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BASIC CONCEPTS AND APPLICATIONS

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The Vernon Roosa Professor of Applied Science Trinity College

Director of the joint Trinity College/Hartford Graduate Center
Biomedical Engineering Program
Hartford, Connecticut

Contributing authors:

Michael R. Neuman, Ph.D., M.D.
Depts. of Reproductive Biology
and Biomedical Engineering
Case Western Reserve University

Frank M. Galioto Jr., M.D.
Children's Hospital National Medical Ctr.
Washington, D.C.

Robert Howard, Director
Biomedical Engineering
Children's Hospital National Medical Ctr.
Washington, D.C.

George V. Kondraske, Ph.D.
The University of Texas at Arlington

Roy B. Davis III, Ph.D.
Assistant Professor of Engineering
Trinity College
Hartford, Connecticut

Richard P. Spencer
Dept. of Nuclear Medicine
Univ. of Connecticut
Health Center
Farmington, Connecticut

Fazle Hosain
Dept. of Nuclear Medicine
Univ. of Connecticut
Health Center
Farmington, Connecticut

Robert A. Peura, Ph.D.
Biomedical Engineering Program
Worcester Polytechnic Inst.
Worcester, Massachusetts

Kenneth D. Taylor, Ph.D.
United Technologies Corp.

PWS Engineering, Boston

Preface

Purpose

In the United States today, modern medical care is extremely dependent upon technology. Since the end of World War II, the disciplines of medicine and engineering have merged continuously. This evolutionary process has given birth to the profession of biomedical engineering and has led to increased cooperation between engineers and physicians in developing new and better devices to monitor, diagnose, and treat their patients. Since this trend is likely to continue, the development of modern medical instruments will increasingly become an interdisciplinary activity. Further, throughout the next decade, the availability of the latest microcomputer-based technology is expected to dominate the field of biomedical instrumentation. Many medical tools will essentially become "smart" processors serving as the entry point for medical data into computerized systems. As a result, microcomputer technology will certainly have a significant impact upon the very nature of the acquisition and processing of almost all physiological information. These developments require that integrated interdisciplinary approaches be promoted to incorporate the latest technology into modern biomedical instrumentation systems.

Audience

Today, new technological developments virtually surround health care professionals as they tend to the well-being of their patients. The roles of the physician and nurse have been drastically altered; in addition to their responsibilities to manage and administer to the needs of their patients, they must understand the operation of a wide variety of new electronically based medical instruments. This change has increased the need for all health professionals to have some technological background. It has clearly become imperative that students interested in careers in the health care field become more knowledgeable about some of these new technologies and their application to and impact on patient care.

Similarly, engineering students interested in applying their talents in instrumentation design and information processing must, in turn, embrace increased exposure and understanding of the function of physiological systems. Further, since microprocessor-based medical instruments will probably become commonplace throughout the next decade, engineering professionals will need to understand clinical procedures as well as the flow of information within the clinical environment. With this background, more efficient and effective instrumentation systems for the collection, processing, storage, analysis, and retrieval of medically related information can be designed.

With this environment in mind, this book provides an integrated, interdisciplinary context for understanding modern techniques in the design, development, and application of biomedical instrumentation. To achieve these objectives, the introductory material is concise, yet comprehensive, treating each application in sufficient depth to let the reader understand the overall clinical and engineering problems being addressed. The result is a text that can serve as a reference to all members of the health care profession and as an instructional vehicle for undergraduate biomedical engineering students.

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Contents

Part Five

Part One

Introduction to Bioengineering and Bioinstrumentation

CHAPTER 1

Biomedical Engineering: An Interdisciplinary Profession

Joseph D. Bronzino, Ph.D., P.E.

The Vernon Roosa Professor of Applied Science,
Trinity College
Director of the Joint Trinity College/Hartford Graduate
Center
Biomedical Engineering Program
Hartford, Connecticut

INTRODUCTION

In a relatively short period of time, technology has affected every facet of our lives, and never has this effect been more apparent than in the area of medicine and the delivery of health care services. Although primitive humans practiced the art of medicine, the evolution of a technologically based health care system is a decidedly new phenomenon. The establishment of the modern hospital as the focal point of this highly technical system, with the "specialist physician" as its primary proponent, has come about only in this century.

Technology has particularly molded medical care, and in the process engineering professionals have become intimately involved in many medical ventures. As a result of many efforts to develop a common basis for the interaction of professionals from different scientific cultures, the discipline of biomedical engineering has emerged as a vital activity. Being an integrating medium for two dynamic professions, medicine and engineering, this discipline has the broad objective of assisting in the struggle against illness and disease by providing tools and techniques for research, diagnosis, and treatment.

