Appendix A
Questions

This chapter contains questions which the reader may find useful in preparing for exams. Teachers may also find these questions useful as the basis for setting exam questions. The questions are based on the text in the book. There are 3 types of questions, multiple-choice questions (MCQs), short-answer questions (SAQs) and long-answer questions (LAQs). The answers to the MCQs are provided in a list at the end of this chapter. A typical exam might be 2 h long with 30 min MCQs, 30 min SAQs and 60 min LAQs.

Multiple-choice questions (MCQs). These consist of a statement followed by 5 choices which are true or false. The reader should select the statements which are true. There is at least 1 true statement, with a maximum of 5 statements true. For example:

Question 1. Concerning red cells.

(a) These have a biconcave shape.
(b) These are spherical in shape.
(c) Their function is concerned with immune defence.
(d) Their function is the transport of oxygen from lungs to tissues.
(e) Have an effective diameter of 5.5 mm.

Answer is: a, d

As a rough guide an exam might have 20 MCQs which must be completed in 30 min.

Short-answer questions. These consist of a short question. The answer typically should be less than half a page of A4. It is acceptable to include simple diagrams. These typically might take 7–8 min to complete. An exam might require the answering of 4 short-answer questions from a choice of 8 in 30 min.

Long-answer questions. These are essay questions which typically would require a 2–3 page answer including simple diagrams as necessary. These typically take 30 min to complete. An exam might require answering 2 long-answer questions from a choice of 6 in 1 h.

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Chapter 1 Questions; Introduction to Solid and Fluid Mechanics

Chapter 1 MCQs

1. A solid:
   (a) is characterised by viscosity and shear rate.
   (b) continually deforms under an applied shear.
   (c) will flow to assume the shape of the container.
   (d) will sustain an applied shear force.
   (e) always has a density of 1025 kg/m^3.
2. The Young's modulus:
   (a) is measured using a tensile testing system.
   (b) is a measure of elasticity.
   (c) is the ratio of tension divided by area.
   (d) is a measure of viscosity.
   (e) is the ratio of stress divided by strain.
3. The Poisson ratio:
   (a) has a value of 0.7 for incompressible materials.
   (b) is the ratio of flow rate to velocity.
   (c) has a value of 0.5 for most soft biological tissues.
   (d) is the ratio of the fractional change in lengths in z and x,y directions.
   (e) is relevant for fluids.
4. Which of the following is not a modulus of mechanical behaviour:
   (a) Young's modulus.
   (b) Bulk modulus.
   (c) Shear modulus.
   (d) Poisson ratio.
   (e) density.
5. A viscoelastic material:
   (a) has linear stress–strain behaviour.
   (b) may be described by an elastic modulus and a viscosity.
   (c) continually deforms under an applied shear force.
   (d) has a time lag between the applied stress and the resulting strain.
   (e) has no time lag between the applied stress and the resulting strain.
6. For an isotropic linear elastic material with a Poisson ratio of 0.5:
   (a) the shear modulus is 3 times the elastic modulus.
   (b) the shear modulus is 9 times the elastic modulus.

(c) the Poisson ratio is 0.7.
(d) the mechanical behaviour is different for different directions.
(e) there is no time lag between the applied stress and the resulting strain.

7. A fluid:

(a) is a substance which changes shape while shear is applied but returns to its original shape when the shear is withdrawn.
(b) is a substance which continually deforms under an applied shear.
(c) is characterised by density and viscosity.
(d) is characterised by elastic modulus and density.
(e) is characterised by magnetic moment and elastic modulus.

8. Hydrostatic pressure:

(a) is the pressure in a fluid arising as a result of the weight of the fluid.
(b) is the pressure in a fluid arising as a result of the volume of the fluid.
(c) is equal to (elastic modulus) × (density) × (depth) Eρd.
(d) is equal to (gravitational constant) × (density) × (depth) gρd.
(e) is equal to (gravitational constant) × (mass) × (depth) gmd.

9. In a moving fluid:

(a) a fixed object such as a wall will give rise to change in velocity with distance from the wall.
(b) a fixed object such as a wall has no effect on local velocity.
(c) the velocity at every point in the fluid is the same.
(d) the shear at every point in the fluid is the same.
(e) the fluid flows as a result of a pressure gradient within the fluid.

10. Which of the following is true for viscosity:

(a) there is an upper limit to the value of viscosity which a fluid can hold of 400 Pa.s.
(b) pitch is a fluid with a viscosity value 2×10^{11} that of water.
(c) viscosity is a measure of the resistance of the fluid to deformation by shear stress.
(d) there is a lower limit to the value of viscosity which a fluid can hold of 0.001 Pa.s.
(e) blood has a viscosity 3–4 times that of water.

11. Which of the following is true for Poiseuille flow:

(a) the velocity profile is parabolic.
(b) the resistance to flow is inversely proportional to diameter to the fourth power.
(c) concerns flow of a fluid in a tube with a square cross section.
(d) the resistance to flow is inversely proportional to radius to the third power.
(e) the velocity profile is described by a cube law.

12. The inlet length:
    (a) is the distance from the entrance of a pipe at which the flow becomes turbulent.
    (b) is the diameter of the pipe at the entrance.
    (c) is the diameter of the pipe divided by the peak velocity.
    (d) is the distance from the entrance of a pipe at which flow has a parabolic velocity profile for steady flow.
    (e) is the distance after which flow is fully developed.
13. Concerning the boundary layer:
    (a) it separates regions of turbulent flow from regions of laminar flow.
    (b) it separates regions of flow dominated by viscous forces from regions where flow is dominated by inertial forces.
    (c) it is absent for fully developed flow.
    (d) it separates laminar from non-laminar flow.
    (e) it separates regions of flow with $Re < 2300$ from areas with $Re > 2600$.
14. Reynolds number of flow of a fluid in a cylinder:
    (a) is proportional to diameter.
    (b) is proportional to viscosity.
    (c) is the ratio of inertial forces to viscous forces.
    (d) is the ratio of viscous forces to inertial forces.
    (e) is inversely proportional to velocity.
15. Turbulent flow:
    (a) does not occur in low viscosity fluids.
    (b) is associated with movement of fluid elements along well defined pathways.
    (c) usually occurs at Re less than about 2300.
    (d) is associated with movement of fluid elements along erratic pathways.
    (e) usually occurs at Re greater than about 2300.
16. Concerning a time-varying pressure gradient for flow in a cylinder:
    (a) the pressure lags the flow by a certain time period due to the inertia of the fluid.
    (b) the flow is steady.
    (c) the flow lags the pressure by a certain time period due to the inertia of the fluid.
    (d) in a cylinder the velocity profile is always parabolic.
    (e) the flow is time-varying.
17. Steady flow of a Newtonian fluid in a long straight tube with stiff walls:
    (a) has a velocity profile skewed to one wall.
    (b) is associated with no change in velocity with time.

(c) has a parabolic velocity profile.
(d) is associated with huge changes in velocity with time.
(e) has maximum velocity in the centre of the vessel.

Chapter 1 SAQs

1. Describe the key differences between a solid and a fluid.
2. What is Young's modulus?
3. What is meant by viscoelasticity?
4. Describe why collagen leads to biological materials having a nonlinear stress–strain behaviour.
5. What does the Poisson ratio refer to?
6. What is hydrostatic pressure?
7. Estimate (with working) the head-toe pressure difference in the cardiovascular system for a person of height 1.4 m ($g = 9.81$ m.s^{-2}, density of blood = 1025 kg m^{-3}).
8. Illustrate stress–strain behaviour for the following fluids; Newtonian, shear-thinning, shear-thickening.
9. Describe a simple way of measuring fluid viscosity using a funnel.
10. Describe flow states and their relationship to Reynolds number.
11. What is Bernoulli's principle?

Chapter 1 LAQs

1. Describe and define Young's modulus and its measurement for a section of soft tissue such as arterial wall; illustrate the answer with typical stress–strain curves
2. Describe viscoelasticity and what methods may be used to characterise viscoelastic behaviour
3. Describe viscosity and how it might be measured for a typical fluid to give data on viscosity-shear rate behaviour. Illustrate with data for different types of viscous behaviour.
4. Describe flow of a Newtonian fluid in a rigid cylinder discussing the relation between pressure and flow rate, resistance, velocity profile, and steady and unsteady flow.

Chapter 2 Questions; Introduction to Mechanics of the Cardiovascular System

Chapter 2 MCQs

1. Concerning the systemic circulation:
   (a) blood is pumped from the left ventricle.
   (b) returns oxygenated blood to the right atrium.
   (c) blood is pumped from the right ventricle.
   (d) involves vessels in the head, legs and arms.
   (e) involves the lungs.
2. Concerning the pulmonary circulation:
   (a) blood is pumped from the left ventricle.
   (b) returns oxygenated blood to the right atrium.
   (c) blood is pumped from the right ventricle.
   (d) involves vessels in the head, legs and arms.
   (e) involves the lungs.
3. The intima:
   (a) is the outermost layer in the arterial wall.
   (b) is not present in capillaries.
   (c) contains a single layer of endothelial cells.
   (d) contains elastin.
   e) contains collagen.
4. Concerning the layers of vessels:
   (a) the adventitia is the outermost layer.
   (b) the media is the middle layer.
   (c) the intima is the inner layer in contact with flowing blood in the vessel.
   (d) there is no medial or adventitial layer in capillaries.
   (e) there is no intima present in capillaries.
5. Concerning the different types of vessel:
   (a) systemic arteries have relatively thick walls in order to withstand high pressure.
   (b) capillaries have larger diameter than venules and arterioles.
   (c) veins have thicker walls than arteries in order to withstand low pressures.
   (d) backflow of blood along medium sized veins is prevented by valves.
   (e) backflow of blood along medium sized arteries is prevented by valves.
6. Concerning transport of molecules in the cardiovascular system:
   (a) oxygenated blood is transported from the lungs to the rest of the body.
   (b) deoxygenated blood is transported from the lungs to the rest of the body.

(c) carbon dioxide is transported from the rest of the body to the lungs where it is discharged.
(d) carbon dioxide is transported from the lungs to the liver where it is consumed.
(e) several types of molecule enter and exit the cardiovascular system via capillaries.

7. Concerning the distribution of blood in the systemic cardiovascular system:

(a) all the blood is contained in the arteries.
(b) most of the blood (2/3) is contained in the venous system.
(c) most of the blood (2/3) is contained in the arterial system.
(d) most of the blood (2/3) is contained in the capillaries.
(e) there is no blood in the systemic cardiovascular system.

8. Concerning the dimensions of vessels:

(a) arteries and veins have diameters from 1 to 30 mm.
(b) arterioles and venules have dimensions of 1–30 mm.
(c) arterioles and venules have dimensions of 15–300 micron.
(d) capillaries have dimensions of 50–100 micron.
(e) most capillaries have dimensions of 5–10 micron.

9. Concerning mean pressure in the systemic circulation:

(a) is typically 900 mm Hg in the aorta.
(b) is typically 90 mm Hg in the aorta.
(c) continuously falls from the aorta to the capillaries.
(d) continuously increases from the aorta to the capillaries.
(e) has a value of 22 mm Hg in capillaries.

10. Concerning blood velocity in the systemic circulation:

(a) mean velocity is the same in all vessels.
(b) mean velocity in the aorta and other large arteries is around 10–25 cm s^{-1}.
(c) mean velocity in the aorta and other large arteries is around 10–25 m s^{-1}.
(d) mean velocity is 0.04 cm s^{-1} in the capillaries.
(e) mean velocity is 400 cm s^{-1} in the capillaries.

Chapter 2 SAQs

1. Describe the different layers in an artery.
2. Describe the three different types of capillary.
3. Describe the difference between muscular and elastic arteries.
4. Describe the role of the cardiovascular system in oxygen transport.
5. Draw the major components of the pulmonary circulation.

6. Draw the major components of the system circulation.
7. Describe briefly the three main functions of the cardiovascular system.
8. Illustrate the change in pressure in the different vessels of the systemic system.
9. Describe and illustrate pressure in the capillary with reference to osmotic pressure and trans-wall flow.

Chapter 2 LAQs

1. Describe the organisation of the cardiovascular system into systemic and pulmonary systems with reference to transport of oxygen and other molecules.
2. Discuss the composition of the wall for different types of vessel.
3. Describe and illustrate the variation in pressure, diameter and blood velocity in the different vessels in the systemic circulation.

Chapter 3 Questions; Blood and Blood Flow

Chapter 3 MCQs

1. The main particles in blood are:
   (a) red cells (40–50 % by volume).
   (b) red cells (0.7 % by volume).
   (c) white cells (40–50 % by volume).
   (d) white cells (0.7 % by volume).
   (e) platelets (0.3 % by volume).
2. Concerning particles in blood; the role of:
   (a) white cells is immune defence.
   (b) red cells is to transport oxygen.
   (c) red cells is to fight infection.
   (d) platelets is blood clotting.
   (e) platelets is osmotic balance.
3. Concerning red cells:
   (a) These have an effective diameter of 5.5 mm.
   (b) These are shaped like plates (hence the term ‘erythrocyte’).
   (c) These are rigid (i.e. cannot be deformed).
   (d) These maintain a constant surface area on deformation.
   (e) These have a biconcave shape.

4. Concerning white cells:

   (a) These are all the same size at 10 micron diameter.
   (b) Monocytes migrate to tissues where they become macrophages which consume foreign bodies.
   (c) White cell volume fraction decreases in infection.
   (d) White cells take longer than red cells to traverse the capillaries due to their greater stiffness.
   (e) They are all shaped like plates (hence the term ‘white cell’).

5. Concerning platelets:

   (a) The usual form of platelets is in the activated form to assist blood clotting.
   (b) These are spherical.
   (c) In the unactivated form these are shaped like plates (hence the term ‘platelet’).
   (d) These have a maximum diameter of 2–3 microns.
   (e) These are activated in regions of damaged endothelium and high shear.

6. The following roll along the arterial wall:

   (a) red cells.
   (b) leukocytes.
   (c) monocytes.
   (d) LDL cholesterol.
   (e) nicotine.

7. For flow of a dense (50 % by volume) suspension of identical particles, the particles:

   (a) are subject to forces which cause them to travel laterally.
   (b) are always distributed uniformly.
   (c) have a tendency to move away from the wall leaving a region near the wall depleted of particles.
   (d) do not flow as the volume fraction is too high.
   (e) have non-uniform distribution, especially at low shear rates.

8. The Segre–Silberberg effect:

   (a) occurs at high Reynolds number.
   (b) occurs at high magnetic field strength.
   (c) is associated with a uniform distribution of particles.
   (d) is associated with particles migrating from the centre and from the wall.
   (e) occurs at low Reynolds number.

9. Concerning electrostatic forces:

   (a) these are not relevant in blood.
   (b) red and white cells and platelets have negative charge and attract each other leading to thrombosis.

(c) red and white cells and platelets have negative charge and repel each other helping prevent thrombosis.
(d) these are shear forces.
(e) these are drag forces.

10. Concerning chemical forces on particles in blood:

(a) Shear induced lateral movement arises through a chemical force.
(b) Chemical forces concern the binding of one biological cell or molecule with another cell or molecule.
(c) red cells will attach to the endothelium through chemical bonding.
(d) leukocytes will attach to the endothelium through chemical bonding.
(e) activated platelets will bond through electrostatic attraction.

11. Identify the three types of forces arising from collisions of particles in a fluid:

(a) Brownian motion.
(b) electrostatic force.
(c) depletion force.
(d) particle–particle forces.
(e) fluid drag.

12. Brownian motion:

(a) produces steady linear motion of the particle.
(b) is an example of a force between the fluid and particles.
(c) is more significant for small particles.
(d) is more significant for large particles.
(e) produces erratic random motion.

13. For flow of a suspension of identical particles in a straight tube:

(a) collisions between particles gives rise to lateral displacement.
(b) particles are distributed homogeneously.
(c) particles are distributed inhomogenously with greater concentration at the vessel centre.
(d) particles are distributed inhomogenously with greater concentration at the vessel wall.
(e) there are no collisions between particles.

14. Collisions between particles in blood leads to:

(a) reduced concentration of platelets at the vessel wall.
(b) reduced concentration of white cells at the vessel wall.
(c) increased concentration of platelets at the vessel wall.
(d) increased concentration of white cells at the vessel wall.
(e) change in packed cell volume.

15. Rouleaux:

(a) are formed at shear rates below about 1 s^{-1}.

(b) are formed at shear rate above 100 s^{-1}.
(c) are clumps of white cells.
(d) lead to decrease in blood viscosity.
(e) at sufficiently low shear (<0.01 s^{-1}) form an interlocking structure like a solid.

16. At high shear (>1000 s^{-1}):

(a) there is considerable red cell aggregation.
(b) the viscosity value in whole blood is about 3–4 mPa s.
(c) there is no red cell aggregation.
(d) red cells are deformed with a stretched appearance.
(e) the viscosity of blood reaches asymptotic value of about 100 mPa s.

17. Farhaeus–Lindqvist effect:

(a) occurs for a pure fluid (i.e. no particles).
(b) occurs in large (>5 mm) vessels.
(c) is lowering of the effective viscosity of blood in small diameter (0.1–0.3 mm) vessels.
(d) is associated with the presence of a cell-free layer near the vessel wall.
e) is associated with a uniform distribution of red cells.

18. Regions free of red cells may occur in arteries:

(a) at regions of low shear.
(b) in the centre of the artery.
(c) at regions of high shear.
(d) at regions of high wall shear.
(e) in the post-stenosis region near the wall.

19. Non-Newtonian flow:

(a) means that the viscosity is dependent on shear rate.
(b) means that the viscosity is independent of shear rate.
(c) occurs in arteries in vivo in humans.
(d) does not occur in arteries in vivo in humans.
(e) leads to no change in observed flow patterns compared to Newtonian flow.

20. Concerning flow in arteries and veins:

(a) some arteries (e.g. aorta) have periods of turbulent flow.
(b) red cell aggregation is present in normal arteries.
(c) red cells are mostly distributed uniformly in arteries.
(d) red cell aggregation is present in normal veins.
(e) some veins have periods of turbulent flow.

Chapter 3 SAQs

1. List the major particles in the blood and their function.
2. Describe drag force and its effect on a particle.
3. Describe shear induced lift force and its effect on a particle.
4. Describe wall induced lift force and its effect on a particle.
5. Describe electrostatic force and its effect on particles in blood.
6. Describe Rouleaux formation.
7. Describe leukocyte adhesion.
8. Briefly describe the three types of forces arising from collision.
9. Describe what margination is in the context of blood.
10. Describe and explain the behaviour of a single red cell in a shear field at low shear ($<10\ s^{-1}$).

Chapter 3 LAQs

1. Describe the different types of forces on particles at low Reynolds number (<30) and their effect on particle distribution.
2. Describe the viscous behaviour of whole blood with shear and explain the shape of the viscosity-shear curve.
3. Discuss whether red cells are distributed uniformly in arteries.
4. Describe the Fahraeus and Fahraeus–Linqvist effects and discuss whether these are relevant for flow in the cardiovascular system.
5. Compare characteristics of flow such as turbulence and viscosity in different parts of the cardiovascular system.

Chapter 4 Questions; Mechanics of Arteries

Chapter 4 MCQs

1. Which of the following statements are true concerning arterial structure:
   - (a) the outermost layer is the endothelium.
   - (b) the outermost layer is the adventitia.
   - (c) elastin fibres are only present within the adventitia.
   - (d) elastin fibres are laid down as parallel sheets.
   - (e) collagen fibres are arranged in a helical pattern.
2. The stress–strain relationship for arteries:
   - (a) is J-shaped.

(b) is linear.
(c) is S-shaped.
(d) is dominated by collagen behaviour at low strain (or low radius).
(e) is dominated by elastin behaviour at high strain (or high radius).

3. The Windkessel model of the arterial system:

(a) consists of a heart, a compliant chamber and a resistance outflow.
(b) predicts a flow waveform with a period of reverse flow.
(c) predicts a flow waveform with monophasic flow.
(d) accounts for pressure pulse propagation.
(e) does not account for pressure pulse propagation.

4. Pressure pulse propagation speeds in healthy arteries:

(a) is in the range 500–600 m/s.
(b) is the same as the blood velocity.
(c) is 5–15 m/s.
(d) is 1540 m/s.
(e) is infinitely fast.

5. Reverse going pressure waves:

(a) are pressure waves which travel towards the heart rather than away from the heart.
(b) combine in a subtractive manner with forward going pressure waves.
(c) arise mainly from the distal arteriolar bed.
(d) are pressure waves which travel away from the heart.
(e) combine in an additive manner with forward going pressure waves.

6. Concerning blood flow-time and velocity-time waveforms:

(a) have quasi-steady flow in arteries supplying the brain (carotid) and kidney (renal).
(b) usually exhibit a period of reverse flow in arteries supplying muscle at rest.
(c) are a plot of pressure versus time.
(d) have typical peak velocities in the range 5–15 m/s in health.
(e) have typical peak velocities in the range 0–1 m/s in health.

