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THE FLUID MECHANICS OF LARGE BLOOD VESSELS

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T. J. PEDLEY, M.A., PH.D.
Lecturer in Department of Applied Mathematics and Theoretical Physics
University of Cambridge and Fellow of Gonville and Caius College

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PREFACE

Some knowledge of fluid mechanics is required before the circulation of the blood can be understood. Indeed, the single fact that above all others convinced William Harvey (1578–1657) that the blood does circulate was the presence in the veins of valves, whose function is a passive, fluid mechanical process. He saw that these could be effective only if the blood in the veins flowed towards the heart, not away from it as proposed by Galen (129–199) and believed by the European medical establishment until Harvey's time. Harvey was also the first to make a quantitative estimate of the output of blood from the human heart and this, although a gross underestimate (36 oz, i.e. about 1 litre, per minute instead of about 5 litres per minute) was largely responsible for convincing the sceptics that the arterial blood could not be continuously created in the liver and, hence, that it must circulate.

The earliest quantitative measurements of mechanical phenomena in the circulation were made by Stephen Hales (1677–1761) who measured arterial and venous blood pressure, the volume of individual chambers of the heart and the rate of outflow of blood from severed veins and arteries, thereby demonstrating that most of the resistance to blood flow arises in the microcirculation. He also realised that the elasticity of the arteries was responsible for blood flow in veins being more or less steady, not pulsatile as in arteries.

Later in the eighteenth and in the nineteenth centuries, a number of well-known fluid dynamicists interested themselves in the circulation of the blood and made significant contributions to our understanding of it. These included Euler, Daniel Bernoulli (actually a professor of anatomy) and Poiseuille (also a physician; this last name in particular makes it clear how an attempt to solve real, applied problems may often lead to important developments in fundamental science). One of the greatest polymaths was Thomas Young (1773–1829), another physician whose research in optics led to both the acceptance of the wave theory of light and an understanding of the perception of colour. The other important area of his research concerned the nature of elasticity, in particular the properties and function of elastic arteries; his theory of wave propagation in elastic tubes is still recognised as a fundamentally correct description of the pressure pulse in arteries. It was in his lecture to the Royal Society of London on this subject (Young, 1809) that he explicitly recognised that 'the inquiry, in what manner, and in what degree, the circulation of the blood depends on the muscular and elastic powers of the heart and of the arteries, supposing the nature of those powers to be known, must become simply a question belonging to the most refined departments of the theory of hydraulics'.

It is with some of the more refined departments of the theory of hydraulics, as applied to the circulatory systems of mammals, that this book is primarily concerned. The object of the research is the same as Young's, to understand the physical events that take place in the normal animal, and thereby make a contribution to physiology. A secondary aim is to make a contribution to medicine, by analysing particular abnormal or diseased states in the hope of improving their diagnosis or treatment. In either case it is the biological (or medical) end that is important, not the mathematical means that are used to achieve it. The applied mathematics should be firmly linked to experiment, using, explaining and predicting experimental results. For this reason considerable space is devoted to a description of the circulatory system, and, where our fluid mechanical understanding has come from in-vivo or model experiments, the experiments are fully described. Furthermore, the mathematical description of a phenomenon may be complicated, but if only simple mathematics is needed or available, only simple mathematics is used. On the other hand, when the phenomenon is so complex that our understanding is still limited, the only way forward may be a lengthy analysis of an idealised model of the real system, with the experimental link as yet absent.

A number of books on the mechanics of the circulation already exist, but these consist *either* of works aimed principally at a biological or medical audience *or* of conference proceedings or collections of invited articles. Of the former, some are too simplified for the student of mechanics, and those that are not naturally try to omit the mathematical development of the theory, describing its results in physical terms. (I am a co-author of one such book (Caro *et al.*, 1978); another important one is by McDonald (1960, 1974).) The collections of articles (of which the best is that edited by Bergel (1972*a*)) often do contain mathematical development of the theory, but it is presented in a piecemeal way. In view of the fact that an increasing number of engineers and applied mathematicians are coming into the field of cardiovascular fluid mechanics, the time seems ripe for a research monograph that concentrates on the mathematical analysis, and this book tries to provide it. The contents include some areas of the subject that are already very well understood, such as the propagation of the pressure pulse (chapter 2), but most of the book concerns relatively novel areas where research is still very much in progress. These include the prediction of flow patterns and, in particular, wall shear stresses in arteries (chapters 3–5), which are important both because of their postulated significance in the genesis of arterial disease (§ 1.2) and because they cannot yet be measured. The other major area of work in progress concerns flow in vessels, such as veins, that undergo collapse; several interesting phenomena are observed and their explanation presents an exciting challenge to fluid mechanics that we have as yet only begun to meet.