As an important new discipline, biomedical engineering has its own history and set of guiding principles that must be understood if any dialogue between disciplines is to flourish. Only when this communication exists can individuals function as a "team" to solve the difficult problems confronting the health care delivery system in this country and to explore the possibilities for improved diagnosis and therapy so necessary for the maximum development of the medical arts. To facilitate this dialogue, this chapter will review the impact technology has had on health care delivery, discuss the evolution of the field of biomedical engineering, and present the roles biomedical engineers can play in the modern health care system.

THE EVOLUTION OF THE MODERN HEALTH CARE SYSTEM

The Beginnings

Primitive humans considered diseases to be "visitations," the whimsical acts of affronted gods or spirits. As a result, medical practice was the domain of the witch doctor and the medicine man and medicine woman. Yet even as magic became an integral part of the healing process, the cult and the art of these early practitioners were never entirely limited to the supernatural. These individuals, by using their natural instincts and learning from experience, developed a primitive science based upon empirical laws. For example, through acquisition and coding of certain reliable practices, the arts of herb doctoring, bonesetting, surgery, and midwifery were advanced. Just as primitive humans learned from observation that certain plants and grains were good to eat and could be cultivated, so the healer or shaman observed the nature of certain illnesses and then passed on their experience to other generations.

Evidence indicates that the primitive healer took an active, rather than simply intuitive interest in the curative arts, acting as a surgeon, a user of tools. For instance, skulls with holes made in them by trephiners have been collected in various parts of Europe, Asia, and South America. These holes were cut out of the bone with flint instruments to gain access to the brain. Although one can only speculate about the purpose of these early surgical operations, magic and religious beliefs seem to be the most likely reasons. Perhaps this procedure liberated from the skull the malicious demons who were thought to be the cause of extreme pain (as in the case of migraine) or attacks of falling to the ground (as in epilepsy). That this procedure was carried out on living patients, some of whom actually survived, is evident from the rounded edges on the bone surrounding the hole, indicating that the bone had grown again after the operation. These survivors also achieved a special status of sanctity, so that after their death pieces of their skull were used as amulets to ward off convulsive attacks. From these beginnings, the practice of medicine has become integral to all human societies and cultures.

It is interesting to note the fate of some of the most successful of these early practitioners. The Egyptians, for example, have held Imhotep, the architect of the first pyramid (3000 B.C.), in great esteem through the centuries, not as a pyramid

builder, but as a doctor. Imhotep's name signified "he who cometh in peace" because he visited the sick to give them "peaceful sleep." This early physician practiced his art so well that he was deified in the Egyptian culture as the god of healing.

Egyptian mythology, like primitive religion, emphasized the interrelationships between the supernatural and health. The mystic sign *Rx,* which still adorns all prescriptions today, has a mythical origin, the legend of the Eye of Horus. It appears that as a child Horus lost his vision after being viciously attacked by Seth, the demon of evil. Then Isis, the mother of Horus, called for assistance to Thoth, the most important god of health, who promptly restored the eye and its powers. As a result of this intervention, the Eye of Horus became the Egyptian symbol of godly protection and recovery, and its descendant Rx serves as the most visible link between ancient and modern medicine (Atkinson 1956).

The concepts and practices of Imhotep and the medical cult he fostered were duly recorded on papyri and stored in ancient tombs. One scroll (dated c. 1500 B.C.), acquired by George Elbers in 1873, contains hundreds of remedies for numerous afflictions ranging from crocodile bite to constipation. A second famous papyrus (dated c. 1700 B.C.), discovered by Edwin Smith in 1862, is considered to be the most important and complete treatise on surgery of all antiquity. These writings outline proper diagnoses, prognoses, and treatment in a series of surgical cases. These two papyri are certainly among the outstanding writings in medical history.

As the influence of ancient Egypt spread, Imhotep was identified by the Greeks with their own god of healing, Aesculapius. According to legend, Aesculapius was fathered by the god Apollo, during one of his many earthly visits. Apparently Apollo was a concerned parent, and, as is the case for many modern parents, he wanted his son to be a physician. He made Chiron, the centaur, tutor Aesculapius in the ways of healing. Chiron's student became so proficient as a healer that he soon surpassed his tutor and kept people so healthy that he began to decrease the population of Hades. Pluto, the god of the underworld, complained so violently about this course of events that Zeus killed Aesculapius with a thunderbolt and in the process promoted Aesculapius to Olympus as a god.

