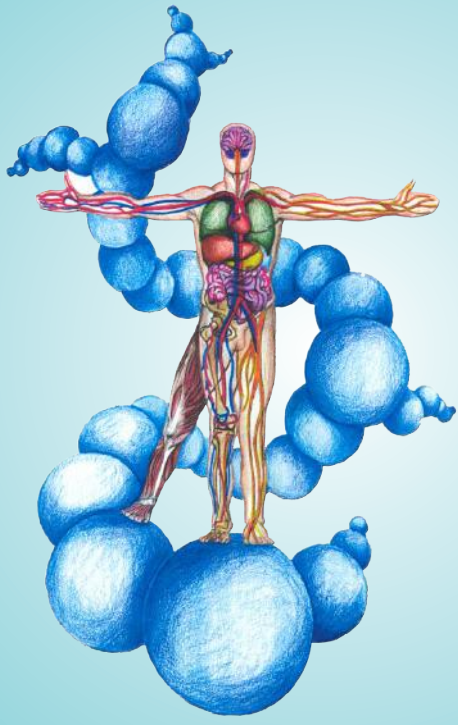
Advances in Bioengineering Research and Applications, Volume 2

Biomechanics of Artificial Organs and Prostheses

Megh R. Goyal, PhD, PE
Vijay K. Goyal, PhD



Apple Academic Press

CRC Press
Taylor & Francis Group

BIOMECHANICS OF ARTIFICIAL ORGANS AND PROSTHESES

BIOMECHANICS OF ARTIFICIAL ORGANS AND PROSTHESES

Megh R. Goyal, PhD, PE, and Vijay K. Goyal, PhD

Apple Academic Press

TORONTO NEW JERSEY

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Apple Academic Press, Inc
3333 Mistwell Crescent
Oakville, ON L6L 0A2
Canada

Version Date: 20140117

International Standard Book Number-13: 978-1-4822-3157-1 (eBook - PDF)

CONTENTS

List of Abbreviations ..... *vii*
Preface ..... *ix*
Foreword ..... *xiii*
Warning/Disclaimer ..... *xvii*
Book Reviews ..... *xix*
About the Book Series: Advances in Bioengineering Research and Applications ..... *xxi*
Titles in the Advances in Bioengineering Research and Applications book series ..... *xxv*
About the Author ..... *xxvii*
About the Author ..... *xxix*

1. Biofluid Dynamics of Cardiopulmonary Bypass Surgery 39
2. Biomechanics of Artificial Heart 75
3. Biomaterials for an Artificial Pacemaker 121
4. Biomaterials for Carotid Stenting 153
5. Biomechanics of Angioplasty: Ballooning and Stenting 177
6. Biomechanics of Artificial Lung 217
7. Biomechanics of Artificial Kidney 307
8. Biomechanics of Arthritis and Human Body Pain 387
9. Biomechanics of Orthopaedic Fixations 433
10. Biomechanics of Total Knee Replacement 481
11. Biomechanics of Dental Prostheses 509

Glossary of Technical Terms *547*
Index *587*

LIST OF ABBREVIATIONS

ACC	American College of Cardiology
AIMBE	American Institute for Medical and Biological Engineering
ANNA	American Nephrology Nurses Association
ASABE	American Society of Agricultural and Biological Engineers
ASAIO	American Society for Artificial Internal Organs
ASAO	Austrian Society for Artificial Organs
ASB	American Society of Biomechanics
ASBMR	American Society of Bone and Mineral Research
ASME	American Society of Mechanical Engineers
BiVAD	Biventricular Assist Device
BMES	Biomedical Engineering Society
CHF	Congestive Heart Failure
CPB	Cardiopulmonary Bypass
CPS	Cardiopulmonary Support System
CVP	Central Venous Pressure
DT	Destination Therapy
ECG	Electrocardiogram
EDTA	European Dialysis and Transplantation Association
EMBS	Engineering in Medicine and Biology
ESAO	the European Society for Artificial Organs
ESB	European Society of Biomechanics
ESEM	European Society for Enginerring and Medicine
FDA	Food and Drug Administration, USA
HSTAT	Health Services Technology Assessment Texts
IABP	Intra Aortic Ballon Pump
IFAO	International Federation for Artificial Organs (formerly ISAO)
ISABB	International Society for Artificial Cells, Blood Substitutes & Biotechnology
ISAO	International Society for Artificial Organs
ISFA	International Society for Apheresis
ISPD	International Society for Peritoneal Dialysis
ISRP	International Society for Rotary Blood Pumps
JSAO	the Japanese Society for Artificial Organs
LVAD	Left Ventricular Assist Device
MedEc	Medical Economics
NCBI	National Center for Biotechnology Information
NIH	National Institute of Health, USA
NIHCBC	National Institute of Health Center for Biomedical Computation at Stanford University