7. Flow in real arteries may exhibit the following flow characteristics:

(a) laminar flow.
(b) spiral flow.
(c) skewing of the velocity profile in curved arteries.
(d) change in velocity profile with time.
(e) change in flow rate with time.

8. Vortices:

   (a) cannot be detected using colour-flow ultrasound.
   (b) commonly occurs in the carotid bulb region.
   (c) refers to regions of circulating flow.
   (d) does not occur in the arterial system.
   (e) commonly occurs in the post-stenosis region.

9. Rotational flow:

   (a) leads to mixing of blood in arteries.
   (b) is induced by curvature and bifurcations.
   (c) cannot be visualised using MRI.
   (d) does not occur in the arterial system.
   (e) is not induced by the heart.

10. If an artery is long and straight:

   (a) there is no rotational flow.
   (b) flow is fully developed.
   (c) the velocity profile is parabolic.
   (d) the velocity profile is axially symmetric.
   (e) maximum velocity is located in the centre of the vessel most of the time.

Chapter 4 SAQs

1. Describe the main layers of the artery wall and their composition.
2. Discuss the role elastin and collagen play in the stress–strain behaviour of an artery
3. Describe the Windkessel model of the arterial system.
4. Describe the origin of reflected pressure waves and their effect on overall pressure in the aorta.
5. What is the origin of rotational flow in arteries?
6. What is recirculating flow (vortices) and where in the arterial system does it commonly occur?
7. Describe when the velocity profile is likely to be symmetric in an artery?

Chapter 4 LAQs

1. Describe the origin of pressure-time and flow-time blood waveforms in arteries, explaining the shape of waveforms for arteries supplying muscle at rest and arteries supplying brain and kidney.
2. Discuss the general characteristics of flow in arteries

Chapter 5 Questions; Biomechanics of Arteries

Chapter 5 MCQs

1. Concerning wall shear stress:
   (a) wall shear stress is equal to longitudinal stress.
   (b) wall shear stress is the viscous drag of blood on the adventitia.
   (c) wall shear stress is the viscous drag of blood on the arterial wall.
   (d) wall shear stress is always aligned with the arterial axis.
   (e) wall shear stress has values in healthy arteries in the human of typically 1–20 Pa.
2. Concerning the forces on the arterial wall:
   (a) the wall shear stress is the stress within the wall in the direction parallel to the vessel axis.
   (b) the mean circumferential stress is typically 1–2 Pa.
   (c) the circumferential stress is the stress within the wall in the direction perpendicular to the vessel axis.
   (d) the mean blood pressure is typically 12,000 Pa.
   (e) the mean blood pressure is typically 1–2 Pa.
3. Concerning forces within the arterial wall:
   (a) an artery is prestressed both longitudinally and from inner to outer wall.
   (b) an artery is prestressed longitudinally but not from inner to outer wall.
   (c) an artery is prestressed from inner to outer wall but not longitudinally.
   (d) an excised artery will be around 40 % greater in length than its native length in the body.
   (e) an excised artery will be around 40 % less in length than its native length in the body.
4. Concerning Murray's law and wall shear stress in the human:
   (a) Murray's law is concerned with the circumferential stress.
   (b) Murray's law implies that mean wall shear stress is constant for all arteries (i.e. independent of diameter).
   (c) In practice mean wall shear stress is the same in different arteries.
   (d) Murray's law implies that mean wall shear stress is proportional to diameter.
   (e) In practice mean wall shear stress is different in different arteries.
5. Concerning circumferential tension and stress for thin-walled cylinders:
   (a) the law of Laplace is: tension equals pressure divided by radius.
   (b) the law of Laplace is concerned with blood flow.
   (c) the law of Laplace is: tension is equal to pressure times radius.

(d) circumferential stress is proportional to wall thickness.
(e) circumferential stress is inversely proportional to wall thickness.

6. Concerning lamellar unit:

(a) the unit of circumferential stress values is called the lamellar abbreviated La.
(b) the tension per lamellar unit in the aorta is 1–3 N/m for all mammals.
(c) a lamellar unit is a structure consisting of muscle, elastin and collagen in the arterial wall.
(d) the number of lamellar units in the wall increases with age from birth to death.
(e) the number of lamellar units in the wall increases during gestation (i.e. before birth).

7. Concerning the vessel wall:

(a) Increase in blood pressure leads to increase in wall thickness.
(b) Increase in blood pressure leads to increase in number of lamellar units during gestation.
(c) Increase in blood pressure leads to increase in the thickness of each lamellar unit after birth.
(d) Decrease in blood pressure leads to increase in the thickness of each lamellar unit after birth.
(e) Increase in wall shear stress leads to increase in wall thickness.

8. Concerning control mechanisms; changes in:

(a) wall shear stress lead to changes in arterial length.
(b) circumferential stress lead to changes in wall thickness.
(c) wall shear stress lead to changes in vessel diameter.
(d) longitudinal stress lead to changes in vessel length.
(e) circumferential stress lead to changes in diameter.

9. Mechanotransduction is the process where:

(a) mechanical forces are translated in biological behaviour.
(b) magnetic forces are translated into biological behaviour.
(c) electrical forces are translated into biological behaviour.
(d) where biological behaviour is translated into magnetic forces.
(e) where biological behaviour is translated in mechanical forces.

10. Concerning mechanosensing:

(a) mechanosensors reside on the endothelium and on no other cell type.
(b) this is the process where the biological response from a mechanical stimulus is produced.
(c) an example of a mechanosensor is the stretch-sensitive ion channel.

(d) this is the process where the mechanical stimulus is detected.
(e) the main underlying physical basis for mechanosensing is changes in protein conformation.

11. Mechanosignalling:

(a) via the cytoskeleton results in more rapid propagation of information compared to chemical signalling.
(b) via the cytoskeleton results in less rapid propagation of information compared to chemical signalling.
(c) is the process where the biological response from a mechanical signal is produced.
(d) concerns the propagation of gravitational waves.
(e) does not occur in endothelial cells.

12. Concerning the endothelium:

(a) mechanosensors are only distributed on the lumen adjacent to blood.
(b) the endothelium aligns itself perpendicular to the shear stress direction.
(c) mechanosensors are distributed throughout the endothelial cell.
(d) the endothelium contains no mechanosensors.
(e) the endothelium is capable of detecting changes in wall shear stress.

Chapter 5 SAQs

1. What are the main forces arising from blood on the arterial wall?
2. What is the functioning of prestressing of the artery wall from inner to outer lumen?
3. Describe Murray's Law.
4. List the principal determinants of artery diameter, wall thickness and arterial length?
5. Describe the effect on diameter when wall shear stress increases long term and explain the control mechanism.
6. Describe the effect of increasing blood pressure on artery wall thickness during gestation and during childhood.
7. Describe why diameter of the aorta increases with age in childhood.
8. Describe why and how wall thickness increases with age in gestation.
9. Describe what is meant by the decentralised model of mechanotransduction and illustrate this.
10. Describe the main steps in the process of mechanotransduction.
11. Describe four responses to a long term increase in wall shear stress in an artery and include timescales.
12. Describe four examples of candidate mechanosensors for the endothelium.

Chapter 5 LAQs

1. Describe the forces on the arterial wall of the adult human and how changes to these forces give rise to changes in arterial structure.
2. Describe the role of wall shear stress in the remodelling of arteries; drawing examples from gestation, childhood, adulthood and intervention.
3. Describe the principle steps of mechanotransduction in the general cell.
4. Describe the principle steps of mechanotransduction in the endothelial cell in relationship to wall shear stress.

Chapter 6 Questions; Biomechanics of the Heart

Chapter 6 MCQs

1. In which region of the heart is a normal heart beat initiated?
   (a) The sinoatrial node.
   (b) The atrioventricular node.
   (c) The Purkinje system.
   (d) The bundle of His.
2. Which of the following act to regulate transmembrane current in cardiac myocytes?
   (a) Ion channels, ion pumps, and ion exchangers.
   (b) Ion channels and the t-tubule system.
   (c) Ion pumps and ion exchangers.
   (d) Ion channels and the sarcoplasmic reticulum.
3. Which part of the normal electrocardiogram is generated by slow conduction of the action potential through the atrioventricular node?
   (a) The ST segment.
   (b) The QRS complex.
   (c) The PQ interval.
   (d) The QT interval.
4. Which of the following features associated with an action potential initiate mechanical contraction in cardiac myocytes?
   (a) Changes in membrane voltage.
   (b) Influx of Ca^{2+} ions.
   (c) Influx of Na^{+} ions.
   (d) Influx of K^{+} ions.

5. Which part of the normal electrocardiogram is generated by slow conduction of the action potential through the atrioventricular node?
   (a) The ST segment.
   (b) The QRS complex.
   (c) The PQ interval.
   (d) The QT interval.

6. What role is played by the sarcoplasmic reticulum in a cardiac myocyte?
   (a) Sink for Na^+.
   (b) Buffer for Ca^{2+}.
   (c) Mechanical support for contractile proteins.
   (d) Store for Ca^{2+}.

7. Under normal physiological conditions, which of following quantities does not contribute to the active isometric tension developed by a myocyte?
   (a) Afterload.
   (b) Intracellular Ca^{2+} concentration
   (c) Preload.
   (d) Sarcomere length.

8. Which of the following quantities contributes to afterload?
   (a) Ventricular volume.
   (b) Ventricular pressure.
   (c) Venous pressure.
   (d) Arterial pressure.

9. Which expression describes the mechanical work done by the left ventricle during a normal beat?
   (a) Total change in LV volume.
   (b) Change in LV pressure multiplied by change in LV volume.
   (c) Change in LV pressure multiplied by heart rate.
   (d) Arterial pressure multiplied by change in LV volume.

10. How does the Frank–Starling mechanism compensate for a transient increase in right ventricular output?
    (a) Increased volume in the systemic circulation, increased RV preload, and hence a decrease in RV output.
    (b) Decreased volume in the pulmonary circulation, increased LV preload, and hence an increase in LV output.
    (c) Increased volume in the pulmonary circulation, increased LV preload, and hence an increase in LV output.
    (d) Decreased volume in the systemic circulation, decreased LV preload, and hence an decrease in RV output.

Chapter 6 SAQs

1. Describe the main anatomical features of the human heart, explaining the functional role played by each.
2. Enumerate the different phases of the cardiac action potential, and describe the direction of the dominant transmembrane current at each phase along with the ionic species that carries the current.
3. Using a sketch of pressure and volume changes during the cardiac cycle, show how the electrical activation sequence of the whole heart is related to the mechanical activation sequence.
4. Compare and contrast preload and afterload.
5. Summarise the main mechanisms responsible for cardiac remodelling.

Chapter 6 LAQs

1. Describe how the cardiac action potential acts to initiate and synchronise mechanical contraction in each part of the heart, focusing on both the subcellular and whole organ mechanisms.
2. Explain how the sliding filaments in myofibrils influence the way that cardiac tissue responds to preload and afterload.
3. Describe the cardiac cycle using the pressure–volume relation, and show how this relation is altered in conditions of reduced and increased contractility.

Chapter 7 Questions; Biomechanics of the Venous System

Chapter 7 MCQs

1. The veins:

   (a) Take blood from the heart to the lungs.
   (b) Return de-oxygenated blood from the periphery to the heart.
   (c) Have thinner walls than the arteries.
   (d) Store 60–80 % of total blood volume.
   (e) Contain more smooth muscle than the arteries.

2. The transmural pressure in the veins:

   (a) depends only on the posture of the subject.
   (b) is important in definition of the tube law.
   (c) is determined by the thickness of the surrounding tissue.
   (d) is given by the difference between internal and external venous pressure.

(e) depends on the bending stiffness of the vessel.

3. The tube law during vessel collapse:

   (a) becomes stiffer when self-contact occurs.
   (b) describes the relationship between transmural pressure and cross-sectional area.
   (c) is nonlinear.
   (d) is linear.
   (e) becomes softer when self-contact occurs.

4. Super-critical flow:

   (a) occurs when the local speed of the fluid, u, is greater than the pulse wave transmission speed, c.
   (b) occurs when the Reynolds number exceeds 2000.
   (c) occurs when the local speed of the fluid, u, is less than the pulse wave transmission speed, c.
   (d) results in more complex flow effects.
   (e) is more likely in vessels which are partially collapsed.

5. Venous return is increased by:

   (a) decrease in venous resistance.
   (b) the activation of the respiratory pump.
   (c) compression of the vena cava.
   (d) the activation of the calf muscle pump.
   (e) an increase in pressure gradient along the venous circulation.

6. As the calf muscle pump relaxes:

   (a) the proximal deep vein valves open and the distal valves close.
   (b) blood flows from the deep to the superficial venous system.
   (c) blood ejected from the calf returns under the influence of gravity.
   (d) the deep veins are re-filled as a result of arterial inflow.
   (e) the deep veins are re-filled as a result of flow from the superficial veins.

7. The venous valves:

   (a) open and close during respiration and muscular contractions.
   (b) include leaflets which are thick relative to the vessel wall.
   (c) are generally found to be bicuspid.
   (d) are always observed to be tricuspid.
   (e) resist venous flow away from the heart.

8. The number of valves in the veins:

   (a) generally increase with distance from the central circulation.
   (b) is greater where the muscle pump is more active.
   (c) is greater in the vena cava than in the deep veins of the leg.
   (d) is the same for all individuals.

   (e) is greater than in the arterial circulation.

9. The geometry of the venous valves:

   (a) is associated with a reduction in venous diameter in the sinus region.
   (b) causes recirculation of blood in front of the valve leaflets.
   (c) results in a narrowing of the lumen at the location of the valve leaflets.
   (d) causes recirculation of blood behind the valve leaflets.
   (e) is associated with an increase in venous diameter in the sinus region.

10. Following change in posture from seated to standing:

   (a) The change in pressure takes around 20 s to establish.
   (b) Venous pressure in the neck increases.
   (c) Local changes in venous volume occur.
   (d) Venous pressure in the foot increases.
   (e) The change in hydrostatic pressure in the veins occurs immediately.

11. Deep vein thrombosis:

   (a) can result in potentially fatal pulmonary embolism.
   (b) is linked to the formation of vortices in the region of the valve.
   (c) has been observed to form at the sites of venous valves.
   (d) has been associated with periods of prolonged activity.
   (e) can result in symptoms including swelling of the limb and change in pigmentation.

Chapter 7 SAQs

1. What proportion of the blood volume is stored in the venous system, what factors influence the venous volume and why?
2. Describe factors that will influence the form of venous collapse, giving examples of two veins where the collapse behaviour will differ.
3. Define the conditions under which sub-critical and super-critical flow occurs.
4. Describe the phases of the respiratory pump, with reference to the abdomen, thorax and vena cava.
5. What non-invasive technique can be used to assess the degree of venous valve reflux and how would this be applied in practice?
6. Sketch the venous valve geometry identifying key features and describe the role of these valves within the circulation.

Chapter 7 LAQs

1. Describe the nonlinear pressure/area response observed during collapse of an unsupported vein with use of appropriate diagrams; identify physiological conditions under which venous collapse might occur.
2. Describe the purpose and mechanism of action of the calf muscle pump including the role of the venous valves. Illustrate your description with a diagram indicating typical venous anatomy in the calf.
3. Describe the phases of action of the venous valve, including discussion of the associated fluid dynamics. Discuss the implications of the fluid dynamics during the open equilibrium phase for the formation of thrombosis local to the valve site.

Chapter 8 Questions; Biomechanics of the Microcirculation

Chapter 8 MCQs

1. Which of the following statements is not true concerning microcirculation vessels:

   (a) molecular exchange primarily occurs through arteriolar walls.
   (b) venules have a diameter in the range 15–300 μm.
   (c) a metarteriole is connected directly to a venule allowing flow to bypass the capillary bed.
   (d) most capillaries have a diameter of 5–10 μm.
   (e) arterioles are vasoactive.

2. Concerning viscosity in the microcirculation; viscosity is:

   (a) constant in all vessels with a value of 3.5 mPa s.
   (b) primarily determined by the number and distribution of white cells.
   (c) primarily determined by the number and distribution of red blood cells.
   (d) increased in capillaries compared to that in major vessels.
   (e) increased in vessels where red cell concentration is reduced at the vessel wall.

3. Concerning the myogenic effect; an increase in input pressure to the arterioles leads to:

   (a) relaxation of smooth muscle in order to constrict arterioles.
   (b) short-term increase in pressure in the capillary.
   (c) constriction of smooth muscle in order to increase the diameter of arterioles.
   (d) short-term decrease in pressure in the capillary.
   (e) constriction of smooth muscle in order to decrease arteriolar diameter.

4. Concerning vasomotion:
   (a) This is the regular change in flow rate in capillaries from 3 to 30 nL s^{-1}.
   (b) This is the movement of blood through vessels at a speed of 3–30 cm s^{-1}.
   (c) This is a general term associated with movement of blood or vessel wall.
   (d) This is regular change in diameter of arterioles at a frequency of 3–30 min^{-1}.
   (e) This is the regular change in viscosity in capillaries from 3 to 30 mPa s.

5. Most cells in the body are within what distance from a capillary:
   (a) 1 μm.
   (b) 10 μm.
   (c) 100 μm.
   (d) 1 mm.
   (e) 10 mm.

6. In Starling's equation transcapillary flow is related to:
   (a) net hydrostatic pressure plus net colloid osmotic pressure.
   (b) net hydrostatic pressure.
   (c) net colloid osmotic pressure.
   (d) intravascular pressure minus intervascular colloid osmotic pressure.
   (e) net hydrostatic pressure minus net colloid osmotic pressure.

7. Which of the following is not a form of molecular movement across the capillary wall?
   (a) Diffusion of glucose through fenestrations and pores in the capillary wall.
   (b) Quantum tunnelling of H^+.
   (c) Bulk flow through pores and clefts in the walls of sinusoidal capillaries.
   (d) Diffusion across the lipid bilayer for CO_2 and O_2.
   (e) Vesicular transport of antibodies.

8. The purpose of autoregulation of perfusion is to:
   (a) ensure that tissues remain ischaemic most of the time.
   (b) maintain adequate perfusion for a wide range of arterial pressure.
   (c) maintain adequate wall shear stress for a wide range of arterial pressure.
   (d) ensure that arteriolar resistance is maintained at a constant level regardless of perfusion values.
   (e) ensure that central blood pressure is maintained constant for a wide range of perfusion values.

Chapter 8 SAQs

1. List the main components of the microcirculation.
2. Describe briefly the origin of red blood cell margination in arterioles and venules.

3. Describe why effective viscosity is lower in the arterioles and venules than in larger vessels.
4. Describe plasma skimming and its cause.
5. Describe and illustrate the Bayliss effect.
6. Describe what is meant by vasomotion.
7. Write down Starling's equation with definitions of each term of the equation.
8. List three mechanisms for transport of molecules across the capillary wall with a sentence explaining each one.
9. Describe briefly metabolic control of perfusion.
10. Briefly explain the meaning of the term 'angiogenesis' and give 3 examples of when this occurs.

Chapter 8 LAQs

1. Describe how viscosity varies in different vessels in the microcirculation and explain why it has such a wide variation in values in different vessels.
2. Describe the Bayliss effect and how this might lead to vasomotion.
3. Explain why capillary intravascular pressure needs to be kept constant and explain the principle mechanism for achieving this.
4. Describe what is meant by flow autoregulation and explain the mechanisms by which local perfusion is controlled.

Chapter 9 Questions; In Vivo Imaging

Chapter 9 MCQs

1. Concerning structural imaging:
   - (a) uses an ingested, inhaled or injected tracer.
   - (b) gives information on biological function.
   - (c) PET is an example of a structural imaging technique.
   - (d) gives information on geometry and motion.
   - (e) CT is an example of a structural imaging technique.
2. Concerning functional imaging:
   - (a) may use an ingested or injected tracer.
   - (b) gives information on physiological function.
   - (c) PET is an example of a functional imaging technique.
   - (d) this primarily provides information on organ geometry.
   - (e) may only be performed by PET.

3. Concerning X-ray imaging:
   (a) involves the use of ionising radiation.
   (b) MRI uses X-rays.
   (c) X-ray images show information related to X-ray attenuation of tissues.
   (d) X-ray images show information related to X-ray speed of propagation.
   (e) X-ray images show information related to T1 and T2 values.

4. Catheter placement in angiography:
   (a) may be undertaken using projection radiography.
   (b) can only be undertaken using a CT scanner.
   (c) may be undertaken using a fluoroscopy system.
   (d) involves injection of an iodine contrast agent.
   (e) involves injection of a barium contrast agent.

5. Concerning CT scanning:
   (a) Only produces 2D images.
   (b) May be obtained using a standard projection radiography system.
   (c) Involves the collection of X-ray data at multiple angles around the patient.
   (d) Has a data acquisition time of 20–60 min.
   (e) Involves production of the 3D dataset using tomographic reconstruction.

