subject guides the robot along a predefined path overcoming a specified joint stiffness matrix. In this mode, the controller provides gravity.

Compensation so that the robot can support its own weight in an arbitrary configuration. The developed graphical interface enables display of the current configuration of the robot in real-time, customize experiments to a specific subject, and collect force and position data during an experiment.

The results of a preliminary study using this test-bed are also presented along

With issues involved in choice of paths and interpretation of the results. Keywords: Robot, Rehabilitation, Assessment, and Physical Therapy.

4.2.1 Introduction

Active exercise is an important component of rehabilitation. Resistance is typically accomplished by using expensive exercise equipment or is applied manually by a therapist. Most available exercise equipment allowing for controlled application of forces to a limb or the trunk limit motion to one plane or forces are applied directly on to a single joint. As such, their relevance to functional movements is extremely limited. And although manual resistance applied by a therapist allows for exercise of multiple degrees-of-freedom (Voss et al., 1985), it requires the therapist's complete attention to only one patient at a time, increasing the cost of treatment.

The need for objective, quantitative and reliable evaluation tools to assess the

Neuromuscular performance of patients is critical to both physical and occupational therapy (Carr and Shepherd, 1990; Chandler et al., 1980).

The ability to quantify movement performance has been a particular problem in these disciplines. This is specially the case in neurological rehabilitation, where most assessments

Of motor function have been based on an ordinal scale of quantification (Barley, 1935; Poole and Whitney, 1988; Rothstein, 1985;Scholz, 1993). These facts indicate that the development of a device that would allow for controlled motion of the entire limb in quasi-functional patternscould improve patient evaluation and treatment effectiveness while reducing its time and cost. Some importantissues that need to be addressed are (i) development of a user friendly robot with a safe control system, (ii) development of a versatile subject

Interface, and (iii) design of suitable experiments to evaluate the effectiveness of the approach. However, there have been only a handful of studies that have attempted to develop complex machines to accomplish this task and that have

Evaluated protocols for their application. Noritsugu et al. (1996) developed a two degree-of-freedom rubber artificial muscle manipulator and performed

Experiments to identify human arm parameters. Impedance control has been suggested as an effective approach to control human-machine systems (Hogan, 1985) and has been studied for direct drive robots (McCormick and Schwartz, 1993). Some preliminary studies have been presented on the application of robot.

Technology to enhance the rehabilitation of stroke patients (Krebs et al., 1995). These studies suggest that robots are promising new tools in this area. A prototype for bimanual lifting (Lump et al., 1995) and MIME (Mirror Image Motion Enabler) has been reported for post stroke therapy (Lum et al., 1997).

This article presents some recent efforts at University of Delaware in the development of a robot test-bed to assist and assess rehabilitation. The salient features of this study are: (i) an in-house developed controller for the robot motivated by safety considerations, (ii) a versatile interface that can be used to customize subject experiments, (iii) a mechanism to collect force and position data during an experiment, (iv) protocols to provide assessments using the robot test-bed. The outline of this article is as follows: Section 2 presents a description of the robot set-up. The design of experiments, data analysis, and results are described in Section 3. These are followed by a discussion of the results,

Their implications and conclusions.

4.2.2 Robot Test-bed

The test-bed consists of a six degree-of- freedom PUMA Mark II 200 series robot arm. Due to inherent limitations of the original controller provided by the manufacturers, an in-house controller was developed that uses LM628 based servo controllers interfaced with a Pentium 233 MHz computer. The computer also handles the user interface and real-time display of the graphics. A schematic of the set-up is shown in Figure 1 along with data flow in the system. The robot joints are equipped with optical encoders that provide a resolution of roughly 0.005 degrees and a 6-axis force-torque sensor, manufactured by JR3 Inc. (Model No. 67M25A). Even though the robot has the capability to move in 3-dimensional space, in this study, the robot motion was restricted to the vertical plane.

A typical session in the active mode is:

The therapist or experimenter recalls a path or defines a new path by describing 40 points on the outer and inner walls. The robot moves the subject to the starting point of the central line and handles the control over to the subject. The subject is in full control of the robot arm and makes an attempt to track the central line while overcoming the stiffness specified at the joints of the robot. The stiffness can be varied along the path using control panels on the screen.

During motion, the position of the end-effectors and subject exerted forces and moments are recorded by the 6 DOF force sensors. During experiment, if the subject hits a wall boundary, the robot temporarily takes over control, nearest point on the centerline, and then returns control to the subject. The color of the wall that is hit changes during this period giving the subject a visual cue of the

Collision. The original color is restored once the robot end is at the central line and the control is handed over to the subject. A trial traverses the path in both forward and reverse directions, although more repetitive trajectories can be specified in principle.

A gravity model for the robot in the vertical plane was developed using analytical approach verified by experimental data (Rao, 1999). It was observed that this model for the gravity loading worked quite well over the useful workspace of the robot. The geometric planning for the robot was done using its inverse kinematics model.

4.2.3 Discussion

This article has described the design and fabrication of an experimental test-bed Consisting of a PUMA 260 robot arm with an in-house designed controller unit, interfaced with a Pentium based computer. The software's written in an object-oriented environment with a graphical user interface that enables one to customize experiments for a subject. The software also provides the user with a

Real time animation of the robot motion and the path traced by the robot robot joints provide position data while a six degree-of-freedom force-torque sensor at the end-effecter provides force and torque data that can be used to assist and quantify patient rehabilitation. Our test-bed provides a means to measure quantitatively the performance of quasi-functional movement patterns by patients with a variety of movement disorders. A significant problem in patients who have suffered a stroke, for example, is the presence of coordination deficits. These are especially difficult to quantify. Although information obtained about

Movement patterns produced by the end-effecter (i.e., hand or foot) does not provide detail about individual impairments, the information provided may be extremely valuable for assessing the effects of specific impairments or different levels of impairment on functional movement patterns. With our test-bed, quantitative assessment of quasi-functional movement patterns is made possible where such information was previously very difficult to obtain. Recent research has indicated that

movement trajectories may be planned by the nervous system in terms of movement of the end-effecter rather than the individual movement

Components Such information may be essential, therefore, for identifying deficits in central planning or the transformation

Of a central plan into action. Most importantly, the information provided will be helpful in customizing a patient's treatment, for helping to determine when to stop treatment because it is yielding no further improvement, and for providing data to evaluate the efficacy of particular treatment approaches. Combining information obtained from our test-bed with other types of data, e.g., video

