TEXTBOOK OF

Medical Physiology

ELEVENTH EDITION

GUYTON & HALL

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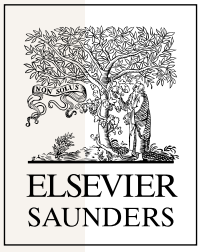

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To

My Family

For their abundant support, for their patience and understanding, and for their love

To

Arthur C. Guyton

For his imaginative and innovative research

For his dedication to education

For showing us the excitement and joy of physiology

And for serving as an inspirational role model

Arthur C. Guyton, M.D.
1919–2003

IN MEMORIAM

The sudden loss of Dr. Arthur C. Guyton in an automobile accident on April 3, 2003, stunned and saddened all who were privileged to know him. Arthur Guyton was a giant in the fields of physiology and medicine, a leader among leaders, a master teacher, and an inspiring role model throughout the world.

Arthur Clifton Guyton was born in Oxford, Mississippi, to Dr. Billy S. Guyton, a highly respected eye, ear, nose, and throat specialist, who later became Dean of the University of Mississippi Medical School, and Kate Smallwood Guyton, a mathematics and physics teacher who had been a missionary in China before marriage. During his formative years, Arthur enjoyed watching his father work at the Guyton Clinic, playing chess and swapping stories with William Faulkner, and building sailboats (one of which he later sold to Faulkner). He also built countless mechanical and electrical devices, which he continued to do throughout his life. His brilliance shone early as he graduated top in his class at the University of Mississippi. He later distinguished himself at Harvard Medical School and began his postgraduate surgical training at Massachusetts General Hospital.

His medical training was interrupted twice—once to serve in the Navy during World War II and again in 1946 when he was stricken with poliomyelitis during his final year of residency training. Suffering paralysis in his right leg, left arm, and both shoulders, he spent nine months in Warm Springs, Georgia, recuperating and applying his inventive mind to building the first motorized wheelchair controlled by a "joy stick," a motorized hoist for lifting patients, special leg braces, and other devices to aid the handicapped. For those inventions he received a Presidential Citation.

He returned to Oxford where he devoted himself to teaching and research at the University of Mississippi School of Medicine and was named Chair of the Department of Physiology in 1948. In 1951 he was named one of the ten outstanding men in the nation. When the University of Mississippi moved its Medical School to Jackson in 1955, he rapidly developed one of the world's premier cardiovascular research programs. His remarkable life as a scientist, author, and devoted father is detailed in a biography published on the occasion of his "retirement" in 1989.[1]

A Great Physiologist. Arthur Guyton's research contributions, which include more than 600 papers and 40 books, are legendary and place him among the greatest physiologists in history. His research covered virtually all areas of cardiovascular regulation and led to many seminal concepts that are now an integral part of our understanding of cardiovascular disorders, such as hypertension, heart failure, and edema. It is difficult to discuss cardiovascular physiology without including his concepts of cardiac output and venous return, negative interstitial fluid pressure and regulation of tissue fluid volume and edema, regulation of tissue blood flow and whole body blood flow autoregulation, renal-pressure natriuresis, and long-term blood pressure regulation. Indeed, his concepts of cardiovascular regulation are found in virtually every major textbook of physiology. They have become so familiar that their origin is sometimes forgotten.

One of Dr. Guyton's most important scientific legacies was his application of principles of engineering and systems analysis to cardiovascular regulation. He used mathematical and graphical methods to quantify various aspects of circulatory function before computers were widely available. He built analog computers and pioneered the application of large-scale systems analysis to modeling the cardiovascular system before the advent of digital computers. As digital computers became available, his cardiovascular models expanded dramatically to include the kidneys and body fluids, hormones, and the autonomic nervous system, as well as cardiac and circulatory functions.[2] He also provided the first comprehensive systems analysis of blood pressure regulation. This unique approach to physiological research preceded the emergence of biomedical

engineering—a field that he helped to establish and to promote in physiology, leading the discipline into a quantitative rather than a descriptive science.