6. A contrast agent in X-ray imaging:
   (a) is not used in angiography.
   (b) is usually based on barium or iodine.
   (c) is usually based on arsenic or uranium.
   (d) is based on iron.
   (e) is used to improve image quality by improving image contrast between tissues.

7. MRI:
   (a) has typical imaging times of 1–2 min.
   (b) is usually undertaken using a 0.15T or 9T magnet.
   (c) mostly concerns imaging of the hydrogen nucleus.
   (d) is usually undertaken using a 1.5T or 3T magnet.
   (e) mostly concerns imaging of the nitrogen nucleus.

8. The Larmor frequency:
   (a) is the frequency of the transmitted ultrasound.
   (b) is the rate of rotation of the magnetic axis of the proton around the magnetic field.
   (c) is equal to 42 MHz per tesla.
   (d) is the rate of rotation of the magnetic axis of the electron around the magnetic field.
   (e) is equal to 420 MHz per tesla.

9. The T1 relaxation time:
   - (a) is also called the spin-lattice relaxation time.
   - (b) is a measure of the rate of decay of the transverse magnetization.
   - (c) is usually longer than the T2 relaxation time.
   - (d) is equal to 0.15 s for all tissues.
   - (e) is a measure of the rate of energy exchange between the protons and the neighbouring molecules.

10. Concerning the various coils in an MRI scanner:
    - (a) Radiofrequency receiver coils are used to detect the RF ultrasound signals from the patient.
    - (b) Radiofrequency receiver coils are used to detect the RF signal from the patient.
    - (c) Gradient coils are used to produce small changes in magnetic field along x, y and z.
    - (d) Gradient coils are not needed for 3T MRI.
    - (e) Radiofrequency transmitting coils are used to change the direction of magnetisation of protons.

11. Ultrasound for medical imaging diagnosis:
    - (a) involves transmission and reception of ultrasound along a narrow beam.
    - (b) uses low frequency sound waves in the range 2–20 kHz.
    - (c) uses high frequency sound waves in the frequency range 2–20 MHz.
    - (d) does not involve real-time imaging.
    - (e) is designed to cause extensive tissue damage.

12. Concerning the ultrasound B-mode image:
    - (a) this is a display of received Doppler mean frequency.
    - (b) this is built up by sweeping of the ultrasound beam through the tissues.
    - (c) involves measurement of echo depth by timing between pulse transmission and echo reception.
    - (d) this is a display of the received ultrasound amplitude.
    - (e) this is a display of the received ultrasound frequency.

13. Concerning Doppler ultrasound:
    - (a) spectral Doppler is a real-time display of Doppler frequency shift versus time.
    - (b) the Doppler shift is proportional to the square of the blood velocity.
    - (c) spectral Doppler is a real-time 2D display of mean Doppler frequency of blood flow.
    - (d) may be used to estimate blood velocity.
    - (e) the Doppler shift is proportional to the cosine of the angle between beam and direction of motion.

14. Concerning ultrasound contrast agents:
    (a) these are based on the use of high atomic number elements such as iodine.
    (b) these have a diameter of 2–6 mm.
    (c) these consist of gas encapsulated by a thin shell.
    (d) these have a typical diameter of 2–6 micron.
    (e) these are based on the use of paramagnetic elements such as iron.

15. In PET imaging, radioactive atoms disintegrate:
    (a) releasing an electron, which collides with another electron producing 2 X-rays.
    (b) releasing a positron, which collides with an electron producing 2 gamma rays.
    (c) releasing a positron, which collides with another positron producing 2 gamma rays.
    (d) releasing an electron, which collides with another electron producing 2 gamma rays.
    (e) releasing a positron, which collides with an electron producing 2 X-rays.

16. For PET imaging of the human:
    (a) spatial resolution is typically 4–6 micron.
    (b) spatial resolution is typically 4–6 mm.
    (c) spatial resolution is typically 0.4–0.6 mm.
    (d) acquisition time is typically 20–60 min.
    (e) PET is a real-time technique with a frame rate of 20–60 frames per second.

17. In PET imaging:
    (a) pairs of gamma rays are created which travel in the same direction and are detected by sensors.
    (b) pairs of alpha rays are created which travel in opposite directions and are detected by sensors.
    (c) pairs of X-rays are created which travel in opposite directions and are detected by sensors.
    (d) pairs of X-rays are created which travel in the same direction and are detected by sensors.
    (e) pairs of gamma rays are created which travel in opposite directions and are detected by sensors.

18. Blood velocity is commonly measured using:
    (a) PET.
    (b) CT.
    (c) Doppler ultrasound.
    (d) MRI.
    (e) projection radiography.

19. In shear wave elastography tissue stiffness is:
    (a) proportional to the square of shear wave velocity.
    (b) inversely proportional to local tissue density.
    (c) proportional to shear wave velocity.
    (d) proportional to local tissue density.
    (e) inversely proportional to shear wave velocity.
20. Concerning shear wave elastography:
    (a) shear waves may be induced by means of a high-output acoustic pulse.
    (b) typically travel at 1–20 m/s in soft tissues.
    (c) shear waves may be induced by an external actuator in contact with the skin of the patient.
    (d) is applicable to CT and rotational angiography.
    (e) typically travel at 1540 m/s in soft tissues.

Chapter 9 SAQs

1. Describe briefly what is meant by structural imaging and functional imaging and gives examples of each.
2. Describe the principle of X-ray imaging for the projection radiograph.
3. Describe the principles of X-ray imaging when used in angiography.
4. Describe briefly why MRI mostly concerns imaging of hydrogen nuclei.
5. Describe briefly the origin of the MRI signal from hydrogen nuclei following application of an RF pulse.
6. Describe what is meant by T1 and T2 in MRI.
7. Describe the pulse-echo technique for ultrasound imaging.
8. Describe how ultrasound is commonly used to measure blood velocity.
9. Describe briefly the different types of contrast agents used in CT and ultrasound.
10. Describe briefly the principles of imaging for PET.
11. Describe the principles of ultrasound elastography.
12. Describe briefly the principles of magnetic resonance elastography.

Chapter 9 LAQs

1. Describe the different types of X-ray imaging techniques; which are suitable for 3D imaging?
2. Describe the principle of formation of an MRI image.
3. Describe the basic principles of formation of the B-mode image and give examples of measurements that may be made using B-mode imaging.
4. Compare and contrast the measurement of blood velocity and volumetric flow using Doppler ultrasound and using MRI.

Chapter 10 Questions; Modelling of the Cardiovascular System

Chapter 10 MCQs

1. Concerning models and modelling, which statements below do you think are correct?
   (a) A model must always be as near to physical reality as possible.
   (b) A model of the cardiovascular system should be 3D to be useful.
   (c) A model is a simplified version of reality.
   (d) A model should be just complicated enough in order to answer a specific question.
   (e) The model complexity should always be the same regardless of the problem to be solved.
2. Which of these is not required in computational modelling e.g. biomechanical arterial applications?
   (a) Output data.
   (b) Boundary conditions.
   (c) Model.
   (d) Input data.
   (e) General physical properties of arteries unrelated to the model.
3. Concerning reduced order models:
   (a) A reduced order model does not account for 1 or more of x, y, z.
   (b) 0D (t) models may be used to investigate pulse wave propagation in arteries.
   (c) 1D (x, t) models may be used to investigate pulse wave propagation in arteries.
   (d) 3D models (x, y, z, t) may be used to investigate pulse wave propagation in arteries.
   e) Computational run time is likely to be greater for reduced order models.
4. Incorporation of 3D geometry in modelling:
   (a) Requires a 0D modelling regime.
   (b) Requires a 1D modelling regime.
   (c) Requires a 3D modelling regime.
   (d) May involve idealised geometry creation in CAD.
   (e) May involve patient specific geometry creation in CAD.
5. Concerning rigid and moving-wall models used in arterial modelling:
   (a) A rigid wall model considers the wall to be compliant.
   (b) Moving walls can be modelled using an FSI approach.
   (c) Moving walls can be measured direct from medical imaging and included into a CFD-only approach.

(d) A moving-wall model considers the wall to be infinitely stiff.
(e) Modelling of pulse wave propagation can be undertaken using a rigid walled model.

6. Concening inlet flow data for CFD modelling in arteries.

(a) The use of a plug flow profile at the inlet accurately represents velocity profiles in all arteries.
(b) The use of a parabolic flow profile at the inlet accurately represents velocity profiles in all arteries.
(c) A Womersley based approach may be used to account for flow assymetry and spiral flow at the inlet.
(d) The use of a development length may be used to account for flow assymetry and spiral flow at the inlet.
(e) The use of a time-varying 2D velocity profile with all 3 velocity components from MRI may be used to account for flow asymmetry and spiral flow at the inlet.

7. For modelling of blood flow it would be necessary to account for deformable red cells in:

(a) Major arteries (1–20 mm diameter).
(b) Major veins (1–20 mm diameter).
(c) Minor arteries (0.3–1 mm diameter).
(d) Minor veins (0.3–1 mm diameter).
(e) Microcirculation vessels <100 μm.

Chapter 10 SAQs

1. Describe briefly what a model is and how complex the model should be.
2. Illustrate the modelling process explaining briefly what each of the components are.
3. Explain what a reduced order model is and why these are used rather than full 3D models.
4. Explain the difference between a rigid walled model and a compliant model used in arterial modelling.
5. For inlet flow conditions for arterial CFD, explain how asymmetric spiral-flow would be accounted for.
6. Explain what assumptions are commonly made concerning the physical properties of blood in CFD in larger arteries and veins.
7. Explain what a multidimensional model is and why these are used.

Chapter 10 LAQs

1. Describe the modelling process, explaining what a model is, how complex it should be in general terms, and illustrate this with an example.
2. Describe rigid and moving-wall models used in arterial modelling and when each model might be used.
3. Describe 3D heart models including the type of data which is simulated and the applications of interest.

Chapter 11 Questions; Patient Specific Modelling

Chapter 11 MCQs

1. Patient specific modelling:
   (a) is the combination of computational modelling with idealised organ geometries.
   (b) is the combination of computational modelling with organ geometries obtained from 3D medical imaging on the patient.
   (c) involving CFD should use patient specific inlet flow data.
   (d) aims to provide data relevant to the individual patient.
   (e) aims to provide data which is relevant to a group of patients.
2. Which of the following has contributed to the growth of patient specific modelling in recent years?
   (a) Improvements in computer power.
   (b) The need for improved methods for diagnosis.
   (c) Improvements in the availability of commercial computational modelling software.
   (d) Availability of high-resolution medical imaging.
   (e) Improvements in data on material properties.
3. Computational mechanics:
   (a) involves a continuum description of tissues.
   (b) involves discretisation of space and time.
   (c) provides an exact solution to the governing equations.
   (d) commonly uses simplified equations involving iteration.
   (e) applies to fluid mechanics but not solid mechanics.
4. Which of the following are ideal characteristics for medical imaging when used to collect data for PSM?
   (a) high noise.
   (b) low tissue contrast.

(c) high resolution.
(d) long image acquisition times.
(e) being MRI.

5. Concerning segmentation:

(a) in the PSM processing chain segmentation is performed after computational modelling.
(b) automated segmentation works best when image quality is worst.
(c) is concerned with identifying boundaries in imaging data.
(d) manual segmentation does not require any input from the operator.
(e) is often concerned with the detection of edges in the image.

6. Which of the following are not in the PSM processing chain?

(a) boundary condition data.
(b) computational modelling.
(c) post processing.
(d) 3D imaging.
(e) patient consent.

7. Concerning the mesh used in computational modelling:

(a) The number of mesh elements should always be as large as possible.
(b) Is commonly composed of tetrahedral or hexahedral elements.
(c) The number of mesh elements is 100,000 for FEA and 1 million for CFD.
(d) The number of mesh elements is chosen to balance solution accuracy with processing time.
(e) Mesh generation is usually a fully automated process.

8. For CFD in a stiff walled artery with no branches, the following information is needed:

(a) Circumferential elastic modulus of the artery wall.
(b) Inlet flow.
(c) Viscosity of blood.
(d) Inlet pressure.
(e) Density of blood.

9. For estimation of tissue stresses in an abdominal aortic aneurysm commonly involves the following:

(a) An FSI modelling regime.
(b) An FEA-only modelling regime.
(c) Information on wall thickness from MRI.
(d) A CFD only modelling regime.
(e) An assumption of constant wall thickness of typically 1.55 mm.

10. An FSI modelling regime:
    (a) is needed for estimation of the 3D flow field in a stiff walled artery.
    (b) is commonly used for estimation of tissue stress in an abdominal aortic aneurysm.
    (c) does not involve CFD.
    (d) involves both CFD and FEA.
    (e) is needed for estimation of flow field or tissue stress data in an artery with a tight stenosis.

Chapter 11 SAQs

1. Describe briefly what is meant by patient specific modelling.
2. Describe briefly the basic steps in computational mechanics.
3. Describe briefly the basic steps in patient specific modelling.
4. Discuss the choice of imaging modality for patient specific modelling of tissue stress in an abdominal aortic aneurysm.
5. Discuss the choice of imaging modality for patient specific modelling of tissue stress in the carotid bifurcation.
6. Describe how images may be segmented for patient specific modelling.
7. Describe what information can be obtained from the patient for use in patient specific modelling of blood flow in the abdominal aortic aneurysm, and what assumptions have to be made.
8. Describe what information can be obtained from the patient for use in patient specific modelling of tissue stress in the abdominal aortic aneurysm and what assumptions have to be made.
9. Describe what is meant by FSI and when this might be needed.

Chapter 11 LAQs

1. Describe the steps of patient specific modelling for estimation of tissue stress in an abdominal aortic aneurysm.
2. Describe the steps of patient specific modelling for estimation of tissue stress in the carotid bifurcation.
3. Describe the steps of patient specific modelling for estimation of flow field data in a non-diseased carotid bifurcation.
4. Describe the steps of patient specific modelling for estimation of flow field data in a cerebral aneurysm.

Chapter 12 Questions; Flow Phantoms

Chapter 12 MCQs

1. Which of these are not components of a typical flow phantom?
   (a) the central construct which mimics the geometry of part of the cardiovascular system.
   (b) blood mimic.
   (c) ultrasound system.
   (d) tissue mimic.
   (e) pump.
2. Which technique can be used to measure blood-mimic velocity in a suitable flow phantom?
   (a) LDA.
   (b) flow visualisation using a video camera.
   (c) CT.
   (d) PIV.
   (e) Doppler ultrasound.
3. Phantoms for PIV and LDA:
   (a) can be constructed from glass or silicone elastomer.
   (b) are optically transparent.
   (c) are optically opaque.
   (d) require seeding with low concentrations of particles.
   (e) are suitable for use with ultrasound imaging.
4. PIV:
   (a) does not require the use of seeded particles.
   (b) uses seeded particles at a typical concentration of <1 %.
   (c) uses ultrasound to measure the particle velocity by a Doppler shift.
   (d) involves a laser to illuminate the particles.
   (e) involves a laser to measure the particle velocity by a Doppler shift.
5. In lost-core phantom construction:
   (a) the lost-core may be manufactured from a mould.
   (b) the tissue mimic is removed once the lost-core has set.
   (c) the lost-core is commonly composed of a low-melting point alloy.
   (d) the lost-core is removed once the tissue mimic has set.
   (e) the lost-core is discarded immediately after it has been manufactured.

6. Phantom materials which attempt to match the imaging properties of tissues are referred to as:
   (a) tissue mimicking (for soft tissue).
   (b) tissue-equivalent (in general).
   (c) blood mimicking (for blood).
   (d) vessel mimicking (for vessel).
   (e) flow phantoms.
7. Solid tissue mimicking materials used in ultrasound phantoms include:
   (a) acrylic.
   (b) agar.
   (c) Urethane.
   (d) PVAc.
   (e) water.
8. A commonly used blood-mimicking fluid for MRI is:
   (a) 60:40 water:glycerol solution by mass containing nylon particles.
   (b) water (100 %).
   (c) 60:40 water:glycerol solution by mass.
   (d) 10 % solution of ethyl alcohol by volume.
   (e) 90:10 water:glycerol solution by mass.
9. A blood-mimicking fluid for ultrasound should have the following properties:
   (a) acoustic velocity of 1570 cm/s ± 10 %.
   (b) attenuation coefficient <0.1 dB cm^{-1} MHz^{-1}.
   (c) acoustic velocity of 1540 cm/s ± 10 %.
   (d) blood equivalent backscatter.
   (e) viscosity of 3–4 mPa s.
10. Which of the following are components of a parallel plate endothelial flow phantom:
    (a) microscope.
    (b) cone viscometer.
    (c) confluent endothelial cell layer.
    (d) blood mimic composed of 60:40 water:glycerol by mass.
    (e) optically transparent window.

Chapter 12 SAQs

1. Describe the advantages and disadvantages of using a flow phantom over an in vivo experiment.
2. Describe three uses of flow phantoms.

3. Briefly describe the principles of PIV.
4. Briefly describe the principles of LDA.
5. Briefly describe the steps for 3D printing of a phantom using the mould and lost-core technique.
6. Describe how corrosion casting might be used to manufacture a 3D anatomical phantom.
7. Describe how PVA may be used to make phantom components for MRI and ultrasound.
8. Describe components of a tissue-equivalent ultrasound phantom incorporating a vessel.
9. Describe components of a tissue-equivalent MRI phantom of an artery.
10. Describe how a low-melting point lost-core may be used to make a vascular phantom for MRI or ultrasound.
11. Describe the design and construction of a parallel plate endothelial flow phantom.

Chapter 12 LAQs

1. Describe the techniques used for visualisation and measurement of the velocity field in optically transparent flow phantoms.
2. Describe how 3D printing may be used to manufacture phantoms for use in flow phantoms.
3. Describe the design, construction and components of a flow phantom incorporating a planar carotid phantom for use with MRI.
4. Describe the design, construction and components of a flow phantom incorporating a non-planar carotid phantom for use with ultrasound.
5. Compare the design and advantages/disadvantages of a parallel plate endothelial flow phantom and a whole artery flow phantom.

Chapter 13 Questions; Measurement and Imaging of the Mechanical Properties of Biological Tissues.

Chapter 13 MCQs

1. In tensile testing of excised tissues the load:

   (a) Should produce the range of stress values in the tissue sample relevant for all biological tissues in vivo.
   (b) Should range from 1 to 10^6 kPa.
   (c) Should be set to zero.

(d) Should produce the range of stress values in the tissue sample relevant for that tissue in vivo.
(e) Is adjusted so that there is tissue failure.

2. In uniaxial tensile testing for measurement of stress–strain properties of tissues:

(a) the sample is compressed until failure.
(b) the tissue is cut into dumbbell- or rectangular-shaped samples.
(c) stretching causes reduction in area in the lateral direction.
(d) the tissue is cut into J-shaped samples.
(e) the sample is elongated until failure.

3. The mechanical properties such as Young's modulus may be measured by:

(a) uniaxial tensile testing on a sample of excised artery in the shape of a rectangle or dumbbell.
(b) biaxial tensile testing on a sample of excised section of artery in the shape of a rectangle.
(c) inflation testing on an excised section of whole artery.
(d) in vivo from measurements of wall motion, wall thickness and pressure.
(e) in vivo from measurement of pulse wave velocity, wall thickness and diameter.

4. Planar biaxial testing of the mechanical properties of excised tissue samples:

(a) typically uses dumbbell-shaped samples of tissue.
(b) enables characterisation of anisotropic behaviour.
(c) concerns loading in 2 or more directions in a 2D plane.
(d) enables characterisation of 3D behaviour.
(e) typically uses square samples of tissue.

5. Which of these equations is the correct formulation for the stiffness index β measured in arteries?

(a) $\beta = \frac{d_d}{2_h} \frac{(P_s - P_d)}{(d_s - d_d)/d_d}$
(b) $\beta = \frac{(P_s - P_d)}{(d_s - d_d)/d_d}$
(c) $\beta = \frac{\ln(P_s/P_d)}{(d_s - d_d)/d_d}$
(d) $\beta = \sqrt{\frac{Eh}{d\rho}}$
(e) $\beta = \frac{d\rho}{h}(\mathrm{PWV})^2$

6. For measurement of the pressure-strain elastic modulus in the carotid artery the following are needed:

(a) systolic and diastolic diameter from ultrasound.
(b) Young's modulus from shear wave imaging.
(c) wall thickness from ultrasound.
(d) pulse wave velocity from tonometry.

(e) systolic and diastolic pressures from an arm cuff.

7. Concerning elastography; which of the following are not steps that are needed in shear wave elastography:

   (a) Use of MRI or ultrasound to measure the shear wavelength or frequency in vivo.
   (b) Induction of compressional waves.
   (c) Induction of shear waves.
   (d) Measurement of local stress from local strain using finite element analysis.
   (e) Estimation of local Young's modulus from the equation: $E = 3\rho c_s^2$.

