Cardiac Perfusion and Pumping Engineering
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REVIEWS

“Cardiac Perfusion and Pumping are inter-related, and hence together constitute an intriguing phenomenon that governs cardiac performance. This fascinating book is unique in addressing the clinical features and bioengineering characteristics of cardiac perfusion and pumping. The book also addresses assisted pumping (in the form of left ventricular assist devices) and cardiac tissue engineering (to replace and regenerate myocardial infarcts). The bioengineering formulations of the various chapters are not only sufficiently rigorous to be instructive for bioengineering courses, but are also clinically oriented. The book should be very useful to biomedical engineers as well as cardiologists and cardiac surgeons.”

Ghassan S. Kassab
Thomas J. Linnemeier Guidant Endowed Chair
and Professor of Biomedical Engineering
Professor of Surgery, Cellular and Integrative Physiology
Indiana-Purdue University, USA

“This book is unique! It describes the multiple aspects of cardiac ventricular contraction (provided by cardiac perfusion and pumping characteristics), by observing the specific features associated with contraction with an amplified attention. The result is an intermediate step between the well-accepted biomechanical interpretations and fully new and original scientific descriptions. This book is not just a book of a collection of accepted and validated concepts. Nor, is it a special issue of a scientific journal (devoted to perfusion and pumping), with proposals of new concepts and descriptions. Rather, it is an intermediate status of the matter. If you are searching for concrete aspects, you will find therein the relevant models and rules currently accepted by the scientific community. However, if your mind wants to fly out of the actual constraints, you have so many opportunities to compare your most original ideas with those described by the authors, that you will be engaged in a fascinating game.

You will find in the book an acceptable and agreeable scent of science, which impregnates every page of the book and drags a bright mind into a knowledge paradise!”

Romano Zannoli
Professor of Medical Physics
University of Bologna, Italy
PREFACE

Cardiac pumping is dependent on cardiac perfusion. Hence, it is only natural that we address both cardiac perfusion and pumping in this book. We have gone one step further in also considering assisted perfusion by coronary bypass surgery and myocardial regeneration by means of stem cells transformed into implantable cardiomyocytes. The book is hence divided into three sections:

(1) Cardiac Perfusion,
(2) Cardiac Pumping Characteristics,
(3) Assisted Perfusion and Pumping, and Myocardial Repair.

Section I on Cardiac perfusion starts out with the chapter on physiomics of coronary microcirculatory perfusion, which supplies nutrients to the heart myocardium for its contraction. The following chapter deals with the phenomenon of myocardial inhomogeneity, and provides an answer to this enigma as the basis of providing cardiac functional reserve. The next chapter is on quantification of cardiac perfusion and function, using nuclear cardiac imaging. The final chapter in this section is a synthesis of cardiac perfusion and pumping. It analyses left-ventricular (LV) pumping in terms of intra-ventricular blood flow velocity and pressure distributions, and also computationally depicts the distribution of pressure and flow velocities in discrete regions of the heart.

Section II is on how cardiac pumping is initiated by myocardial contraction, causing stresses and strains in the myocardium. More importantly, the mechanism of how myocardial contraction causes LV torsion is also discussed. The LV myocardial fibers are spirally wound inside its wall. Thereby, when they contract, the LV twists and then unwinds during relaxation. While this LV torsion is an end-product of LV myocardial fibers geometry and contraction, it can also serve as an index of contractility. Finally, in order for LV to contract or to depict its inability to contract adequately for adequate blood outflow, we have developed indices to assess its contractility, in the form of some intrinsic indices that correlate well with the traditional contractility index of \((dP/dt)_{\max}\). In doing so, we have also addressed a hitherto unexplained phenomenon of LV suction during its early filling state. The LV sarcomere is still contracting (albeit decreasing
it's contractile force and shortening velocity) during early filling. It is this mechanism that causes LV suction (and resulting LV pressure decrease), before the left atrium starts to contract and cause LV filling.

Cardiovascular disease results in \textit{in vivo} bioelectrical abnormalities, blocked coronary vessels and consequently myocardial infarcts. Hence, it is but natural that this book also deals (in Section III) with methods of augmented myocardial perfusion by coronary bypass surgery, mechanical circulatory support in the form of cardiac-assist devices, and myocardial regeneration by means of implantable three-dimensional cardiomyocyte constructs converted from embryonic stem cells. In this regard, this section discusses in detail the reasons for blocked distal coronary graft-occluded vessel anastomosis, the mechanical analysis of circulatory-support ventricular-assist systems, and in particular of an axial blood pump. The last two chapters deal with the basis and prospects of tissue engineering and novel approaches to cell transplantation following the conversion of embryonic stem cells into cardiomyocyte scaffolds for implantation.

