1 Introduction: What Is Biomedical Engineering?

LEARNING OBJECTIVES

After reading this chapter, you should:

- Be familiar with how changes in medicine have enhanced life span and quality of life.
- Understand a few examples of the role of engineering in defining medical treatments.
- Have developed your own definition of biomedical engineering.
- Understand some of the subdisciplines that are included in biomedical engineering.
- Understand the relationship between the study of biomedical engineering and the study of human physiology.
- Be familiar with the structure of this book, and have developed a plan for using it that fits your needs.

1.1 Prelude

The practice of medicine has changed dramatically since you were born. Consider a few of these changes, some of which have undoubtedly affected your own life: Couples can test for pregnancy in their homes, a new vaccine is available for chicken pox, inexpensive contact lenses provide clear vision, artificial hips allow recipients to walk and run, ultrasound imaging follows the progress of pregnancy, and small reliable pumps administer insulin continuously for diabetics. For your parents, the changes have been even more sweeping. Overall life expectancy—that is, the span of years that people born in a given year are expected to live—increased from 50 in 1900 to almost 80 by 2000 (Figure 1.1). You can expect to live 30 years longer than your great-grandparents; you can also expect to be healthier and more active during all the years of your life.

How has this happened? One answer is obvious. People are living longer because they are not dying in situations that were previously fatal, such as childbirth and bacterial infections. The growth of biomedical engineering is a major factor in this extension of life and improvement of health. Biomedical engineers have contributed to every field of medicine—from radiology to obstetrics to cancer treatment—but in the next few paragraphs this growth is illustrated with examples from emergency medicine.

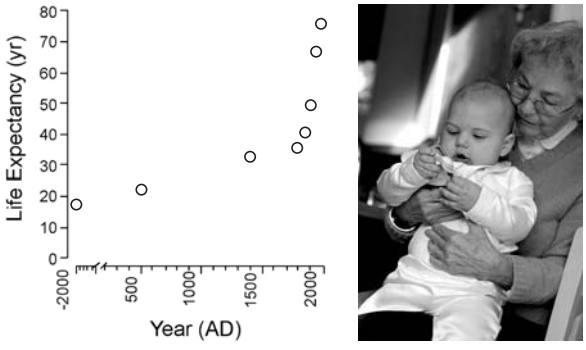

Figure 1.1 **Human life expectancy.** Human life expectancy has increased dramatically in the past 200 years.

Accidents and trauma are major causes of death and disability around the world. In the United States, it is overwhelmingly the leading cause of death among people of college age, and it is ranked fifth among causes of death for all ages (1). Automobile accidents account for many of these deaths: 42,116 people were killed in automobile accidents in the United States in 2001. Victims of trauma often have internal injuries, which are life threatening but not easy to diagnose by visual observation. Many accident victims are rushed to emergency rooms for treatment, and actions performed in the first few minutes after arrival can often mean the difference between life and death. Emergency room treatment has improved enormously over the past few decades, chiefly due to advances in the technology for looking inside of people quickly and accurately (Figure 1.2). Ultrasound imaging, which can provide pictures of internal bleeding within seconds, has replaced exploratory surgery and other slower, more invasive approaches for localization of internal injuries. Old ultrasound imaging machines weighed hundreds of pounds, but new instruments are smaller and lighter—some weighing only a few pounds, making it possible to get them to the patient faster. Other imaging technologies have also improved: Helical computed tomography (CT) scanners produce rapid three-dimensional internal images of the whole body, and new magnetic resonance imaging (MRI) techniques can reveal the chemistry, not just the shape, of internal structures. As a result of faster and better diagnosis of internal injuries, more accident victims are saved today.

In the near future, emergency medicine providers will probably use ultrasound imagers that are small enough to be carried in a pocket and inexpensive enough for every physician to own, like a stethoscope is today. Reduction in size and cost will surely save the lives of more accident victims. A pill-sized sensor is already available that patients can swallow; it continuously reports internal temperature as it passes through the intestinal tract. In the future, similar devices will probably be used to report other internal conditions such as sites of bleeding or abnormal cells. Further in the future, these small devices will be guided to specific locations in the body, where they can initiate repair of disease that is deep within the body.