Analysis of joint motion and/or electromyography should provide a means for assessing the relationship between whole limb motion and the underlying impairments. In our very preliminary tests of the device, we have shown that information on end-effecter position and force can be obtained which may be useful for characterizing changes in performance. The ultimate goal of rehabilitation is to improve the patient's functional capabilities, regardless of the

Underlying pathology. Our test-bed can potentially provide a number of advantages for neuromuscular rehabilitation. For example, when there is weakness of many muscles that act to control movement and stability of a limb, strength training of each of these muscles is necessary. The use of single degree-of-freedom dynamometers to train the affected muscles can be very time-consuming. Our device, on the other hand, would allow for simultaneous strength training of many muscles through the performance of quasi-functional

Patterns of movement. Although free weights or pulley systems allow for simultaneous strength training of many muscles as well, it may be impossible for a patient to control free weights in the early stages of rehabilitation. Moreover, because our device can, in principle, be made to provide accommodating resistance throughout the range of motion, a patient would never work against more resistance than he or she can handle. By providing real-time animation of Robot motion and movement constraints, our test-bed provides a means for providing immediate feedback to the patient about the results of their movement along a specified spatial path (e.g., patient keeps the hand centered, deviates toward the outer wall, etc.), which may be made simple or complex according to the current abilities of the patient. In addition, more performance oriented

Feedback can be provided to the patient after one or several trials (e.g., the force field generated by the hand during the movement). Such information is essential for motor

learning (Weinstein, 1990). Ultimately, our goal is to use the graphics interface to make therapy game-like for the patient with the goal of increasing patient interest and motivation. Most functional tasks involve movement of an entire limb or a substantial number of joints at the very least. It is also common for such tasks to be carried out in all three spatial dimensions simultaneously. An important goal, therefore, is to design training paradigms that approximate as closely as possible this reality. The tests reported in this article-evaluated movement of the entire upper extremity, although the movements were limited to a single plane. Thus, an important future direction will be to extend the development of the robot's use to three-dimensional movements. This will require more complicated graphic displays to provide the patient with convincing information about the hand's position in three-dimensional space. However, it will first be important to improve the robots

Performance in the current set-up and to perform more quantitative tests of its

Performance with human subjects, including patients with movement deficits. Although the Puma robot was designed for industrial use, we have shown that it has potential for use in rehabilitation as well. However, several problems will need to be resolved before this particular robot can be used effectively with patients. Currently, we are working to improve the interface of the robot handle with the subject's hand so that it can be accommodated to the different grasping abilities of patients. This is a general problem faced with the use of any robot, however. In terms of controlling forces applied to a subject's hand, it would be ideal to be able to specify the Cartesian stiffness at the end-effecter rather than a matrix of joint stiffness. To date, this has been difficult because of difficulty in characterizing and accounting for joint friction. This problem does not preclude the robot's use for quantifying movement deficits or in training movement patterns, although it may limit its overall usefulness. The most encouraging result of our work to date has been the development of a graphical user interface that is flexible and easy to use. As described in the Results section, subjects learned to minimize deviations from the centerline in repeated trials. Also, the torque they applied to the end-effecter became smoother over blocks of experiment. These results suggest that robot set-ups like these possess the potential of providing effective aids for rehabilitation.

4.3 Robot-Aided Neuro-Rehabilitation In Stroke: Three-Year Follow-Up

We are applying robotics and information technology to assist, enhance, and quantify neuron-rehabilitation. Our goal is a new class of interactive, user affectionate clinical devices designed not only for evaluating patients, but also for delivering meaningful therapy via engaging "video games." Notably, the Robot MIT-MANUS has been designed and programmed for clinical neurological applications, and has undergone extensive clinical trials for more than four years at Burke Rehabilitation Hospital. Recent reports showed that stroke patients treated daily with additional robot-aided therapy during acute rehabilitation had Improved outcome in motor activity at hospital discharge, when compared to a Control group that received only standard acute rehabilitation treatment.

This paper will review results of a three-year follow-up of the 20 patients enrolled in that clinical trial. The three-year follow-up showed that:

- The improved outcome was sustainable over three years.
- The neuron-recovery process continued far beyond the commonly

Accepted 3 months post-stroke interval.

- Neuron-recovery was highly dependent on the lesion location.

4.3.1 Introduction

Over four million Americans suffer from disabilities and impairments as a result of the leading cause of permanent disability in the U.S.: stroke. Physical and occupational therapy provides a standard, presumably beneficial treatment, but it is labor-intensive, often requiring one or two therapists to work with each patient.

Demand for rehabilitation services is also certain to increase in the coming decades due to the graying of the population.

The expected increase in the number of stroke patients will increase the nation's health care financial burden, which continues to grow above the rate of inflation (HCFA). Until recently, health care providers have attempted to reduce the costs of caring for patient's rehabilitation primarily by shortening inpatient stays. Once the practical limit of abbreviated inpatient stays is reached, further efficiencies will be attainable chiefly

by addressing clinical practices themselves. Our research suggests that robotics and information Technology can provide an overdue transformation of rehabilitation clinics from primitive manual operations to more technology-rich operations. Claims that manipulation of the impaired limb influences recovery remains controversial. Therefore, we tested in a pilot study whether manipulation of the impaired limb
Influences recovery during the inpatient rehabilitation period. The results were
Positive and reported elsewhere (Aisen, 1997; Krebs, 1998). This paper describes our efforts to assess whether the previously reported improved
Outcome during inpatient rehabilitation was sustainable after discharge, or alternatively, whether manipulation of the impaired limb influenced the rate of
Recovery during the inpatient phase, but not the "final" plateaus.