We hope that this book can serve as a major reference resource in cardiology and cardiac surgery, as well be employable as a course text for a course on this topic in a biomedical engineering program. With these aims in mind, the individual chapters deal in adequate rigor with both theory and clinical applications.

Thank you.

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October 2006
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BOOK SUMMARY

Section I. Cardiac Perfusion

Chapter 1. Physiomics of Coronary Perfusion and Cardiac Pumping by Fumihiko Kajiya, Masahito Kajiya, Taro Morimoto, Tatsuo Iwasaki, Yousuke Inai, Masanori Hirota, Takahiko Kiyooka, Yuki Morizane, Takehiro Miyasaka, Satoshi Mohri and Juichiro Shimizu

Physiome is considered to be a powerful successor to the genome. Physiome refers to a quantitative description of the physiologic dynamics or functions of the intact organism. It includes integration of knowledge through functional modules and modelling of hierarchic system elements of biologic systems. Biomechanics offers potent tools to promote the physiome concept. By using modern microvisualization technology with physiomic model of coronary circulatory network, this chapter introduces our physiomic approach to coronary microcirculation, which supplies oxygen and nutrients to heart muscles.

The heart is unique, among other organs, in that coronary arterial flow is exclusively diastolic while venous flow is systolic. That is, blood pooled in coronary microvessels (during diastole) is squeezed out to the coronary vein by myocardial contraction. In this chapter, we first describe the biomechanical interaction between coronary blood flow and cardiac contraction. Then, the physiome of coronary capillary network and its functions are discussed.

Chapter 2. Left Ventricular Inhomogeneity and the Heart’s Functional Reserve by Felix Blyakhman

This chapter concerns with the study of myocardial inhomogeneity in the left ventricular wall. Inhomogeneity is an attribute of both the normal heart and the pathologically compromised heart. In the course of the last couple of decades, this phenomenon has revealed that myocardial inhomogeneity is a modulator of cardiac contractility and/or pump function, although the significance of inhomogeneity for the normal heart has not yet been clarified. Why has nature created such an inhomogeneous device? In this chapter, we seek an answer to this question. We present evidence that the possible role of inhomogeneity in the normal heart is to provide functional reserve.
for the left ventricle, which is tapped (as needed) to maintain stability of cardiac pumping function throughout the course of life.

Chapter 3. Quantification of Cardiac Perfusion and Function Using Nuclear Cardiac Imaging by Ru-San Tan, Liang Zhong, Terrance Chua and Dhanjoo N. Ghista

Myocardial ischemia occurs when tissue metabolic needs outstrip coronary blood flow or perfusion. The deficiency of the latter is commonly caused by atherosclerotic coronary artery disease, and is diagnosed by various myocardial perfusion imaging techniques that track blood flow heterogeneity between myocardium supplied by normal versus narrowed arteries. Nuclear myocardial perfusion imaging, the most established and ubiquitous of these methods, uses radioactive isotopes (commonly thallium-201- or technetium-99m-based tracer agents) combined with stress and rest imaging protocols, to evaluate regional relative coronary flow reserves, and hence diagnose areas of myocardial ischemia and infarction. Modern image acquisition, using single photon emission computed tomography, allows the reconstruction of a three-dimensional image dataset that facilitates visual analysis as well as quantitation of perfusion. This increases reproducibility of interpretation, and is especially useful in the assessment of myocardial viability. Further, electrocardiographic gating, during the scan acquisition, allows assessment of left ventricular function, which has great prognostic significance. Quantitated perfusion and functional data can be displayed as polar maps that are amenable to comparison with normal databases, thus enhancing the clinical applicability of the technique.

Chapter 4. Regional Mechanics of the Beating Heart by Martyn P. Nash and Peter J. Hunter

Mathematical modeling provides a useful tool to understand the normal and abnormal mechanical function of the heart. The large deformations that take place during the cardiac cycle require that finite deformation elasticity must be used with the governing laws of physics. In addition, the complex geometry and microstructural arrangement of cardiac muscle requires that numerical and computational methods need to be used to solve the resulting nonlinear equations. This chapter summarizes a continuum mechanics approach to analyzing myocardial soft tissues, and details how the orthotropic nature of the ventricular myocardium may be efficiently represented. Based on this framework, a finite element analysis of canine ventricles is presented, and