NKF	National Kidney Foundation
ORS	Orthopaedic Research Society
REMATCH	Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart
RMTES	Regenerative Medicine and Tissue Engineering Society
SMB	Society for Mathematical Biology
TAH	Total Artificial Heart
TERMIS	Tissue Engineering and Regenerative Medicine International
VAD	Ventricular Assist Device
VSD	Ventricular Septal Defect

PREFACE

I have been teaching fluid mechanics to undergraduate and graduate students since 1971. I decided to apply principles of fluid mechanics to human body systems: When my respiratory system collapsed in 1989 and I had three strokes in 2002 and my vagus nerve failed in 1999; my mother broke her hips and orthopedic surgeon did "Total Hip Replacement (THR)" and my mother survived 12 more years; my elder brother had a heart mitral valve replaced in 2003 and he feels perfectly fine; my mother-in-law passed away in 2010 with three heart valves damaged (she did not want to have a heart operation and she lived for next 4 years after diagnosis of heart disease); our neighbor in Puerto Rico had "Total Knee Replacement (TKR)" for both knees and now she can do her daily activities. I thought why would this happen to a human body, and I was able to understand that Almighty Supreme God grants serenity and knowledge to physicians so that we can live longer and happier. I also know a friend of mine with amputation of both legs and he does his daily activities using a wheel chair. All this fascinates my soul. Let us all keep our spirits high so that our life is always dynamic to be happier today/tomorrow and forever. This is how idea for this book was born.

Engineering mechanics deals with response of bodies at rest or in motion due to applied external forces/couples/torques/rotation/and moments. Biomechanics deals with living organisms: Agricultural plants, animals and humans. In this book, I will consider only human body systems. One is interested in variation of velocity, pressure, density, volume, momentum, heat, mass, nutrient or other parameter throughout the body. In the human body, I will consider only continuous bodies (i.e., there is no discontinuity at any point for a specific body part). Biomechanics and Computational Fluid Dynamics (CFD) is one of the specialty areas of biomedical engineering. Biomechanics applies classical mechanics (bodies at rest or in motion, thermodynamics, and continuum mechanics) to biological or medical problems. It includes the study of motion flow within our body and in medical devices, and transport of chemical constituents across biological and synthetic media and membranes. Progress in biomechanics has led to the development of the artificial organs and prostheses: Heart valves, stents, TKR, THR, etc.

Biomechanics is widely used in orthopedic industry to design orthopedic implants for human joints, dental parts, external fixations and other medical purposes. It also includes study of the performance and function of biomaterials used for orthopedic implants. It plays a vital role in improving the design and producing successful biomaterials for medical and clinical purposes.

The mission of this compendium is to serve as a textbook or a reference manual for graduate and undergraduate students of biomedical engineering, biotechnology, nanotechnology, nursing, and medicine and health sciences. I hope that it will be a valuable reference for professionals that work with medicine and health sciences, for nursing institutes, and other agencies that work with human health.

My book complements other similar books in the market and is unique because it is complete, simple, one-stop manual worldwide on *Biomechanics of Artificial Organs and Prostheses*. This textbook includes basic principles and applications of mechanics and materials for human body. This book is a must for physicians, scientists, educators, and students.

This book on *Biomechanics of Artificial Organs and Prostheses* consists of 12 chapters consisting of: Introduction on artificial organs; biofluid dynamics of cardiopulmonary bypass surgery; biomechanics of the artificial heart; biomaterials for an artificial pacemaker; biomechanics of the angioplasty: ballooning and stenting; biomechanics of carotid stenting; biomechanics of an artificial lung; biomechanics of the human kidney system and artificial kidney; biomechanics of the arthritis and human body pain; biomechanics of orthopedic fixations; biomechanics of total knee replacement; and biomechanics of dental prostheses. Each chapter includes an introduction, body of the chapter, conclusions, summary, key words and a bibliography. Book also includes a glossary of terms. This book is Volume 2 for the AAP series titled *Advances in Bioengineering Research and Applications*.

