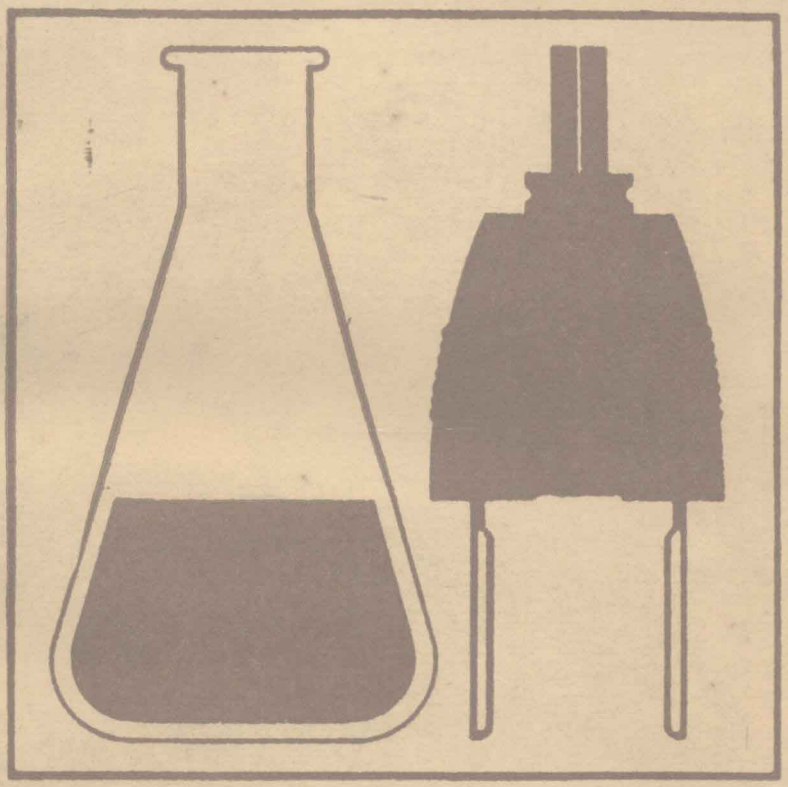
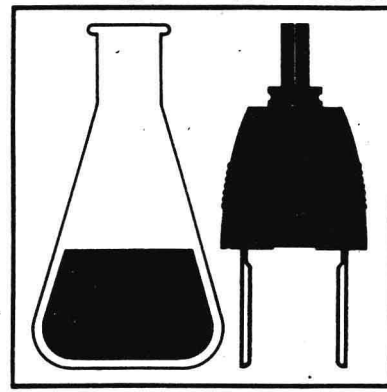
Introduction to BIOMEDICAL ELECTRONICS



Joseph DuBovy

Joseph DuBovy
Biomedical Consultant

Introduction to BIOMEDICAL ELECTRONICS



Gregg Division
McGraw-Hill Book Company

New York
St. Louis
Dallas
San Francisco
Auckland
Bogotá
Düsseldorf
Johannesburg
London
Madrid
Mexico
Montreal
New Delhi
Panama
Paris
São Paulo
Singapore
Sydney
Tokyo
Toronto

Library of Congress Cataloging in Publication Data

DuBovy, Joseph.
Introduction to biomedical electronics.

Includes index.
1. Medical electronics. I. Title.
R856.D7 610'.28 77-17920
ISBN 0-07-017895-X

INTRODUCTION TO BIOMEDICAL ELECTRONICS

1234567890 DODO 7854321098

The editors for this book were George J. Horesta and Alice V. Manning, the designer was Charles A. Carson, the cover designer was Jackie Merri Meyer, the art supervisor was George T. Resch, and the production supervisors were Kathleen Morrissey and May Konopka. It was set in Melior by Progressive Typographers.
Printed and bound by R. R. Donnelley & Sons Company.

PREFACE

When one thinks of an electric generator, the generator a power company uses to produce electricity comes to mind. It is a miracle of modern technology, whose magic is only exceeded by another far more complex electric generator—the human body.