4.3.2 Methods

We used the novel robot MIT-MANUS, which has been designed for clinical neurological applications. Unlike most industrial robots, MIT-MANUS was designed to have a low intrinsic end-point impedance (i.e., be back drivable), with a low and nearly-isotropic inertia and friction [Hogan, 1995; Krebs, 1998].
Twenty sequential hemi paretic patients were enrolled during 1995 and part of
1996 in the pilot study. Patients were admitted to the same hospital ward and assigned to the same team of rehabilitation professionals. They were enrolled in either a robot-aided therapy group (RT, N=10) or in a group receiving "sham" robot-aided therapy (ST, N=10). Both groups were described in detail elsewhere (Aisen, 1997; Krebs, 1998). Patients and clinicians were blinded to the treatment
Group (double blind study). Both groups received conventional therapy; the RT group received an additional 4-5 hours per week of robot-aided therapy consisting of peripheral manipulation of the impaired shoulder and elbow correlated with audio-visual stimuli, while the ST group had an hour of weekly robot exposure. Twelve of these 20 inpatients were successfully recalled and evaluated almost three years post-stroke (of the remaining 8 patients, 4 could not be located, 1 died, 3 had a second stroke or other medical complications). Six patients in the RT and in the ST group were comparable in gender distribution, lesion size (RT = 53.8 ±22.9 cm, ST = 53.9 ± 28.2 cm and length of time from stroke to follow-up (RT: 1113.3 ± 59, ST: 960 ± 81 days).

There was no control over patients' activities after hospital discharge. The same standard assessment

Assess all patients during rehabilitation was used at recall three years post hospital discharge (RT and ST groups). This assessment was performed by the

Same "blinded" rehabilitation professional. Patients' motor function was assessed by standard procedures including: the upper limb subsection of the Fugal-Meyer (F-M), Motor Power for shoulder and elbow (MP), Motor Status Score for shoulder and elbow (MS1), and Motor Status Score for wrist and fingers (MS2).

Results

The improved outcome observed in the first phase of the pilot study was sustained after three years. The change in scores for the twenty patients enrolled in the first phase of trial between admission and discharge from the rehabilitation hospital. Table II shows the same change in score during this first phase limited to the twelve patients successfully recalled (Volpe-a, 1999). This table also shows the change in scores between recall and discharge, as well as total change (between recall and admission to the rehab hospital). This data should be interpreted with caution due to the small number of subjects. Nevertheless, the group of patients treated daily with additional robot-aided therapy during acute rehabilitation had improved outcome in motor activity at hospital discharge, when compared to a control group that received only standard acute rehabilitation treatment. Improved outcome was limited to the muscle groups trained in the robot-aided

Therapy, i.e., shoulder and elbow (Table II MS1 - D1 score). The improved outcome during inpatient rehabilitation was sustainable after discharge. Note that, comparing the overall recovery (between admission and recall) the MS1 for shoulder and elbow (which were the focus of robot training) of the experimental group improved twice as much as the control group (Table II MS1 - D3 score). Note also that both groups had comparable improvement between hospital discharge and three-year recall (period without robot-aided therapy, Table II - D2 score). Furthermore, eight out of twelve patients successfully recalled continued to improve substantially in the period following discharge (RT & ST

Subjects). This finding challenges the common perception that patients stop improving motor function after about 11 weeks post-stroke (e.g., Jorgensen, 1995, The

Copenhagen Stroke Study). It suggests that there may be an opportunity to further improve the motor recovery of stroke patients by continuing therapy in the outpatient phase, for example, using the technology that is the focus of our project.

4.4 Minimally Invasive Surgery

Minimally invasive surgery covers a wide variety of surgical and medical procedures that reduce the actual "opening" of the body. The endoscope has been the key advancement tool for minimally invasive surgery. According to a project sponsored by the European Commission, nearly all-surgical procedures can be partially or completely replaced by new minimally invasive procedures.

One example of the effects of minimally invasive surgery on today's medical community is the rapidly spreading use and development of laparoscopic cholecystectomy. This technology has spread faster than any other medical technology due to the growing demand by the patient community. The technique requires much less recuperation time than traditional surgical methods. People with gall bladder problems which required surgery, traditionally experienced four to six week recuperation periods whereas with less invasive procedures, patients are often able to leave hospital care the same day they have the surgery. Also where the traditional open surgery caused patients to experience considerable pain, the new techniques are much more comfortable. Patients who receive a laparoscopic cholecystectomy nearly always return to normal activities within a few days of their surgery. This procedure appears to be safer than traditional methods and will probably completely replace older surgical methods in the future.

Safety considerations must be taken into account whenever introducing a new medical procedure. Many medical professionals, particularly surgeons, feel that minimally invasive surgical techniques have been rushed onto the medical forefront without proper evaluation by the medical community. These new techniques often require specialized training by experienced professionals before the technique can be considered safe to perform. Due to heavy pressure from the patient and medical communities, the new minimally invasive surgical procedures and techniques have been practiced and advanced while viewed by many as unsafe. Many health care professionals feel that the benefits of many of the less invasive procedures have not been established well enough to be as widespread as they are. In many past cases, procedures have spread with wide ranging acceptance only to be found useless or dangerous.

Many in the health care profession feel that some minimally invasive techniques have been too slow to approach the forefront of the medical community. The lack of political interest and financial funding are the two main contributors to the slow advancement of some less invasive procedures. Many of these procedures have great potential benefits and are very worthy of financial funding for medical studies. [4,9]

Coronary artery bypass surgery:

The coronary artery bypass graft (CABG) surgery is a commonly performed procedure worldwide. A device that would enable surgeons to perform the operation on a beating heart would make this procedure less invasive, thus reducing the post-operative complications.

The occlusion of a coronary artery prevents perfusion of the heart tissue and it may result in necrosis of the tissue and an infarct with a severe and life threatening damage to the myocardium [April96]. The purpose of the CABG operation is to provide blood flow through the coronary circulation by attaching a blood vessel (graft) from some other part of the body to a coronary artery. The sewing of the bypass graft to the coronary arteries entails very little detrimental physiologic impact to the patient t and could, if there were no other issues, be considered a minor procedure in terms of patient recovery [Treat97]. What makes the operation fairly invasive and detrimental to the patient in the short run is the need to open the chest cavity ("sternotomy ") to obtain access to the heart and also to place the patient's entire circulation on a cardio-pulmonary bypass machine. Although the negative effects, such as the post-operative pain, of the sternotomy are real, they are greatly overshadowed by the neg ative effects of the cardiopulmonary bypass machine. Placing a patient on the bypass machine is quite destructive to the circulating blood elements such as red cells and platelets and produces profound and sometimes life-threatening post-operative comply captions including bleeding and cerebrovascular strokes [Treas97]. The reason for placing the patient on the bypass machine is to keep the heart still while the surgeon performs the sewing of the graft onto the coronary arteries that are fairly small and require optimum conditions to work on [Borst97]. Although cardiac surgeons are attempting to sew grafts onto the beating heart, this procedure is obviously difficult and is at the outer limits of human surgical skill. Surgical operations on the beating heart would be much easier to perform if the surgeon had a steady view of the heart surface. A video camera can