The chapters in this book are based on my research and teaching materials and special projects by my students in the courses on fluid mechanics/engineering mechanics/and mechanics of materials at University of Puerto Rico at Mayagüez and the course on biofluid mechanics at Florida International University. The contribution by my students at University of Puerto Rico at Mayagüez and Florida International University has been most valuable in the compilation of this compendium. Their names are mentioned in each chapter. In July of 2001, students of my course (INGE4015) in Fluid Mechanics conducted the first congress on "*Biofluid Dynamics of Human Body Systems*." The purpose of this congress was to show and learn how the biofluids of the many body systems function and help to maintain a great physical state. In this congress, student groups discussed Biofluid Dynamics of: Brain system; Ear/throat/nose system; Circulatory system; Reproductive system; Digestive system; Respiratory system; Urinary system; Arthritis; Instrumentation and measurements for the human body; Challenges in Biofluid dynamics of human body systems. In July of 2002, students conducted second congress on "*Biofluid Dynamics and Engineering of Artificial Organs*." The purpose of this congress was to learn biofluid dynamics of Bioheat Transfer in a Human Body, Biomass Transfer in a Human Body, Biofluid Mechanics of Artificial heart, Biofluid Mechanics of Artificial lung, and Biofluid Mechanics of Artificial kidneys. In April of 2003, students of my course on – BME4999 Human Body Systems – conducted third congress on "*Biofluid Dynamics of Human Body Systems*" to discuss: Circulatory System; Artificial Heart; Cardiovascular Bypass Surgery; Respiratory System; Kinetics of Drug Transport; Digestive System; Maternal Fetal System; Stenting of Intracranial Arteries as Endovascular Bypass of Berry Aneurysms (Baruch Barry Lieber, PhD, PE, University of Miami). In July of 2004, we conducted fourth congress on Biofluid Dynamics of Human Body Systems to discuss: Our Body Fluids; Properties of body fluids; Ear/nose and throat system; Balloning and stenting; Urinary system; Artificial kidney; Advances in human body fluids; dimensional analysis; Biomass transfer; Body pain; Instrumentation and measurements. It has been an excellent learning experience for me. I thank all of them at University of

Puerto Rico at Mayagüez and at Florida International University who have enriched my knowledge in Biomedical Engineering.

This book would not have been written without the valuable cooperation of a group of engineers and physicians at the University of Puerto Rico at Mayagüez (UPRM) and Florida International University (FIU). I am grateful to my colleagues: Paul Sundaram, Ricky Valentin, Carlos Rinaldi, David Suleiman, Madeline Torres, Eduardo Juan, Alejandro Acevedo, and Ivette Ríos Lamberty. Dr. Vijay K. Goyal, an associate professor of the Department of Mechanical Engineering at the University of Puerto Rico at Mayagüez with over 17 years of experience in advanced computational methods applied to structures, joins me as coauthor for this volume. He has been exploring and researching this field for a couple of years as he tried to develop a toolkit to predict bone regeneration. His insights and collaboration was invaluable for this volume. The reader will not have this edition in front of you without his offer without his professional contribution.

I owe special gratitude to Anthony McGoron at FIU and Richard Schoephoerster, now Dean of the College of Engineering at the University of Texas at El Paso – Texas, who taught me to love biomedical engineering during my sabbatical leave in 2003 at FIU. I had the opportunity to work closely with all of them including other faculty members. The author also thanks executive officers at UPRM Campus to initiate research in biomedical engineering and nanotechnology.

I would like to thank Ashish Kumar, Publisher and President, and Sandra Jones Sickels, VP, at Apple Academic Press, Inc., for making every effort to publish the book when the human health is a major issue worldwide. Special thanks are due to AAP Production Staff for typesetting the entire manuscript and for the quality production of this book.

I request the reader to offer me your constructive suggestions that may help to improve the next edition. The reader can order the copy of this book for the library, the institute or gift from www.appleacademicpress.com.

Finally, a river of thanks flows from my heart and soul to my wife Subhadra for the understanding and collaboration of sharing the responsibility, time and devotion necessary to prepare this book. With my whole heart and best affection, I dedicate this book to our youngest son Vinay Goyal and his wife Stacey Carpenter. They always motivate me to live longer and happier to serve the world community. I also dedicate this book to "*those who want to live happily*" by making personal health as first priority. One should not hesitate to discuss any personal health issues with a physician who are dedicated and blessed by Almighty Supreme God to do the maximum for alleviating our body pain. Good health not only makes us happy but also makes happy everyone around us.