Chapter 13 SAQs

1. Describe three steps in sample preparation in uniaxial testing of stress–strain behaviour of an excised artery.
2. List and describe briefly three methods for estimation of the circumferential Young's modulus of an artery.
3. Write down the equation for pressure-strain elastic modulus Ep in terms of diameter and pressure and state how ultrasound may be used to estimate *Ep*.
4. Describe the main steps in shear wave elastography leading to the calculation of local Young's modulus.

Chapter 13 LAQs

1. Describe how uniaxial testing may be used to estimate the stress–strain behaviour of a sample of excised tissue and how Young's modulus may be measured from the output data.
2. Describe how shear waves may be used to measure local Young's modulus in vivo giving reference to both ultrasound and MRI methods.

Chapter 14 Questions; Hypertension and Ageing

Chapter 14 MCQs

1. The definition of hypertension is:

   (a) systolic blood pressure ≥90 mmHg and/or diastolic pressure ≥140 mmHg measured in the arm.
   (b) systolic blood pressure ≥160 mmHg measured in the arm.
   (c) diastolic blood pressure ≥100 mmHg measured in the arm.

(d) systolic blood pressure ≥140 mmHg and/or diastolic pressure ≥90 mmHg measured in the arm.
(e) systolic blood pressure ≥140 mmHg and/or diastolic pressure ≥90 mmHg measured in the thigh.

2. Primary hypertension:

(a) constitutes 5–10 % of all hypertension cases.
(b) has no clear underlying cause.
(c) is caused by anti-depressants and cocaine.
(d) is caused by kidney disease.
(e) has the same origins as secondary hypertension.

3. Mixed hypertension:

(a) involves increase in both systolic and diastolic pressure.
(b) involves decrease in systolic and increase in diastolic pressure.
(c) is the most common pattern of hypertension >50 years.
(d) is the most common pattern of hypertension in age 30–50.
(e) involves increase in systolic pressure and no change in diastolic pressure.

4. Concerning blood pressure and ageing:

(a) Systolic blood pressure decreases with age.
(b) The biological cause of blood pressure increasing with age is cyclic fatigue fracture of elastin.
(c) Systolic blood pressure increases with age.
(d) Biological ageing is the main cause of increasing blood pressure with age in the Western world.
(e) Biological ageing is the main cause of increasing blood pressure with age in primitive societies.

5. Stiffening of arteries:

(a) leads to decrease in the return-time of reflected pressure waves in the aorta.
(b) is associated with a decrease in pulse wave velocity in the aorta.
(c) leads to increase in the return time of reflected pressure waves in the aorta.
(d) can lead to increase in the systolic pressure in the aorta.
(e) can lead to reduction in systolic pressure in the aorta.

6. Medium-term increase in mean blood pressure leads to:

(a) decrease in PWV.
(b) increase in wall thickness to normalise circumferential stress.
(c) increase in PWV.
(d) decrease in wall thickness to normalise circumferential stress.
(e) no change in PWV.

7. Modern invasive measurement of blood pressure involves:
   (a) use of a catheter containing a flexible membrane and fluid-filled column.
   (b) use of a catheter containing a piezoelectric transducer.
   (c) use of an arm cuff.
   (d) use of a tonometry system.
   (e) use of an NIBP.
8. Concerning applanation tonometry:
   (a) This produces a pressure-time waveform.
   (b) This produces a blood velocity-time waveform.
   (c) Produces measurements of pressure which require calibration using another device (e.g. arm cuff).
   (d) This is applicable to deep arteries (e.g. aorta).
   (e) This is applicable to arteries near the surface (e.g. carotid, brachial, radial).
9. Central blood pressure:
   (a) is estimated from a calibrated femoral pressure waveform using a transfer function.
   (b) is the blood pressure in the radial artery.
   (c) may be estimated using an arm cuff.
   (d) is the blood pressure in the ascending aorta.
   (e) is estimated from a calibrated radial pressure waveform using a transfer function.
10. Concerning augmentation pressure:
   (a) is the additional systolic pressure in the ascending aorta arising from reflected waves.
   (b) is the systolic pressure in the ascending aorta.
   (c) the augmentation index is the augmentation pressure divided by the pulse pressure.
   (d) may be estimated using an arm cuff.
   (e) the augmentation index is the augmentation pressure multiplied by the pulse pressure.

Chapter 14 SAQs

1. Define hypertension and discuss the prevalence and origins of primary and secondary hypertension.
2. Illustrate the change in stiffness with age and discuss biological and pathological contributions.
3. How do reflected waves lead to increase in central pressure?

4. Describe what happens to the aorta following a medium-term (weeks) increase in blood pressure.
5. Compare the performance of fluid-filled and piezoelectric catheter systems for measuring pressure.
6. Describe the principle of measurement of blood pressure using an arm cuff.
7. Describe the process whereby central pressure is estimated using a tonometry system.
8. Describe what is meant by augmentation and how central pressure augmentation index is calculated.

Chapter 14 LAQs

1. Describe what is meant by hypertension and discuss the causes of hypertension, including the effect of ageing.
2. Describe the relationship between arterial stiffness and central blood pressure and how this is measured using tonometry.
3. Describe 3 methods by which arm blood pressure may be measured.

Chapter 15 Questions; Atherosclerosis

Chapter 15 MCQs

1. Cardiovascular disease are responsible for what percentage of world deaths;

   (a) 1 %.
   (b) 11 %.
   (c) 31 %.
   (d) 61 %.
   (e) 81 %.

2. Atherosclerosis;

   (a) does not occur in the carotid arteries.
   (b) begins in old age.
   (c) is associated with deposition of fatty deposits in the medial layer.
   (d) is concerned with increase in diameter of the inner lumen.
   (e) leads to lumen reduction in advanced disease.

3. For an isolated 50 % stenosis by diameter in an artery;

   (a) blood velocity is maximum where cross-sectional area is minimum.
   (b) flow rate at the point of minimum lumen is 4 times flow rate in the pre-stenotic region.

(c) blood velocity is maximum a small distance downstream from the point of minimum area.
(d) wall shear stress is highest in upstream part of the stenosis.
(e) there is a pressure drop associated with viscous and turbulent energy losses.

4. With increasing degree of stenosis;

(a) flow rate gradually increases reaching a peak value at around 70 % stenosis by diameter.
(b) blood velocity gradually increases reaching a peak at around 84 % stenosis by diameter.
(c) flow rate is maintained constant until around 70 % stenosis.
d) the downstream arteriolar bed dilates until it is fully dilated at around 70 % stenosis.
(e) the downstream arteriolar bed resistance to flow is maintained constant.

5. Concerning atherosclerotic plaque:

(a) stable cap are associated with thin cap walls and large lipid pools.
(b) rupture occurs when the mechanical stress within the cap exceeds the cap strength.
(c) high wall shear stress leads to cap thickening.
(d) rupture occurs when the wall shear stress exceeds the cap strength.
(e) plaque tend to grow downstream through a process of upstream erosion and downstream growth.

6. In the conventional model of atherosclerosis disease is initiated at regions of:

(a) low wall shear stress and/or low oscillatory index.
(b) high wall shear stress.
(c) high blood velocity.
(d) low wall shear stress and/or high oscillatory index.
(e) high circumferential stress.

7. In the early stages of atherosclerosis:

(a) plaque volume increases.
(b) lumen is maintained constant.
(c) there is inward remodelling.
(d) there is outward remodelling.
(e) there is no remodelling.

8. Estimation of the degree of stenosis using ultrasound is based mainly on measurement of:

(a) intima-media thickness from the B-mode image.
(b) diameter from the B-mode image.
(c) peak systolic velocity from spectral Doppler.
(d) flow rate using the B-mode image and spectral Doppler.
(e) mean velocity from spectral Doppler.

9. The decision to offer carotid surgery for patients with atherosclerosis is based on:
   (a) flow rate below a critical value of 50 ml/min (NASCET) or 70 ml/min (ECST).
   (b) degree of stenosis above a critical value of 50 % (NASCET) or 70 % (ECST).
   (c) wall shear stress above a critical value of 50 Pa (NASCET) or 70 Pa (ECST).
   (d) maximum velocity is above a critical value of 500 cm/s (NASCET) or 700 cm/s (ECST).
   (e) plaque volume above a critical value of 0.5 cm^3 (NASCET) or 0.7 cm^3 (ECST).

10. Quantitative information on the severity of a coronary artery stenosis can be obtained from:
    (a) a knowledge of the upstream and downstream pressure.
    (b) the angiogram.
    (c) the diameter of the artery.
    (d) the severity of chest pain.
    (e) body mass index.

Chapter 15 SAQs

1. Describe briefly the progression of atherosclerosis from initiation to rupture.
2. Describe the relationship between velocity, flow rate and degree of stenosis.
3. Describe the changes in pressure across a stenosis.
4. Describe what is meant by stable and vulnerable plaque and their typical composition.
5. Describe the role of wall shear stress in atherosclerosis initiation and progression.
6. Explain the phenomenon of outward remodelling and explain why this occurs.
7. Explain how ultrasound may be used to estimate the degree of stenosis.
8. Describe the typical warning signs of imminent plaque rupture in carotid and coronary arteries.
9. Describe the typical clinical management of a patient who is suspected of a carotid stenosis.
10. Describe the typical clinical management of a patient who is suspected of a coronary stenosis.

Chapter 15 LAQs

1. Describe the physical characteristics of the flow-field for a stenosis.
2. Describe the progression of atherosclerosis from initiation to rupture, the clinical consequence of atherosclosis in the patient, and the management of the patient with examples from 1 of heart, brain or lower limb.
3. Describe and explain the relationship between velocity, flow rate and degree of stenosis and describe how ultrasound is used to estimate the degree of stenosis.
4. Describe the role of wall shear stress and tissue stress in the initiation, progression and rupture of atherosclerotic plaque.

Chapter 16 Questions; Aneurysms

Chapter 16 MCQs

1. Aneurysms:
   (a) Occur only in the abdominal aorta.
   (b) Involve a reduction in the diameter of the inner-wall of an artery.
   (c) Are associated with loss of elastin leading to increased stiffness.
   (d) Can rupture causing spillage of plaque contents into the bloodstream.
   (e) Involve an increase in the inner and outer wall diameter of an artery.
2. Concerning tension and stress within the wall of a thin-walled sphere or cylinder (Law of Laplace):
   (a) Tension is proportional to pressure.
   (b) Tension is proportional to wall thickness.
   (c) Circumferential stress is inversely proportional to pressure.
   (d) Circumferential tension is proportional to diameter.
   (e) Circumferential stress is proportional to $(\text{diameter})^2$.
3. In the early stages of disease local loss of elastin from the artery wall may:
   (a) lead to formation of an aneurysm.
   (b) lead to formation of an atherosclerotic plaque.
   (c) lead to remodelling involving laying down collagen fibres to mechanically stabilise the artery.
   (d) lead to degradation of collagen fibres in order to mechanically stabilise the artery.
   (e) lead to loss of the endothelium.
4. Concerning rupture of a saccular cerebral aneurysm:
   (a) Rupture occurs when wall shear stress exceeds wall strength.
   (b) Risk of rupture increases with aspect ratio.

   (c) Never occurs when the aneurysm diameter is less than 3 mm.
   (d) Risk of rupture decreases with aneurysm diameter.
   (e) Rupture occurs when circumferential stress exceeds wall strength.

5. For an unruptured saccular aneurysm:

   (a) Treatment is not considered to be cost effective or worthwhile.
   (b) Treatment is normally considered if the diameter is less than 2 mm.
   (c) Treatment is normally considered if the diameter is greater than 7 mm.
   (d) If there are other risk factors treatment is considered if the diameter is greater than 3 mm.
   (e) If there are other risk factors treatment is considered if the diameter is greater than 7 mm.

6. For unruptured abdominal aortic aneurysm, surgical repair is considered if:

   (a) the maximum diameter is greater than 5.5 cm for men.
   (b) the patient has symptoms of imminent rupture, such as abdominal pain, lower back pain or a pulsatile mass in the abdomen.
   (c) the maximum peak wall stress is greater than 0.50 MPa.
   (d) the maximum diameter is greater than 5.5 mm for men.
   (e) treatment is not considered worthwhile.

7. An abdominal aortic aneurysm generally:

   (a) is a Berry aneurysm.
   (b) is stiffer than a normal artery.
   (c) does not contain intraluminal thrombus.
   (d) has greater elastin content as a result of laying down of elastin sheets.
   (e) has greater collagen content as a result of collagen synthesis in the wall.

8. Concerning rupture of an abdominal aortic aneurysm:

   (a) Aneurysms whose diameter is less than 5.5 cm never burst.
   (b) Mortality rate is only 10 %.
   (c) Risk of rupture increases with diameter.
   (d) Survival rate is only 10 %.
   (e) Risk of rupture decreases for greater peak wall stress.

Chapter 16 SAQs

1. Describe what an aneurysm is and where in the body these typically occur.
2. Describe the law of Laplace and how this relates to risk of rupture of an aneurysm.
3. Describe two different flow patterns in a saccular cerebral aneurysm and state the blood velocity, wall shear stress and dome pressure compared to the parent artery.

4. Describe and illustrate measurement of diameter and aspect ratio of a saccular cerebral aneurysm.
5. Describe briefly modern methods for treating a saccular cerebral aneurysm.
6. Describe modern clinical practice for patient-selection and repair of abdominal aortic aneurysm.
7. Describe changes to elastin and collagen in an abdominal aortic aneurysm and how these relate to changes in stiffness.
8. Describe the relationship between haemodynamics and thrombus formation in a growing abdominal aortic aneurysm.

Chapter 16 LAQs

1. Describe prevalence, causes, diagnosis and treatment of a saccular cerebral aneurysm.
2. Describe theories on the role of wall shear stress in the initiation, development and rupture of a saccular cerebral aneurysm.
3. Describe the measurement or estimation of diameter, asymmetry index and peak wall stress on an abdominal aortic aneurysm.
4. Describe theories on the role of mechanical forces and growth of abdominal aortic aneurysm.

Chapter 17 Questions; Cardiovascular Prostheses

Chapter 17 MCQs

1. A clinician's first line approach to the treatment of chronic cardiovascular disease is:

   (a) correctional surgery.
   (b) surgical implantation of an appropriate cardiovascular device.
   (c) introduction of a device using a minimally invasive approach.
   (d) use of one or more appropriate drugs.
   (e) to advise the patient to stop all exercise with immediate effect.

2. Which procedures can be carried out using a minimally invasive approach?

   a) replacing an aortic heart valve.
   (b) balloon angioplasty.
   (c) balloon angioplasty with stenting.
   (d) femoral bypass grafting.
   (e) pacemaker implantation.

3. Which of the following are classified as active implantable devices?
   (a) vascular graft.
   (b) mechanical heart valve.
   (c) ventricular assist device.
   (d) vascular stent.
   (e) balloon catheter.
4. The following are used as biological grafts:
   (a) saphenous vein.
   (b) fabric grafts with velour surface for endothelial attachment.
   (c) Dacron grafts.
   (d) autologous internal mammary artery.
   (e) chemically stabilised bovine artery.
5. Neointimal hyperplasia involves:
   (a) proliferation of smooth muscle cells.
   (b) migration of smooth muscle cells.
   (c) formation of extracellular matrix.
   (d) restoration of the natural vessel wall.
   (e) movement of lipid into the vessel wall.
6. Nitinol is:
   (a) an alloy of nickel and titanium.
   (b) 316L Stainless steel.
   (c) a polymer.
   (d) a shape-memory metal.
   (e) resorbed in the body.
7. The following are types of mechanical heart valve:
   (a) bileaflet.
   (b) TAVI.
   (c) tilting disc.
   (d) stentless.
   (e) porcine.
8. The following are used to characterise the flow field downstream of a replacement valve:
   (a) pressure difference.
   (b) percentage backflow.
   (c) flow visualisation.
   (d) root mean square flow.
   (e) laser Doppler anemometry.

9. Implantable pacemakers have the following basic components:
   (a) pulse generator.
   (b) lead system.
   (c) an external power source.
   (d) gel electrodes.
   (e) an alarm system.
10. The following are pacemaker operation modes:
    (a) transcutaneous.
    (b) dual chamber.
    (c) asynchronous.
    (d) removable.
    (e) demand.

Chapter 17 SAQs

1. Describe the steps involved in delivering and deploying a coronary artery stent to the site of vessel occlusion.
2. What are the failure modes associated with artificial heart valves? Describe the underlying design issues.
3. Cardiovascular devices are considered to be safety critical devices. Explain why this is the case giving a specific example.
4. List the factors which need to be considered when classifying a device in order to determine the level of assessment required for regulatory compliance.

Chapter 17 LAQs

1. Discuss the major bioengineering challenges to be considered when developing implantable cardiovascular devices. Illustrate your answer with examples of different types of devices.
2. Describe how the performance of an artificial heart valve can be assessed in vitro. Explain the measures that can be calculated and indicate their clinical significance.
3. Describe the use of cardiac pacemakers including the clinical indications for their use, the types of devices available and their modes of operation.

Answers to MCQs

Chapter 1 Answers

1: d	2: a, b, e	3: c, d	4: e	5: b, d
6: a, e	7: b, c	8: a, d	9: a, e	10: b, c, e
11: a, b	12: d, e	13: b, c	14: a, c	15: d, e
16: c, e	17: b, c, e			

Chapter 2 Answers

1: a, d	2: c, e	3: c	4: a, b, c, d	5: a, d
6: a, c, e	7: b	8: a, c, e	9: b, c, e	10: b, d

Chapter 3 Answers

1: a, d, e	2: a, b, d	3: d, e	4: b, d	5: c, d, e
6: b, c	7: a, c, e	8: d, e	9: c	10: b, d
11: a, c, d	12: b, c, e	13: a, c	14: c, d	15: a, e
16: b, c, d	17: c, d	18: a, e	19: a, c	20: a, c, d

Chapter 4 Answers

1: b, d, e	2: a	3: a, c, e	4: c	5: a, c, e
6: a, b, e	7: a, b, c, d, e	8: b, c, e	9: a, b	10: a, b, d, e

Chapter 5 Answers

1: c, e	2: c, d	3: a, e	4: b, e	5: c, e
6: b, c, e	7: a, b, c	8: b, c, d	9: a, e	10: c, d, e
11: a	12: c, e			

Chapter 6 Answers

1: a	2: a	3: c	4: b	5: c
6: d	7: a	8: d	9: b	10: c

Chapter 7 Answers

1. b, c, d	2. b, d	3. a, b, c	4. a, d, e	5. a, b, d, e
6. b, d, e	7. a, c, e	8. a, b, e	9. c, d, e	10. a, c, d
11. a, b, c, e				

Chapter 8 Answers

1: a	2: c, d	3: b, e	4: d	5: c
6: e	7: b	8: b		

Chapter 9 Answers

1: d, e	2: a, b, c	3: a, c	4: c, d	5: c, e
6: b, e	7: c, d	8: b, c	9: a, c, e	10: b, c, e
11: a, c	12: b, c, d	13: a, d, e	14: c, d	15: b
16: b, d	17: e	18: c, d	19: a, d	20: a, b, c

Chapter 10 Answers

1: c, d	2: e	3: a, c, d	4: c, d	5: b, c
6: e	7: e			

Chapter 11 Answers

1: b, c, d	2: a, b, c, d, e	3: b, d	4: c	5: c, e
6: e	7: b, d	8: b, c, e	9: b, e	10: d, e

Chapter 12 Answers

1: c	2: a, d, e	3: a, b, d	4: b, d	5: a, c, d
6: a, b, c, d	7: b, c, d	8: c	9: a, b, d, e	10: a, c, e

Chapter 13 Answers

1: d, e	2: b, c, e	3: a, b, c, d, e	4: b, c, e	5: c
6: a, e	7: b, d			

Chapter 14 Answers

1: d	2: b	3: a, d	4: b, c, e	5: a, d
6: b, c	7: b	8: a, c, e	9: d, e	10: a, c

Chapter 15 Answers

1: c	2: c, e	3: c, d, e	4: b, c, d	5: b, e
6: d	7: a, b, d	8: c	9: b	10: a

Chapter 16 Answers

1: c, e	2: a, d	3: a, c	4: b, e	5: c, e
6: a, b	7: b, e	8: c, d		

Chapter 17 Answers

1: d	2: a, b, c, e	3: c	4: a, d, e	5: a, b, c
6: a, d	7: a, c	8: c, e	9: a, b	10: c, e

Appendix B: Glossary

0D model Computational model where there is no spatial variation of relevant quantities within model compartments

1D model Computational model in which there are spatial variations of relevant quantities in only 1 spatial dimension; e.g., for PWV propagation in arteries

2D ultrasound Ultrasound where the data is collected in 2D, and displayed in 2D

2D velocity profile Referring to measurement of the velocity profile in which the velocity is measured at each point within a 2D cross section