The subject matter is limited to large blood vessels (the heart, arteries and veins) for two reasons. The first is that the problems presented by the microcirculation are much more difficult because (*a*) there has been little detailed measurement of pressures and velocities there, (*b*) the inhomogeneous and non-Newtonian character of blood cannot be ignored, and (*c*) active changes in the calibre of arterioles are important, and cannot be accounted for in passive mechanical terms. The second reason, probably consequent upon the first, is that my own research has been restricted to vessels in which the Reynolds number is considerably greater than 1. The topics selected for analysis reflect my research interests over the last 10 years. They include most of the cardiovascular work with which I have been involved in that time, set in its physiological context and broadened by the work of others to form what I hope is a fairly complete account of those topics. The most obvious omission is an analysis of flow through arterial stenoses (constrictions). A lot of experimental and theoretical work has been done on this subject and its neglect can be justified only on the grounds that stenoses are an abnormal geometrical feature, whereas I have elsewhere concentrated on understanding physiologically normal events.

Mention should also be made of the appendix, a separate, self-contained chapter on the behaviour of hot-film anemometers in steady and unsteady flow. This is included partly because it is an area in which I have myself been active, but principally because hot-film anemometry is at the moment the most reliable and widely used method of measuring blood velocity in living arteries. Hot-film measurements form the basic experimental data on which much of the theory of this book is based. Nevertheless, there are a number of inherent difficulties in making accurate measurements in unsteady flow, and I hope that this appendix will serve to warn the theoretical reader to take care in interpreting published data. Perhaps it may also help experimentalists to avoid some of the less obvious pitfalls.

Finally, a note about units. In the text I have endeavoured to quote all data in SI units, but in redrawing diagrams from other works, in particular those containing physiological data, I have usually retained the units employed by the original authors. Pressure units are the most difficult since both millimetres of mercury ($1\ \mathrm{mmHg} = 133\ \mathrm{N\ m^{-2}}$) and centimetres of water ($1\ \mathrm{cmH_2O} = 98\ \mathrm{N\ m^{-2}}$) are commonly used in cardiovascular physiology in place of the newton per square metre (or pascal). I hope that I have managed to avoid confusion by often quoting both SI units and physiological units.

The first draft of this monograph was completed in December 1976 and, together with the review article ‘Pulmonary fluid dynamics’ (Pedley, 1977), was awarded the Adams Prize of the University of Cambridge for 1975–6.

Thomas Young was part of the great tradition of eighteenth- and nineteenth-century science in paying little regard to the distinction between biological and physical science. By the end of the nineteenth century, however, a gulf was opening up between the two, which has only recently begun to close again (at least in circulatory physiology) by the development of interdisciplinary teams. While it is unrealistic nowadays to expect the applied mathematician to perform all the biological or engineering experiments to which his mathematics is applied, the application will not be useful unless he works closely with those who do perform them. For my introduction to, and continued close contact with, physiological reality I am profoundly grateful to my ex-colleagues at the Physiological Flow Studies Unit, Imperial College, London, especially Colin Caro, Robert Schroter, Anthony Seed and Michael Sudlow. In addition, I have benefited greatly from contact with many senior scientists who have worked at that Unit, especially James Fitz-Gerald, Joseph Milic-Emili, Robert Nerem and Kim Parker. I also owe a lot to my research students Sholaum Springer, Ian Sobey, Simon Farthing and Rosemary Wild, but for whom even fewer of the problems discussed in this book would have been solved, to my associate Christopher Bertram for his collaboration in the computational work of chapter 6, and to everyone, especially Berenice Schreiner, Denise Thomas and Judith Roberts, who co-operated in typing this manuscript with such patience and accuracy. I would finally like to acknowledge a special debt of gratitude to Professor Sir James Lighthill who has taken a keen interest in my work and has strongly supported it since I first turned to physiological fluid mechanics in 1968.

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T. J. PEDLEY