provide a stabilized image of the heart. The idea behind this CABG surgery device is to move the video ca mere in concert with the heart and provide the surgeon with a view free of cardiac motion. The camera and custom-designed surgical instruments are mounted on a robotic manipulator. The camera motion is controlled by a heart motion-tracking algorithm. This provides the surgeon with a stationary picture of the heart on the video camera's monitor. The surgeon can then control the surgical instruments telerobotically and perform the surgery more easily. This thesis describes a manipulator, which will be used to move the camera and the surgical tools with high velocities and high accuracy. A parallel link manipulator called the Stewart Platform is proposed because of its advantages over serial link main epilators. The sections that follow review the current state of the art, describe the proposed mechanism, analyze its kinematics properties, and discuss design tradeoffs in building the mechanism. Simulation results are also presented for a number of design s.

Minimally invasive coronary artery bypass surgery

Minimally invasive coronary artery bypass (CABG) surgery is a relatively new technique with increasing numbers of operations performed every year. Research is directed towards operation on the beating heart without need for cardiopulmonary bypass and heart access through small incisions. Most minimally invasive CABG procedures are limited to the cases of a single-vessel disease. The heart can then be accessed through a minithoracotomy, allowing anastamosis of the left internal mammary artery (LIMA) to left anterior descending coronary artery (LAD) [Mishra97]. The heart surface is stabilized using commercially available systems, for example the Access Platform and Stabilizer (CardioThoracic Systems, Inc., Cupertino, CA) [Cremer97] or by a suction device the Octopus Tissue Stabilizer (Medtronic, Inc., Minneapolis, MN) [Mack97a]. The motion of a marker on the unrestrained heart surface covers an area of 15mm x 15mm. If the Octopus device is used to restrain the movements of the heart then the marker displacement is reduced to about 1mm x 1mm [Borst97]. The animal trials of a totally endoscopes CABG (E-CABG) are performed, using a stereo camera to obtain a three-dimensional video image. The heart is stabilized and a three-dimensional video hears d-mounted display is used for visualization of the operative field [Mack97a]. According to Mack, the procedures can be made more users friendly by means of robotic virtual immobilization of the heart surface. A high-speed

tale-operated surgical robot would be placed in the chest cavity through ports and sit there in a "cardio stationary orbit", tracking a fixed point on the heart while the surgeon would be viewing a "virtually immobile" surgical field. Alternatives to the visual imaging are laser speckle surface imaging, three-dimensional co focal laser microscopy and mechanical spectroscopic imaging. Utilizing some of these technologies, only the structures of interest could be imaged creating virtually bloodless field for the perform a cue of the procedure.

Robot Assisted Surgery

Robots are widely used for orthopedic surgery and stereo tactic microsurgery. They offer high precision positioning of the surgical instruments and better stability of the bone machining tools. Some examples of such robots are given in [Troccaz97]. ROBODOC is an active six Degree-Of-Freedom (6-DOF) robotic system for femoral bone machining in hip surgery, and AESOP (Computer Motion Inc) is a SCARA robot for laparoscopes with six DOF. The AESOP system can be controlled by the surgeon's voice. Four of its six DOF are active and two passive, which gives it some safety features. Some of the robot assisted surgical tools are configured as synergistic devices and utilize the force feedback. These include the Passive Arm with Dynamic Constar nits (Paddy, TIMC Laboratory) and the knee surgery Active Constraint ROBOT (ACROBOT, Imperial College of London). ACROBOT employs back drivable motors so that both the user and the motors together actuate the tool. These areas were, until recently, dominant Ed by serial link manipulators as it can be seen from other overviews of medical robots [Burdea96], [Khoda96]. [Lavallee96] describes a system for stereo tactic microsurgery in clinical use since 1989. The system uses a robotic arm with 6-DOF with repeatable alit of ±0.2mm. Commercially available robots like PUMA-560 [Santos95] and IBM Sacra 7565 [Rovetta96] are often used. All these systems tried to integrate visual imaging with the three-dimensional data obtained by CT or MRI, but the surgeon was responsible le for the control of the robotic tool. [Taylor96] presents a telerobotic system for laparoscopic surgery with intelligent trajectory and motion control, where the surgeon just points to the structure of interest and an algorithm handles the trajectory Ge nation. Recently, Stewart Platform (SP) type manipulators have been used for robotic assisted surgery. Stewart Platform with Fixed Actuators has been designed for ophthalmic surgery by Grace [Grace93]. An SP manipulator is being

tested for image guided orthopedic dice surgery. After the registration of the manipulator position, a tool is mounted on the manipulator platform and the bone is machined. The problem of small workspace of the parallel link mechanisms is solved by adding special adapters that can reach the region of interest while the robot is moving within its working envelope. The robot workspace is 65x65x65 mm^3 if the angle between the base and the platform is less than 15° and the robot maximal velocity is 10mm/s [Brandt97]. Tele-robotic systems have also been proposed to solve problems in microsurgery and remote surgery. The idea of using robots in microsurgery is to scale down a surgeon's motion by a master-slave manipulator. A cable driven 6-DOF manipulator for micros roguery called RAMS has been developed at JPL [Schener95]. An experimental master-slave 6-DOF scaling teleportation system has been developed at the University of British Columbia, Canada. The manipulator is positioned near the region of interest by a large r 6-DOF robot. Both master and slave are magnetically levitated manipulators, the motion of the master is scaled-down to smaller motions of the slave and the scaled-up force feedback is applied to the master, in proportion to the force sensed by the slave end-effector [Salcu97]. Mitsuishi et al. implemented a master-slave tele-robotic system for micro blood vessel suturing with two small robotic arms. The surgeon can see on a monitor a magnified image from a small CCD microscope. The display monitor move s, tracking the motion of the operator's face while the CCD microscope rotates correspondingly about the focal point of the microscope. The operator controls two rotational-force-feedback-free master-slave manipulators (only translational forces feedback) [Mitsu97]. Tele-robotic principles are applied also at larger distances: a robot in Italy was remotely controlled by a surgeon in the United States performing an operation on a model with a pig's organs. The two laboratories 10,000 km far from each other were connected via a satellite link [Rovetta96].