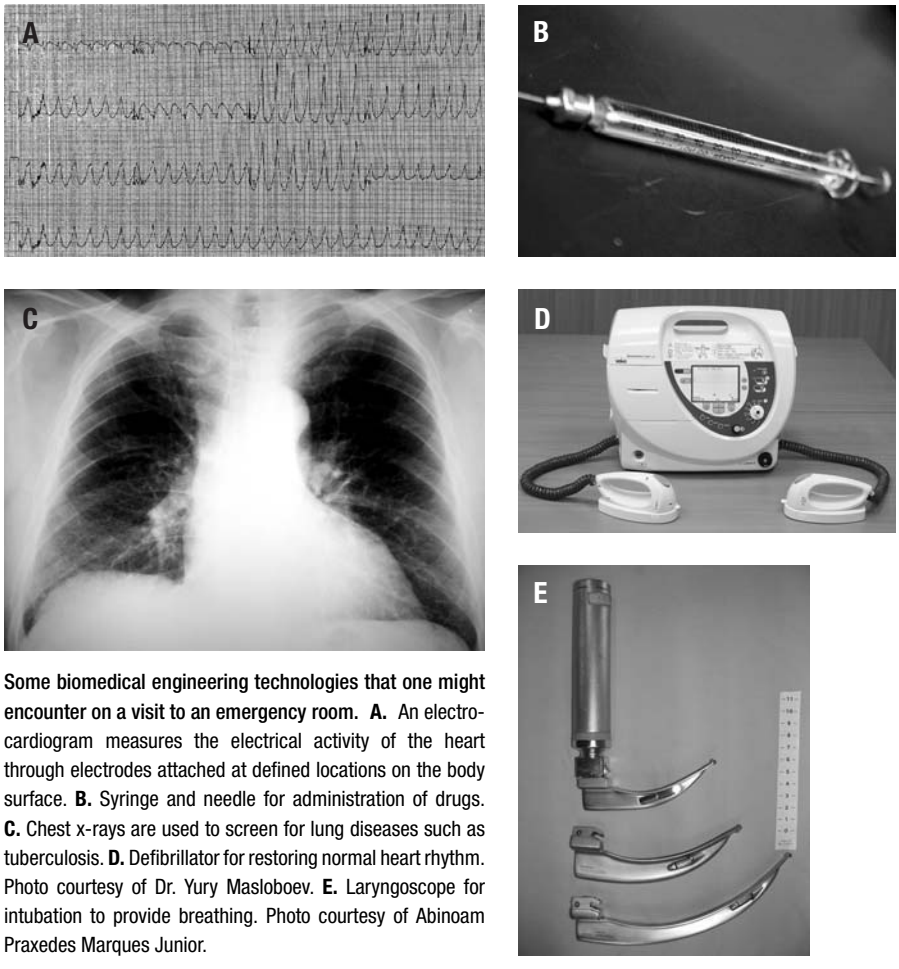

Figure 1.2 **Some biomedical engineering technologies that one might encounter on a visit to an emergency room. A.** An electrocardiogram measures the electrical activity of the heart through electrodes attached at defined locations on the body surface. **B.** Syringe and needle for administration of drugs. **C.** Chest x-rays are used to screen for lung diseases such as tuberculosis. **D.** Defibrillator for restoring normal heart rhythm. Photo courtesy of Dr. Yury Masloboev. **E.** Laryngoscope for intubation to provide breathing. Photo courtesy of Abinoam Praxedes Marques Junior.

The trends in emergency medicine are not unique. Innovations produced by biomedical engineers are saving lives once lost to kidney failure, improving eyesight lost to disease and aging, and producing artificial hips, knees, and hearts.