— Megh R. Goyal, PhD, PE

December 31st 2013

FOREWORD

In 1994, Dr. Megh R. Goyal taught me courses on soil and water management and farm machinery when I was an undergraduate student at the University of Puerto Rico – Mayaguez Campus. He was one of my favorite professors. After receiving my BSc degree in agriculture sciences, I decided to enter the medical school to become a specialist in internal medicine and respiratory mechanics. After reading and editing this manuscript, I feel honored to write a foreword for this book, thus paying tributes to my professor.

I want to share with the readers what I learnt from textbooks on medical physiology by Arthur Guyton and other authors. The human body is a fascinating job of our Almighty God. It is made up of a head, neck, torso, two arms and two legs. The human body is made to stand erect, walk on two feet, use the arms to carry and lift, and has opposable thumbs (able to grasp). The adult body is made up of 100 trillion cells, 206 bones, 600 muscles, and 22 internal organs. Every square inch of the human body has about 19 million skin cells. Every hour about 1 billion cells in the human body must be replaced. The average human head has about 100,000 hairs. The arteries, veins and capillaries are about 100,000 kilometers long. The heart beats more than 2.5 billion times in an average lifetime. The human heart creates enough pressure to squirt the blood 30 feet high. It takes about 20 seconds for a red blood cell to circle the whole body.

The human body has nine major systems: circulatory system; respiratory system; musculoskeletal system; nervous system; reproductive system; digestive system; urinary system; lymphatic system; integumentary (dermal) system. Five minor systems are: immune system; excretory system; endocannabinoid system; endocrine system and vestibular (sensory) system. Each system plays a vital part in the health and well-being of the entire body.

The circulatory system pumps and channels blood to and from the body and lungs with heart, blood, and blood vessels. Blood is a medium that transports oxygen, from the respiratory system to the cells. Blood also transports sugars, chemicals, proteins, hormones and many other substances around the body for use and elimination. As the heart pumps blood, a pulse beat can be felt at various locations in the body and each pulse beat corresponds to one heartbeat. The heart rate of the average adult at rest is between 80 to 120 beats per minute, depending on age, medical conditions and general fitness.

The respiratory system is composed of the airway (mouth, nose, trachea, larynx, bronchi and bronchioles) and the lungs (including the small air sacs called alveoli). The respiratory system provides oxygen to the blood and takes away the waste product called carbon dioxide. Oxygen is extracted from air inhaled through the airway and goes into the blood stream through the membranes of the lungs. For the first aider, maintaining a casualty's airway is of primary importance.

The musculoskeletal system is composed of muscles that provide movement and a skeleton that provides structural support and protection with bones, cartilage, ligaments, and tendons. Most muscles used for movement work by contracting and relaxing in conjunction with a bone.

The digestive system helps in digestion and processing of food with salivary glands, esophagus, stomach, liver, gallbladder, pancreas, small and large intestines, rectum, and anus. Fluid and solids are passed through the esophagus to the stomach where they are processed for further digestion. They are then absorbed into the body through the membranes of the intestines. Some organs, such as the liver and pancreas, are considered accessories to the digestive system as they help process food into various chemical substances used by the body.

The urinary system (kidneys, ureters, bladder and urethra) is involved in fluid balance, electrolyte balance and excretion of urine. This system flushes waste products suspended in fluid from the body. It plays a vital role in keeping the body healthy. Should the urinary system fail (especially the kidneys), then the affected person requires external assistance to get rid of the waste products by 'flushing' the blood. This is called hemodialysis or dialysis.

The integumentary (dermal) system is composed of skin, hair and nails. The skin is the body's largest organ and plays an important role in protecting the body from infections. The other functions of skin include acting as a shield against injury and keeping body fluids in. The skin is made from tough, elastic fibers, which have the ability to stretch without tearing easily.

As a physician and a specialist in internal medicine and pulmonary mechanics, I work closely with my colleagues namely: cardiologist Marcos A Velazquez; dentist Luis Camacho; foot surgeon Andres Maymi; gastroenterologist Carlos Micames; gynecologist Walter Banch; hand surgeon Oscar Vargas; maxi-facial surgeon Juan C. Garcia; nephrologist Justiniano Alfredo; orthopedic surgeons Hector Vargas/Gilberto Baez/Jose Cancio; surgeon Juan A. Diaz; urologist Benjamin Perez; and including others. I see them with a smiling face and joy every time each one of them comes out of an operating room. We all are here to extend the best treatment in the market to our patients so that they feel happy and do not feel the body pain.

