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REVIEWS

Cardiovascular Fluid Dynamics. Edited by D. H. Bergel. Academic Press, 1972. Vol. I, 365 pp. Vol. II, 398 pp. £7.50 each volume.

Gas Transfer in the Lung. By B. A. Hills. Cambridge University Press, 1974. 176 pp. £4.90.

The publication of these two books reflects the growing recognition among both engineers and physical scientists on the one hand, and physicians and life scientists on the other, that in certain areas of biomedical research a cooperative, inter-disciplinary approach is essential. This is particularly true in the physiology of the circulation and respiration (of man as of all other animals) because these systems fulfil their functions by largely mechanical means: the blood is made to flow in the blood vessels by the pumping action of the heart, and air flows in the airways, driven by the changing volume of the thorax. In either case, flow is necessary in order for the vital mass transfer of gases and nutrients to take place. A complete understanding of each system therefore involves an application of the principles of fluid mechanics, and a prerequisite for success is that life scientists should understand some fluid mechanics, and that physical scientists should learn the relevant physiology. These books are both intended to help bridge the gap.

In 1960 McDonald published his monograph *Blood Flow in Arteries*, which introduced many important fluid mechanical ideas in language which a physiologist could understand, and at the same time described the arterial system in enough detail that an engineer could form a realistic picture of it without having to learn too much jargon. The purpose of *Cardiovascular Fluid Dynamics* is to bring McDonald's book up to date by giving a detailed survey of the progress which has been made since 1960, in a way which both a biologist and a physical scientist, without previous experience in the other's field, can comprehend. The book should be judged, therefore, on how well it achieves these aims, although readers of this journal will also want to know how well it fulfils the promise of its title. The authors of the different chapters have had to try to review the latest work in their fields without either being completely empirical or relying heavily on mathematics, but rather showing by physical argument how the theoretical ideas and the experimental investigations have developed together. Many of the contributions provide evidence of how difficult this is.

The titles and authors of the nineteen chapters are as follows.

Volume I

1. Introduction, by D. H. Bergel.
2. Pressure measurement in experimental physiology, by I. T. Gabe.
3. Measurement of pulsatile flow and flow velocity, by C. J. Mills.
4. The measurement of lengths and dimensions, by D. H. Bergel.
5. The use of control theory and systems analysis in cardiovascular dynamics, by K. Sagawa.

6. Some computer models in cardiovascular research, by J. E. W. Beneken.
7. The meaning and measurement of myocardial contractility, by J. R. Blinks & B. R. Jewell.
8. The fluid mechanics of heart valves, by B. J. Bellhouse.
9. Pressure and flow in large arteries, by D. L. Schultz.
10. Vascular input impedance, by V. Gessner.

Volume II

11. The rheology of large blood vessels, by D. J. Patel & R. N. Vaishnav.
12. The influence of vascular muscle on the viscoelastic properties of blood vessels, by B. S. Gow.
13. Poststenotic dilatation in arteries, by M. R. Roach.
14. Flow conditions at bifurcations as determined in glass models, with reference to the focal distribution of vascular lesions, by G. G. Ferguson & M. R. Roach.
15. Blood rheology, by S. E. Charm & G. S. Kurland.
16. The mechanics of capillary blood flow, by J. M. Fitz-Gerald.
17. Flows across the capillary wall, by C. C. Michel.
18. Pulmonary haemodynamics, by W. R. Milnor.
19. Synthesis of a complete circulation, by R. Skalak.

The editor in his introduction gives a brief outline of the anatomy of the human cardiovascular system, and indicates those areas in which fluid mechanics is important. Chapters 2, 3 and 4 are all concerned with techniques of measurement. While the need to base all physiological research on reliable experimental evidence should be emphasized, and while these are excellent guides to a number of widely used techniques, the reader will not learn much physiology, nor much fluid mechanics, from any of them. Chapter 5 is one of those whose author has been unable to reconcile his desire to present an up-to-date review with the avowed educative purpose of the book. In his second paragraph he states that "elementary knowledge of classical control theory...is assumed, as well as some knowledge of the neural control of the cardiovascular system"; the result is a specialist review, packed with jargon, which a fluid dynamicist will find very hard to read, and a biologist virtually impossible. This chapter also reinforces one's impression that a deep understanding of a physiological system can rarely be achieved by treating it as a black box.

