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# REVIEW

**The Mechanics of the Circulation.** By C. G. CARO, T. J. PEDLEY, R. C. SCHROTER and W. A. SEED. Oxford University Press, 1978. 527 pp. £22.00 (hardback) or £11.00 (paperback).

That large area of medical and physiological research which is concerned with the circulation depends, of course, upon many sub-disciplines. Among these, however, an increasingly important role is played by the subject of this book: the *mechanics* of blood flow, and of blood vessels, and of their interactions. Because the necessary mechanics is relatively refined, it has now become widely accepted that progress in this field will almost always require collaborative work by a team of workers trained in different branches of science: some in the life sciences and some in the mechanical sciences. Several such teams in various parts of the world have been gradually built up so as to work successfully in the field. Hitherto, however, the process of team build-up has been slow because of the lack of texts suitable for facilitating that mutual education of members (each in the others' disciplines) which is needed if effective communication of ideas based on a certain common background of essential knowledge is to make the collaboration useful.

Fortunately, such a text is at last available. Here is a book on the mechanics of the circulation that is equally accessible to those trained in the life sciences and in the mechanical sciences. Furthermore, it succeeds remarkably in laying down a common foundation of mechanical, anatomical and physiological facts and principles strong enough to support the building-up of major collaborative research structures that can lead to significant new advances in the field. Its four authors, as might be expected, are of different disciplinary backgrounds (the two doctors of medicine are a physiologist and a physician, while the two doctors of philosophy are a mathematician and an engineer), and have enjoyed an extended period working together in the interdisciplinary Physiological Flow Studies Unit at Imperial College, London. Every section of the book is the work of more than one of the authors, who have jointly sought to ensure everywhere that no reader, whether grounded in the life sciences or the mechanical sciences, will be at sea because unfamiliar terminology and ideas are introduced without explanation.

Certainly, this is a book which every research worker (with either type of background) concerned with the mechanics of the circulation will wish to possess. Remarkably enough, there is only quite a small portion (just the first five chapters, comprising 15 % of the book) that consists of material which might be assumed familiar to typical readers of the *Journal of Fluid Mechanics*. Conversely, there is perhaps another 15 % of the book that might be assumed familiar to readers with a general medical training: just the introductory sections, giving essential anatomical background, to each of the last six chapters (on the blood; the heart; the systemic arteries, microcirculation and veins; and the pulmonary circulation). The remaining 70 % of the book will lead both types of reader to a common understanding of a wide range of specialized material on the mechanics of the circulation without using any unduly difficult ideas or terminology.

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It is especially valuable that this material has been made *quantitative* to the maximum extent possible on the basis of present knowledge. Indeed, a most comprehensive range of numerical data on all aspects of the circulation is presented here for the most fully studied experimental animal (the dog), and this will be of the greatest help to those pursuing further experimental and theoretical researches on canine circulation. In addition, comparable data on man are given wherever they are available. Furthermore, comparative measurements on *arterial* characteristics in a wide range of mammals are given to throw light on size dependence; although, necessarily, numerical data on the structure of the microcirculation are confined in the main to preparations such as bat's wings that lend themselves to convenient observation.

In many cases, a member of an interdisciplinary research team will enthusiastically welcome parts of this book which he can effectively use as a clearly written text suitable for putting essential background material in his own field over to colleagues in complementary disciplines. Fluid-mechanics experts, for example, will appreciate how those first five chapters give great clarity to essential concepts (on particle dynamics, units and dimensions, pressure, viscous stress, mass conservation, Bernoulli's equation, Poiseuille flow, Reynolds number, turbulence, boundary layers, separation, secondary flows, jets and wakes) while motivating the analyses for life scientists with various physiological illustrations. A modest level of calculus (ordinary derivatives only) is developed through the dynamics, but the book admirably avoids unnecessarily using any advanced calculus in its exposure of the essential ideas of fluid mechanics.

The next four chapters, although nominally continuing to expose 'background mechanics', contain rather more material which is likely to be new to readers with a general fluid-mechanics background. Relevant parts of the theory of elasticity are expounded alongside a very thorough treatment of the properties of blood vessel walls which gives a comprehensive account of their nonlinear elastic properties. This clearly explains also the use of a local linearization and goes on to treat the effects of elastic hysteresis, viscoelasticity and the 'tethering' of arteries by adjacent tissue. Similarly, dimensional analysis is expounded alongside an account of 'scale effects' for mammals in different size ranges; while waves and their analysis are expounded in relation to aspects important for haemodynamics. Finally, an excellent chapter on mass transfer emphasizes not only Fickian diffusion and the associated boundary layers, but also the various ramifications of osmotic and 'active' mechanisms of transport that play such important roles in physiology.

After these nine chapters on background mechanics, the book's remaining six chapters (pp. 151–514) are concerned with the circulation's structure and function and, especially, with its mechanics. The chapter on blood begins with a rather thorough account of aspects of its composition relevant to blood flow. This is followed by a comprehensive treatment of the mechanics of red cells, and of the effect of suspended elements in general on haemorheology (including material on tendencies to form rouleaux); together with introductions to sedimentation behaviour, blood osmotic pressure and the mechanics of clotting.

A particularly excellent chapter of this book is concerned with properties of the heart, viewed both as a muscle and as a matched pair of pumps. This is concerned, first, to summarize the extensive amount of information available on cardiac muscle, and, then, to apply it to understand as far as possible 'Starling's law of the heart'; that is, the good matching (over a wide range of cardiac outputs) between the initial

filling of both the right heart and the left heart and the subsequent volume of blood ejected from each. Additionally, the reader of this chapter will obtain a clear understanding of electrocardiograms and the phase relationships between ECG's and left ventricular pressure and flow; an analysis of left-ventricle shape during contraction and its relation to ejection flows; an extended appreciation of heart valves and the dynamics of their closure; and a useful survey of what is known of the mechanics of heart sounds and murmurs.

