edited by D. H. Bergel

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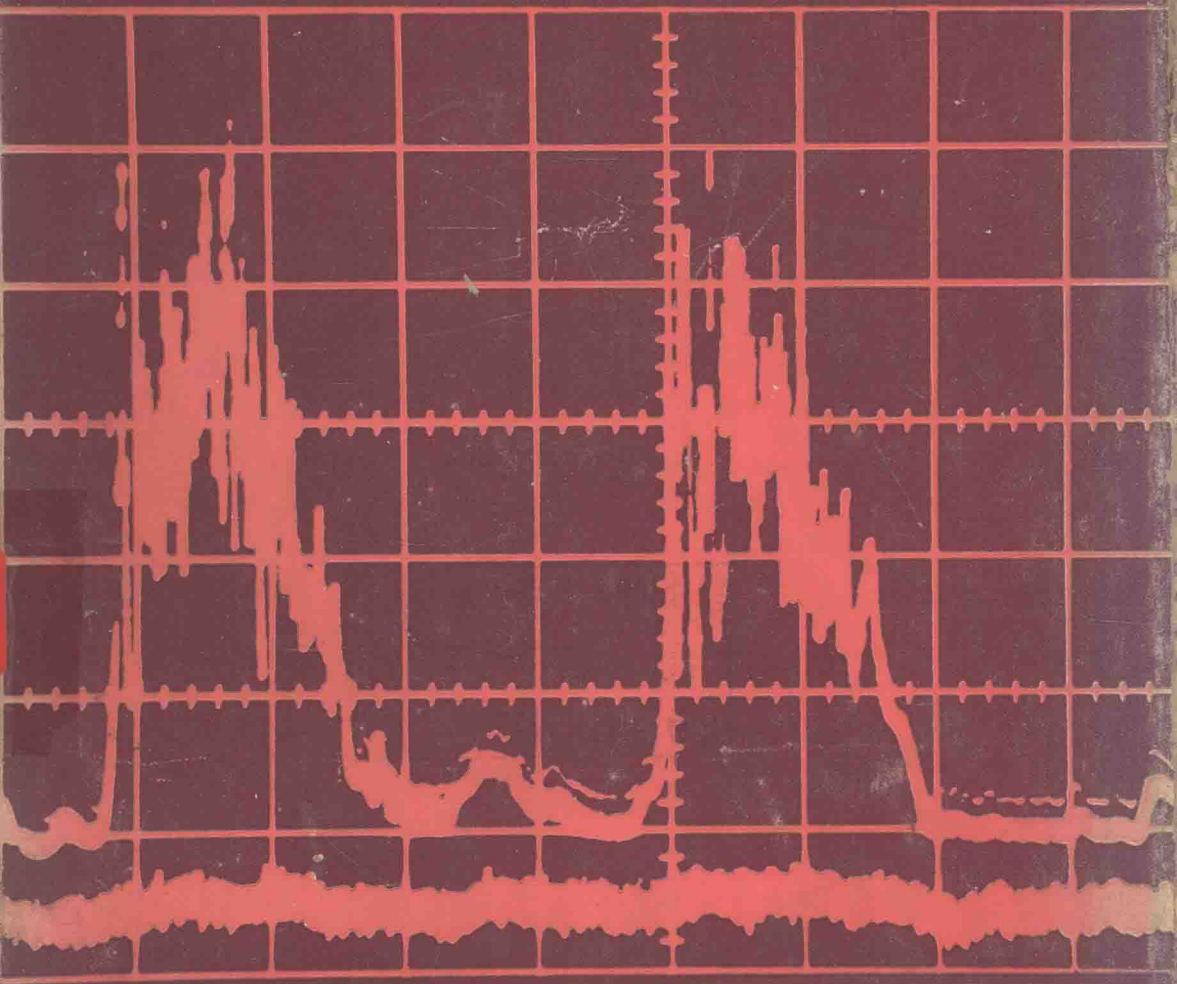
CARDIOVASCULAR FLUID DYNAMICS



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CARDIOVASCULAR FLUID DYNAMICS

Edited by

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VOLUME 1

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Preface

The purpose of this book is to make available, in as concise and manageable a form as possible, the results of the intensive study of the fluid dynamics of the mammalian cardiovascular system undertaken in the previous decade. In the ten years that have elapsed since the publication of McDonald's monograph on "Blood Flow in Arteries", so much has been achieved that a new assessment is needed.