There are some 425 muscles that would never move if internal and external electric signals did not bid them to. The brain has been compared to a computer of some advanced age. It receives data and is programmed by the senses. It can store over 6 billion bits of information. All 6 billion bits can be evoked by proper stimulation. In sleep, in a coma, or in any other state, the brain generates electrical activity. When this activity ceases, life ceases with it. In fact, this activity has become the definition of life itself, indicating the dividing line between life and death. The pacemaker inside the wall of the right atrium emits a series of pulses which cause the heart to pump blood through the arteries. Without electric signals sensing a lateral pressure differential within our head, we would find our sense of balance impaired. Everything we sense must be converted into electrical activity before the brain will respond to it. A well-regulated feedback loop consisting of electric signals functions through the autonomic nervous system to regulate heart rate and other organs. As a source of electrical activity, the human body is far more sophisticated than anything humans have invented.

Of all the revolutions that have taken place in history, by far the most radical is the revolution in medical electronic technology. Yet the biomedical engineering revolution is in its infancy. The best is yet to come. At present we can monitor physiological data or use it for diagnosis. In the future, physiological electrical activity will become an automatic extension of the nervous system itself, with the results completely programmable. In the past, medicine has treated disease and organic dysfunction after they have occurred. Computerized tabulations of norms in physiological data are making preventive medicine a reality through mass population screening. Electronics can reveal advance clues to every known disease and malfunction. The flights of the

astronauts dramatized the fact that human physiological data can be telemetered around the world at the speed of light. By combining advanced telemetering technique with satellite communications technology, the most renowned medical specialist could be at the bedside of any patient anywhere on the face of the earth.

The revolution in medical electronics technology has created one problem. That is the desperate need for biomedical engineering technicians (BMETs) with the following qualifications:

1. A thorough understanding of the concepts involved in the application of biomedical instrumentation and systems
2. An ability to maintain equipment in good operating condition even when only second-rate test equipment is available
3. A talent for communicating effectively with physicians, describing both the capabilities and the limitations of the hardware, to help physicians make the most of their electronic tools

This text begins with a basic exploration of the biomedical frequency spectrum and its physiochemical origins, then continues with a discussion of how physiological data are changed into electric signals or amplified. Once the electric signals are ready to be processed, we had better make certain that no unwanted or nonmedical data are included. Therefore, Chapter 4 explores interference and instability. Second only to interference as a problem is maintaining biomedical fidelity in the readout device. That is covered in Chapter 5. It would be impossible for a text of this type to contain every circuit to be found in biomedical instrumentation. Instead, this text explores in detail only those circuits which are most commonly found in various types of medical instrumentation.

Chapters 8 to 10 explore the troubleshooting of solid-state devices, integrated circuits, and the entire system. Readers familiar with TTL and CMOS concepts will find in those chapters a review of what they

already know. However, an attempt has been made to relate this material specifically to medical instrumentation. In addition, preventive maintenance is constantly emphasized. Equipment failure at a critical time can cost the patient's life. The pages devoted to calibration are specifically for the BMET who must meet high standards of reliability, often with a limited or nonexistent test-equipment budget.

The population explosion and the expansion of rural medical facilities point to an increasing reliance upon medical electronic tools. In some of the larger hospitals in the country, the single BMET has already been updated by a team of biomedical technicians. The trend in this direction will accelerate as the rapid influx of new electronic instruments into hospitals continues.

As biomedical instrument systems become more and more complex, performing an increasing number of functions, the BMET will be obliged to continue to study beyond the material presented in this text. This material has been written to serve as a general reference to facilitate subsequent in-depth study in a particular area.

The problem-solving material after each chapter will test the reader's comprehension of the various concepts discussed. The questions do not belabor specific numbers and details, as these are soon forgotten. Instead, the questions are geared to determine the extent of the reader's overall understanding of that chapter.

Joseph DuBovy

CONTENTS

Preface			**xiii**
Chapter 1	**Electric Signals from the Body**		**1**
Part 1:	**Electrical Activity of Cells, Tissue, Muscle, and the Nervous System**		**1**
	1-1	Genesis	1
	1-2	Molecules	1
	1-3	Ions in Solution	2
	1-4	Cells	3
	1-5	The Cell's Electrical Activity	3
	1-6	Membrane Potential	4
	1-7	The Active Cell	7
	1-8	The Autonomic Nervous System	8
	1-9	Nerve and Muscle Disease	10
	1-10	The Synapse	10
Part 2:	**Electric Signals from the Heart and Brain**		**11**
	1-11	The Heart	11
	1-12	Abnormalities	14
	1-13	Phonocardiography	17
	1-14	Systolic Time Intervals	18
	1-15	The Brain	23
	1-16	The Electroencephalogram	26
	1-17	Long-Term Cycles of the Autonomic Nervous System	30
	1-18	The Adrenal Cortex and Homeostasis	31
	1-19	The Respiratory System	32
	1-20	Respiratory Parameters	33
	1-21	Spirometry	36
	1-22	Plethysmography	36