Do you want to be a part of this story or similar stories that are changing the conduct of medicine in operating rooms, doctors' offices, emergency vehicles, and homes? Then you want to be a biomedical engineer. This book will introduce you to the field of biomedical engineering and show how your knowledge of math, chemistry, physics, and biology can be used to understand how the human body works. It will show you how biomedical engineers work to develop new methods to diagnose problems with the human machine and new approaches to treat disease efficiently and inexpensively. This book will also show you how biomedical engineering and medicine will grow in the future, and point you in some directions that you can pursue to be part of this future. Biomedical engineering has been performed under different titles throughout history (Box 1.1); this book will help put this development into perspective, so that you can focus on how biomedical engineers will contribute to the future.

Box 1.1 Too many names?

As you read about the subject of biomedical engineering, you will encounter a variety of names that sound similar: bioengineering, biological engineering, biotechnology, biosystems engineering, bioprocess engineering, biomolecular engineering, and biochemical engineering. Some of the differences between these names are important, but unfortunately the terminology is not used consistently. Therefore, students of biomedical engineering need to approach the terminology with care (and without assuming that the person using the terminology has the same definition that they do!).

Biomedical engineering and bioengineering are often used interchangeably [e.g., see ref. (2)]. This is certainly true in the case of names of academic departments at universities. Some departments are called Department of Biomedical Engineering and others Department of Bioengineering, but in most cases the educational mission and research programs associated with these departments are similar. Still, it is wise for prospective students to look closely at the classes that are offered at each university and to decide if the emphasis of the department is the right one for them.

Some of the terms represent subsets of the larger discipline of biomedical engineering. Biomolecular engineering, for example, is now used to describe the contributions of chemical engineering to the larger field of biomedical engineering. In that sense, biochemical engineering and bioprocess engineering, which have historically been used to indicate the use of chemical engineering tools in the development of industrial processing methods for biological systems, are now embraced by the larger subdiscipline of biomolecular engineering. One could argue that all of these are subsets of the larger field of bioengineering or biomedical engineering.

Biotechnology is a trickier term to characterize because it has been used in a variety of different contexts over the past few decades. To many people, biotechnology is the end result of DNA manipulation: for example, transgenic animals, recombinant proteins, and gene therapy. Some common definitions are "the application of the principles of engineering and technology to the life sciences"; "the application of science and engineering to the direct or indirect use of living organisms, or parts or products of living organisms, in their natural or modified forms"; or "the use of biological processes to solve problems or make useful products." Again, one could argue that these definitions are equivalent to biomedical engineering. Even the technologies most commonly associated with biotechnology (e.g., production of recombinant proteins as pharmaceuticals) are examples of biomedical engineering. They are treated as such in this textbook, and are discussed in Chapters 13 and 14.

1.2 Engineering in modern medicine

Our experience of the world is shaped by engineering and technology. Because of the work of engineers, we can move easily from place to place, communicate with people at distant sites (even on the moon!), live and work in buildings that are safe from natural elements, and obtain affordable and diverse foods. It is

widely, although not universally, accepted that the quality of life on our planet has improved as a result of the proliferation of technology that occurred during the 20th century. There is little doubt that the presence of technology creates constraints on the way that we live, and that the daily choices we make are shaped by the technologies that have infiltrated widely (think about the ways that television, computers, airplanes, cell phones, and ATMs have influenced your progress through this past day). Choices that we make in the future, and maybe even historical trajectories, will be influenced by future technologies such as (perhaps) nanomachines, efficient fuel cells, and small, inexpensive global positioning devices. It is the work of engineers to make technology possible, and then to make that technology reliable and inexpensive enough to influence people throughout the world.