The book's longest chapter is on the systemic arteries. Both the gross anatomy of the arterial tree and the microstructure of arterial walls are especially well treated. These treatments include accounts of characteristic changes with age. There follows a massive account (85 pages) of pulse-wave propagation and other effects determining the nature of unsteady blood flow. This describes the observed distributions of fluctuating pressure and velocity in different parts of the arterial tree, and interprets them in terms of wave theory. It exhibits clearly the relations between wave speed and distensibility for the practically important case of 'tethered' tubes. It analyses the pulse wave into harmonics (of which just ten normally suffice). Observations and theory on simple and multiple reflexions are explained, together with the implications of resonance effects. A careful account of impedances and how they are combined is given, and applied in the manner pioneered by M. G. Taylor to understand the remarkably low impedance opposing the fluctuating part of a normal heart's power output. Wave attenuation by blood viscosity and wall viscoelasticity are analysed, alongside some account of nonlinear wave propagation effects. Substantial information is given, too, on more complicated features of flow distribution such as entrance regions, secondary flows and 'bursts' of turbulence. The chapter ends with a section on mass transport, including aspects relevant to 'atherogenesis' and to the indicator-dilution method of measuring blood volume.

A chapter on the systemic microcirculation again begins with a clear account of the anatomy and microstructure; covering arterioles, capillaries and venules and the associated lymphatic circulation, and explaining the role of smooth muscle in controlling the distribution of peripheral perfusion. There is an analysis of the elastic behaviour of vessel walls, followed by an extended treatment of how the flow in small vessels is strongly affected by the deformability of red cells. Factors that bring about a redistribution of red cells over a cross-section are clearly enumerated.

However, the explanation of how the cell-free layer near a wall produces the Fahraeus–Lindquist effect (reduction of apparent viscosity in small arterioles or large capillaries) ought to have been clearer. A simple diagram could explain how the flow in a cross-section is obtained by adding up velocity *increments* with decreasing distance from the tube axis, each multiplied by the area of the part of the cross-section within that radius. Another diagram would show how each such velocity increment is proportional to the axial pressure gradient, the radius, and the local value of the reciprocal viscosity $\mu^{-1}$. It then follows that the reciprocal apparent viscosity is a weighted mean of the local reciprocal viscosities $\mu^{-1}$ with a weighting function equal to the radius *cubed* (area times radius); then the abnormally large value of this weighted mean would be seen as a necessary consequence of the large local reciprocal viscosity in the 'cell-free layer' where the weighting function is a maximum.

This chapter continues with a good account of how red cells are necessarily deformed to pass through the narrowest capillaries, and of how a lubricating layer of plasma

facilitates that deformation. It concludes with an important section on mass transport, including an account of the different mechanisms that affect filtration and reabsorption in capillaries.

An especially important chapter of this book is concerned with the systemic veins, which in general have been the most seriously neglected region for circulatory mechanics studies (although, as the authors point out, veins normally contain about four-fifths of the total volume of blood in the systemic vessels). Compared with arteries, veins are extremely thin-walled. Furthermore, in the physiologically interesting range of transmural pressures, their elastic behaviour is even more markedly nonlinear. Broadly speaking, veins at higher levels than the heart experience negative transmural pressures (the blood in them is at a lower pressure than the tissue outside) and this leads to a deformation of their cross-sections; which take on an oval or 'dumb-bell' shape at moderate or larger values (respectively) of the negative transmural pressure. The mechanics of this deformation and of the consequent changes in flow resistance are analysed, and related to experimental studies of flow in collapsible tubes, which can exhibit more than one interesting type of flow oscillation, or discontinuous transition between different flow modes. There is a good discussion of the possible relevance of such studies to the real flow in veins. In addition, various types of wave propagation observed in veins are traced to their probable causes (for example, a backward wave propagation in the *venae cavae*, generated by the contraction of the right heart), and limitations on such propagation (including effects of the venous valves) are indicated.

This book's excellent level is maintained right through to the last chapter, on the pulmonary circulation. Compared with the systemic circulation this is a low-pressure network (carrying the same flow at around one-sixth of the excess-pressure), and the artery walls are correspondingly thinner. The quantitative data here given on numbers, diameters, etc., for different orders of capillary, arteriole and artery in the human pulmonary circulation (based on the anatomical studies of G. Cumming and his colleagues) are particularly valuable and comprehensive. Also, fine micrographs of the structure of the alveolar–capillary barrier are included; while the important discoveries of recent years by Y. C. Fung and his colleagues on blood flow in the 'alveolar sheet' are faithfully reflected. Finally, wave propagation in pulmonary arteries is described, and the book ends with an account of the well-known 'zonal' character of blood flow in the lung; that is, differences in the nature of perfusion in three different bands as a function of the level of the alveolar–capillary transmural pressure in relation to the arterial and venous pressure levels.

Although I have primarily emphasized the value of this book to teams conducting research on the mechanics of the circulation, it will clearly be valuable also to a much wider readership. This will no doubt include established cardiological physicians and surgeons, as well as many aspirants to such positions. The book can also be strongly recommended to general readers interested in fluid mechanics who may wish to learn more about one of the most important contemporary areas of active application of that science.

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