3D model Computational model in which there are spatial variations of relevant quantities in all 3 spatial dimensions; e.g., for patient-specific modelling

3D printing Technologies which enable manufacture of a 3D model from a computer design; usually involving building up the object in layers in a manner similar to printing

3D ultrasound Ultrasound where 3D data is collected

7D imaging Measurement of blood velocity in which there is measurement of the full flow-field data; i.e. all 3 velocity components (v_x, v_y, v_z) within a volume of space (x, y, z) and with time

α Womersley number; relating to pulsatile (time-varying) flow of a fluid in a vessel

β Arterial stiffness index

μ Abbreviation of 'micro' meaning one millionth or 10^{-6}; e.g. μm

Abdominal aortic aneurysm Aneurysm of the lower aorta

Acoustic impedance Fundamental property of a medium in the context of sound wave propagation

Acoustic matching (phantoms) Ensuring that the ultrasound properties of the phantom material are similar to those in the relevant human tissue

P.R. Hoskins et al. (eds.), *Cardiovascular Biomechanics*,
DOI 10.1007/978-3-319-46407-7

Acrylic (phantom material) Material used in construction of phantoms; the most common acrylic is perspex; see 'perspex'

Activated platelet Platelet which has become more sticky leading to accumulation at sites of endothelial injury

Active contour Another name for a 2D deformable model

Active surface Another name for a 3D deformable model

Actuator (MRE) Device which produces shear waves which travel through the body

Adaptability (cardiovascular) Ability of the cardiovascular system to change in terms of heart and vessel geometry, flow rates and pressures

Adhesion protein Proteins in the cell membrane to which the cytoskeleton is connected; see 'focal adhesion site'

Adhesion site See 'focal adhesion site'

Adulthood Time after childhood; from 20 years to death at age up to around 100 years

Adventitia Outermost layer of the artery wall mainly consisting of collagen fibres

Afterload Tension generated by the left (or right) ventricle during the ejection phase of the cardiac cycle

Agar (for tissue mimic) Jelly-like organic material used in the construction of MRI and ultrasound phantoms

Aggregation (red cell) Accumulation of red cells into a single larger structure which occurs at very low shear ($<10\ s^{-1}$); consists of rouleaux

Albumin Protein present in blood whose function is concerned with maintenance of osmotic pressure

Alpha See 'Womersley number'

Ammonia One of the waste products of metabolism

Anaemia Abnormally low haematocrit and/or haemoglobin level leading to lowered ability of the blood to carry oxygen; leading to tiredness and related symptoms

Aneurysm Localised increase in diameter of an artery characterised by loss of elastin

Aneurysm rupture Tearing of the wall of an aneurysm leading to leakage of blood into the surrounding tissues

Angiography X-ray imaging techniques which are aimed at producing images of blood vessels

Angioplasty Procedure used to widen arteries which have become occluded or narrowed as a result of atherosclerosis; usually performed under imaging guidance such as fluoroscopy

Anisotropic Physical properties in a material are different in different directions

Annihilation Complete conversion of the mass of a particle and its anti-particle into energy

Anti-particle Fundamental particle of matter but with opposite charge and magnetic moment; every sub-atomic particle has an anti-particle; e.g. positron is the anti-particle of the electron; extremely short lived in this universe due to collision and annihilation

Aorta The main artery in the systemic circulation originating at the heart and ending in the lower abdomen where it divides into the left and right common iliac arteries

Aortic valve Heart valve between the left ventricle and the aorta preventing backflow of blood into the left ventricle

Applanation tonometry Measurement of pressure using a probe pressed against the skin

Arachnoid membrane One of the membranes which surrounds the brain

Arrhythmia Disturbance to normal heart rhythm

Arterial biomechanics Study of the structure and function of arteries using the methods of mechanics

Arterial mechanics Synonymous with the term ‘arterial biomechanics’

Arterial remodelling Change in diameter or shape of an artery; e.g. in response to changes in wall shear stress, changes in longitudinal stress or circumferential stress

Arteriolar resistance The resistance offered by the arteriolar bed; this affects flow rate and pressure drop across the arteriolar bed (see ‘resistance to flow’)

Arteriole Small vessel connecting arteries to capillaries; diameter 10–100 μm

Artery Large vessels involved in transport of blood from the heart; diameter 1–30 mm

Aspect ratio Ratio of the longest to shortest side in a mesh element; a metric used in evaluation of mesh quality; ratios near 1 are ideal

Aspect ratio The ratio of the neck width to height for a saccular cerebral aneurysm

Atherosclerosis A common disease of arteries in which lipid deposits (atheroma) accumulate in the vessel wall

Atherosclerotic plaque Later stage of atherosclerosis in which, for a localised region of an artery, the intimal layer contains a mix of lipid, fibrous tissue, white cells, smooth muscle cells and calcifications

Atria Chambers of the heart which receive blood from the venous system; left atrium receives blood from the pulmonary venous system, right atrium receives blood from the systemic venous system

Atrioventricular node Component of the electrical conduction system of the heart, which provides an activation pathway from atria to ventricles

Augmentation index The ratio of augmentation pressure divided by pulse pressure

Augmentation pressure Difference between the peak pressure which would have occurred in the absence of reflected waves and peak pressure in practice

Autocrine molecules Signalling molecules produced by a cell which act on the same cell

Autolysis Self-digestion of or destruction of cells by its own enzymes

Axial Relating to a vessel, in the direction of the vessel

Axial accumulation Increase in the concentration of cells near the centre of a vessel; e.g. red cells in arterioles

Axial flow Relating to flow in a vessel in which the velocity vectors are all in the axial direction, with no transverse flow component (i.e. no secondary or rotational flow)

Axisymmetric flow Flow in a tube or vessel where the velocity profile is not radially symmetric; there is some skewing to one wall and the maximum velocity is not located at the centre of the vessel

Back-projection Method used in CT to reconstruct the image

Balloon angioplasty Angioplasty which uses a balloon catheter to widen the artery the balloon is inflated to high pressure which widens the artery

Balloon catheter Catheter used in angioplasty which has an inflatable balloon near the distal end of the catheter which can be inflated for the purpose of widening diseased arteries

Barium contrast agent Liquid containing barium used to improve image contrast in X-ray imaging of the gastrointestinal system

Basement membrane Part of the intima, a layer of extracellular matrix on which the endothelial cells are attached

Bayliss effect Myogenic effect in arterioles

Bernoulli equation Equation for flow of an inviscid fluid; an expression of conservation of energy in a streamline whereby gravitational potential energy plus pressure energy plus kinetic energy is a constant

Bernoulli principle For an inviscid flow (i.e. no viscosity), an increase in fluid velocity is associated with decrease in pressure

Berry aneurysm See 'saccular aneurysm'

Biaxial testing Mechanical testing of materials with stretching in 2 or more directions

Biconcave Having surfaces which are concave (curving in) on both sides

Bicuspid valve A valve with two leaflets

Bifurcation Splitting of a vessel into 2 or more branches

Bilipid membrane Cell membrane formed from two layers of lipid molecules

Binding site Region (site) of a protein to which specific molecules can attach (bind)

Bingham plastic Fluid which has a yield stress before it will flow

Biomechanics Study of the structure and function of biological systems using the methods of mechanics

Bioreactor Laboratory device which supports biological activity

Black blood imaging MRI technique in which blood in vessels appears dark

Blood Fluid pumped around the cardiovascular system

Blood mimic See blood-mimicking fluid

Blood-mimicking fluid Fluid used in a flow phantom to mimic the blood; mimicking viscous properties and relevant imaging properties

Blood velocity Velocity of blood; different quantities include maximum velocity (during the cardiac cycle), mean velocity at a particular time (averaged over a vessel) mean velocity (average over the vessel and the cardiac cycle). Common units are cm s^{-1}, m s^{-1}

Blunt profile Velocity profile which is flattened apart from near the wall

BMF Abbreviation for 'blood-mimicking fluid'

B-mode Ultrasound imaging mode in which the received echo amplitude is displayed in 2D, usually in grey scale; short for 'brightness mode'

Boundary conditions Set of additional constraints used in computational modelling in order that a unique solution can be obtained

Boundary conditions Set of constraints required for execution of a computational model

Boundary layer Region between flow dominated by viscous effects (e.g. near the vessel wall) and flow dominated by inertial effects (e.g. in the vessel centre near an inlet)

Bright blood imaging MRI technique in which blood in vessels appears bright

Brightness-mode See B-mode

Brownian motion Random variations in collisions between the fluid molecules and a particle lead to erratic movements called Brownian motion

Bulk modulus Property of a solid or liquid describing elastic behaviour, concerned with changes in volume; defined as the negative ratio of change in pressure divided by change in volume

Buoyant force Force on an object in a fluid (e.g. particle) arising from hydrostatic pressure

C-11 See carbon-11

Calcium ion channel Ion channel for the passage of calcium ions (Ca^{2+}) into or out of the cell

Calcium wave An influx of calcium ions via the calcium ion channel pass through the cell in the form of a wave; this is one type of mechanosignalling

Calf muscle pump The muscular anatomy in the region of the deep veins which acts to expel blood from the deep venous circulation during muscle contraction

Capillary Smallest vessels of the cardiovascular system where there is exchange of oxygen and other molecules with the surrounding tissues (diameter 4–10 μm, up to 40 μm in sinusoidal capillaries)

Carbon dioxide Molecule produced as a consequence of metabolic activity; transported in blood and discharged via the lungs

Carbon-11 Isotope of carbon which is unstable, decaying to boron-11 (B-11) and also producing a positron; half life of 20.3 min, used in PET

Cardiac action potential Transient electrical activation and recovery of a cardiac cell, manifest as an excursion of membrane potential

Cardiac output Flow rate of blood leaving the heart, usually averaged over the cardiac cycle; units are usually L min^{-1}

Cardiovascular biomechanics Study of the structure and function of the cardiovascular system using the methods of mechanics

Cardiovascular disease Umbrella term for a range of diseases of the cardiovascular system

Cardiovascular system Organs in the body which are concerned with pumping and transport of blood; consisting of heart, arteries, arterioles, capillaries, venules and veins; divided into the systemic circulation and the pulmonary circulation

Carotid endarterectomy Removal of the inner layers of the carotid arteries including any atherosclerotic plaque

Catheter Flexible tube inserted into the body; e.g. along an artery via an arterial puncture

Catheter based imaging Medical imaging systems in which a miniature imaging system mounted on the end of a catheter passed along the arterial system to the point of interest

Cell alignment See 'endothelial cell alignment'

Central pressure Pressure of blood in the aorta near the heart

Central pressure waveform Variation of blood pressure with time in the aorta near the heart

Cerebral aneurysm Aneurysm of a cerebral artery (usually involving the Circle of Willis)

CFD See 'computational fluid dynamics'

C-flex (vessel mimic) Commercially available tube which has similar speed of sound to that in soft tissue and has been used in ultrasound flow phantoms

Childhood From birth to adulthood in which there is increase in the child's height and growth of organs; 0–20 years in the human

Circulation Abbreviation of 'circulatory system'; another name for the cardiovascular system

Circulatory system Another name for the cardiovascular system

Circumferential stress Stress within the vessel wall in the circumferential direction (i.e. in the direction perpendicular to the vessel axis)

Circumferential wall stress See 'circumferential stress'

Claudication Pain in the calf after walking for a certain distance, caused by atherosclerosis in the arteries of the leg

Claudication distance Distance that a person can walk before claudication develops. See 'claudication'

Cleaving Splitting into 2 parts; e.g. cleaving a molecule

Clinical ultrasound Sound with frequencies in the range used in clinical scanning; commonly 2–20 MHz for non-invasive use, 20–60 MHz for invasive use in the form of intravascular ultrasound

Clip Metallic device surgically placed at the neck of a saccular cerebral aneurysm to seal it from the parent artery

Clotting Normal coagulation of blood at sites of vascular damage to prevent bleeding

Co-culture phantom Example of an endothelial flow phantom in which there are adjacent layers of endothelial cells and smooth cells

Coil Coiled metal wire of small dimensions inserted into a saccular cerebral aneurysm to induce thrombosis within the aneurysm

Collagen A protein with high tensile strength, in vessels of the cardiovascular system it is present mainly in the adventitial layer of the artery wall

Collagen/elastin ratio Ratio of collagen to elastin content in the vessel wall is an indicator of vessel stiffness

Collateral circulation Network of small arteries in parallel to the main artery; as main artery atherosclerosis progresses the collateral vessels enlarge and may be able to take over blood supply to the tissues

Colloid osmotic pressure Osmotic pressure exerted by albumin in the blood (equal to around 22 mm Hg); also called 'oncotic pressure'

Colour flow (ultrasound) General term describing a range of techniques which are used for 2D imaging of blood flow using methods based on the Doppler equation

Competent venous valve A venous valve which is able to resist flow of blood away from the heart due to closure of the leaflets

Compliant-wall model Model used in arterial CFD in which vessel walls are compliant (rather than stiff) and hence allowed to move during the cardiac cycle

Composite Relating to materials or biological tissues; containing 2 or more types of material or tissue with different physical properties

Computation time Length of time it takes for completion of a single run of a computer programme

Computational fluid dynamics Numerical method for calculation of flow-field data in complex geometries (generally used where analytical solutions are not available)

Computational fluid dynamics A branch of computational mechanics, concerned with estimation of flow-field data

Computational mechanics The area concerned with the solution of mechanical problems by the use of computers, in which the governing equations are solved at discrete points within the 3D volume

Computational modelling General term referring to the use of computers to simulate complex phenomena where behaviour is summarised by governing equations; in which the governing equations are replaced by simpler equations and a process of iteration

Computed tomography See CT

Computer simulation See ‘computational modelling’

Conductance Measure of the movement of electrical charge through an ion channel, pump, or exchanger

Conduction defect Disturbance to the normal sequence of electrical activation in the heart

Cone plate viscometer Device for measuring the viscosity of a fluid as a function of shear rate; consisting of a fixed flat plate and a rotating plate in the shape of a cone

Conformation 3D arrangement of atoms within a molecule; e.g. a protein

Constitutive equations Equations of a solid which govern the relationship between stress and strain, or of a liquid which govern the relationship between shear stress and shear strain rate

Constitutive model The set of equations which describe the governing physical behaviour of the fluid or solid

Continuous capillary The most common type of capillary in which the endothelium is continuous (with no gaps or pores)

Continuous elastic compression Compression applied with constant pressure, typically to the lower limb, using elastic bandages

Continuous media A material which has physical or mechanical properties at all positions in space (x, y, z) and time (t)

Contrast agent A material which when injected into the patient provides a significant change (increase or decrease) in the imaged quantity enabling improved visualisation of particular structures; or in other words an agent which improves image contrast

Contrast agent (MRI) Contrast agent used for improving image quality in MRI; mostly based on gadolinium or iron; see ‘contrast agent’, ‘gadolinium (contrast agent)’, ‘iron (contrast agent)’

Contrast agent (targetted) See ‘Targetted contrast agent’

Contrast agent (ultrasound) Contrast agent used for improving image quality in ultrasound; based on the use of microbubbles. See ‘contrast agent’, ‘microbubble’

Contrast agent (X-ray) Contrast agent used for improving image quality in X-ray imaging; based on the use of iodine or barium. See ‘contrast agent’, ‘iodine contrast agent’, ‘barium contrast agent’

Coronary sinus Part of the venous system that drains myocardial tissue

Corrosion casting Process for creating a cast of the vasculature in which a material (e.g. resin) is injected into the vasculature, allowed to set, and the tissues are chemically removed

Crack Localised fracture of a material as result of high stress

Crack propagation Increase in size and extent of a crack with time

Critical stenosis For flow in an artery; the value of lumen reduction above which flow decreases

Cross-correlation Technique used in ultrasound strain imaging in which consecutive A-lines are taken and cross-correlation undertaken to estimate local displacement from which local strain is calculated

Cross-linking Formation of chemical bonds between molecules; e.g. between polymer molecules

CT X-ray imaging technique involving collection of data around the patient followed by image reconstruction in the computer

Cultured endothelium Laboratory preparation in which a layer of endothelial cells is prepared on substrate such as glass; typically the cultured endothelium is incorporated into a flow phantom which allows experiments to be performed on the response of the endothelial cells to changes in flow conditions (e.g. changes in wall shear rate)

Cyclic fatigue Reduction in strength of a material which is subject to repeated stretching and unstretching

Cyclic fatigue (wrt pressure) Increase in arterial stiffness associated with elastin fibre fracture arising from repeated stretching and unstretching over many years

Cyclic stress (wrt pressure) See ‘cyclic fatigue (wrt pressure)’

Cyclic stretch fatigue (wrt pressure) See ‘cyclic fatigue (wrt pressure)’

Cyclic stretching Repeated stretching and unstretching of the vessel wall (in both circumferential and longitudinal directions) as a result of variations in blood pressure during the cardiac cycle

Cyclotron Device for the production of radioactive isotopes, for use in PET

Cytoskeleton Structure within a cell that allows the cell to maintain its shape and internal structure, and allows transmission of force; composed of microtubules and filaments

Dashpot In the context of viscoelastic models; purely viscous component where stress is proportional to strain rate

Decentralised model (of endothelial mechanotransduction) Model of endothelial mechanotransduction in which mechanosensors are distributed throughout the endothelial cell rather than just being on the luminal surface

Deep Vein Thrombosis (DVT) Formation of thrombus in the deep veins, typically in the calf

Deep venous circulation The venous circulation which lies beneath the fascial boundary

Deformable model A type of segmentation method in which a line (2D) or surface (3D) is deformed so that it matches the boundary within an image

Deformable particle Particle which can be deformed; e.g. red cell

Deformation Alteration in shape of a structure

Deformation (red cell) Change in the shape of the red cell at high shear

Degree of stenosis The reduction in lumen diameter or area of an artery, usually arising through atherosclerotic disease

Density Property of a liquid or solid; mass divided by volume; unit kg m^{-3}

Deoxygenated blood Blood depleted of oxygen

Depletion force Concerning a fluid in which there are larger particles (e.g. red cells) and smaller particles (e.g. macromolecules). Random reductions in the concentration of the smaller particles causes the larger particles to be in close contact which is equivalent to a force called a ‘depletion force’

Deployment The action of placing and expanding a stent

Depolarisation Initial phase of the cardiac action potential where membrane voltage changes from around −85 mV to around +20 mV

Destruction imaging (ultrasound) Ultrasound imaging technique used with contrast agents in which bubbles accumulate within tissue and are caused to destruct by use of a high power pulse; this produces a Doppler shift signal allowing bubbles to be visualised

Development (fetal and embryo) Process by which the organ systems are laid down and grow from fertilisation to birth

Dialysis fistula Fistula created to provide a high-flow allowing blood to be drawn for the purposes of cleansing using a dialysis system; usually created in the arm

Diameter Distance of a circle from one side to another where the distance passes through the centre of the circle

Diastole The portion of the cardiac cycle in which the heart is not contracting

Diastolic pressure The lowest pressure in an artery during the cardiac cycle

Diffusion tensor imaging MRI technique which images the Brownian motion of water molecules

Digital model A model of a material which has physical or mechanical properties at discrete locations in space and time, see 'mesh'

Dilatant Another word for 'shear thinning'

Discrete model See 'digital model'

Discretization The process of approximation of the governing equations by simpler equations which are suitable for iterative solution using a computer

Dislocation Irregularity in the structure of a material, especially those with a regular crystal structure

Dissection of a vessel wall Partial tearing or delamination

Disturbed flow Flow state in which vortices are produced which may travel downstream

Dome (of cerebral aneurysm) Relating to a saccular cerebral aneurysm; the rear wall of the aneurysm

Doppler equation Equation describing the relationship between the Doppler shift frequency, the target velocity and the direction of motion of the blood or tissue

Doppler frequency See Doppler shift

Doppler shift (ultrasound) Difference in frequency between reception and transmission of ultrasound arising due to motion of the object

Doppler ultrasound (a) Term used to describe ultrasound systems whose design is based on use of the Doppler equation. (b) Ultrasound which has been frequency shifted as a result of scattering from a moving target

Drag force Relating to an object in a fluid; force on the object when there is relative motion between the fluid and the object, arising from inertial and viscous effects

DTI Diffusion tensor imaging; MRI technique concerned with the diffusion of molecules; used for investigation of orientation of fibres in the body

Ductus arteriosus Hole between the pulmonary artery and the aorta connecting the pulmonary and systemic circulations in the fetus

ECST Abbreviation for the European Carotid Surgery Trial

ECST criteria Criteria for selection of patients for carotid surgery arising from the ECST trial

Ectopic beat Abnormal heart beat, not arising from the sinoatrial node

Ehlers–Danlos syndrome Genetic disorder of connective tissues, including tissues in arteries

Ejection fraction Stroke volume as a fraction of the total volume of the left ventricle

Elastic Description of a solid material which recovers its original shape fully after release of the applied stress