Medical technology is one of the most visible aspects of the modern world; it is impossible to avoid and uniquely compelling. People from all walks of life are eager to hear about new machines, new medicines, and new devices that will uncover hidden disease, treat previously untreatable ailments, and mend weary or broken organs. Evidence for this high interest is everywhere; for example, new medical technology appears routinely on the covers of news magazines such as *Time* and *Newsweek* and in daily newspaper reports. We know that modern medicine is built on steady progress in science, but it is just as heavily dependent on innovations in engineering. It is engineers who transfer scientific knowledge into useful products, devices, and methods; therefore, progress in biomedical engineering is arguably more central to our experience of modern medicine than are advances in science. Some of the most fascinating stories of the 20th century involved the development of new medical technologies (Figure 1.3). Whole-organ transplantation, such as the first heart transplant in 1967, could not occur until there were machines to sustain life during the operation, tools for the surgeons to operate with and repair the wounds they created, and methods for preserving organs during transport. Thousands of transplants are performed annually in the United States today, but the need for organs far exceeds the supply. Biomedical engineers have been working for many decades to create an artificial heart, and there is no doubt that this work will continue until it is successful (see Chapter 15). Clinical testing of the Salk polio vaccine, in which millions of doses were administered to children, could not happen without the engineering methods to cheaply produce the vaccine in large quantity (see Chapter 14). The Human Genome Project would have not been possible without automated machines for deoxyribonucleic acid (DNA) sequencing.

Medical technology has also invaded our homes in surprising and influential ways. Every home has a thermometer, specially designed to permit the recording of body temperature. But we can now also test for pregnancy at home, so that one of the most life-changing medical discoveries can be done in privacy. Blood glucose tests,which are essential for proper treatment of diabetes, have advanced rapidly and now are commonly done at home. Your home can be easily equipped to be a screening center for high blood pressure, high cholesterol, glucose monitoring, and ovulation prediction.