Tracking

A series of robotic systems for neurosurgery have been developed as a result of the ET project. Through its ten-year development, the systems went through a number of modifications, most of which involved different devices for track in the position of an object in three-dimensional space [Reinhardt96]. The system was used to superimpose coordinates of the surgical instrument with the three-dimensional images recorded by a CT, so that the surgeon could accurately operate the tissues in the brain not easily

identified by a human. The first version of the system employed a mechanical digitizer to determine the tool position and achieved an accuracy of ±3mm. The next version used the same principle to resolve the tool position, but an h heavier and more robust digitizer arm yielded an accuracy of ±2mm. In the next stage of the project, ultrasonic spatial localization device Sonic Digitizer GP8-3D (Science Accessories Corp., Stratford, Conn.) could determine the positions of ultrasound tar smatters in space, sampling the distances between the transmitters at the rate of 24kHz. The surgical instrument was now hand held, with the transmitters attached to it. The accuracy of the system was ±1mm. Three CCD line-scan cameras manufactured by Pix sys Inc. (Boulder, CO) were used in the following version of the system to detect positions of Leeds with the measuring accuracy of ±1mm. Tracking of an object can be performed using ultrasound. Several piazza-electric transducers can be attached to the mobile object and to some known points in space. Ultrasonic systems determine the position of the object by measuring the distances bet even the transducers. These systems can acquire the distances very fast, but the computation of the object position is very time consuming. Zoometrics Inc. system has been used to determine the shape of the heart surface but the actual position computation n is done off-line [Dickstein96]. In order to speed-up the position estimation, the transducers can be arranged on the vertices of a cube.

Another system, often used for tracking the spatial position, is Protract manufactured by Northern Digital, Inc. It is an optical system with active IR beacons that are flashing one at a time, while their position is sensed by three line-scan CCD camera as, with an absolute accuracy better than ±0.1mm [Cutting96], [Taylor94]. Instead of active IR beacons that are connected to the electronic device with wires, some optical tracking systems use passive markers illuminated by an IR source Brain LAB (Brain LAB GmbH, Germany, VISLAN (Guy's Hosp., London, U.K.). If the markers are to be occluded during the surgical procedure, an electromagnetic system can be used (Phloem's Inc, Ascension Technologies Inc.), but large errors can occur if a ferromagnetic material is brought near the measuring system. Taylor implants three pins into the bone and uses an off-the-shelf video camera to determine the position of the bone. An object can be tracked using a video camera by detecting four co-planar markers on the object, utilizing the principles of unclear acted stereo. Sometimes an object to be tracked does not have a planar surface that can be used to attach the

markers, for example a human leg. Unaware and Canada attach several markers on the object surface, record the images of the moving object and the n choose only four of those markers that appear to be closely co-planar. Later, they use these four markers for tracking the object in space [Uenoh95]. Marker detection is simplified if an image of the region of interest is analyzed and a histogram of the colors in the image is created. [Wei97] describes color-coding for tracking of laparoscopic instruments based on the green color that does not appear in a laparoscopic image.

5.1 Physiological Effects of Electricity

For a physiological effect to occur, the body must become of an electric circuit. Current must enter the body at one point leave at some other point. The magnitude of the current is equal the applied voltage divided by the impedance of the body and con tact interfaces between the two areas of contact. Three general effects can occur when electric current flows through biological tissue: (1) resistive heating of tissue, (2) electrical stimulation at excitable tissue (nerve and muscle), and (3) electrochemical (for direct current).

Let us now discuss psychophysical and physiological effects humans in the order that these effects occur for increasing current, the chart in Figure 13.1 summarizes the approximate range of currents that produce each effect in a 70-kg man for 1- to 3-s expose. To 60-Hz current applied to the hands. Susceptibility parameters for variations in these conditions are considered.

Wires, the lowest thresholds are about 0.5 mA at 60 Hz. Thresholds for dc current is

Threshold of perception

For the conditions just stated, when the local current density is large enough to excite nerve endings in the skin, the subject feels~ a tingling sensation. The threshold of perception is the minimum current that an individual can detect. This threshold varies considerably among individuals, and according to the measurement conditions: When someone with 'moistened hands grasps small copper to 10 mA, and slight warming of the skin is perceived.

Let-go current

For higher levels of current, nerves and muscles are vigorously stimulated, eventually resulting in pain and fatigue. Involuntary contractions of muscles or reflex withdrawals by a subject experiencing any current above threshold may cause secondary physical injuries, such as falling from a ladder. As the current increases further, the involuntary contractions of the muscles can prevent the subject from voluntarily withdrawing. The let-go current is defined as the maximum current for which the subject can withdraw voluntarily. For men, the percentile for the let-go current threshold is 9.5 mA.

Respiratory paralysis, pain, and fatigue

Still higher currents cause involuntary contraction of respiratory muscles severe enough to cause asphyxiation if the current is not interrupted. During let-go experiments, Dalziel (1973) observed respiratory arrest at 18 to 22 mA. Strong involuntary contractions of the muscles and stimulation of the nerves can be painful and cause fatigue if there is long exposure.

Ventricular fibrillation

The heart is susceptible to electric current in a special way that is particularly dangerous. Part of the current passing through the chest flows through the heart. If the magnitude of the current is sufficient to excite only part of the heart muscle, then the normal propagation of electrical activity in the heart muscle is disrupted. Once the activity in the ventricles is desynchronized, the pumping action of the heart ceases and death occurs within minutes.

This desynchronization of cardiac muscle tissue is called fibrillation. Unfortunately it does not stop when the current that triggered it is removed. Ventricular fibrillation is the major cause of death due to electric shock. The threshold for ventricular fibrillation for an average-sized man varies from about 75 to 400 mA. Normal rhythmic activity will return only if a brief high-current pulse from a defibrillator is applied to simultaneously depolarize

all the cells of the heart muscle. After all the cells relax together, a normal rhythm usually returns.

Sustained myocardial contraction

When the current is high enough, the entire heart music contracts. Although the heart stops beating while the current is applied, the normal rhythm ensues when the current is interrupted, just as in defibrillation. Data from ac-defibrillation experiments on animals show that minimum currents for complete myocardial cons traction are in the range from 1 to 6 A. No irreversible damage the heart is known to result from these currents.