Chapter 2	**Patient Safety**		**38**
		Introduction	38
	2-1	Natural Protective Mechanisms against Electricity	38
	2-2	Electrical Hazards	39
	2-3	Inspection	41
	2-4	Grounding	44
	2-5	Patient Isolation	54
	2-6	Leakage-Current Measurements	61
Chapter 3	**Converting Physiological Changes into Electric Signals**		**65**
	3-1	Measuring Physical and Electrical Parameters	65
	3-2	The Input Device	67
	3-3	Electrodes	70
	3-4	Pressure Transducers	76
	3-5	Ultrasonic Transducers	83
	3-6	Flow Probes	85
	3-7	Thermistors	89
	3-8	Biochemical Transducers	91
	3-9	Transducers for Radioactivity Tracing	94
	3-10	Photoelectric Transducers	96
Chapter 4	**Interference and Instability**		**105**
		Introduction	105
	4-1	Sixty Hertz	106
	4-2	The Magnetic Component	108
	4-3	The Electric Component	110
	4-4	Leads as a Path of Least Resistance	110
	4-5	Minimizing the Interference	112

	4-6	Filters	116
	4-7	Determining Frequency of Interference	127
	4-8	Carrier Current and Line Noise	127
	4-9	RFI	131
	4-10	The Unknown Frequency	135
	4-11	Base-Line Shift	137
Chapter 5	**The Readout**		**145**
		Introduction	145
	5-1	Pen Recorders	146
	5-2	Thermal Recorders	148
	5-3	Recorder Linearity	153
	5-4	Storage and Recall	160
	5-5	Recording Transients	161
	5-6	The Neurograph N-3	166
	5-7	Time Compression	168
	5-8	The MED EEG-5000	168
	5-9	The Digital Readout	170
Chapter 6	**Ultrasonics and Telemetry**		**174**
Part 1:	**Ultrasonics**		**174**
		Introduction	174
	6-1	Theory of Reflectance	174
	6-2	Absorption	176
	6-3	The Doppler Effect	177
	6-4	Doppler Arteriography	179
	6-5	B-Mode Doppler Scanning	179
	6-6	Echo-Tone	181
	6-7	Obstetrics	182
	6-8	Echoencephalography	182

	6-9	The A-Scan Technique	184
	6-10	The B-Scan Technique	184
	6-11	Cardiology	185
	6-12	Internal Medicine	185
	6-13	Simplified A-Scope Circuit	186
	6-14	Criteria for Clinical Echo Scanning	187
	6-15	The Echostat	188
	6-16	The Midliner Echoencephalograph	191
	6-17	The Unirad Echoencephalograph	192
Part 2:	**Telemetry**		**196**
		Introduction	196
	6-18	What Can Be Telemetered	196
	6-19	Deciding Whether to Use Telemetry	196
	6-20	The Best Way to Acquire Telemetered Data	198
	6-21	Modulation and Multiplexing	199
	6-22	Telemetry Systems	200
	6-23	Telemetry Electrodes	206
	6-24	Applications Involving the Active Subject	209
	6-25	The Biophone	210
	6-26	Wired Telemetry	211
	6-27	The Biotone	213
	6-28	Outpatient Monitoring	213
	6-29	MEPC	215
Chapter 7	**Biomedical Computers and Microprocessors**		**219**
	7-1	The Computer and Health-Care Delivery	219
	7-2	Coordinating Patient Data	220
	7-3	The Terminal as a Retrieval System	221