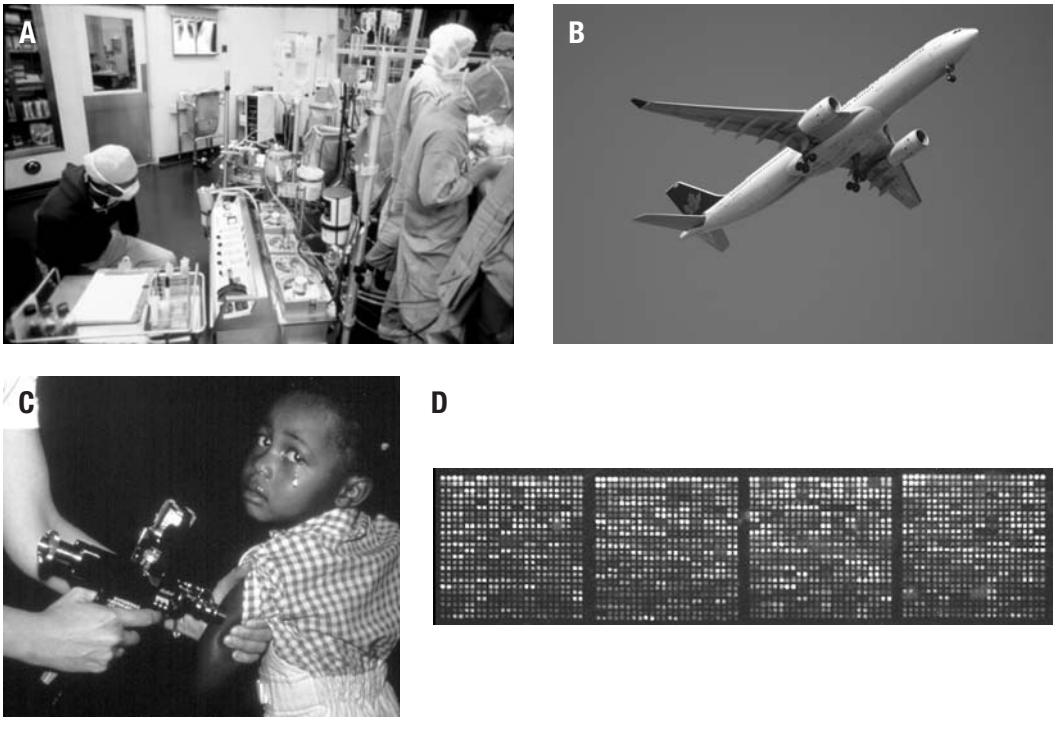

Figure 1.3 **Examples of new technology that permitted medical advances. A.** Heart–lung machine that permits heart transplantation and surgery. Photo courtesy of National Institutes of Health. **B.** Jet airplanes are used for rapid transport of a preserved organ to a distant operating room. **C.** An injector for vaccine delivery. Photo courtesy of The Centers For Disease Control and Prevention. **D.** DNA microarrays can be used to measure the expression of genes in cells and tissues. Photo courtesy of the W.M. Keck Foundation at Yale University. (See color plate.)

In addition, medical technologies have entered our bodies. Many people now elect to use contact lenses instead of eyeglasses; this change has resulted from the development of materials that can remain in contact with the eye for extended periods without causing damage. Artificial joints and limbs are common, as are artificial heart valves; synthetic components, usually metals and polymers, are fashioned into implantable devices that can replace the function of the human skeleton. We are not yet able to reanimate dead tissue (as Shelley predicted in *Frankenstein*), but we are close to the technology required for a 6 million dollar man.

This book supplies an introduction to biomedical engineering, the most rapidly growing of the engineering disciplines. Biomedical engineers invent, design, and build new technologies for diagnosis, treatment, and study of human disease. Usually, they work as a part of a team of engineers, scientists, and physicians, but the role of the engineer is essential. It is the engineer who is responsible for converting new knowledge into a useful form.

1.3 What is biomedical engineering?

New students to the field of biomedical engineering ask versions of this question: "What is biomedical engineering?" Often, they ask the question directly but, just

as often, they ask it in indirect and interesting ways. Some of the forms of this question that I have heard in the past few years are:

- Do biomedical engineers all work in hospitals?
- Do you have to have an MD degree to be a biomedical engineer?
- How can I learn enough biology to understand biomedical engineering and enough engineering to be a real engineer?
- Is biomedical engineering the same as genetic engineering?
- How much of biomedical engineering is biology, chemistry, physics, and mathematics?

Some versions of the question are easy to answer. For example, most biomedical engineers do not work in hospitals and do not hold MD degrees. Other questions can inspire answers that take up whole books (such as this book), and still be incomplete. All of the chapters in this book are designed to address these questions from different perspectives. In this introduction, the overall question is examined from several different angles.

1.3.1 We can learn something about biomedical engineering from standard definitions

Our working definition of biomedical engineering can start in an obvious place. According to the Merriam-Webster Dictionary:

> engineering *noun*: a) the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people; b) the design and manufacture of complex products.

Biomedical engineering is engineering that is applied to human health. Because human health is multifaceted—involving not only our physical bodies but also the things that we put in our bodies (such as foods, pharmaceuticals, and medical devices) and the things that we put on our bodies (such as protective clothing and contact lenses)—biomedical engineers are interested in a wide range of problems. The breadth of modern biomedical engineering is reflected in the table of contents for this book (shown in diagrammatic form in Figure 1.4).

The work of engineers is often hidden from view of the general public, occurring in laboratories, office buildings, construction sites, pilot plants, and testing facilities. This is true for biomedical engineering as well as civil engineering and other engineering disciplines. Although the work might be hidden, the end result is often visible and important (e.g., the Brooklyn Bridge or the artificial heart; see Figure 1.5). Because of this, society has huge expectations for engineers, and engineers have large goals for themselves.