I hope that the various chapters will show what is the present situation in this field, and how this point has been reached through experimentation based on a proper understanding of the physical background. The methods and concepts used in this work will be only partly familiar to biologists, physicians and fluid dynamicists. It has been my intention to produce a book which will serve these specialists in introducing them to a very active field of experimental research and will allow them to enter it with a good understanding of the established physical and biological features of the fascinating cardiovascular system.

At this point it is customary for the editor to thank all those who have contributed to the work. I hope it will be clear that my expressions of thanks are a great deal more than conventional. My own contribution here has been quite modest, for although I have myself worked in many of the areas discussed, I have been aware that others are much better qualified now to deal with these subjects. It has been a great privilege to work with so large and varied a team and I can only hope that our friendship will survive the strain. I wish especially to thank all the Oxford authors, and also Dr. Colin Clark, whose continuing criticisms and suggestions have helped me greatly. Finally, the publishers, who have transformed a great heap of paper into what I hope is now a coherent whole; may they never regret the effort.

D. H. BERGEL

Oxford
June, 1972

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Glossary

Adventitia	The outermost coat of a blood vessel.
Aneurysm	A localized dilation of an artery.
Angiogram	An X-ray picture in which the contents of the blood vessels have been rendered radio-opaque by the injection of a contrast medium.
Arteriole	The finest subdivision of the arterial tree, typically vessels of 100–200 μm in diameter. The walls are relatively muscular and variations in the activity of this muscle play a major part in the control of the circulation.
Arteries	The vessels carrying the blood from the left or right ventricles to the tissues.
Atherosclerosis, arteriosclerosis	Varieties of degenerative disease of the arteries. Atheroma is a fatty degeneration of the inner layers of an artery; in the early stages intimal plaques of atheromatous material may be visible.
Attenuation	See Decibel, Neper.
Baroreceptors	Areas of the vascular system which function as pressure receptors. Nerve endings in the vessel wall respond to its deformation. The most important systemic arterial baroreceptors are found in the arch of the aorta (near its origin) and near the point at which the carotid artery in the neck divides into two branches, at about the level of the angle of the jaw.
Blood	Blood is a suspension of cells in the fluid plasma. The cells comprise the red cells (erythrocytes), white cells (leucocytes) and the platelets (thrombocytes), the average numbers of each per mm^3 of blood being about 5×10^6, 10^4, and 3×10^5, respectively.
Bode plot	A diagram which presents the frequency response of a system as an amplitude ratio (gain) and the phase shift as functions of frequency, on a logarithmic scale. The unit of gain is the decibel where gain in dB = 20 log (output amplitude/input amplitude). For a first-order system (q.v.) the gain is zero up to the corner frequency (q.v.) and falls thereafter with a slope of −20 dB/decade. The phase shift tends towards −90° (90° lag) at high frequencies and has a value of −45° at the corner frequency. For a second-order system the attenuation is −40 dB/decade and the maximal phase shift is −180°.
Boundary conditions	Known conditions at one or several of the boundaries of the physical process considered; they are in general required in order to obtain full solutions to the equations governing the process.

Boundary layer (viscous)	Usually a rather thin layer of fluid adjacent to a solid surface in which shear forces due to viscosity predominate and give rise to steep velocity gradients.
Capillary	The finest blood vessels, normally about 5–6 μm in diameter, and about 0·5 mm long in the systemic circulation.
Cavitation	The formation of cavities filled with vapour or gas within a moving liquid due to the local pressure being reduced to below the vapour pressure for the liquid.
Cervical rib	An abnormal small rib in the lower neck.
Coarctation	An isolated narrowing of an artery; generally refers to a congenital defect of the aorta.
Complex number	A complex number is an expression of the form $X = a + ib$, where a and b are real numbers, and i is the imaginary unit $\sqrt{(-1)}$. Such numbers are used to describe time varying quantities which are characterized by an amplitude or modulus ($M = (a^2 + b^2)^{\frac{1}{2}}$), together with a phase relationship with some time reference. They may be visualized as vectors in a Cartesian coordinate system. The projection on one axis has the value a and is termed the real part (Re X), the projection on the other axis is ib, the imaginary part (Im X). A real number, A, can be considered as a vector lying along the real axis, rotation by 90° will result in an imaginary number, iA, with no real part. A further rotation by 90° returns the vector to the real axis but it is reversed, i.e. $-A$. Thus if one rotation is indicated by multiplication by the imaginary operator i, two such rotations are equivalent to multiplying by -1; i can then be seen to be equal to $\sqrt{(-1)}$.
Compliance (distensibility)	A measure of the ability of a hollow structure to change its volume, generally the ratio of volume change to internal pressure change (dV/dP). The inverse of compliance is elastance.
Corner frequency (break frequency)	A frequency analogous to the resonant frequency of a mechanical system. For a first-order system the relation of the corner frequency to the time constant, τ, is $\tau = 1/\omega_0$. where ω_0 is the corner frequency in radians/second. In the electrical analog of a first-order system the product RC has the value $\omega_0/2\pi$.
Decibel (dB)	A logarithmic measure of the ratio between two quantities. The gain of a system may be expressed in dB, where gain = 20 log (output amplitude/input amplitude).
Diastole (atrial or ventricular)	The resting phase of the cardiac cycle.
Drag	A force induced on a solid surface by fluid moving past it, and in the direction of the fluid motion. Drag may be due to viscous shear forces alone, for example, on the