It is a tribute to Arthur Guyton's genius that his concepts of cardiovascular regulation often seemed heretical when they were first presented, yet stimulated investigators throughout the world to test them experimentally. They are now widely accepted. In fact, many of his concepts of cardiovascular regulation are integral components of what is now taught in most medical physiology courses. They continue to be the foundation for generations of cardiovascular physiologists.

Dr. Guyton received more than 80 major honors from diverse scientific and civic organizations and universities throughout the world. A few of these that are especially relevant to cardiovascular research include the Wiggers Award of the American Physiological Society, the Ciba Award from the Council for High Blood Pressure Research, The William Harvey Award from the American Society of Hypertension, the Research Achievement Award of the American Heart Association, and the Merck Sharp & Dohme Award of the International Society of Hypertension. It was appropriate that in 1978 he was invited by the Royal College of Physicians in London to deliver a special lecture honoring the 400th anniversary of the birth of William Harvey, who discovered the circulation of the blood.

Dr. Guyton's love of physiology was beautifully articulated in his president's address to the American Physiological Society in 1975,[3] appropriately entitled *Physiology, a Beauty and a Philosophy*. Let me quote just one sentence from his address: *What other person, whether he be a theologian, a jurist, a doctor of medicine, a physicist, or whatever, knows more than you, a physiologist, about life? For physiology is indeed an explanation of life. What other subject matter is more fascinating, more exciting, more beautiful than the subject of life?*

A Master Teacher. Although Dr. Guyton's research accomplishments are legendary, his contributions as an educator have probably had an even greater impact. He and his wonderful wife Ruth raised ten children, all of whom became outstanding physicians—a remarkable educational achievement. Eight of the Guyton children graduated from Harvard Medical School, one from Duke Medical School, and one from The University of Miami Medical School after receiving a Ph.D. from Harvard. An article published in *Reader's Digest* in 1982 highlighted their extraordinary family life.[4]

The success of the Guyton children did not occur by chance. Dr. Guyton's philosophy of education was to "learn by doing." The children participated in countless family projects that included the design and construction of their home and its heating system, the swimming pool, tennis court, sailboats, go-carts and electrical cars, household gadgets, and electronic instruments for their Oxford Instruments Company. Television programs such as *Good Morning America* and *20/20* described the remarkable home environment that Arthur and Ruth Guyton created to raise their family. His devotion to family is beautifully expressed in the dedication of his *Textbook of Medical Physiology*[5]:

To
My father for his uncompromising principles that guided my life
My mother for leading her children into intellectual pursuits
My wife for her magnificent devotion to her family
My children for making everything worthwhile

Dr. Guyton was a master teacher at the University of Mississippi for over 50 years. Even though he was always busy with service responsibilities, research, writing, and teaching, he was never too busy to talk with a student who was having difficulty. He would never accept an invitation to give a prestigious lecture if it conflicted with his teaching schedule.

His contributions to education are also far reaching through generations of physiology graduate students and postdoctoral fellows. He trained over 150 scientists, at least 29 of whom became chairs of their own departments and six of whom became presidents of the American Physiological Society. He gave students confidence in their abilities and emphasized his belief that "People who are really successful in the research world are self-taught." He insisted that his trainees integrate their experimental findings into a broad conceptual framework that included other interacting systems. This approach usually led them to develop a quantitative analysis and a better understanding of the particular physiological systems that they were studying. No one has been more prolific in training leaders of physiology than Arthur Guyton.

Dr. Guyton's *Textbook of Medical Physiology*, first published in 1956, quickly became the best-selling medical physiology textbook in the world. He had a gift for communicating complex ideas in a clear and interesting manner that made studying physiology fun. He wrote the book to teach his students, not to impress his professional colleagues. Its popularity with students has made it the most widely used physiology textbook in history. This accomplishment alone was enough to ensure his legacy.