The importance of engineers to human progress is worthy of celebration. Consider this quote about the role of engineers from the president of the American

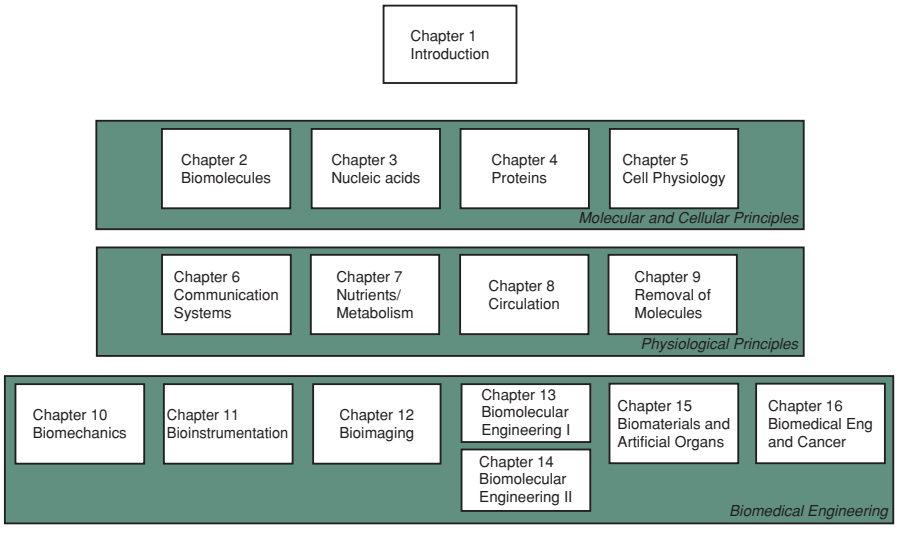

Figure 1.4 Organization of this book.

Society of Civil Engineers, Robert Moore. Mr. Moore, in a speech to the society in May 1902, said [from ref. (3)]:

> And in the future, even more than in the present, will the secrets of power be in his keeping, and more and more will he be a leader and benefactor of men. That his place in the esteem of his fellows and of the world will keep pace with his growing capacity and widening achievement is as certain as that effect follow cause.

Mr. Moore was speaking in the shadow of incredible engineering achievements: The work of engineers to build bridges over large spans of water changed the flow of society, for example. The substance of this quote—although not its selection of pronouns—is relevant today. Engineers of today have ambitious visions for their profession, and they are still called upon to be worthy inheritors of the engineering

Figure 1.5 **Examples of engineering on the heroic scale.** **A.** Brooklyn Bridge (opened May 24,1883). **B.** AbioCor™ artificial heart (reprinted with permission from Jewish Hospital & St. Mary's HealthCare and the University of Louisville).

tradition to do good works. Imagine the confidence in your profession that is required to suggest that you can build a machine to replace the human heart, which is one of the most durable, reliable, and complex of machines. As we will see in Chapters 13 and 15, biomedical engineers now imagine that the creation of reliable replacement tissues and organs such as the heart is achievable. The success of the Abiomed artificial heart (called AbioCor™, Figure 1.5, which had been implanted into 10 patients as of March 2003), is an example of progress in this heroic effort.

A simple definition of engineering might be this: Engineering is the art of making practical application of the knowledge of pure science (3). Engineering is a creative discipline (like sculpture, poetry, and dance), but the end result is often intended to be durable, useful, abundant, and safe. Engineering art is not produced for museums, but intended to infiltrate the world.

Technology is a broader and more comprehensive term than engineering; in general, technology is the end result of a practical application of knowledge in a particular area. Anyone can produce technology, but engineers—because their training is focused on providing the knowledge tools needed to produce technology—have had the dominant role.

1.3.2 Biomedical engineers seek to understand human physiology and to build devices to improve or repair it

Other textbooks and review articles have described the origins of biomedical engineering, which can be identified even in ancient sources (2). Rather than reviewing this history in detail, we instead offer a schematic, speculative view of progress in biomedical engineering (Figure 1.6). Early humans learned that tools could improve the quality of their life; one might argue that the first engineers were the clever individuals who either recognized the value of wheels, levers, and sharpened rocks or figured out new ways to use these tools. As humans used tools, and as a result found new leisure time for other activities, some curious individuals probably began to use these implements to study themselves. As people learned more about the structure and function of their own bodies (that is, as they learned more about human anatomy and physiology), they were able to apply this knowledge to the creation of improved tools for repair of function (such as splints and sutures).