	wall of a pipe, or may also have a component due to relatively low pressures in the wake region behind an immersed body.
Elasticity	A measure of a material's resistance to deformation. See Modulus.
Electrocardiogram (E.C.G.)	A record of the electrical activity of the heart, normally obtained with electrodes on the skin.
Endothelium.	The layer of cells lining the blood vessels.
Energy (ML^2T^{-2})	Unit energy or work is that exchanged when unit force acts through unit displacement in the direction of the force. One joule is the work done when one newton acts through one metre. (J = 10^7 ergs.)
First-order delay (or lag) system	A system whose input-output relationships are those of a parallel resistance-capacitance unit (time constant = RC). As such a system is excited with an input of increasing frequency the output becomes reduced and lags progressively with a maximal lag of 90°. The performance of a first-order system depends both on the input function and its first time-differential.
Force (MLT^{-2})	Unit force is that which gives unit acceleration to unit mass. One newton gives an acceleration of 1 m s^{-2} to 1 kg, one dyne gives an acceleration of 1 cm s^{-2} to 1 g. Unit force (gravitational) is the force of gravitation on unit mass in the locality in question and is therefore expressed in mass units. Thus a mass of M grams is attracted to the earth with a force of M grams weight which is equal to Mg dynes, where g is the local acceleration due to gravity in cm s^{-2}. The accepted value for g is 9·80665 m s^{-2}.
Haematocrit	The relative volume of the cells in blood, normally about 45 per cent.
Heart	The mammalian heart consists of four chambers, right and left atria, right and left ventricles. The atria are thin walled chambers into which blood flows at low pressure from the veins. Between atria and ventricles are the tricuspid (right) and mitral (left) valves. Blood at high pressure leaves the ventricles by the pulmonary artery (right) and aorta (left); there are valves at the origin of each of these. The blood supply to the heart itself comes from the coronary arteries which spring from the aorta at its origin. Normally both atria beat together a short time before the synchronous beat of the ventricles.
Histology	The microscopic study of tissue structure.
Hookean material	An ideally elastic material for which tensile stress is proportional to strain, i.e. the Young's modulus, E, is constant.
Hypertension, pulmonary or systemic	A condition in which the arterial blood pressure is abnormally high (cf. hypotension, which is low pressure).

Intima	The innermost coat of a blood vessel, comprises the endothelium and a thin connective tissue layer.
Isometric contraction	One in which no change of muscle length is allowed to occur.
Isotonic contraction	One in which the load on the muscle is constant.
Impedance (Z, electrical, acoustic, mechanical, hydraulic)	The resistance to disturbance of a system or material. It is measured as the complex ratio of a force (voltage, pressure, stress) to the resulting change (current, fluid flow, strain) at a specified frequency. An impedance plot shows the impedance as a function of frequency. The hydraulic input impedance is the complex ratio of pressure to flow at the input to a hydraulic system, e.g. the root of the aorta or pulmonary artery, and is both a function of frequency and of position.
Inertia	In fluid flows inertia is represented by the property density and is the force required to accelerate fluid particles, provided by a pressure gradient.
Inlet length (entrance length)	The region of a pipe or channel near the inflow point, in which the thickness of the boundary layer progressively increases. At the end of this region, where the final velocity profile is established, the flow is said to be fully developed.
Karman trail (or vortex steet)	A regular series of fluid vortices in a wake region, in which alternate eddies rotate with opposite sense.
Kinetic energy	The energy associated with the velocity of a material particle or system, and is given by: $\frac{1}{2}$ (speed)^2 per unit mass.
Laminar flow	In laminar pipe flow the fluid velocity remains constant on cylindrical surfaces within the fluid which are concentric with the axis. The flow is well ordered and stable and can be considered as individual cylindrical laminae of fluid sliding over each other.
Laplace transform	The Laplace transform of a function is expressed by an integral formula. This enables the algebraic solution of linear differential equations in terms of initial conditions. For fuller details the reader is referred to the textbooks listed in the references to Chapter 5.
Media	The middle coat of a blood vessel, generally the thickest. It contains the fibrous proteins elastin and collagen, and smooth muscle.
Modulus	The real part of a complex number. Such a number can be visualized as a vector whose length is the modulus and whose angle with the real axis is its phase.
Modulus, of elasticity	A measure of the resistance to deformation of a material, the stress (force/unit area, $ML^{-1}T^{-2}$) required to cause unit strain. The three moduli are the tensile modulus (Young's modulus, E), the shear modulus (G) and the bulk modulus (modulus of compressibility, K).
Murmur (bruit)	An abnormal sound heard over a blood vessel or the heart.