	7-4	Nursing Station Applications	221
	7-5	Serving Remote Patients with a Visiting Mobile Van	222
	7-6	Sending Medical Data to the Computer with a Unique Terminal	223
	7-7	Computerized Batch Sampling	224
	7-8	Computer Terminology	225
	7-9	Microprocessors	228
Chapter 8		**Common Biomedical Circuits**	**246**
		Introduction	246
	8-1	The Power Supply	247
	8-2	Voltage Multiplication	249
	8-3	Differential Amplifiers	249
	8-4	Chopper Circuits	253
	8-5	A/D Conversion	256
	8-6	Thermometer Circuits	257
	8-7	Pacemaker Circuits	258
	8-8	Telemetry Circuits	260
	8-9	Remote Control Circuits	261
	8-10	Vacuum-Tube Circuits	263
	8-11	Safety Circuits	269
	8-12	Learning through Doing	270
Chapter 9		**Troubleshooting Biomedical Components**	**273**
		Introduction	273
	9-1	Tools	273
	9-2	Troubleshooting Starts at the Power Supply	274
	9-3	Signal Substitution	274
	9-4	The Transistor	275
	9-5	Curve Tracers	277

	9-6	Testing a FET	284
	9-7	Testing Signal and Rectifier Diodes	287
	9-8	Testing Zener Diodes	291
	9-9	Testing Unijunction Transistors	291
	9-10	Testing Silicon Controlled Rectifiers (SCRs)	294
	9-11	Testing Triacs	297
	9-12	Testing Tunnel Diodes	297
	9-13	Diacs and ICs	298
	9-14	Integrated Circuits	298
	9-15	Digital Troubleshooting	314
Chapter 10	**Troubleshooting the System**		**323**
		Introduction	323
	10-1	Dipper-Servicing Techniques	324
	10-2	The AM Radio Probe	329
	10-3	The Dipper Probe	330
	10-4	Ultrasonic Transducers	331
	10-5	Frequency Response	332
	10-6	The Ground Loop Problem	339
	10-7	Calibration	350
	10-8	Noise in Transistors	353
		Appendix *LCXf* Nomograph	356
		Answers	359
		Index	369

chapter 1

Electric Signals from the Body

PART 1: ELECTRICAL ACTIVITY OF CELLS, TISSUE, MUSCLE, AND THE NERVOUS SYSTEM

1-1 GENESIS

In 1775 Austrian mystic and physician Franz Mesmer announced that he had discovered a force he called "animal magnetism," which permeated the universe. Mesmer's concept of a mysterious force at work within animals and humans was ridiculed by his fellow physicians. He soon was forced to give up his flourishing medical practice.

However, only 16 years later, in 1791, physiologist Luigi Galvani made a startling observation. An electric suture had accidently touched the dissected legs of a frog and the legs twitched violently. Galvani declared that there was indeed a mysterious force at work within animals and humans as Mesmer had proclaimed. Galvani called this force "animal electricity." The process through which animal electricity functioned became known as *galvanism* or a *galvanic reaction.* Several years later Galvani's friend Alessandro Volta placed dissimilar metal pieces on both sides of his tongue and noticed a strong, unpleasant taste. He had discovered more evidence of Galvani's animal electricity. Only this time it applied to humans. With the invention of the galvanometer, this new force could be measured.

As technology advanced, the vacuum tube finally permitted bioelectric potentials of very small magnitudes to be observed, classified, and analyzed. Bioengineering became a discipline that revolutionized medical science, and thus far we have only seen its early stages.

1-2 MOLECULES

Galvani's animal electricity, or bioelectric potential, exists in all living nerves, muscles, tissues, and cells. Its origin can be traced as far back as

the molecule that combines to make up the cell. Even the molecule is subject to the laws that govern the atom itself. However, once the electrochemical energy of the atoms has bound them into a molecule, the smallest unit in existence with its own chemical properties has been created. A molecule may have identical atoms, as does hydrogen (H_2), or it may have dissimilar atoms, as does water (H_2O). Molecules of rare gases and hydrocarbons are highly volatile and easily evaporate (obtain enough energy to leave the liquid and enter the surrounding atmosphere). They are one extreme of the nonpolar family of molecules. At the other extreme are the nonpolar ionized (charged) molecules, such as sodium chloride (table salt). These ions move about in all directions in a uniform electric field and exert intense electrostatic energy on their neighboring molecules.

A polar molecule, on the other hand, does not develop into an ion capable of moving about freely in a uniform electric field. The polarized molecule will quickly orient itself whenever it encounters an electric field. All polar molecules (like the nonpolar ion) will exert a powerful attractive force on their neighbors. Polar molecules are less volatile than nonpolar molecules, boiling at a much higher temperature. Most of the organic compounds (alcohols, amines, esters, ketones, and nitriles) except for the hydrocarbons are polar molecules. Their electrostatic force or electric moment is stronger than that of nonpolar molecules.