In this textbook, Professor Goyal applies principles of biomechanics and biomaterials to artificial organs and prostheses. He has wisely discussed all the topics with an abundance of illustrations and technical data. In the world of medicine, one of the greatest advancements has been the ability to create artificial organs and prostheses that can restore the proper function of a patient's body. They can be used both for functions that are essential to the quality of life of a patient. The organs that can be replaced artificially are quite numerous, including the ears, ovaries, and even the heart and brain. I will discuss only one example to emphasize the importance of engineering of artificial organs.

The most common manifestation of an artificial organ is found with mechanical aids that are used to improve a person's ability to hear and distinguish sounds. Called cochlear implants, the organs have been successful with nearly 200,000 people across the globe. In addition to improving the sense of hearing in those patients with impaired ears, the artificial organs are also able to provide a limited hearing ability to people

who are deaf. As this device becomes less expensive and more available, it is thought that the worldwide incidence of deafness will decrease dramatically. One case of a survival situation where an artificial organ will make the difference between life and death is in a heart transplant. If a patient is awaiting a new heart, an artificial heart can be temporarily used to keep the person alive until the new heart becomes available. In recent times, models have been created that can stand alone and provide a permanent replacement for a heart that has functional impairment. This new type of artificial heart is currently in the process of being evaluated and it is thought that it will be ready for widespread live use beginning in the year 2013. The availability of artificial organs can do much to improve a person's life, from providing the essential bodily functions for survival to improving sensory capabilities, such as sight and hearing.

I hope that this concise textbook by Dr. Megh R. Goyal and Apple Academic Press Inc. will be definitely appealing and valuable to the health sciences community. It is unique, user-friendly and introductory, focusing on essential aspects of *Biomechanics of Artificial Organs and Prostheses*. I will like to see more books on such topics.

Jesús Manuel Román Vélez, MD
Practicing Specialist in Internal Medicine, Pulmonary Mechanics
Fellow-American Society of Internal Medicine
Mayaguez, PR, USA

WARNING/DISCLAIMER

READ CAREFULLY

This textbook guides the world community on *Biomechanics of Artificial Organs and Prostheses* for better health. The reader must be aware that the dedication, commitment, honesty, and sincerity are most important factors in a dynamic manner for a complete success. It is not a one-time reading of this manual. Read and follow every time; it is needed. To err is human. However, we must do our best. Always, there is a space for learning new experiences.

The editor, the contributing authors, the publisher and the printing company have made every effort to make this book as complete and as accurate as possible. However, there still may be grammatical errors or mistakes in the content or typography. Therefore, the contents in this book should be considered as a general guide and not a complete solution to address any specific situation in the human body. For example, all humans are not same and behave differently.

The authors, the publisher and the printing company shall have neither liability nor responsibility to any person, any organization or entity with respect to any loss or damage caused, or alleged to have caused, directly or indirectly, by information or advice contained in this book. Therefore, the purchaser/reader must assume full responsibility for the use of the book or the information therein.

The mentioning of commercial brands and trade names are only for technical purposes. It does not mean that a particular product is endorsed over to another product or equipment not mentioned. Author, cooperating authors, educational institutions, and the publisher Apple Academic Press Inc. do not have any preference for a particular product.

All weblinks that are mentioned in this book were active on December 31st 2013. The editor, the contributing authors, the publisher and the printing company shall have neither liability nor responsibility if any one of the weblinks is inactive at the time of reading of this book.

BOOK REVIEWS

"I am enthusiastic to know that Apple Academic Press Inc. and Dr. Megh R. Goyal (whom have I known since 1979) have published this textbook that is user-friendly and easy-to-read. The book includes key aspects of *Biomechanics of Artificial Organs and Prostheses*."

— Miguel A. Muñoz Muñoz, PhD, President of University of Puerto Rico, USA

"I hope that this concise textbook on artificial organs and prostheses by Dr. Goyal and Apple Academic Press Inc. will be definitely appealing and valuable to the health sciences community. It is unique and introductory focusing on essential aspects of *Biomechanics of Artificial Organs and Prostheses*. I will like to see more books on such topics."

— Jesús Manuel Román Vélez, M.D., Practicing Physician, Specialist in Internal Medicine and Pulmonary Mechanics, Fellow of American Society of Pulmonary Medicine, Mayaguez, PR, USA.

"What a gem, with simple language and vivid illustrations! The photos and data deepened my understanding on biomechanics and biomaterials of artificial organs and prostheses the way it applies to our daily life. Before I sat down to read this book, I was not sure how much I would understand the content. But each chapter builds understanding on the content and shows the author's mastery on the subject. I firmly believe that this book is a must read for all with interest in bioengineering and readers who want to make their health as their first priority."

— Prof. Raj Bansal, New Jersey, USA