Inevitably mythology has become entangled with historical facts, and it is not certain whether Aesculapius was in fact an earthly physician like Imhotep, the Egyptian. However, one thing is clear; by 1000 B.C., medicine was already a highly respected profession. In Greece the Aesculapia were temples of the healing cult and may be considered among the first hospitals. In modern terms, these temples were essentially sanatoriums that had strong religious overtones. In them, patients were received and psychologically prepared, through prayer and sacrifice, to appreciate the past achievements of Aesculapius and his physician priests. After the appropriate rituals, they were allowed to enjoy "temple sleep." During the night, "healers" visited their patients, administering medical advice to clients who were awake or interpreting dreams of those who were sleeping. In this way, patients became convinced that they would be cured by following the prescribed regimen (diet, drugs, or blood-letting). On the other hand, if they remained ill, it would be the result of their lack of faith. With this approach, patients, not treatments, were at fault if they did not get well. This early use of the power of suggestion was effective then and is still important in medical treatment today. The notion of "healthy mind, healthy body" is still encountered today.

One of the most celebrated of these "healing" temples was on the island of Cos, the birthplace of Hippocrates, who as a youth became acquainted with the curative arts through his father, also a physician. Hippocrates was not so much an innovative physician as a collector of all the remedies and techniques that existed up to that time. Since he viewed the physician as a scientist instead of a priest, Hippocrates also injected an essential ingredient into medicine: scientific spirit. For him diagnostic observation and clinical treatment began to replace superstition. Instead of blaming disease on the gods, Hippocrates taught that disease was a natural process, one that developed in logical steps, and that symptoms were reactions of the body to disease. The body itself, he emphasized, possessed its own means of recovery, and the function of the physician was to aid these natural forces. Hippocrates treated each patient as an original case to be studied and documented. His shrewd descriptions of diseases are models for physicians even today. Hippocrates and the school of Cos trained a number of individuals who then migrated to the corners of the Mediterranean world to practice medicine and spread the philosophies of their preceptor (Sigerest 1951). The work of Hippocrates and the school and tradition that stem from him constitute the first real break from magic and mysticism and the foundation of the rational art of medicine. However, as a practitioner, Hippocrates represented the spirit, not the science, of medicine, embodying the good physician: the friend of the patient and the humane expert.

As the Roman Empire reached its zenith and its influence expanded across half the world, it became heir to the great cultures it absorbed, including their medical advances. Although the Romans themselves did little to advance clinical medicine (the treatment of the individual patient), they did make outstanding contributions to public health. For example, they had a well-organized army medical service, which not only accompanied the legions on their various campaigns to provide "first aid" on the battlefield but even established "base hospitals" for convalescents at strategic points throughout the empire. Also the construction of sewer systems and aqueducts were truly remarkable Roman accomplishments, which provided their empire with the medical and social advantages of sanitary living. The medical men's insistence on clean drinking water and unadulterated foods effected the control and prevention of epidemics. However primitive, it made urban existence possible. Unfortunately, without adequate scientific knowledge about diseases, all the preoccupation of the Romans with public health could not avert the periodic medical disasters, particularly the plague, that mercilessly befell its citizens.

Initially, their Roman masters looked upon Greek physicians and their art with disfavor. However, as the years passed, the favorable impression these disciples of Hippocrates made upon the people became widespread. As a reward for their service to the peoples of the Empire, Caesar (46 B.C.) granted Roman citizenship to all Greek practitioners of medicine in his empire. Their new status became so secure that when Rome suffered from famine that same year, these Greek practitioners were the only foreigners not expelled from the city. On the contrary, they were even offered bonuses to stay!

Ironically, Galen, who is considered the greatest physician in the history of Rome, was himself a Greek. Honored by the emperor for curing his "imperial fever," Galen became the medical celebrity of Rome. He was arrogant and a brag-

gart and, unlike Hippocrates, reported only successful cases. Nevertheless, he was a remarkable physician. For Galen, diagnosis became a fine art; in addition to taking care of his own patients, he responded to requests for medical advice from the far reaches of the empire. He was so industrious that he wrote more than 300 books of anatomical observations, his selective case histories, the drugs he prescribed, and his boasts. His version of human anatomy, however, was misleading because he objected to human dissection and drew his human analogies solely from the studies of animals. However, because he so dominated the medical scene and was later endorsed by the Roman Catholic Church, Galen actually inhibited medical inquiry. His medical views and writings became both the "bible" and "the law" for the pontiffs and pundits of the ensuring Dark Ages (Calder 1958).

With the collapse of the Roman Empire, the Church became the repository of knowledge, particularly of all scholarship that had drifted through the centuries into the Mediterranean. This body of information, including medical knowledge, was literally scattered through the monasteries and dispersed among the many orders of the Church.