1-3
IONS IN SOLUTION

Ionized molecules such as sodium chloride (NaCl) move about in all directions in a uniform electric field and exert a strong electrostatic force on neighboring molecules. In liquid solutions these ions migrate and thus conduct electric energy. These ions have become charge carriers. In living tissue, it is ions that conduct the charge. In tissue or solutions there are majority and minority carriers. A majority carrier may be sodium or chlorine ions or intercellular potassium. Such ions occur in large concentrations and are extremely mobile. When current flows, they carry most of the charge. Minority ions exist in low concentrations and carry very little charge. For example, in a battery, ions move about between electrolytes and thus are able to supply a substantial amount of current. To a far lesser degree this "battery effect" occurs in living tissue. In the living cell, if the concentration of ions is low on one side of a barrier and high on the other side, pressure builds up for an equalization to take place, that is, for the high concentration to move over to the low concentration. In other words, nature attempts to balance the concentration gradient.

Each ion can also be considered a charge carrier. Inside an electric field, an electron (close to zero mass) is a charged particle influenced by the surrounding field. Ions in solutions seek to equalize their concentrations across barriers as electrons move in accordance with the surrounding field. An electric potential has thus been created. The thrust to equalize the concentration gradient is counterbalanced by the electric charge. For example, in a pH glass electrode, only hydrogen ions pass in a solution with pH below 7. This is called a *hydrogen-ion concentration.* The voltage (electric potential) is determined by the concentration of hydrogen ions outside the electrode.

The pH electrode, like the living cell, is selective as to the ions that can pass through it. The pH electrode permits us to measure ion concentrations because a calibrated buffer (whose ion concentration is known) is compared to the test solution outside (where the concentration is unknown).

1-4
CELLS

The cell is the smallest system having all the characteristics that we associate with life. The cell will reproduce itself. The offspring of this reproductive process will be affected by material within the parent cell and the surrounding environment. As the new cell is formed, it will collect data from the parent cell and store these data in nucleic acid polymers. This storage takes place according to a specific code, and the new cells contain functioning protein corresponding to that code. The genetic code only serves as a foundation. The environment then becomes the leading influence on the future of the genetically coded data. The building block of the genetic data is adenosine triphosphate (ATP). Bioengineering as a discipline allows the researcher to plot the cell's growth and determine its future pattern.

1-5
THE CELL'S ELECTRICAL ACTIVITY

Electric potentials in living tissue begins with the chemical reaction within each cell. In this process, oxygen (O_2) is brought to the cell and waste is eliminated. Osmosis is the key to this process. Its function depends on the body-water concentration remaining within narrow limits. When the lower moisture limit is approached, osmoreceptors inform the brain by causing the secretion of ADH, an antidiuretic hormone. ADH is carried to the kidneys, slowing the removal of water from the body. Chemoreceptors monitor the carbon dioxide (CO_2) and oxygen (O_2) levels and the pH of the blood. When the CO_2 level in-

creases, the inspiratory center is commanded to breathe more, bringing more air into the lungs and sending more O_2 to the tissues.

The proper chemical balance within cells and tissue both depends on and determines their electrical activity. Every cell has a similar resting electrical property. The outside of the cell has a potential of 65 millivolts (mV) compared to the inside of the cell. Potassium ions are concentrated inside the cell [155 milliequivalents per liter (mEq/L)] and sodium ions are concentrated outside the cell (145 mEq/L). There is also a concentration of chloride ions outside the cell (105 mEq/L). The cell has an electric resistance of 1000 to 10,000 ohms per centimeter (Ω/cm), a capacitance of 1 microfarad (μF), a dielectric constant of 5, and a phase angle of 75°. DNA and RNA in the cell's nucleus carry the information that determines how the cell will grow. The cell's energy plant, mitochondria, is found in the cytoplasm surrounding the cell's nucleus. Glycogen (a form of glucose) is stored in the chemical generator of the cell consisting of small canals. Enzymes in these canals change glucose to glycogen for storage. When energy is needed, glycogen is changed back into glucose.