Chapter 6 is another which has only rather loose associations with fluid mechanics. After reminding us of the principles governing the creation of a model, the author gives a critical account of some of the successful and unsuccessful computer models in cardiovascular mechanics. He then breaks one of the principles, by ignoring Taylor dispersion in a mathematical account of whether mass transport in blood vessels can be described by means of different equations. He also advocates "parameter estimation" (curve-fitting) procedures for gaining quantitative understanding of a system with many parameters, without noting the great dangers associated with possible non-uniqueness of the answer, especially when the underlying model is itself speculative.

Chapter 7 is probably the best in volume I. The authors review the major principles of muscle mechanics, which were developed for skeletal muscle, and which led in that case to a useful simple model of muscle as a contractile element and an elastic element in series. They explain how measurements on isolated strips of heart muscle have shown the inadequacy of this model, and of any other yet proposed, in describing the behaviour of heart muscle. They examine all the experiments, and conclude that the intrinsic contractile capability of a piece of heart muscle can be described at best by a surface in the three-dimensional space of muscle length, tension, and time after stimulation; no single index of 'myocardial contractility' can possibly be found. Finally they point out that all the experimental work which has for years gone into the study of isolated strips of muscle is almost completely irrelevant as far as the intact heart is concerned, while interpretation of the experiments so far performed on an intact heart has required such oversimplification as to be of very little value. There is clearly scope for a breakthrough in this field.

Chapter 8 is the first specifically fluid mechanical one. In it the author gives a concise description of his experiments on models of the aortic and the mitral valve, and is entirely convincing in his conclusion that these valves are operated fluid mechanically. The vortices which are set up behind the valve cusps retain their strength while the flow through the orifice is decelerating, and the resulting small pressure difference causes them to close smoothly, with little backflow, before the forward-moving blood has come to rest. The theoretical analysis of this behaviour leaves a lot to be desired, based as it is on the arbitrary assumption that the peak velocity in the vortex is directly proportional, at all times, to the forward velocity a little way downstream.

Chapters 9 and 10 are those in which we might have expected to see a review of all the fluid mechanics which has been done on blood flow in arteries since the publication of McDonald's book, with particular emphasis on pulse-propagation, which was his chief concern. Instead Dr Schultz chooses to describe (*a*) measurements of the velocity profile at various stations in the aorta, (*b*) the results of a nonlinear theory of the evolution of the pressure and velocity wave forms in the aorta (with little physical discussion either of the model or of the results), and (*c*) the presence of turbulence in the jet downstream of a stenosed valve (unable to open fully), but not the occurrence of turbulence in normal subjects. Whole areas of arterial fluid mechanics are omitted, and it is only in chapter 19 that some of them are briefly touched on. Dr Gessner does have a coherent theme, and gives a good summary of how impedance is calculated at different frequencies, for the measured pressure and flow rate in the aorta. He is also careful to explain the approximations involved in using the linear concept of impedance in the cardiovascular system. However he does not explain how impedance values are useful, his development of many of the ideas is too mathematical, and he too prefers not to describe the mechanics of the phenomena which give rise to his results.

The first two chapters of volume II comprise a detailed description of the mechanical properties of blood vessel walls, of which any fluid dynamicist working in the field should be aware. In chapter 11 the properties of a segment of the aorta, subjected to axisymmetric loading, are exhaustively examined.

The authors present the evidence for or against many of the basic assumptions that are usually made, like the incompressibility of vessel walls, their homogeneity, etc. They quantify the effects of the tethering of an artery to the surrounding tissue, and outline the range of experiments needed before all the coefficients of orthotropic viscoelasticity can be determined. One is made very aware of the crudeness of the usual approximation representing the properties of a vessel wall by a single Young's modulus, which varies with pressure, and is complex to account for viscoelasticity. However, one does question the need for the precise determination of quite so many constants, when most theoretical or diagnostic applications of the data are themselves crude. Even with all these constants, real physiological events like the collapse of a vein cannot be described. Dr Gow's approach is more simple-minded (he is content with a single complex Young's modulus), but even at that level there is still much to be learnt about the effect of the contraction of the muscle in vessel walls on the mechanics of the circulation. For instance, the evidence is still contradictory as to whether muscular contraction results in a stiffer or a floppier blood vessel, because the stiffening effect of the contracted muscle is offset by the reduction in vessel diameter, which increases its distensibility because of the nonlinear elasticity of the other components of the wall.

The next two short chapters are excellent examples of the interaction between fluid mechanics and medicine. Chapter 13 examines the (reversible) dilatation of an artery wall which often occurs just downstream of a stenosis (partial blockage). In a most elegant account, Dr Roach presents the incontrovertible evidence that turbulence in the downstream jet is solely responsible for the dilatation, because it causes the vessel wall to vibrate at frequencies which affect the cross-linking between the substances comprising the wall. In chapter 14 the possible influence on vascular disease of flow patterns in bifurcations is examined, mainly with reference to the earlier transition to turbulence in bifurcations, in steady and pulsatile flow. Here the connexion with disease is more tenuous, and the fluid mechanics is rather naive; in particular a unique Reynolds number is not defined for pulsatile flow.