Muscle	Three broad types of muscle are distinguished. Skeletal or striated muscle is normally used for conscious movement and is that commonly referred to as "muscle". Cardiac muscle is the muscle forming the walls of the cardiac chambers. Smooth muscle is a broad term describing the muscle, normally not under voluntary control, which is contained in the walls of the alimentary canal, blood vessels, and other structures. Papillary muscles are strands of cardiac muscle which support the mitral and tricuspid valves and are convenient for studies on the properties of cardiac muscle.
Myocardium	The muscle of the heart.
Neper	A measure of attenuation. If a wave attenuates with distance travelled (L) as $\exp(-\alpha L)$, the attenuation is α nepers/unit length.
Nerva vasorum	The nerves that supply the wall of a blood vessel.
Newtonian fluid	One in which the ratio of shear stress to shear strain is constant.
Nyquist diagram	An alternative to the Bode plot (q.v.) for plotting the frequency response of a system. The transfer function is plotted as a vector with its amplitude representing the gain and the angle with the real axis as the phase shift. The locus of the vector tips at different frequencies is the Nyquist plot. By convention, for a negative feedback system the phase delay at zero frequency is plotted as zero degrees rather than as $-180°$. Thus a delay on this diagram of 180° represents a difference of 360° between input and output. If the plot shows a gain >1 at a phase shift of 180° then the system is likely to be unstable and go into feedback oscillations at the frequency at which the 180° phase shift line is crossed.
Peripheral resistance	The ratio of the mean pressure drop across a circulatory bed to the mean flow through it.
Phonocatheter	A catheter bearing a small microphone for the recording of intravascular sounds.
Plethysmograph	A device for measuring the volume changes of an organ or part of the body.
Polycythaemia	An abnormal increase in the number of red cells in blood.
Potential energy	The energy associated with position in a gravitational field relative to some datum level at which the potential energy may arbitrarily be set equal to zero.
Power ($M L^2 T^{-3}$)	Unit power is that rate of doing work in which unit energy is exchanged in unit time. 1 watt (W) is 1 J s^{-1}.
Power, hydraulic	The energy flux associated with a given flow and having, in general, "pressure", kinetic and potential components.
Pressure ($M L^{-1} T^{-2}$)	A measure of the force per unit area exerted by a fluid. The SI unit of pressure is one newton/sq. metre (N m^{-2}) or one pascal (pa). This is equal to 10 dynes cm^{-2}. The