Burns and physical injury

Very little is known of the effects of currents in excess of 10 A, particularly for currents of short duration. Resistive heating causes burns, usually on the skin at the entry points, because skin resistance is high. Voltages greater than 240 V can puncture the skin. The brain and other nervous tissue lose all functional excitability when high currents are passed through them. Also, excessive currents may force muscular contractions that are strong enough to pull the muscle attachment away from the bone.

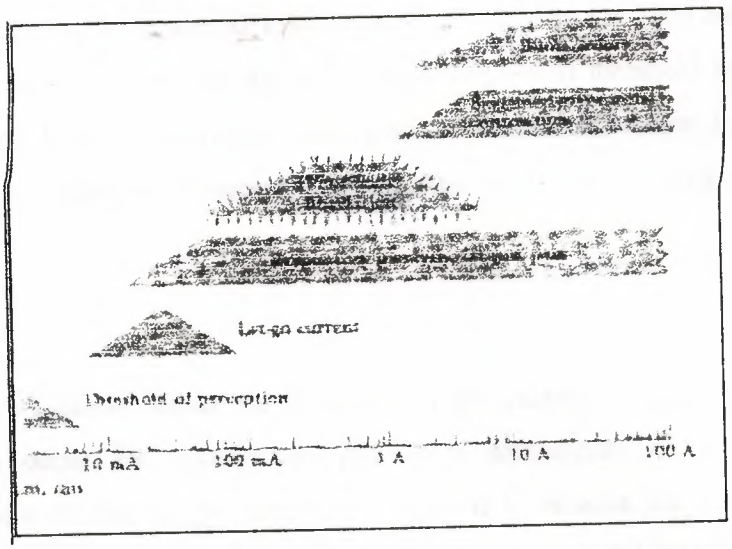

Figure 5.1 physiological effects of electricity

5.2 Important Susceptibility Parameters

The physiological effects previously described are for an average 70-kg man and for 60-Hz Current applied for 1 to 3 s to moistened hands grasping a No. 8 copper wire. The current Needed to produce each effect depends on all these conditions, as explained below. Minimal rather than average values are often most important for safety considerations.

Threshold and let-go variability

the variability of the threshold of perception and the let-go current for men and women (Dalziel, 1973). On this plot of percentile rank versus rms current in milliamperes, the data are close to the straight lines shown, so a Gaussian distribution may be assumed. For men, the mean value for the threshold of perception is 1.1 mA; for women, the estimated mean is 0.7 mA. The minimum threshold of perception is 500 ptA.

Let-go currents also appear to follow Gaussian distributions, with mean let-go currents of 16 mA for men and 10.5 mA for women. The minimum threshold let-go current is 9.5 mA for men and 6 mA for women. Note that the standard deviation for let-go current is much greater than the standard deviation for threshold-of-perception currents.

Frequency

A plot of let-go currents versus the frequency of the current. Unfortunately, the minimum let-go currents occur for commercial power-line frequencies of 50 to 60 Hz. For frequencies below 10 Hz, let-go currents rise, probably because the muscles can partially relax during part of each cycle. And at frequencies above several hundred hertz, the let-go currents rise, perhaps because of the well-known strength-duration trade off, and the refractoriness of excitable tissue

Duration

Fibrillating-current thresholds for animals increase sharply for shocks that last less than about 1 s. The heart is known to be more vulnerable to fibrillation during about 100 ms of the heart cycle that corresponds approximately to the T wave in the EGG. Shocks of short duration, applied during other parts of the heart cycle, have much higher fibrillation thresholds.

Body weight

Several studies using various sizes of animals show that the Fibrillation threshold increases with body weight. However, there is considerable scatter in the data, even for dogs only. also demonstrates the dependence of fibrillating current on body weight. These findings deserve more studies. Because they are used to extrapolate fibrillating currents for humans.

Points of entry

When current is applied at two points on the surface of the body, only a small fraction f the total current flows through the heart. These large externally applied currents are alled macro shocks. The magnitude of current fibrillate the heart is far greater when the urrent is applied The surface of the body than it would be if the current were applied irectly to the heart. The importance of the location for the two-macroshock entry points is ften overlooked. If the two points are both on the same extremity, the risk of fibrillation is mall, even for high currents. Geodes (1973) showed that for dogs, the current needed for ibrillation is greater for ECG lead I (LA-RA) electrodes than for ECG leads II and III (LL-RA, LL-LA). Protection afforded by the skin resistance (15 k to 1 Mf/cm^2) is eliminated by many

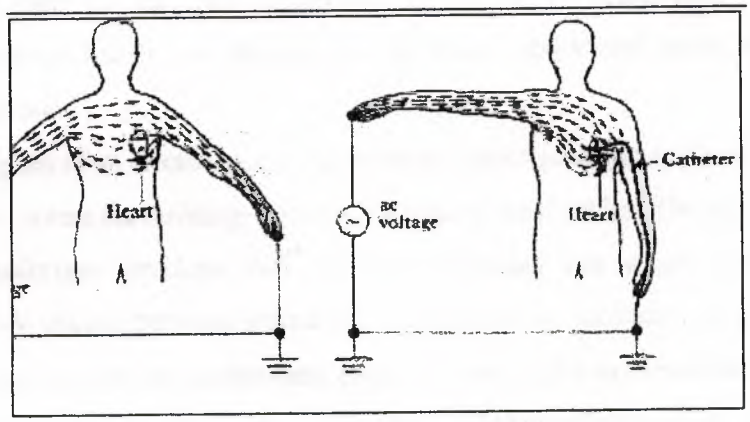

Figure 5.2 effects of entry points on current distribution

Macro shock and micro shock.

edical procedures that require insertion of conductive devices into natural openings or isions in the skin. If the skin resistance is bypassed, less voltage is required to produce fficient current for each physiological effect.

ients are particularly susceptible when devices are placed into or near the heart. A ice is especially hazardous if it provides a conductive path from outside the body to a nt on or within the heart, and if this conductor is insulated from the body except at the near the heart. All the current flowing through such a conductive device flows through.