Elastic-linear Concerning the stress–strain graph which is linear in the elastic region (i.e. before the yield point)

Elastic-nonlinear Concerning the stress–strain graph which is nonlinear in the elastic region (i.e. before the yield point)

Elastic instability Instability of equilibrium in elastic systems, including elastic buckling of thin structures

Elastic modulus See ‘modulus’

Elastin Protein with high elasticity; in vessels of the cardiovascular system it is present mainly in the medial layer of the artery wall

Elastography Medical imaging techniques for measurement of the stiffness of tissues in vivo

Elective surgery Surgery which is planned in advance but which is not an emergency

Electrocardiogram (ECG) Electrical potential on the body surface arising from electrical activation of the heart

Electrolytes Ions present in blood, including calcium ion (Ca^{2+}), chloride (Cl^-), potassium (K^+) and sodium (Na^+)

Electromagnetic flow probe Device for measurement of flow rate in a vessel; requires exposure of the vessel and placement of the probe around the vessel; the device operates by inducing a magnetic field; a voltage field is produced in the flow (proportional to flow rate) which is measured

Electromagnetic spectrum The range of frequencies of all electromagnetic radiation; from radio waves, microwaves, infrared, light (visible radiation), ultraviolet to X-rays and gamma rays

Electron One of the fundamental particles of matter, charge of −1, orbits the nucleus, mass is 1/1837 of the mass of a proton

Electrostatic force Force between two objects which carry an electric charge; opposite charges (positive/negative) attract, identical charges (positive/positive or negative/negative) repel

Element Building block of a mesh used in computational modelling

Embryo An unborn mammal from conception and before the fetal stage (i.e. from fertilisation to 8 weeks in humans)

Embryogenesis Formation of the embryo

Endarterectomy Removal of the inner layers of an artery including any atherosclerotic plaque

Endocardial Inner surface of the heart

Endoscope Long flexible instrument which is inserted into a body orifice such as the oesophagus for examination of the tissues from the inside

Endothelial cell alignment Alignment of the cell direction with the wall shear stress vector

Endothelial cell culture phantom See 'endothelial flow phantom'

Endothelial flow cell See 'endothelial flow phantom'

Endothelial flow phantom Flow phantom incorporating a layer of endothelial cells used for investigation of the relationship between endothelial behaviour and mechanical forces

Endothelium A single cell layer of specialised cells in contact with flowing blood; important because of their role in mechanotransduction

Enzyme Molecule which increases the rate of a chemical reaction occurring in the body

Epicardial Outer surface of the heart

Epidemiology The study of the causes, distribution and control of disease in populations

Erythrocyte Another name for 'red cell'

Erythrocyte volume fraction See 'haematocrit'

Essential hypertension Elevated blood pressure where there is no clear underlying cause

Euheart See www.euheart.eu

Experimental flow system Another name for 'flow phantom'

Expiration Concerning lungs, breathing out

Ex-vivo From the Latin 'outside of the living', referring to experiments on tissues or organs which have been removed from a living subject and kept metabolically alive

F-18 See fluorine-18

Fahraeus effect Fahraeus effect is that the haematocrit of blood in a tube of small diameter is less than the haematocrit of blood in the receiving tank (after the 1929 paper by Fahraeus)

Fahraeus-Lindqvist effect The Fahraeus–Lindqvist effect is that the viscosity in the tube (measured from pressure and flow) depends on tube diameter, reaching a minimum viscosity at a tube diameter of 7 μm; after the paper by Fahraeus and Linqvist in 1931

Fascia The sheet of connective tissue which separates muscle groups within the lower limb

Fatty streak Small yellow area on the inner lumen of an artery consisting of white blood cells and lipid deposits in the intimal layer; the first stage of atherosclerosis

FDG Abbreviation for fluorodeoxyglucose; used in PET

FEA See 'finite element analysis'

Fenestrated capillary Type of capillary cell which contains fenestrations (pores) to allow the passage of certain molecules

Fenestrations Pores present in the wall of some capillaries which allow the passage of certain molecules

Fetus An unborn mammal after the embryonic stage (i.e. from 9 weeks after fertilisation in humans)

Fibrinogen Large molecule present in blood; part of the clotting system

Fibroblast Connective tissue cell that provides mechanical support within heart tissue

Fibrous cap (plaque) Layer between the arterial lumen (where blood flows) and the lipid pool in an atherosclerotic plaque.

Fibrous cap thickness (plaque) Thickness of the fibrous cap

Fibrous tissue (plaque) Component of atherosclerotic plaque

Filaments See cytoskeleton

Filtered back projection See 'back projection'

Finite difference method One type of discretization method; commonly used in fluid modelling

Finite element analysis Solid modelling which uses the finite element discretization method

Finite element method One type of discretization method; commonly used in solid modelling

Finite element model A numerical model which captures complex behaviour through solution of a system of equations describing the interaction of many small regions (elements)

Finite volume method One type of discretization method; used in fluid modelling

Fistula Connection between an artery and a vein, bypassing the microcirculation

Flash pulse High peak pressure ultrasound pulse used to cause bubble destruction, used as the basis for 'destruction imaging'; see 'destruction imaging'

Flow diverter Device placed in the parent artery of a cerebral aneurysm to reduce flow within the aneurysm (which eventually thromboses)

Flow limitation An effect where flow ceases to increase with increasing pressure gradient due to dynamic increase in resistance

Flow phantom Apparatus for mimicking the flow of blood in a part of the cardiovascular system; consisting of pump, pump controller, tubing, reservoirs and a central construct which mimics the cardiovascular geometry

Flow probe Device for measurement of flow rate in a vessel; usually by exposure of the vessel (e.g. electromagnetic flowmeter, transit time flowmeter)

Flow rate Volume of fluid flowing through a cross section per unit time; e.g. flow of blood in an artery; common units in blood flow are ml min^{-1}, ml s^{-1}, L min^{-1}

Flow recirculation Flow which goes around in a circle; e.g. in the post-stenosis region

Flow separation May occur where there is flow in a tube where the cross-sectional area increases, e.g. post-stenosis; there are two adjacent regions of flow with little mixing of fluid

Flow state Term describing the behaviour of fluid elements in time and space; see 'laminar flow', 'transitional flow', 'disturbed flow', 'turbulence'

Flow visualisation Visualisation of flow in a flow phantom; by eye or by recording using a video camera

Flow waveform The plot of flow rate versus time; e.g. in an artery

Flow-field The 7D dataset of velocity within a 3D volume consisting of all 3 velocity components (v_x, v_y, v_z) at each location (x, y, z) and as a function of time t

Fluid A liquid; formally a material unable to maintain a shear force at rest

Fluid kinematics Behaviour of fluids which are in motion

Fluid mechanics The branch of mechanics which studies the behaviour of fluids

Fluid modelling See 'computational fluid dynamics'

Fluid statics Behaviour of fluids which are not in motion

Fluid-particle force See Brownian motion

Fluorine-18 Isotope of fluorine which is unstable, decaying to oxygen-18 (O-18) and also producing a positron, half life of 110 min, used in PET

Fluorodeoxyglucose See FDG

Fluoroscopy X-ray imaging technique in which X-rays are produced and detected continuously forming a 2D real-time image sequence

FMRI Functional MRI; technique that provides information on brain activity

Focal adhesion See 'focal adhesion site'

Focal adhesion site Structures within the cell membrane to which the cytoskeleton connects on the inner side, and on the outer side the extracellular matrix connects

Foramen ovale Hole between the left and right atria connecting the left and right sides of the heart in the fetus

Force A physical effect which gives rise to change in motion or deformation

Force-extensional Force acting perpendicular to a surface causing extension of the material

Force-shear Force acting parallel to a surface causing shearing of the material

Force-compression Force acting perpendicular to a surface causing compression of the material

Force-extension graph Concerning the stretching of a sample of a solid material; the graph of applied force versus the length in the direction of the force

Forward wave (flow) Blood flow where the flow direction is away from the heart

Forward wave (pressure) Pressure wave which travels along arteries away from the heart

Fracture Concerning stretching of a material; the point (stress) above which the material breaks

Frame rate (a) General: number of frames displayed per second for a display monitor. (b) Ultrasound: number of image frames acquired per second

Frank–Starling law Relates the stroke volume to preload of the heart

Free energy A measure of chemical potential energy; useful in describing chemical reactions; also called 'Gibb's free energy'

Frequency Property of a wave; the number of oscillations passing a given point per second; unit is hertz or Hz

Friction The force between 2 moving surfaces (e.g. between a fluid layer and a solid wall, between 2 fluid layers)

Fully developed flow Relating to flow in a tube; flow in which the velocity profile (for steady flow) or the change in velocity profile with time (for pulsatile flow) does not change with distance along the tube. More formally—flow in which the boundary layer reaches to the centre of the tube

Functional imaging Medical imaging techniques which provide information related to physiological function, including regional blood flow (perfusion), chemical and biological function

Fusiform aneurysm Aneurysm in which there is widening at all points around the entire artery

G Abbreviation of 'giga' meaning one billion or 10^9; e.g. GPa

Gadolinium (contrast agent) Metallic element which is strongly paramagnetic and used as a contrast agent for MRI

Gamma camera Imaging system used in nuclear medicine in which gamma rays from radioactive atoms are detected

Gamma ray Photon produced by radioactive decay or by positron-electron annihilation

Gangrene Death of tissues commonly caused by inadequate blood supply followed by decay and decomposition

Gap junction Pore in the intercalated disc that connects the intracellular space of two adjacent myocytes

Gauge length Length over which data will be extracted in relationship to mechanical testing

Generator Device used in nuclear medicine in which a short half-life isotope is produced by radioactive decay of a longer half-life parent (e.g. Mo-99, Tc-99 m generator)

Ghost See 'red cell ghost'

Gigapascal One billion (10^9) Pa, abbreviated GPa

Glass (phantom material) Material which is optically transparent and has been used in the construction of optically transparent phantoms

Globulins Family of proteins in the blood including albumin

Glycerol (for blood mimic) Liquid with high viscosity; component of blood mimics for MRI and ultrasound

Glycocalyx Network of molecules covering the endothelium, typically 0.2–4.5 μm depending on vessel type, probable role in mechanosensing

Governing equations The equations which summarise the behaviour of a complex system

Gradient coil Part of an MRI system; provides a smooth change in field strength along *x*, *y* and *z*; enabling positional information to be encoded into the received MRI signal

Granulocyte Type of white cell; responsible for absorbing and digesting bacteria, viruses and other parasites

Gravitational force Force on an object arising from gravity; in a fluid will lead to particles sinking

Grid See 'mesh'

Gridding See 'meshing'

Ground substance

Haematocrit Volume fraction of red cells in blood, typically 40–50 %

Half life Time it takes for the number of atoms of a particular radioactive isotope to halve in number

Hard tissue General term referring to biological tissues with high calcium content and/or high stiffness (e.g. bone, enamel, ligaments)

Heart Organ responsible for pumping blood round the circulation

Heart rate Frequency of heart beats, usually given as beats per minute

Helical flow Flow which has a rotational component so that particle streamlines have a helical appearance

Helical scanning Scanning method used in a CT scanner in which data is collected continuously with continuous rotation of the tube-detector around the patient and continuous movement of the patient through the CT system

High WSS hypothesis (cap thinning) Theory that high wall shear stress in a stenosis leads to thinning of the cap, leaving the cap prone to rupture

Homogeneous Generally; the same value of a physical property throughout a volume; in the context of red cell concentration; the same red cell concentration throughout the vessel

Hoop stress See 'circumferential stress'

Hydrogen nucleus Nucleus of hydrogen consisting of just one proton

Hydrostatic pressure The pressure gradient which arises due to the weight of a column of fluid

Hyperaemia Increased blood flow associated with dilation of the arteriolar bed; mechanism for increasing local flow rate

Hyperelastic Constitutive model for a purely elastic material derived by considering the strain energy density function

Hypertension Abnormally high blood pressure

Idealised (general) Simplified representation which captures key features

ILT See 'intraluminal thrombus'

Image 2D or 3D representation of a 2D or 3D object; in colour or greyscale; for which local image values are related to some property of the object

Image formation The process by which an image is produced from the object

Image guided modelling Integration of imaging with computational modelling

Image noise Generally, any feature of the image which is unwanted which obscures the feature of interest; see 'photon noise', 'speckle'

Imaging Process of recording/acquiring an image. See 'image'

Immune system The systems in the body which deal with defence against disease including bacteria, viruses and other pathogens

Impedance Generally, property of a material which leads to wave reflection when there is a discontinuity in impedance

Impedance (acoustic) See 'acoustic impedance'

Incremental elastic modulus Referring to the graph of stress versus strain obtained using a tensile testing system, the slope of the stress–strain curve when the stress–strain curve is not linear

Inertial force Force on a fluid element arising from the mass of adjacent fluid elements

Infarction Local tissue death caused by reduction in blood supply below a critical value

Inferior vena cava Large vein which delivers deoxygenated blood from the lower body to the right atrium

Inflammation (imaging) Imaging methods which provide information on the degree of inflammation in tissues

Inflation testing Method for mechanical testing of cylinders involving inflation under pressure and measurement of changes in diameter and wall thickness

Inhomogeneous Generally, differences in the value of a physical property throughout a volume; in the context of red cell concentration, differences in red cell concentration in a vessel (e.g. depletion near the wall)

Inlet Relating to the entrance to a tube (e.g. from a large reservoir); region at the beginning of the tube where flow is not fully developed (see 'inlet length')

Inlet length Distance from the entrance to a tube beyond which flow is fully developed

Inner diameter Relating to a tube/vessel, the diameter of the lumen (i.e. diameter of the region occupied by the fluid/blood flowing within the tube/vessel)

Input data In relation to computational modelling; data which is provided as input to a computational model

Inspiration Concerning lungs, breathing in

Intercalated disc End to end connections between myocyctes

Intermittent pneumatic compression Compression applied with varying pressure, typically to the lower limb, using a cuff inflated with air

Internal elastic membrane Layer of elastic material which forms the outer part of the intimal layer

Intervertebral disc Shock absorber between vertebral discs in the vertebral column; the intervertebral discs thin (reduce in thickness) with age leading to reduction in height later in life

Intima Innermost layer of the artery wall including a layer of endothelial cells in contact with flowing blood

Intima-media layer Term for the intimal and medial layers, whose combined thickness can be measured using ultrasound imaging

Intima-media thickness Combined thickness of the intima and media measured using ultrasound imaging

Intracranial aneurysm See 'cerebral aneurysm'

Intraluminal thrombus Thrombus present within the lumen of some aneurysms

Intrasaccular flow disruptor Device placed in the sac of a saccular aneurysm to seal the aneurysm

Invasive imaging Medical imaging technique which does lead to some damage (temporary or long term) to the organism; see IVUS, OCT

Inviscid No viscosity

Inviscid flow Flow in which there are no viscous effects

In-vitro From the Latin 'in glass' (a reference to use of a glass test-tube); referring to experiments undertaken in the lab on tissue samples which are no longer living, or on cultured cells

In vitro imaging Imaging of an organism or part of an organism which is kept metabolically alive but is no longer connected to the rest of the organism. See 'in vitro'

In vivo From the Latin 'in the living'; referring to experiments or tests undertaken on a living subject

In vivo imaging Imaging of the living organism; i.e. imaging which can be undertaken on an organism (human, animal) while the organism is alive (see 'Medical imaging')

Iodine contrast agent Injectable liquid containing iodine used to improve image contrast in X-ray imaging of vessels and heart chambers

Ion channel Protein embedded in a cell membrane which enables ions to move into or out of a cell under concentration or electrical gradients

Ion exchanger Protein embedded in a cell membrane, which actively pumps ions into or out of a cell, while pumping another ion out of or into the cell

Ion pump Protein embedded in a cell membrane, which actively pumps ions into or out of a cell

Ionising radiation Radiation which causes ionisation (creation of ions); causes damage to tissues; examples of ionising radiation include alpha, beta and gamma rays

Iron (contrast agent) Metallic element which is strongly paramagnetic and used as a contrast agent for MRI

Ischaemia Metabolic disturbance resulting from interruption of blood supply

Isolated systolic hypertension Elevated blood pressure characterised by an increase in systolic pressure

Isotonic A fluid with the same concentration of sodium chloride as occurs in blood

Isotropic Physical properties in a material are the same in all directions (i.e. same along x, y and z)

IVUS Abbreviation for 'intravascular ultrasound'; an IVUS system produces a cross-sectional image of an artery using a high frequency ultrasound transducer mounted on the distal end of a catheter

k Abbreviation of 'kilo' meaning one thousand or 10^3; e.g. kPa

Kelvin model Model of viscoelastic behaviour consisting of a Maxwell model and a spring in parallel

kilopascal One thousand (10^3) Pa, abbreviated kPa

Kinetic energy Energy arsing from motion

Konjac-carrageenan (for tissue mimic) Combination of 2 organic chemicals used in the construction of ultrasound flow phantoms

Lamellar unit Unit of structure within the medial layer of an artery; consisting of smooth muscle, elastin and collagen

Laminar flow Flow state where fluid elements follow clearly defined paths and there is little mixing between adjacent layers of fluid

Laplace's law See 'Law of Laplace'

Larmor frequency Rate of precession for a hydrogen nucleus in a magnetic field; equal to the field strength in tesla (T) times 4.2×10^7

Laser Doppler anemometry Method for estimation of fluid velocity involving overlapping laser beams and the Doppler effect

Laser sheet Referring to a laser which is swept back and forth in a 2D plane; e.g. for the purpose of illumination of particles in PIV

Law of Laplace For a thin-walled cylinder the circumferential tension is equal to pressure times radius; modern version is that circumferential stress equals pressure times radius divided by wall thickness

LDA Abbreviation for 'laser Doppler anemometry'

LDL cholesterol Low density lipoprotein (LDL) or 'LDL cholesterol' is a molecule which is ingested from foods and is associated with atherosclerosis

Leukaemia Cancer resulting in over-production of white cells

Leukocyte Another name for 'white cell'

Leukocyte adhesion Attachment of leukocytes to endothelial cells arising from molecular binding between ligands on the leukocyte and selectin molecules on the endothelial cell surface

Lift force Relating to fluid flowing past an object; force on the object perpendicular to the direction of fluid motion

Ligand A molecule whose function is to bind to another specific molecule (e.g. see leukocyte adhesion)

Lipid core (plaque) The region of an atherosclerotic plaque composed mainly of lipid

Lipid pool (plaque) See 'lipid core'

Loading Gradual increase in stress applied to a solid

Longitudinal relaxation Magnetisation in the direction of the main magnetic field

Longitudinal wall stress Stress in a vessel in the longitudinal direction

Lost-core Method of manufacture of a complex object (e.g. anatomical phantom) in which a core is created, placed in a box, liquid (e.g. TMM) is poured in and allowed to set and the core is removed by melting or by physical action

Low melting point alloy Alloy of various metals which has a low melting point (around 50–99 °C); see 'lost-core'

Low wall shear hypothesis (atherogenesis) Theory that atherosclerosis develops at regions of low wall shear stress

Lumen The inner part; e.g. of an artery or vein; the part through which blood flows

Lumen The space bounded by the vessel wall in which the blood flows

Lymphocyte Type of white cell; responsible for attacking invading bacteria and viruses; also help destroy cells in the body which have become diseased through virus infection or cancer

m Abbreviation of 'milli' meaning one thousandth or 10^{-3}; e.g. mm

M Abbreviation of 'mega' meaning one million or 10^{6}, e.g. MPa

Macromolecule Large molecule; blood contains a number of macromolecules including globulins, albumin, fibrinogen, vitamins, hormones and waste products; make up 9 % of plasma volume

Macrophage Type of white cell which engulfs and removes microorganisms and damaged or diseased cells

Magnetic axis The line joining the two poles of a magnet

Magnetic field The region of space near a magnet over which the effects of the magnet are experienced

Magnetic resonance elastography MRI technique in which the stiffness of tissues is estimated from measurements of the local speed of propagation of shear waves

Magnetic resonance imaging See MRI

Magnus effect One of a number of wall induced inertial lift forces

Malaria Disease spread by mosquitoes in which a parasite enters the bloodstream; potentially fatal; common in tropical areas

Marfan's syndrome Genetic disorder of connective tissue, including tissues in arteries

Margination Increase in the concentration of cells near the wall; e.g. platelets and white cells flowing in whole blood

Maxwell model Model of viscoelastic behaviour in which the spring and dashpot are in series

Mean arterial pressure Average arterial pressure during the cardiac cycle

Mean pressure Average pressure during the cardiac cycle

Mean velocity Velocity of blood averaged over space (e.g. over the cross section of a vessel), or more commonly over space (cross section) and time (cardiac cycle). Common units are cm s^{-1}, m s^{-1}

Mechanics Science which covers the forces on and subsequent motions of solids and liquids

Mechanobiology Field relating the mechanical forces on tissues to the biology of tissues