Observed in this way, the history of biomedical engineering involves a sequential and iterative process of discovery and invention: new tools for studying the human body leading to a deeper understanding of body function leading to the invention of improved tools for repair and study of the human body, and so forth. The dual nature of biomedical engineering is alive today; some biomedical engineers are concerned with careful analysis and study of the operation of body systems, others are concerned with the development of new techniques for the study and repair of the body, and still others do a bit of each.

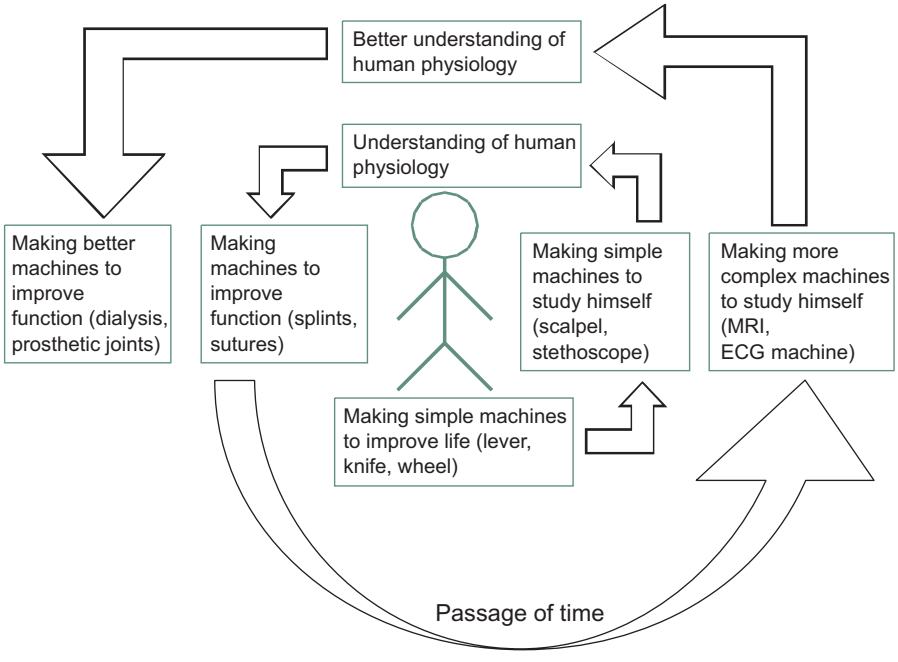

Figure 1.6 **Advances in biomedical engineering.** Figure shows a schematic view of advancement in biomedical engineering, which relies on sequential development of improved tools for studying physiology and the subsequent increased understanding of physiology that results. MRI, magnetic resonance imaging; ECG, electrocardiogram.

This speculative view of biomedical engineering can be confirmed through history; consider the timeline provided in Table 1.1, which shows highlights in the development of contact lenses. Many vision problems can now be corrected in humans; how did we get to this state? It was probably recognized very early in human history that the eye was involved in human vision; placing a hand in front of the eye blocks vision, and injuries to the eye destroy it. This knowledge of the source of vision was eventually translated into efforts to repair faulty vision with lenses (by Bacon in 1249 and Nicholas of Cusa in 1451); these developments could not happen until people (we would later call them engineers) had developed sufficient experience with the optical properties of materials and the construction of the lens. Leonardo da Vinci suggested a lens that was directly applied to the human eye early in the 15th century, but the technical skill required to make polished glass lenses shaped like the eye did not appear until 1887, in the hands of the German glassblower F. E. Muller. These early lenses were difficult to make (and therefore expensive), and they were not well tolerated by the eye. Study of the response of the eye to the presence of these materials revealed new aspects of eye physiology, such as the eye's nonspherical geometry and the circulation pathway for tears. New materials were developed especially for lenses; plastics were particularly valuable (Figure 1.7). Long wear contact lenses required an understanding of the cornea's need for oxygen (which is a wonderful engineering problem that illustrates an aspect of physiology, see Problem 15 in Chapter 2). Today, lenses are