5.3 Distribution of electric power

Electric power is needed in health-care facilities not only to operate medical ruments, but also for lighting, maintenance appliances, patient conveniences (such as hair curlers, and electric toothbrushes), clocks, nurse call buttons, and an endless list of r electrical devices. A first step in providing electrical safety is to control the lability of electric power and grounds in the patients' environment. This section is cerned with methods for safe distribution of power in health-care facilities. Let us ider this material before we discuss various macro shock and micro shock hazards in ollowing sections.

nplified diagram of an electric-power-distribution system is shown in figure 5.3. High age (4800 V) enters the building—usually via underground cables. The secondary of a down transformer develops 240 V. This secondary has a grounded center tap to de two 120-V circuits between ground and each side of the secondary winding. Some y-duty devices such as air conditioners, electric dryers, and x-ray machines) require V are placed across the entire secondary windingnnTricians do this by making ections to the two ungrounded menials. Ordinary wall Receptacles and lights operate 20 V from either one of the ungrounded hot (Black) transform. Terminals and the al (white) grounded center tap. In additional For health-care facilities, the National ic Code (NEC) for requires that all receptacles Be grounded by a separate insole n) copper conductor (Article 5 17-1 1). Some older Installed used metal conduit as a d conductor. This type of grow is generally Unsatisfactory, because corrosion and connections are unreliable.

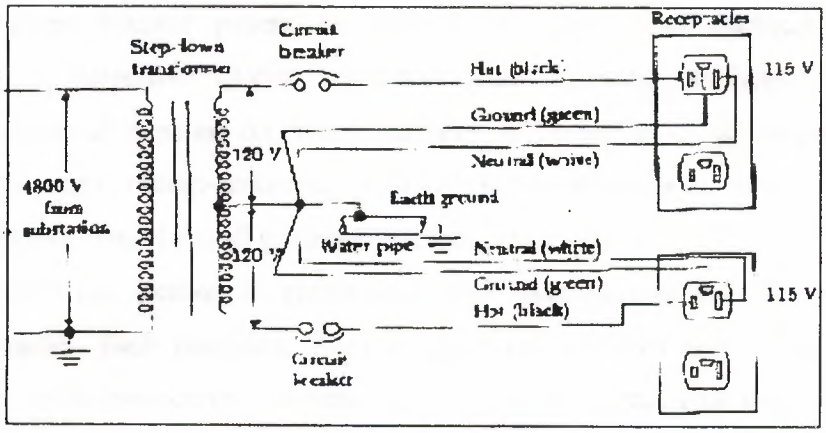

Figure 5.3 simplified electric power distribution. 115v circuits.

Power frequency is 60 Hz

Patients' Electrical Environment

Of course, a shock hazard exists between the two cons supplying either a 240-V or a V appliance. Since the nettle wire on a 120-V circuit is connected to ground, a ection between the hot conductor and any grounded object poses a shock hazard. ks can also occur if sufficient potentials exist between exposed conductive surfaces in patients' environment. Minimum potentials permitted between any two exposed uctive surfaces in the vicinity of the patient are specified by the 197 NEC, Article 517- d 517-81 (frequency < 1000 Hz measure across 1000-ft resistance):

I General-care areas 500 mV under normal operation

2 Critical-care areas 100 mV under normal operation

general-care areas, patients have only incidental contact with electrical devices. For *al-care areas, hospital patient are intentionally exposed to electrical devices, and tion of ex eternalized cardiac conductors from conductive surfaces is requir&1 In* l-care areas, all exposed conductive surfaces in the victim it' of the patient must be ded at a single patient-grounding point. Also, frequent periodic testing for continuity en the patient ground and all grounded surfaces is required.

Each patient-bed location in general-care areas must have at least four single or two x receptacles. Each receptacle must be grounded. At least two branch circuits with ite auto math over current devices must supply the location of each patient be For l-care areas, at least six single or three duplex reacceptance are required for each on of a patient bed. Two branch circuit are also required, at least one being an dual branch cir from a single panel board. An equipotent grounding system is also ed for critical-care areas. (For details, S~ NEC 70—1978, Article 517.)

Emergency-power systems

Article 517 of the National Electrical Code (1978) specifies emergency electrical n required for health-care Facilities. An emergency system is required that natically restores power specified areas within 10 s after interruption of the normal e The emergency system may consist of two parts: (1) the life-safe' branch nination, alarm, and alerting equipment), and (2) critical brand (lighting and tacles in critical patient-ca areas). (For additional details, see Article 5 17—61, 62, 3.)

Macro Shock Hazards

The high resistance of dry skin and the spatial distribution current throughout the body a person receives an electric shock are two factors that reduce the danger of cular fibrillate don. Also electrical equipment is designed to minimize the possibility nans coming into contact with dangerous voltages.

and body resistance

The resistance of the skin limits the current that c through a person's body when the n comes into contact.

rical faults in equipment

All electrical devices are of course designed to minimize exposure of humans to dous voltages. However, many devices have a metal chassis and cabinet that can be ed by medical personnel and patients. If the chassis and cabinet are not grounded, an insulation failure or shorted capacitor between the black hot power lead and the is results in a 115-V potential between the chassis and any grounded object. If a n simultaneously touches the chassis and any grounded object, a macros hock results.

The chassis and cabinet can be grounded via a third green wire in the power cord and ical system. This ground wire is connected to the neutral wire and ground at the r-distribution panel. Then, when a fault occurs between the hot conductor and the is, the current flows safely to ground on the green conductor. If the ground-wire ance is very low, the voltage between the chassis and other grounded objects is gible. If enough current flows through the ground wire to trip the circuit breaker, this all people's attention to the fault.

Note that direct faults between the hot conductor or any high voltage in the device and nd are not common. Little or no current flows through the ground conductor during al operation. Of electrical devices. The ground conductor is not needed for protection st macro shock until a hazardous fault develops. The broken ground wire or a poor

connection of a receptacle ground is not detected during normal operation of the device. Consequently, continuity of the ground wire in the device and the receptacle must be periodically tested.

Faults inside electrical device may result from failures of in-isolation, shorted capacitors, or mechanical Failures that cause short. Power cords are particularly susceptible to strain and physical abuse, as are plugs and receptacles. Ironically, it is possible for a device's chassis and cabinet to become hot because a ground wire is in the power cord. If the ground wire is open anywhere between the power cord and ground, then a frayed cord could permit contact between the hot conductor and the broken ground wire leading to the chassis. Often, macro shock accidents result from carelessness and failure to correct known deficiencies in the power-distribution system and in electrical devices.

Fluids—such as blood, urine, IV solutions, and even baby formulas—can conduct enough electricity to cause temporary short circuits if accidentally spilled into normally safe equipment. This hazard is particularly real in hospital areas that are subject to wet conditions, such as hem dialysis areas. Cabinets of many electrical devices have holes and vents for cooling that provide access for spilled conductive fluids. Designers of devices should protect patient electrical connections from this hazard.