	conventional millimetre of mercury (mmHg) is equal to $13{\cdot}5951 \times 980{\cdot}665 \times 10^{-2}$ N m^{-2}. One Torr is equal to 1 mmHg to within 2×10^{-7} Torr. One bar is 10^5 N m^{-2}.
Pressure gradient	The pressure drop per unit length along a flow channel.
Pressure, static	The pressure measured in still fluid; ideally that also measured in flowing fluid with a device sensitive only to the force perpendicular to the direction of flow. The dynamic pressure is that measured with a device sensitive to force parallel to the direction of flow, and is different from the static pressure by the quantity $\frac{1}{2}\rho V^2$ where ρ is the fluid density and V the local velocity vector.
Pressure, transmural	The difference in pressure between the inside and outside of a hollow structure.
Radian (r or rad)	A measure of angle. An angle of 360° is equal to 2π radians, thus 1 r = 57·34°, 1° = 0·017453 r.
Reynolds number (*Re*)	An important dimensionless group in fluid mechanics defined as the product of a characteristic length and flow speed divided by the kinematic viscosity of the fluid. The magnitude of the number represents the relative importance of inertia forces compared with viscous forces.
Sarcomere	The functional unit of a fibre of striated muscle.
Sarcoplasm	The material in which the contractile apparatus of a muscle cell is embedded.
Second-order system	A system whose transfer function depends on terms up to the second time-differential of the input. Such properties are shown, for example, by a mechanical system containing elements with frictional, elastic and inertial properties.
Stenosis	A narrowing of a blood vesel or of a valve.
Strain	A measure of the deformation of a material relative to some reference dimension. Tensile and volumetric strains are changes in length (along some defined axis) and in volume, respectively. Shear strain refers to a relative displacement of material elements in two parallel planes in a direction within the planes.
Stream function	A measure of the flux of fluid volume; it remains constant along streamlines. Velocity components may be computed as appropriate derivatives of the stream function.
Stress ($M L^{-1} T^{-2}$)	A measure of the deforming force applied to a material, the units are force/unit area.
Surfactant, pulmonary	A material lining the finest air spaces of the lungs, the alveoli, which is normally present and which lowers the surface tension at the air–fluid interface.
Sympathomimetic drug	A drug whose action is similar to that produced by stimulation of the sympathetic nervous system, this being generally an increase in the rate and force of cardiac contraction and an increase in the peripheral

vascular resistance. Catecholamines are a chemically defined group of sympathomimetic agents including adrenalin and noradrenalin.

Systemic circulation — The circulation to the body, the term excludes the pulmonary circulation which contains the gas-exchanging pulmonary capillaries.

Systole (atrial or ventricular) — The active part of the cardiac cycle.

Transportation lag (dead time, latency) — If there is a time lag, L, between an input signal change and the alteration in the output the system is said to have a transportation lag. This is often represented in control system engineering by the transfer function $\exp(-sL)$ where s is the Laplace operator.

Transfer function — The transfer function of a control system (or subsystem) is the ratio of the Laplace transforms of its output and input, and so characterizes the response of the system.

Turbulence — Turbulent flows are characterized by random fluctuations of the fluid motions which cannot be predicted in detail. These fluctuations may be superimposed upon a particular average direction of flow as occurs, for example, in pipe flow. This feature is due to the inherent instability of the flow, i.e. induced disturbances will grow with time whereas, in laminar flow, such disturbances would be damped out.

Vasa vasorum — The blood vessels that supply the walls of the larger blood vessels.

Vasomotor control system — A term describing the physiological mechanisms, both nervous and endocrine, which alter the hydraulic resistance of the vascular bed. This is brought about by changes in the activity of the muscle in the vessel walls, thereby altering the size of the vascular lumen.

Veins — The vessels carrying blood from the tissues to the atria of the heart.

Venomotor control system — The physiological control system whereby the compliance of the veins, and hence the volume of contained blood, may be altered by changes in the activity of the muscles in their walls.

Viscoelasticity — A viscoelastic material is one in which both the strain (elastic response) and the rate of strain (viscous response) are functions of the imposed stress.

Viscosity ($M L^{-1}T^{-1}$) — The property of resisting deformation in a fluid, it gives rise to tangential or shear stresses. Kinematic viscosity is the dynamic viscosity divided by density and can be considered as the diffusion coefficient governing the transport of molecular momentum within a fluid. The units of viscosity are the poise (P) and the centipoise (cP), one poise is the viscosity of that material which requires unit shear stress (1 dyne cm^{-2}) to maintain a shear velocity gradient of 1 ($cm\,s^{-1}\,cm^{-1}$) or

	$1\ s^{-1}$. The SI unit of viscosity is the newton second per sq. metre ($N\ s\ m^{-2}$) and is equal to 10 poise. The unit of kinematic viscosity is the Stoke (St). ($1\ St = 10^{-4}\ m^2\ s^{-1}$.)
Windkessel	A term used by Otto Frank in 1899 to describe the elastic reservoir function of the aorta. In the simple windkessel theory the systemic bed was modelled as an elastic reservoir connected to a peripheral hydraulic resistance.
Zero-order system (zero-memory system)	A system in which the output follows the input with no lag. The electrical analogue is an ohmic resistance.

Contents of Volume 2

To Nicolette, Timothy, Stephen, Oliver
and Matthew; with great love