Mechanoresponse The final step of mechanotransduction in which a biological change is effected as a result of the detected mechanical signal

Mechanosensing One step of mechanotransduction in which sensors within the cell detect a transmitted force

Mechanosensor Biological sensors which detect mechanical forces; leading to some change in biological behaviour

Mechanosignalling One step of mechanotransduction in which the detected force results in events which are transmitted elsewhere in the cell

Mechanotransduction The process whereby mechanical forces are translated into biological behaviour and vice versa

Mechanotransmission One step of mechanotransduction involving transmission of a force to mechanosensors within the cell

Media Middle layer of the artery wall mainly consisting of elastin and smooth muscle

Medical image 2D or 3D representation of a 2D or 3D object; in colour or greyscale; for which local image values are related to some property of the object; used for diagnosis or treatment planning (see X-ray, CT, MRI, nuclear medicine, ultrasound, IVUS, OCT)

Medical imaging Process of recording/acquiring a medical image. See ‘medical image’

Megapascal One million (10^6) Pa, abbreviated MPa

Mesenteric circulation Circulation supplying the mesentery which is part of the abdominal region

Mesh The set of points which represents a 3D volume in computational mechanics

Mesh quality Characteristics of a computational modelling mesh concerned with accuracy and speed of solution (see ‘mesh size’, ‘skewness’, ‘aspect ratio’)

Mesh size Number of elements in a mesh used for computational modelling

Meshing The process in which the mesh is created for computational modelling

Metabolism Chemical activity which sustains life

Metarteriole An arteriole which is directly connected to a venule allowing the capillary bed to be bypassed

MI See 'myocardial infarction'

Microbubble Contrast agent used for ultrasound; an individual bubble consists of gas encapsulated by a thin shell, diameter 2–6 micron

Microcalcification Small calcium deposit within tissue, a sign of early disease

Microcalcification (imaging) Imaging methods which provide information on the degree of microcalcification in tissues

Microcalcifications (plaque.) Component of atherosclerotic plaque

Microcirculation Term describing the part of the cardiovascular system consisting of arterioles, capillaries and venules

Microfluidics Branch of science concerned with devices which rely on the flow of fluids through small channels

Micron-sized particles of iron oxide See MPIO

Microtome Cutting tool used to generate very thin slices used for mechanical testing or microscopy

Microtubules See cytoskeleton

Mini-stroke See 'Transient ischaemic attack'

Mitral valve Heart valve between the left atrium and left ventricle, preventing backflow of blood into the left atrium

Mixed (systolic/diastolic) hypertension Elevated blood pressure characterised by an increase in diastolic and systolic blood pressure

Model Simplified version of reality, often in the form of a set of equations, designed to answer a specific question

Modelling See 'computational modelling'

Modulus Property of a material describing elastic behaviour; there are 3 main elastic moduli; Young's modulus E shear modulus G and bulk modulus K

Moens Korteweg equation Equation allowing estimation of the pulse wave velocity from artery diameter, wall thickness, Young's modulus and density

Molecular binding force Force between tissues arising from chemical bonds (e.g. ligand–receptor bond)

Molecular imaging Medical imaging technique which primarily provides information related to biological function of tissues at the molecular and cellular level; see SPECT, PET, targetted ultrasound contrast imaging, targetted MR contrast imaging

Monocyte Type of white cell; carried to different tissues where they transform into macrophages which engulf and remove microorganisms and damaged or diseased cells

Mooney–Rivlin model A hyperelastic constitutive model

Moore's law Predication made in 1965 by Gordon Moore that the density of transistors on an integrated circuit doubles every 2 years

Mould Container which has been created with an internal shape into which a molten substance is poured and allowed to set; removal of the container leaves the solid substance in the desired shape

Moving-wall model Model used in arterial CFD which allows movement of the wall during the cardiac cycle

MPIO Abbreviation for micron-sized particles of iron oxide, referring to paramagnetic particles with a diameter of 0.75–1.75 μm, used as a contrast agent for MRI

MR fluoroscopy MRI technique in which the beating heart is imaged

MRE See magnetic resonance elastography

MRI Medical imaging technique based on magnetisation of the nuclei of atoms (mostly hydrogen atoms)

MRI magnet Large magnet in the form of a cylinder made from superconducting wire; cooled by liquid helium; typically 1.5T or 3T for clinical use

Mullin's effect Variation in stress–strain data in loading–unloading during the first few cycles

Multidimensional model A model that spans more than one spatial dimension

Multislice Imaging detector for CT enabling acquisition of several imaging slices simultaneously

Murray's law Law developed by Murray (1926) to describe the diameter relationship of arteries in a bifurcation; the diameter of the parent artery to the third power is equal to the sum of the diameters of the daughter arteries to the third power

Muscular tone The degree of constriction of smooth muscle in the vascular wall

Myocardial infarction (MI) Region of tissue death in the heart resulting from blockage of a coronary artery

Myocardial tagging Technique used in MRI tracking of the motion of myocardial tissue, enabling measurement of local strain

Myocyte Cardiac cell that generates tension following electrical activation

Myogenic effect Response of small arteries and arterioles to a change in blood pressure; following an increase in blood pressure there is decrease in diameter caused by constriction of the smooth muscle cells in the media

n Abbreviation of 'nano' meaning one billionth or 10^{-9}; e.g. nm

N-13 See nitrogen-13

NASCET Abbreviation for the North American Symptomatic carotid Surgery Trial

NASCET criteria Criteria for selection of patients for carotid surgery arising from the NASCET trial

Navier Stokes equations Equations which govern the motion of fluids

Neck (of cerebral aneurysm) Relating to a saccular cerebral aneurysm; the inlet to the aneurysm

Neo-Hookian model A hyperelastic constitutive model

Neointimal formation Formation of new lining within a vessel- comprises smooth muscle calls and extracellular matrix

Nernst equation Gives the potential difference arising from differences in ion concentration across a cell membrane

newton Unit of force, abbreviated N

Newtonian fluid Fluid in which the viscosity is constant as a function of shear rate

NIBP See 'Non-invasive blood pressure monitor'

Nitric oxide An important molecule concerned with the regulation of vascular function; abbreviated NO; NO is produced by the endothelium in response to a rise in wall shear stress and has vasodilatory properties; abnormalities in NO production are associated with abnormal endothelial function

Nitrogen-13 Isotope of nitrogen which is unstable, decaying to carbon-13 (C-13) and also producing a positron, half life of 10.0 min, used in PET

NO Abbreviation for nitric oxide

Node One point of a digital model

Noise (image) See image noise

Non-axial flow Flow which is non-axial, where there are components in the plane perpendicular to the vessel axis (i.e. rotational flow)

Non-invasive blood pressure device Device for measurement of blood pressure using an arm cuff

Non-invasive imaging Medical imaging technique which leads to negligible damage to the organism; see X-ray, CT, MRI, PET, ultrasound

Nonlinear imaging (ultrasound) Ultrasound imaging based on display of higher frequency components generated from the tissue or from contrast agents

Non-Newtonian fluid Fluid which is not Newtonian (i.e. viscosity is not constant as a function of shear rate)

Nuclear medicine Techniques used to diagnose and treat clinical disorders using radioactive isotopes

Nucleus Part of the cell which contains the DNA

Numerical modelling See ‘computational modelling’

O-15 See oxygen-15

Occlusion Blockage or obstruction

Occluder Moving part of a mechanical heart valve. Closes to prevent backflow

OCT Abbreviation for optical coherence tomography; an OCT system produces a cross-sectional image (e.g. of an artery) using infrared light

Oedema Excess fluid in tissues arising from disturbances in the osmotic balance

One-D model See ‘1D model’

Optically transparent phantom Phantom which is transparent to visible light; used in flow visualisation, PIV and LDA

Orthotropic Solid which is anisotropic along 3 perpendicular planes of symmetry

Oscillatory index An index which describes the variation of shear stress magnitude through the cardiac cycle

OSI See ‘oscillatory index’

Osmotic balance Concerning osmosis; when there is no net flow of liquid across the membrane separating fluids of different particle concentrations

Outer diameter Relating to a tube/vessel; the diameter which includes the wall

Output data In relation to computational modelling; data which is outputted from the computational model

Outward remodelling Response of an artery to increasing degree of atherosclerotic material whereby the inner lumen diameter is maintained constant but the outer lumen diameter increases

Oxygen Molecule required for metabolic activity, transported in blood via the lungs and taken up in tissues throughout the body

Oxygen-15 Isotope of oxygen which is unstable, decaying to nitrogen-15 (N-15) and also producing a positron, half life of 122 s, used in PET

Oxygenated blood Blood rich in oxygen

Pacemaker Origin of spontaneous electrical activation in the heart. The natural pacemaker is the sinoatrial node

Packed cell volume See 'haematocrit'

Parabolic profile Velocity profile which has the shape of a parabola (associated with steady Poiseuille flow)

Paramagnetic Material which becomes magnetised while placed in a magnetic field

Paramagnetism Magnetism in which the material becomes magnetised while placed in a magnetic field

Particle Molecule or cell which is not part of the main fluid; blood particles consists of red cells, white cells, platelets and macromolecules

Particle image velocimetry Method for estimation of fluid velocity in a flow phantom; involving laser illumination of seeded particles and video capture of particle positions

Particle tracking velocimetry Method for estimation of fluid velocity in a flow phantom; involving laser illumination of seeded particles and video capture of particle positions

Particle–particle force Force arising from collisions between particles; has little effect at low volume concentrations but is the dominant effect on particle distribution at higher volume concentrations

pascal Unit of force divided by area, abbreviated to Pa

Patency Open, unobstructed

Pathway Series of actions concerning molecules in a cell; for the purpose of metabolism, signalling or gene expression

Patient specific modelling Integration of imaging with computational modelling which provides output data relevant to the individual patient

Patient-specific Data from measurement or modelling which is relevant to a particular patient

Peak velocity (ultrasound) Maximum blood velocity during the cardiac cycle; used in ultrasound imaging to estimate the degree of stenosis

Peak wall stress The maximum value of wall stress in an organ (e.g. aneurysm); estimated using FEA

Perforating veins Veins which run between the deep and superficial circulation

Permeability Measure of the movement of ions through an ion channel, pump, or exchanger

Perspex Material which is optically transparent; is used in the construction of phantoms

PET Abbreviation for 'positron emission tomography'; medical imaging technique involving injection or inhalation of radioactive chemicals which undergo radioactive decay producing a positron, which then collides with an electron undergoing annihilation producing gamma rays which are detected

PET-CT Combined imaging system in which there is both a PET scanner and a CT scanner

Phantom In the context of a flow phantom this is the central construct which mimics the cardiovascular geometry

Photon Particle of electromagnetic radiation; e.g. RF photon emitted from the nucleus following nuclear energy transitions, or light photon emitted as a result of changes in the energy level of an electron

Photon noise Random noise in the image due to random variations in the number of photons detected in an area or volume

Photon-limited Referring to medical imaging systems in which the image is built up from many individual photons; the significance being that the image noise is related to the number of photons and hence image quality is limited by the number of photons which are acquired

Physiological solution Fluid which is isotonic; used in e.g. experiments involving tissue samples

Pipeline See 'processing chain (PSM)'

PIV Abbreviation for 'particle image velocimetry'

Pixel 'Picture element'; the smallest component of a 2D digital image; typically rectangular

Plaque Local region of atherosclerosis within an artery

Plaque constituents The different tissues present within an atherosclerotic plaque; i.e. Lipid, fibrous tissue, white cells, smooth muscle cells and calcifications

Plaque erosion Decrease in volume of an atherosclerotic plaque with time

Plaque growth Increase in volume of an atherosclerotic plaque with time

Plaque rupture Fracture of the wall (cap) between the arterial lumen (where blood flow) and the lipid pool in the plaque

Plasma The liquid constituent of blood consisting of water and a number of macromolecules

Plasma skimming Phenomenon whereby flow in a side-branch contains little or no red cells as a result of cell depletion near the wall in the parent vessel

Plastic Description of a solid material which does not recover its original shape after release of an applied stress but instead undergoes some permanent deformation

Platelet Particles within blood concerned with clotting; 0.03 % by volume of blood; greatest diameter of 2–3 μm

Platelet activation Process whereby a platelet becomes activated (more sticky); activation is effected through contact with collagen in regions of damaged vessel wall

Platelet adhesion Attachment of activated platelets to tissues (e.g. Collagen exposed by vascular damage) in connection with thrombus formation

Platelet aggregation Clumping of activated platelets, in connection with thrombus formation

PMMA Abbreviation for 'polymethyl methacrylate'; also known as perspex; see 'perspex'

Poiseuille equation Equation relating flow rate to pressure, diameter, length and viscosity for flow of a Newtonian fluid in a long straight stiff tube

Poiseuille flow Flow of a Newtonian fluid in a long straight stiff cylindrical tube

Poisson ratio The ratio of the fractional change in lengths in z and x, y directions (where z is the direction of compression)

Polyester (phantom material) Type of polymer; can be manufactured transparent; used in construction of optically transparent phantoms

Polymethyl methacrylate See Perspex

Polyurethane See urethane

Polyvinyl alcohol See PVA

Positron One of the fundamental particles of matter, the anti-particle of the electron, charge of +1, mass is 1/1837 of the mass of a proton, produced by radioactive decay, after production the positron combines with an electron annihilating producing 2 gamma rays

Positron emission tomography See PET

Post-processing Processing of the output data from modelling for the purposes of visualisation and estimation of particular quantities

Post-buckling behaviour The form of the pressure/area relationship once the critical buckling pressure has been exceeded; e.g. in veins

Potassium channel Ion channel for the passage of potassium ions (K^+) into or out of the cell

Potassium channel activation Process whereby the potassium channel is opened allowing potassium ions to flow through the channel

Potential energy Energy arising from height (vertical position within a gravitational field)

Precapillary sphincter Band of smooth muscle wrapped around arterioles which can constrict to reduce or stop flow into the capillary bed

Precess Where the axis of rotation of an object sweeps out a cone around the direction of the relevant force field; e.g. a spinning top will precess around the gravitational field direction, the magnetic axis of rotation of the hydrogen nucleus will precess around a static magnetic field

Precession See precess

Preconditioning Concerning tensile testing protocols: initial load–unload cycles performed to achieve stability in the stress–strain data

Preferential channel Channel formed by the metarteriole and a venule bypassing the capillary bed

Preload Tension in the left (or right) ventricle at the end of the filling phase of the cardiac cycle

Pressure Force divided by area; units are Pascals (Pa)

Pressure difference The difference in pressure between 2 points

Pressure energy Energy arising from pressure

Pressure gradient Difference in pressure over a given distance between two regions of flow

Pressure measurement (catheter) Blood pressure measured invasively using a catheter

Pressure measurement (cuff) Blood pressure measured non-invasively using an arm cuff

Pressure waveform Usually the plot of pressure versus time in an artery; also can mean the plot of pressure versus distance (e.g. along the aorta)

Pressure-stiffness graph Graph of blood pressure plotted against the stiffness of an artery

Pressure-strain elastic modulus Index of arterial stiffness which does not take account of wall thickness

Pre-stress Internal stresses in a tissue when it is in an unloaded state

Primary cilia Thin tubular structure which projects from the endothelium; probable role in mechanosensing

Primary hypertension Elevated blood pressure where there is no clear underlying cause

Prism element Type of mesh element used in computational modelling

Processing chain (for PSM) Series of steps for patient specific modelling starting with image data and ending with displayed data

Projection radiograph X-ray imaging technique in which a 2D image is produced with both tube and detector remaining fixed in position during the taking of the X-ray

Propagation model Model of the arterial system which accounts for propagation and reflection of pressure and flow waves

Protein phosphorylation Addition of a phosphate group to a protein

Proteins Large molecules present in all living things; have the ability to change shape (conformation) which is important in mechanotransduction

Proton One of the fundamental particles of matter, present in the nucleus of atoms; the hydrogen atom contains 1 proton

Pseudoplastic Another words for 'shear thickening'

PSM See 'patient specific modelling'

PTV Abbreviation for 'particle tracking velocimetry'

Pullback Method used in catheter based imaging to obtain 3D data in which the catheter is slowly pulled back while continuously acquiring 2D slices

Pulmonary artery Main artery from the heart to the lungs; arises from the right ventricle and after about 5 cm divides into the left and right pulmonary arteries

Pulmonary circulation Part of the cardiovascular system which transports blood to and from the lungs

Pulmonary valve Heart valve between the right ventricle and the pulmonary artery preventing backflow of blood into the right ventricle

Pulse pressure The difference between systolic and diastolic pressure in an artery

Pulse wave velocity The speed of propagation of pressure waves in arteries; abbreviated to PWV

Pulse-echo Technique used in ultrasound imaging to provide information on the depth from which received echoes arise, involving timing the delay between transmission and reception, dividing by 2, and multiplying this by the assumed average velocity of 1540 m s^{-1}

Purkinje fibres Component of the electrical conduction system of the heart, which provides a fast activation pathway to ventricular tissue

Pushing beam In ultrasound shear wave elastography, a high output beam which is used to produce deformation of tissue at the focal region, hence producing shear waves

PVA Abbreviation for polyvinyl alcohol; used in the construction of MRI and ultrasound phantoms

PVAc (vessel mimic) Abbreviation for polyvinyl alcohol cryogel; referring to PVA which has undergone 1 or more freeze-thaw cycles which causes cross-linking of the polymer molecules

PWV See 'pulse wave velocity'

QRS complex ECG deflections that correspond to electrical activation of the ventricles

Radial pressure waveform Variation of blood pressure with time in the radial artery

Radioactivity Particles emitted from nuclei during radioactive decay; the 3 main particles are the alpha particle consisting of 2 protons and 2 neutrons; the beta particle is either an electron or a positron, the gamma particle is a high energy photon usually called the gamma ray; gamma rays are useful for medical imaging

Radiofrequency Frequencies which are in the radio part of the electromagnetic spectrum; from 3 kHz to 300 GHz

Radioisotope Version of an element which is unstable and hence radioactive; e.g. O-16 (8 neutrons, 8 protons) is the most abundant stable isotope of oxygen, O-15 (8 protons, 7 neutrons) is radioactive, decaying to N15 and a positron

Radius Distance of a circle from one side to the centre (equal to half the diameter)

Rapid prototyping Creation of a 3D object from a computer design quickly; first used in manufacturing industry to reduce the time for creation of a demonstration model (the prototype) which was traditionally time-consuming; the term rapid-prototyping has been superseded by '3D printing'. See '3D printing'

Reactive hyperaemia Temporary increase in blood flow following a period of reduced or absent flow (e.g. Caused by application of an arm cuff)

Real-time Occurring now, as in 'real-time ultrasound' which provides information with negligible delay between acquisition and visualisation; as opposed to off-line imaging such as CT where the data is acquired then visualised with a delay of a few seconds or minutes

Received frequency (ultrasound) Frequency of the received ultrasound

Receiving coil Part of an MRI system; involved in receiving the RF data from nuclei while they gain their original magnetisation

Reception (of ultrasound) The process of detection of ultrasound echoes arriving at the face of the transducer, following transmission

Recirculation See 'flow recirculation'

Red cell Particle within blood concerned with oxygen transport; also called erythrocytes; 40–50 % by volume of blood, greatest diameter 7.5 μm

Red cell ghost Red cells rendered optically transparent by removal of their haemoglobin

Reduced velocity Ratio of blood velocity to vessel diameter, units s^{-1}, surrogate measure of wall shear rate

Reduced-order model Model in which there are a reduced number of dimensions; reality is 3D (x, y, z) + time; a reduced order model might be 0D(t) or 1D(z, t)

Re-entry Arrhythmia, in which electrical activation continually propagates into regions of tissue that are electrically recovering

Reflected waves Generally, waves which travel towards their point of origin; in relation to arteries, pressure waves which travel towards the heart

Refraction (light) Change in direction of light when passing from one material to another where the refractive index is different

Refractive index (light) Ratio of the speed of light in a vacuum to the speed of light in the material

Refractive index matching (light) Ensuring that the refractive index of 2 adjacent materials is the same, hence eliminating refraction of light

Refractory period Period following depolarisation when an action potential cannot be elicited by a further stimulus

Regurgitation Leakage or backflow

Relaxation Change in the MRI signals with time following an RF transmission pulse

Remodelling See 'arterial remodelling'

Repolarisation Later phase of the cardiac action potential where membrane voltage returns to its resting value of around −85 mV

Resistance (to flow) Ratio of pressure gradient to flow rate (e.g. in a tube)

Respiratory pump The action of the respiratory system on the veins within the abdomen and thorax

Reverse wave (flow) Blood flow where the flow direction is towards the heart

Reverse wave (pressure) Pressure wave which travels along arteries towards the heart

Reynolds number Dimensionless number used in fluid mechanics which is related to the flow state of the fluid (i.e. whether flow is laminar, disturbed, transitional or turbulent); formally the ratio of inertial to viscous forces