5.6 Micro shock hazards

Micro shock accidents in electrically susceptible patients having direct electrical connections to the heart are usually caused by circumstances unrelated to macro shock hazards. Micro shocks usually result from leakage currents in line-operated equipment or differences in voltage between grounded conductive surfaces due to large currents in the grounding system. The micro shock current can flow either into or out of the electrical connection to the heart.

Leakage currents

Small currents (usually on the order of microamperes) that inevitably flow between any adjacent insulated conductors that are at different potentials are called leakage currents. Although most of the leakage current in line-operated equipment flows through the capacitance between the two conductors, some resistive leakage current flows through insulation, dust, and moisture.

The most important source of leakage currents is the currents that flow from all conductors in the electrical device to leads connected either to the chassis or to the patient. Leakage current flowing to the chassis flows safely to ground if a low-resistance ground wire is available. If the ground wire is broken, then the chassis potential will rise above ground, and a patient who touches the chassis and has a grounded electrical connection to the heart may receive a micro shock. If there is a connection from the chassis to the patient's.

Conductive surfaces

Between any two conductive surfaces near the patient can cause a micro shock if either
Surface makes contact to the heart and the other surface contacts any part of the body.
Some examples are given later in this section.

Conductive paths to the heart

Specific types of' electrical connections to the heart can be identified. The following clinical devices make patients electrically susceptible to micro shock.

1 Electrodes of externalized cardiac pacemakers

2 Electrodes for intracardiac ECG measuring devices

3 Liquid-filled catheters placed in the heart to:

A Measure blood pressure

B Withdraw blood samples

C Inject substances such as dye or drugs into the heart

It should be emphasized that an electrically susceptible patient is in danger of micro shock only if there is some electrical connection to the heart. The internal resistance of liquid-filled catheters is much greater (50 k~ to 1 M~) than the resistance of metallic conductors in pacemaker and ECG electrode leads. Internal resistance of the body to micro shock is about 300, and the resistance of the skin can be quite variable, as discussed previously.

Roy (1976) showed that in dogs the surface area of the intracardiac electrode is an important determinant of minimum fibrillating current. As catheters get smaller, so do the total current needed to fibrillate. This means that current density at the tip of the intracardiac electrode is the important micro shock parameter. Smaller catheters tend to offer larger internal resistance.

Let us now discuss three examples of possible micro shock incidents, to illustrate how subtle microshock hazards can be. These examples are illustrative only. They are certainly not the only ways that microshock can occur; they are not even necessarily the most probable.

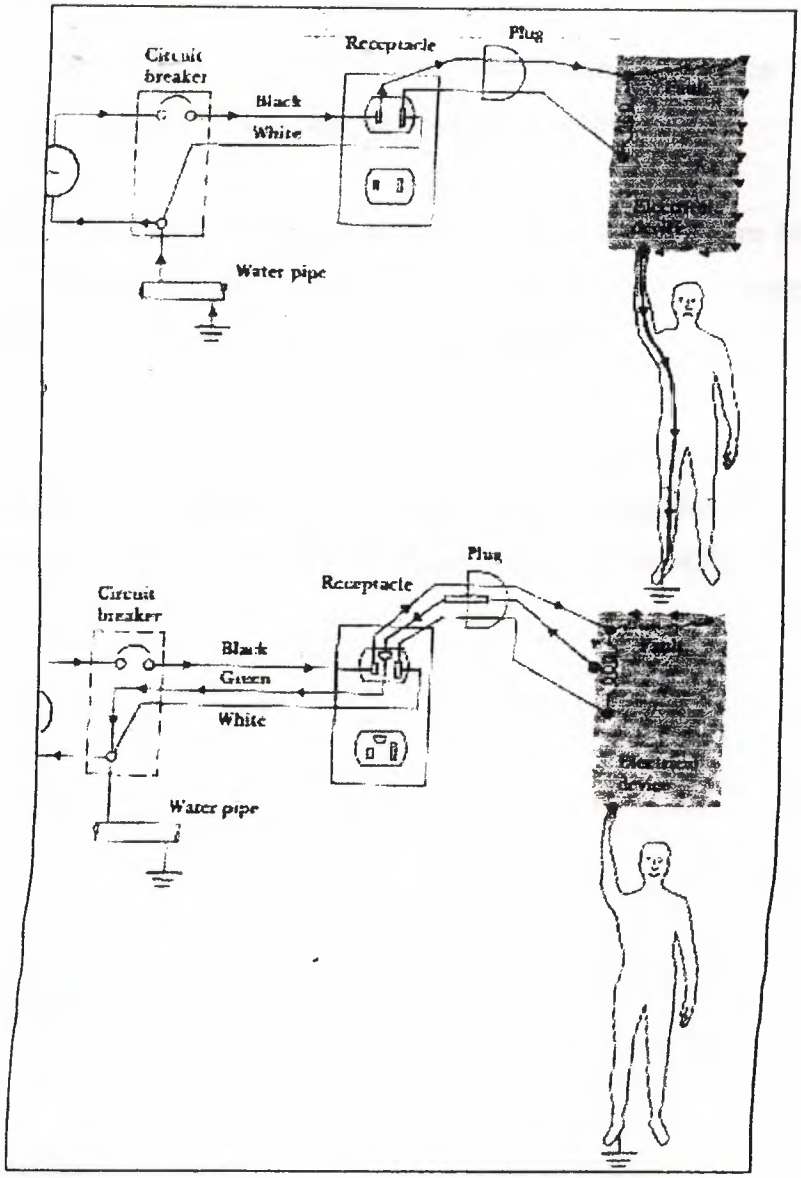

Figure 5.4 macroshock due to a ground fault from hot line to equipment Grounded and ungrounded cases.

CONCLUSION

Human been is proved to be related with electrical potential from many aspects. Electricity is fatal and in the same time we use it to save lives.

Applications of ECGs to detect, monitor and repair life functions are of major role. If a disorder already happened we try to apply biomedical engineering solutions to substitute life functions (rehabilitation engineering).

Engineers generally have a good physical insight into the nature of electromagnetic fields produced by bioelectric sources, and then a comprehensive understanding to the physical problem, they may then contribute to the solution of the problem.

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