The *Textbook of Medical Physiology* began as lecture notes in the early 1950s when Dr. Guyton was teaching the entire physiology course for medical students at the University of Mississippi. He discovered that the students were having difficulty with the textbooks that were available and began distributing copies of his lecture notes. In describing his experience, Dr. Guyton stated that "Many textbooks of medical physiology had become discursive, written primarily by teachers of physiology for other teachers of physiology, and written in language understood by other teachers but not easily understood by the basic student of medical physiology."[6]

Through his *Textbook of Medical Physiology*, which is translated into 13 languages, he has probably done

more to teach physiology to the world than any other individual in history. Unlike most major textbooks, which often have 20 or more authors, the first eight editions were written entirely by Dr. Guyton—a feat that is unprecedented for any major medical textbook. For his many contributions to medical education, Dr. Guyton received the 1996 Abraham Flexner Award from the Association of American Medical Colleges (AAMC). According to the AAMC, Arthur Guyton ". . . for the past 50 years has made an unparalleled impact on medical education." He is also honored each year by The American Physiological Society through the Arthur C. Guyton Teaching Award.

An Inspiring Role Model. Dr. Guyton's accomplishments extended far beyond science, medicine, and education. He was an inspiring role model for life as well as for science. No one was more inspirational or influential on my scientific career than Dr. Guyton. He taught his students much more than physiology—he taught us life, not so much by what he said but by his unspoken courage and dedication to the highest standards.

He had a special ability to motivate people through his indomitable spirit. Although he was severely challenged by polio, those of us who worked with him never thought of him as being handicapped. We were too busy trying to keep up with him! His brilliant mind, his indefatigable devotion to science, education, and family, and his spirit captivated students and trainees, professional colleagues, politicians, business leaders, and virtually everyone who knew him. He would not succumb to the effects of polio. His courage challenged and inspired us. He expected the best and somehow brought out the very best in people.

We celebrate the magnificent life of Arthur Guyton, recognizing that we owe him an enormous debt. He gave us an imaginative and innovative approach to research and many new scientific concepts. He gave countless students throughout the world a means of understanding physiology and he gave many of us exciting research careers. Most of all, he inspired us—with his devotion to education, his unique ability to bring out the best in those around him, his warm and generous spirit, and his courage. We will miss him tremendously, but he will remain in our memories as a shining example of the very best in humanity. Arthur Guyton was a real hero to the world, and his legacy is everlasting.

References

1. Brinson C, Quinn J: Arthur C. Guyton—His Life, His Family, His Achievements. Jackson, MS, Hederman Brothers Press, 1989.
2. Guyton AC, Coleman TG, Granger HJ: Circulation: overall regulation. Ann Rev Physiol 34:13–46, 1972.
3. Guyton AC: Past-President's Address. *Physiology, a Beauty and a Philosophy.* The Physiologist 8:495–501, 1975.
4. Bode R: A Doctor Who's Dad to Seven Doctors—So Far! Readers' Digest, December, 1982, pp. 141–145.
5. Guyton AC: Textbook of Medical Physiology. Philadelphia, Saunders, 1956.
6. Guyton AC: An author's philosophy of physiology textbook writing. Adv Physiol Ed 19: s1–s5, 1998.

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PREFACE

The first edition of the *Textbook of Medical Physiology* was written by Arthur C. Guyton almost 50 years ago. Unlike many major medical textbooks, which often have 20 or more authors, the first eight editions of the *Textbook of Medical Physiology* were written entirely by Dr. Guyton with each new edition arriving on schedule for nearly 40 years. Over the years, Dr. Guyton's textbook became widely used throughout the world and was translated into 13 languages. A major reason for the book's unprecedented success was his uncanny ability to explain complex physiologic principles in language easily understood by students. His main goal with each edition was to instruct students in physiology, not to impress his professional colleagues. His writing style always maintained the tone of a teacher talking to his students.