Rheology Branch of science concerned with the study of the flow of matter

Rigid-wall model Model commonly used in arterial CFD in which the walls are assumed to be rigid; i.e. not to move during the cardiac cycle

Rotational angiography X-ray technique which uses a fluoroscopy system to acquire images around the patient enabling a 3D dataset to be obtained using CT reconstruction techniques; mostly used in cerebral imaging

Rotational flow See 'helical flow'

Rouleaux Clumps or aggregates of red cells in which the red cells are arranged face to face; only occurs at low shear ($<10\ s^{-1}$)

Rupture Breaking or bursting of an organ; tearing of a vessel with leakage of contents into the surrounding tissues; see 'plaque rupture', 'aneurysm rupture'

Saccular aneurysm Aneurysm arising from one side of the artery; roughly spherical in shape; also referred to as a 'Berry aneurysm'

Sarcomere Contractile unit within myocyte

Sarcoplasmic reticulum Region inside myocytes that acts to store calcium

Scar tissue Region of connecting tissue that forms following a myocardial infarction

Scattering (of ultrasound) Generation of a wave which travels in all directions, after an incident wave has encountered a small object (dimensions $\ll$ wavelength), where the object has an impedance different to the surrounding material

Screening programme The process of identifying healthy people who may be at increased risk of disease, with the aim of offering treatment at an early stage

Secondary circulation See collateral circulation

Secondary flow Flow which is non-axial, where there are components in the plane perpendicular to the vessel axis (i.e. rotational flow)

Secondary hypertension Elevated blood pressure arising from disease (e.g. kidney disease, endocrine disorders)

Secondary motion Another name for 'secondary flow'. Also see 'helical flow'

Segmentation Image processing method in which the boundaries of an organ or of a region within an organ are identified

Segre Silberberg effect Relating to flow of neutrally buoyant particles in a tube for Reynolds number around 30; particles accumulate in a ring at a distance of 0.6 of the tube radius from the centre; named after the authors of the 1962 paper; also called the ‘tubular pinch effect’

Selectin Cell adhesion molecules found on white cells

Self-excited oscillations Oscillations in a flexible structure which occur spontaneously without a time-varying loading condition

Set-point hypothesis Concerning the control of wall shear stress in arteries; hypothesis that there is a value of wall shear stress which is maintained through a control mechanism involving wall shear stress sensors and arterial remodelling; it is noted that the set-point value is different in different arteries

Shear induced inertial lift Relating to an object in a fluid at high Reynolds number where inertial forces dominate; force on the object arising from differences in shear on either side of the object; gives rise to transverse movement (across streamlines); in steady flow the particles move towards the wall

Shear modulus Property of a solid describing elastic behaviour, concerned with the ability of a solid to withstand a shear force

Shear rate Change in fluid velocity with perpendicular distance arising from a shear force; units s^{-1}

Shear strain Relating to shearing of a liquid or solid; is the deformation in the direction of shear divided by the original length of the vertical; equal to the tangent of the shear angle θ

Shear-thickening fluid Fluid where the viscosity increases with increasing shear rate

Shear-thinning fluid Fluid where the viscosity decreases with increasing shear rate

Shear wave elastography Techniques that provide information related to the elastic modulus of tissue in vivo, based on the measurement and display of shear wave velocity

Shear wave velocity Velocity of shear waves (e.g. in tissues during elastography)

Sickle cell Diseased red cell which has the shape of a sickle rather than the normal biconcave shape

Sickle cell disease Disease associated with abnormally shaped red cells (sickle cells)

Silicone (phantom material) Type of material with similar properties to rubber; can be manufactured optically transparent; used in the construction of optically transparent phantoms

Simulation (general) See ‘computational modelling’

Simulation (specific) One run of a computational model; involving specification of input data and production of output data

Single photon emission computed tomography See SPECT

Single-beam (ultrasound) Ultrasound system where information on only 1 scan line is collected at a time

Sinus node Natural pacemaker of the heart

Sinusoidal capillary Type of capillary cell in which the basement membrane is incomplete allowing flow of molecules from the extracellular fluid into the blood stream

Skewness A metric of mesh shape which characterises long thin elements

Slip process Movement within a material of adjacent planes resulting in plastic deformation

Smooth muscle Type of muscle cell found in the walls of arteries, mainly in the medial layer

Soft tissue General term referring to biological tissues with low stiffness and low calcium content (e.g. artery, muscle, abdominal organs)

Solid Material able to maintain a shear force at rest

Solid mechanics The branch of mechanics which studies the behaviour of solids

Solid modelling A branch of computational mechanics, concerned with estimation of displacements and stresses within solids

Solid particle Particle which cannot be deformed; rigid particle

Solver The part of the computational modelling workflow which is concerned with finding a solution to the governing equations

Sound Vibrations in the form or pressure waves which travel within a medium (solid, liquid or gas); divided into infrasound (frequency <20 Hz), audible sound (frequency 20 Hz–20 kHz), ultrasound (frequency >20 kHz)

Sound wave Pressure waves within a medium such as a solid, liquid or gas; divided into infrasound (frequency <20 Hz), audible sound (frequency 20 Hz–20 kHz), ultrasound (frequency >20 kHz)

Spatial resolution Minimum separation in space for which 2 separate point or line targets can be identified or, size on the image of a point object

Speckle Noise appearing on ultrasound images, arising from variations in the position and scattering strength of the various scatterers within the beam

SPECT Single photon emission computed tomography; method of using a gamma camera to produce 3D images

Spectral Doppler Doppler ultrasound technique which produces Doppler frequency shift versus time waveforms with full Doppler frequency shift data estimated and presented at each time point

Spectral element method One type of discretization method; used in fluid modelling

Spectrin Protein which is the major component of the cytoskeletal structure that gives the red cell its biconcave shape

Speed of sound Distance that the crest of the sound wave (or other similar point) travels per second. Values in soft tissue are 1400–1600 m s^{-1}, with an average value of about 1540 m s^{-1}

Spin (of nucleus) Property of a nucleus of an atom concerned with its magnetic behaviour

Spin-lattice relaxation See T2 relaxation

Spin-spin relaxation See T1 relaxation

SPIO Abbreviation for 'superparamagnetic iron oxide', referring to paramagnetic particles with a diameter of 4–50 nm, used as a contrast agent for MRI

Spiral flow Another name for helical flow

Spring In the context of viscoelastic models; purely elastic component with linear stress–strain behaviour

Starling's equation Equation in which transcapillary flow is related to the net hydrostatic pressure minus the net colloid osmotic pressure

Statins Medicine that is used to lower cholesterol and reduce the risk of plaque rupture

Stenosis A local narrowing of the vessel lumen

Stenosis Localised reduction in the cross-sectional area of an artery caused by an atherosclerotic plaque

Stent Structure in the form of a tube inserted into an artery under imaging guidance to help keep the artery open

Stiffness Property of a solid; describing the degree to which it will deform when subject to a force

Stiffness index (β) Elastic modulus of a vessel which does not account for wall thickness

Stokes domain Relating to a particle in a moving fluid; particular type of flow occurring at very low Reynolds number where flow is dominated by viscous forces

Strain Ratio of extension divided by original length (for a material that has applied stress)

Strain elastography Measurement of strain in vivo using ultrasound imaging where strain is used as a surrogate for stiffness

Strain imaging Measurement of strain in vivo using medical imaging

Streamline Path followed by a fluid element

Stress Ratio of force divided by area; units are pascals (Pa)

Stress–strain graph Concerning the stretching of a sample of a solid material; the graph of stress versus strain

Stretch-sensitive ion channel Ion channel which is opened as a result of stretching of the surrounding lipid bilayer (e.g. if there is swelling of the cell)

Stroke volume Volume of blood ejected from left ventricle during each heart beat

Stroke work Work performed by the left ventricle during each cardiac cycle

Structural imaging Medical imaging technique which primarily provides information on geometry and motion; see X-ray, CT, ultrasound, MRI

Subarachnoid haemorrhage Bleeding into the space beneath the arachnoid membrane, usually caused by rupture of a cerebral aneurysm

Sub-critical/ super-critical flow (vein) Where the local speed of blood within the vein is less than/ greater than the speed of wave propagation

Suction pressure Force associated with flow of a fluid into a low pressure region, whereby the low pressure acts to propel the fluid forward

Superficial venous circulation The venous circulation which lies between the skin and the fascial boundary

Superior vena cava Large vein which delivers deoxygenated blood from the upper body to the right atrium

Superparamagnetic iron oxide particles See SPIO

Supine Lying face upwards

Suspension Fluid containing particles (i.e. not a pure fluid)

Symmetric flow Flow in a tube or vessel where the velocity profile is radially symmetric; the maximum velocity is mostly located at the centre of the vessel apart from when flow changes direction where the maximum velocity is located off-centre

Systemic circulation Part of the cardiovascular system which transports blood from the heart to the tissues of the body apart from the lungs

Systole The portion of the cardiac cycle in which the heart is contracting

Systolic pressure The highest pressure in an artery during the cardiac cycle

T1 In an MRI scanner, following a transmission pulse; T1 is the time for the longitudinal magnetization to achieve 63 % of its equilibrium value

T1 relaxation In an MRI scanner, change in the T1 signal with time following an RF transmission pulse

T2 In an MRI scanner, following a transmission pulse; T2 is the time at which there is 37 % loss of the original transverse magnetization

T2 relaxation In an MRI scanner, change in the T2 signal with time following an RF transmission pulse

Tachycardia Rapid heart rate, often arising from an arrhythmia

Tank-treading Relating to a deformable particle suspended in a moving fluid; the particle appears to be stationary but is in fact rotating; the membrane of the particle surface deforms in manner similar to the treads of a tank

Targetted contrast agent Contrast agent which binds to specific biological sites

Targetted MR contrast imaging Targetted contrast agent used in MRI

Targetted ultrasound contrast imaging Targetted contrast agent used in ultrasound imaging

Tensegrity Structural principle based on stiff components in compression linked by elastic components in tension

Tensile testing Measurement of the stress–strain or force-extension behaviour of material, measured by gradually stretching the material until it breaks

Tension Force within an object which is stretched

Tethering See 'tethering forces'

Tethering forces Forces on a vessel as a result of the proximity of surrounding tissues

Tetrahedral element Type of mesh element used in computational modelling

Thermal irreversibility Process which is not thermally reversible; e.g. here the material setting temperature is higher than the melting temperature

Thermodilution Method for measurement of flow rate in a vessel; requires insertion of a device into the vessel; liquid (e.g. saline) is injected at a higher temperature than blood at the proximal end of the device, at the distal end of the device the temperature is recorded and from this flow rate can be determined

Thermoregulation Mechanism by which temperature is maintained at a constant level

Thick filament Part of the contractile apparatus composed of myosin

Thin filament Part of the contractile apparatus composed of titin

Thoroughfare channel See 'preferential channel'

Three-D model See '3D model'

Thrombosis Formation of a blood clot

Thrombus Blood clot

TIA See 'Transient ischaemic attack'

Tight junction Region between two adjacent cells where cell membranes are connected which prevents fluid flow between the cells

Tissue mimic See 'tissue mimicking material'

Tissue mimicking material Component of a flow phantom which mimics the tissues; for which key imaging physical properties are matched to those in human tissues

TMM Abbreviation for 'tissue mimicking material'

TOE Transoesophogeal echocardiography; method for imaging the heart using an endoscope

Tonometry Measurement of pressure

Tortuous artery Arteries which are more elongated than is normal and as a result twist and turn; may be due to reduction in height (through vertebral collapse with ageing), more commonly due to artery elongation because of a genetic defect

Tracer In medical imaging; substance which mimics particular molecules in the body and which can be imaged

Transducer Component of the ultrasound system which generates and receives the ultrasound beam, and sweeps the beam through the tissues to produce an image

Transient ischaemic attack Symptoms of a stroke which last for less than 24 h

Transit time flow probe Device for measurement of flow rate in a vessel; requires exposure of the vessel and placement of the probe around the vessel; the device operates by measuring the time of propagation of a pulse of ultrasound through the moving blood

Transitional flow Flow state which oscillates between laminar and turbulent flow

Transmission (of ultrasound) The process of production of ultrasound from the transducer

Transmitted frequency (ultrasound) Frequency of the transmitted ultrasound

Transmitting coil Part of an MRI system, involved in transmitting an RF pulse which causes change in the direction of magnetisation of nuclei

Transmural pressure The difference between pressure acting on the wall from the inside (blood pressure) and the pressure acting on the wall from the outside

Transmural pressure The pressure given by the internal pressure minus the external pressure acting on a vessel

Transoesophogeal echocardiography See TOE

Transverse magnetization Magnetization in the plane 90° perpendicular to the main magnetic field direction

Trans-WSS An index which describes the variation of shear stress direction through the cardiac cycle

Tricuspid valve Heart valve between the right atrium and the right ventricle preventing backflow of blood into the right atrium

Tricuspid valve A valve with three leaflets

Tube-law The relationship used to define the pressure-area response of a vessel

Tubing (vessel mimic) Commercially available tube used as a convenient vessel mimic in a flow phantom

Tubular pinch effect See 'Segre Silberberg effect'

Turbulent flow Flow state in which fluid elements follow erratic paths and there is mixing between adjacent layers of fluid

Ultimate strength Concerning stretching of a material; the maximum stress which can be applied which does not result in fracture

Ultrasmall superparamagnetic iron oxide particles See USPIO

Ultrasound Sound with frequencies above the limit of hearing for humans; i.e. frequencies >20 kHz

Ultrasound elastography Ultrasound technique in which the stiffness of tissues is estimated from measurements of the local speed of propagation of shear waves

Umbilical cord Flexible cylindrical structure approximately 1 m in length connecting the embryo to the placenta; contains 2 umbilical arteries and 1 umbilical vein; oxygenated blood passes down the vein from placenta to fetus and deoxygenated blood along the arteries from fetus to placenta

Unactivated platelet Platelet which has not been activated and is not sticky

Uniaxial testing Mechanical testing of materials with stretching in a single direction

Unloading Gradual decrease in stress applied to a solid

Upstream–downstream asymmetry Difference in the flow-field upstream and downstream of an object such as a stenosis in an artery

Urea One of the waste products of metabolism

Urethane (tissue mimic) Material used as a TMM in ultrasound phantoms

USPIO Abbreviation for 'ultrasmall superparamagnetic iron oxide', referring to paramagnetic particles with a diameter of 10–40 nm, used as a contrast agent for MRI

Valve Structure which prevents backflow of blood, present in medium sized veins and in the heart

Valve plane Plane in which the main cardiac valves lie

Valve sinus A local increase in diameter in the vein at the location of the venous valve

Valvular agger A fibroelastic structure located at the base of the venous valve which connects the valve leaflets to the vessel wall

Varicose veins Veins which have become enlarged and tortuous

Vascular graft Vessel replacement—can be natural (e.g. Vein graft) or synthetic

Vasoconstriction Contraction of the smooth muscle cells in the vessel wall causing slight decrease in lumen diameter for muscular arteries), large decrease in diameter (for arterioles)

Vasodilation See 'vasorelaxation'

Vasomotion Regular change in diameter of arterioles, occurring at a frequency of 3–30 min^{-1}

Vasorelaxation Relaxation of the smooth muscle cells in the vessel wall causing slight increase in lumen diameter (for muscular arteries), large increase in diameter (for arterioles)

Vein Large vessels involved in transport of blood to the heart; diameter 1–25 mm

Velocity Distance travelled per unit time; units $m\ s^{-1}$

Velocity (shear wave) See shear wave velocity

Velocity field See 'flow field'

Velocity profile Velocity as a function of radial position in a tube

Velocity waveform The plot of blood velocity versus time; e.g. in an artery. Note 'velocity' may refer to maximum velocity or mean velocity

Vena cava The 2 largest veins in the systemic circulation which deliver deoxygenated blood to the right atrium; consisting of inferior vena cava and superior vena cava

Vena contracta Relating to flow in a vessel past a partial obstruction; region where the flow stream has minimum diameter, located just after (but not coinciding with) the point of minimum cross-sectional area

Venous insufficiency Lack of reduction of pressure in the deep veins of the lower limb during exercise and is associated with a range of complications which present clinical symptoms associated with poor venous return from the lower limb

Venous reflux Reverse flow of blood in the veins, typically observed following muscle pump activity if venous valves are incompetent

Venous return The volume of blood returning to the right atrium from the systemic venous circulation

Venous valve Valves present in medium sized veins preventing backflow of blood in the vein

Ventricles Chambers of the heart concerned with pumping of blood into the arterial system; left ventricle pumps into systemic arterial system, right ventricle into pulmonary arterial system

Venule Small vessel connecting veins to capillaries; diameter 10–200 μm

Vesicle Fluid-filled structure formed from the lipid bilayer

Vesicular transport Movement of molecules into and out of a cell by containment within vesicles

Vessel compliance The degree to which a vessel distends following increase in transmural pressure

Vessel length Longitudinal length of a vessel

Vessel lumen diameter Diameter of the lumen (i.e. of the region occupied by the fluid/blood flowing within the tube/vessel)

Vessel mimic See ‘vessel mimicking material’

Vessel mimicking material Component of a flow phantom which mimics the vessel wall; for which key imaging physical properties are matched to those in human vessels

Vessel wall thickness Thickness of the wall of a vessel

Virtual histology Method used in IVUS imaging involving identification of plaque component (e.g. fibrous, lipid, calcified) by analysis of the RF data

Viscoelastic Term concerning a solid material whose stress–strain behaviour demonstrates both fluid (viscous) and solid (elastic) behaviour

Viscometer Device for measuring the viscosity of a fluid

Viscometry The science of measurement of viscosity

Viscosity The ability of a fluid to resist deformation by a shear force

Viscous force Force on a fluid element arising from friction with adjacent fluid elements or a surface

VMM Abbreviation for 'vessel mimicking material'

Voigt model Model of viscoelastic behaviour in which the spring and dashpot are in parallel

Volumetric flow rate See 'flow rate'

Von Willebrand factor A blood protein involved in thrombus formation

Vortex Region of rotating flow; may be located to one region (e.g. post-stenosis) or may travel downstream

Vortex shedding Term describing the creation of vortices (e.g. post-stenosis) which then travel downstream

Vortices Regions in which the flow locally rotates around a point

Voxel Volume element; smallest component of a 3D digital image

Wall induced inertial lift Relating to an object in a fluid at high Reynolds number where inertial forces dominate; force on the object occurring when the object is near a wall; force is directed away from the wall; for flow in a tube the particles move away from the wall

Wall shear rate Change in fluid velocity with perpendicular distance arising from a shear force measured at the wall; units s^{-1}

Wall shear stress Viscous drag of a fluid on the wall of a vessel; e.g. viscous drag of blood on an arterial wall

Wall shear stress control Control mechanism whereby the wall shear stress in an artery is maintained within a narrow bound; involves sensing of wall shear stress (mechanosensing) and change in arterial diameter (remodelling)

Wall thickness Thickness of the wall of vessels in the cardiovascular system

Water hammer equation Equation relevant for a fluid relating the variation of pressure with velocity to the pulse wave velocity

Wave inversion In magnetic resonance elastography, method used to estimate the local stiffness from the measured displacement associated with passage of shear waves

Waveform The plot of wave amplitude versus time or wave amplitude versus distance (e.g. flow-time waveform)

Wavelength Property of a wave; the distance between two consecutive crests or other similar points on the wave

White cell Particles within blood concerned with immune defence; also called leukocytes; a variety of different white cells exist each with a different function; occupy 0.7 % of blood volume; diameter 7–15 μm

WHO See 'World Health Organisation'

Whole artery phantom Flow phantom incorporating an excised section of an artery

Whole-body Referring to medical imaging in which the entire body is imaged

Windkessel model A simple model of the arterial system consisting of a pump, a chamber and an outflow resistance; provides estimates of the pressure-time waveform and the flow-time waveform; from the German word 'Windkessel' meaning 'air chamber'

Wolff–Parkinson–White syndrome Syndrome in which an additional electrical activation connection between atria and ventricles that together with the atrioventricular node provides a pathway for re-entry

Womersley number Relating to the Womersley equations, α is the Womersley number; a dimensionless number for pulsatile flow equal to the square root of the ratio of inertial force to viscous force

Workflow See 'processing chain (PSM)'

Workflow See 'processing chain (PSM)'

World Health Organisation Organisation concerned with directing and coordinating international health within the United Nations system

WSS See 'wall shear stress'

X-ray imaging Medical imaging technique based on the use of X-rays; see projection radiograph, fluoroscopy, CT and rotational angiography

X-ray venogram An X-ray examination using contrast medium to visualise the blood within the veins

Yeoh model A hyperelastic constitutive model

Yield point Concerning stretching of a material; the point (stress) above which the material behaves plastically

Young's modulus Property of a solid describing elastic behaviour, concerned with deformation along one axis; ratio of stress divided by strain

Z-disk End-to-end connections between sarcomeres

Zero-D model See 'OD model'

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