In biomedical engineering we take advantage of the fact that a collection of living cells always has properties of resistance, displacement, capacitance, and impedance. Transducers can be designed to convert any of these parameters into electric signals. The cell's power plant (mitochondria) manufactures ATP (adenosine triphosphate) by the reaction of O_2 with nutrients supplied by cellular cytoplasm. CO_2 (a product of this reaction) is carried to the lungs, where it is eliminated and new O_2 is received. This cycle as well as all other bodily cycles is governed by the body's electric signals. An intricate feedback loop is the result. As each part of the body measures its own critical parameters, it sends signals in response to those measurements to maintain cyclical balance. Every time a muscle is moved, synapses in the spinal chord respond to action potential pulses. Body regulators maintain a fixed level for whatever variables they are responsible for, such as the regulation of body temperature, blood composition, or blood pressure. However, for these functions to maintain their balance, the entire electric system must be working properly, from the giant potentials of large muscles down to the tiny voltages across the membrane of each cell.

1-6 MEMBRANE POTENTIAL

The skin that covers a sausage might be compared to the membrane that surrounds the protoplasm of a living cell. A positive charge exists on the outside of the cell, while a negative charge exists on the inside. When the cell is stable or at rest, there is a 70-mV potential between the

inside and outside of the cell. The human muscle can be compared to thousands of individual biological batteries or fibers lined up in parallel. The nerve is draped across this bundle of fibers, as shown in Fig. 1-1b. When a nerve carries an electric impulse to the muscle, it sets in motion a series of processes in which the membrane potential (70 mV) disappears in the individual muscle fibers. The result is the contraction of the muscle. After the collapse of the membrane potential, tissue cells immediately recharge to reestablish the membrane potential. This charging time can be as high as a thousandth of a second, or a millisecond. Both nerve and muscle tissue oxidize oxygen to maintain their charge potential and their ability to quickly recharge. It was this charge-and-discharge cycle in the frog's leg which startled Galvani into his discovery of animal electricity. Sixty years later (1848) Hermann von Helmholtz applied electric shocks to frog muscles at two different locations. Then he measured the time between the nerve shock and the muscle's contraction, first at one location, then at another. Helmholtz measured 0.0013 second (s) between the two locations. He then was able to conclude that the impulse travels down the nerve at the rate of 30 meters/second (m/s), or 65 miles/hour (mi/h). Since those early experiments it has been discovered that electric impulses travel faster down larger-diameter nerve fibers and slower through narrower nerve fibers. A fiber about 1 micrometer (μm) wide, such as the nerves telling your eyelids to blink, will conduct at approximately 1 m/s. However, nerve fibers causing your thigh muscle to contract (25 μm in diameter) can conduct up to 100 m/s. Nerve-fiber temperature also determines how fast electric signals can propagate, since nerve-conduction velocity in-

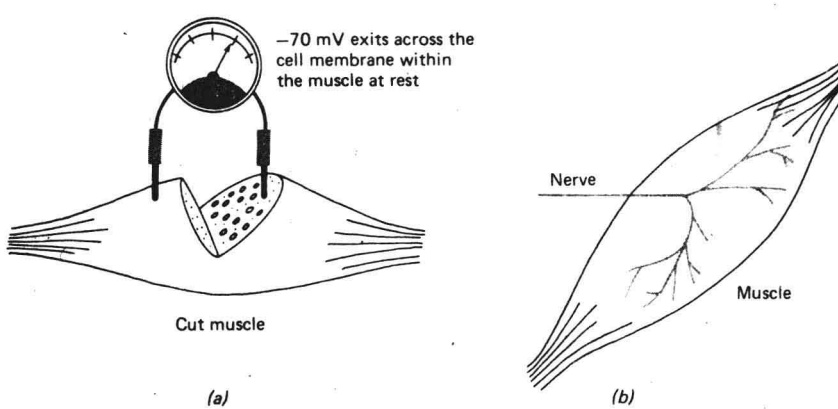


Fig. 1-1 (*a*) Voltmeter leads are attached to a section of cut muscle. A muscle can be compared to thousands of individual batteries or fibers connected in parallel. Thus the voltage difference between the surface and the interior will reflect the voltage across the cell membrane. The voltmeter reads the voltage, which is −70 mV. (*b*) The nerve is draped across a bundle of muscle fibers.