I had the privilege of working closely with Dr. Guyton for almost 30 years and the honor of helping him with the 9th and 10th editions. For the 11th edition, I have the same goal as in previous editions—to explain, in language easily understood by students, how the different cells, tissues, and organs of the human body work together to maintain life. This task has been challenging and exciting because our rapidly increasing knowledge of physiology continues to unravel new mysteries of body functions. Many new techniques for learning about molecular and cellular physiology have been developed. We can present more and more the physiology principles in the terminology of molecular and physical sciences rather than in merely a series of separate and unexplained biological phenomena. This change is welcomed, but it also makes revision of each chapter a necessity.

In this edition, I have attempted to maintain the same unified organization of the text that has been useful to students in the past and to ensure that the book is comprehensive enough that students will wish to use it in later life as a basis for their professional careers. I hope that this textbook conveys the majesty of the human body and its many functions and that it stimulates students to study physiology throughout their careers. Physiology is the link between the basic sciences and medicine. The great beauty of physiology is that it integrates the individual functions of all the body's different cells, tissues, and organs into a functional whole, the human body. Indeed, the human body is much more than the sum of its parts, and life relies upon this total function, not just on the function of individual body parts in isolation from the others.

This brings us to an important question: How are the separate organs and systems coordinated to maintain proper function of the entire body? Fortunately, our bodies are endowed with a vast network of feedback controls that achieve the necessary balances without which we would not be able to live. Physiologists call this high level of internal bodily control *homeostasis*. In disease states, functional balances are often seriously disturbed and homeostasis is impaired. And, when even a single disturbance reaches a limit, the whole body can no longer live. One of the goals of this text, therefore, is to emphasize the effectiveness and beauty of the body's homeostasis mechanisms as well as to present their abnormal function in disease.

Another objective is to be as accurate as possible. Suggestions and critiques from many physiologists, students, and clinicians throughout the world have been sought and then used to check factual accuracy as well as balance in the text. Even so, because of the likelihood of error in sorting through many thousands of bits of information, I wish to issue still a further request to all readers to send along notations of error or inaccuracy. Physiologists understand the importance of feedback for proper function of the human body; so, too, is feedback important for progressive improvement of a textbook of physiology. To the many persons who have already helped, I send sincere thanks.

A brief explanation is needed about several features of the 11th edition. Although many of the chapters have been revised to include new principles of physiology, the text length has been closely monitored to limit the book size so that it can be used effectively in physiology courses for medical students and health care professionals. Many of the figures have also been redrawn and are now in full color. New references have been chosen primarily for their presentation of physiologic principles, for the quality of their own references, and for their easy accessibility. Most of the selected references are from recently published scientific journals that can be freely accessed from the PubMed internet site at http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=PubMed. Use of these references, as well as cross-references from them, can give the student almost complete coverage of the entire field of physiology.

Another feature is that the print is set in two sizes. The material in small print is of several different kinds: first, anatomical, chemical, and other information that is needed for immediate discussion but that most students will learn in more detail in other courses; second, physiologic information of special importance to certain fields of clinical medicine; and, third, information that will be of value to those students who may wish to study particular physiologic mechanisms more deeply.

The material in large print constitutes the fundamental physiologic information that students will require in virtually all their medical activities and studies.

I wish to express my thanks to many other persons who have helped in preparing this book, including my colleagues in the Department of Physiology & Biophysics at the University of Mississippi Medical Center who provided valuable suggestions. I am also grateful to Ivadelle Osberg Heidke, Gerry McAlpin, and Stephanie Lucas for their excellent secretarial services, and to William Schmitt, Rebecca Gruliow, Mary Anne Folcher, and the rest of the staff of Elsevier Saunders for continued editorial and production excellence.

Finally, I owe an enormous debt to Arthur Guyton for an exciting career in physiology, for his friendship, for the great privilege of contributing to the *Textbook of Medical Physiology*, and for the inspiration that he provided to all who knew him.

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