In any study of cardiovascular mechanics the properties of blood must always be central. Chapter 15, "Blood rheology", is unfortunately not mechanical enough. There are useful descriptions of how blood cells and plasma, separately and together, behave in various viscometers, but there is little guidance as to what rheological model is most useful in practice, and no help is given in understanding why blood behaves as it does; the authors ignore all the work of people like Goldsmith and Mason. Furthermore this is the chapter in which we would expect a full discussion of blood flow in arterioles (tube diameters = 2–15 cell diameters), where control of the local distribution of blood flow is located, but there is hardly any. The flow of blood in the narrowest vessels, the capillaries, is examined in chapter 16. This is good fluid mechanics, based on Lighthill's (*J. Fluid Mech.* **34**, 1968, 113) and the author's theories, in which a real understanding of the flow is achieved, although whether a physiologist will find it easy to understand is doubtful.

Chapter 17, like chapter 7, is an example of a physiological review at its best.

There is a coherent account of the experimental evidence on where and how transport of different substances across the capillary wall occurs, and this is guided and interpreted in terms of a clear and simple theoretical framework. The subject is particularly important in the analysis of vascular diseases, in which alterations in the rate of transport of materials across the wall may be of central importance. Chapter 18 is also classically physiological, discussing primarily experimental results, and although it does not contain much fluid dynamical discussion of blood flow in the lung, it does provide a very good summary of the essential differences between the pulmonary and the systemic circulations.

In the final chapter, Dr Skalak demonstrates how far we still are from a complete theoretical model of the whole circulation, and points the direction in which future work, based on the theories of pulse propagation which should have been described elsewhere, should go. Any fluid dynamicist can here obtain a realistic overall view of the field, and many will surely be stimulated to enter it.

In summary, then, there is a lot of excellent material in *Cardiovascular Fluid Dynamics*, especially in volume II, and the book should be available to anyone wishing to acquaint himself with the field. The omission of the physics of pulse propagation in arteries, the mechanics of veins, and blood flow in arterioles is disappointing, but even the worst chapters are partially redeemed by excellent bibliographies, which are of a uniformly high standard throughout. Both volumes should find a place in fluid mechanics libraries, but an individual will get best value if he buys only volume II.

Dr Hills's book is a research monograph rather than a review although perhaps the best part of it, too, is the exhaustive list of references. His intention (I suppose) is to provoke a more critical evaluation, by respiratory physiologists, of some of the methods and assumptions which they traditionally employ, and to stimulate a more widespread use of fundamental physical principles. For that he is to be commended. He analyses each of eight separate contributions to the difference in the partial pressure of oxygen between inspired air and arterial blood, and it appears that three of them dominate in the normal lung: convective mixing during flow in the airways (about 75 %); "shunt", i.e. direct by-pass of the lungs by venous blood (about 10 %); and the imbalance between the air and blood supplies to different regions of the lung (about 7 %). The resistance to diffusion across the alveolar membrane, conventionally regarded as important, is seen to be negligible. The predominance of convective mixing in the airways is a revolutionary idea, to be welcomed, but although Dr Hills frequently criticizes the traditional assumptions, he makes no attempt to put his own results into perspective, and it is almost impossible to assess how his contributions will influence respiratory physiology.

In any case, it is most unlikely that many respiratory physiologists will be able to read this book, because although he is ostensibly writing for them, it is full of dense mathematical notation which will be quite daunting; it is pretty indigestible for physical scientists too, especially when combined with the frequent unexplained use of physiological jargon. Furthermore, since flow and mixing in the airways are important, Dr Hills should have been more concerned to explain the fluid mechanics properly: an incorrect description of boundary layers, a confusion between entry flow and transitional flow, and a totally inadequate account of Taylor dispersion are likely to be positively misleading to any physiologist who gets that far. Finally, I must comment on the patronizing way Dr Hills treats both non-mathematical biologists and non-physiological mathematicians or engineers. I quote: "With such specific statements of boundary conditions, it is now possible to refer to the standard mathematical texts for the relevant solutions, or to invoke the assistance of a mathematician or engineer who need not understand the physical nature of the problem." A sure recipe for disaster, especially if he were to find a mathematician or engineer who would be content with that role. This book, then, is a good idea, but poorly executed, and overpriced.

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