The teachings of the early Roman Catholic Church and the belief in divine mercy made inquiry into the causes of death unnecessary and even undesirable. Members of the Church regarded curing patients by rational methods as sinful interference with the will of God. The employment of drugs signified a lack of faith by the doctor and patient, and scientific medicine fell into disrepute. As a result, for almost a thousand years, medical research stagnated. It was not until the Renaissance in the 1500s that any significant progress in the science of medicine occurred. Hippocrates had once taught that illness was not a punishment sent by the gods, but a phenomenon of nature. But now, under the Church and a new God, the older views of the supernatural origins of disease were renewed and promulgated. Since disease implied demonic possession, the sick were treated by the monks and priests through prayer, laying on of hands, exorcism, penances, and exhibition of holy relics: practices officially sanctioned by the Church.

Although deficient in medical knowledge, the Dark Ages were not entirely lacking in charity toward the sick poor, for the Christian physicians treated the rich and poor alike. The Church actually assumed responsibility for the sick. The evolution of the modern hospital began with the advent of Christianity and is considered a major contribution of monastic medicine. The rise in A.D. 335 of Constantine I, the first of the Roman emperors to embrace Christianity, all pagan temples of healing were closed, and hospitals were established in every cathedral city. The word *hospital* comes from the Latin *hospes,* meaning "host" or "guest"; the same root has provided *hotel* and *hostel.* These first hospitals were simply houses where weary travelers and the sick could find food, lodging, and nursing care. All these hospitals were run by the Church, and the art of healing was practiced by the attending monks and nuns.

As the Christian ethic of faith, humanitarianism, and charity spread throughout Europe and then to the Middle East during the Crusades, so did its "hospital system." However, trained "physicians" still practiced their trade primarily in the homes of their patients, and only the weary travelers, the destitute, and those considered hopeless cases found their way to hospitals. Conditions in these early hospitals varied widely. Although a few were well financed and well

managed and treated their patients humanely, most were essentially custodial institutions to keep troublesome and infectious people away from the general public. In these establishments, crowding, filth, and high mortality among both patients and attendants were commonplace. Thus, the hospital was an institution to be feared and shunned.

The Renaissance and Reformation in the fifteenth and sixteenth centuries loosened the Church's stronghold on both the hospital and the conduct of medical practice. During the Renaissance, "true learning," the desire to pursue the true secrets of nature including medical knowledge, was again stimulated. The study of human anatomy was advanced and the seeds for further studies were planted by the artists Michelangelo, Raphael Dürer, and, of course, the genius Leonardo da Vinci. They viewed the human body as it really was, not simply as a text passage from Galen. The Renaissance painters depicted people in sickness and pain, sketched in great detail, and in the process, demonstrated amazing insight into the workings of the heart, lungs, brain, and muscle structure. They also attempted to portray the individual and to discover emotional as well as physical qualities. In this stimulating era, physicians began to approach their patients and the pursuit of medical knowledge in similar fashion. New medical schools, *similar* to the most famous of such institutions at Salerno, Bologna, Montpillier, Padua, and Oxford, emerged. These medical training centers once again embraced the Hippocratic doctrine that the patient was human, disease was a natural process, and commonsense therapies were appropriate in assisting the body to conquer its disease.

During the Renaissance, these fundamentals received closer examination, and the age of measurement began. In 1592, when Galileo visited Padua, Italy, he lectured on mathematics to a large audience of medical students. His famous theories and inventions (the thermoscope and the pendulum, in addition to the telescopic lens) were expounded upon and demonstrated. Using these devices, one of his students, Sanctorius, made comparative studies of the human temperature and pulse. A future graduate of Padua, William Harvey, later applied Galileo's laws of motion and mechanics to the problem of blood circulation. This ability to measure the amount of blood moving through the arteries helped to determine the function of the heart (Calder 1958).

Galileo encouraged the use of experimentation and exact measurement as scientific tools that could provide physicians with an effective check against reckless speculation. Quantitation meant theories would be verified before being accepted. Individuals involved in medical research incorporated these new methods into their activities. Body temperature and pulse rate became measures that could be related to other symptoms to assist the physician in diagnosing specific illnesses or disease. Concurrently, the development of the microscope amplified human vision, and an unknown world came into focus.

Unfortunately, new scientific devices had little impact upon the average physician, who continued to blood-let and to disperse noxious ointments. Only in the universities did scientific groups band together to pool their instruments and their various talents.

In England, the medical profession found in Henry VIII a forceful and sympathetic patron. He assisted the doctors in their fight against malpractice and supported the establishment of the College of Physicians, the oldest purely medical institution in Europe. When he suppressed the monastery system in the early