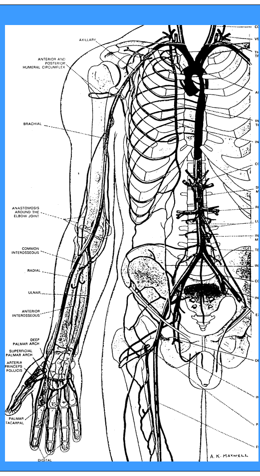
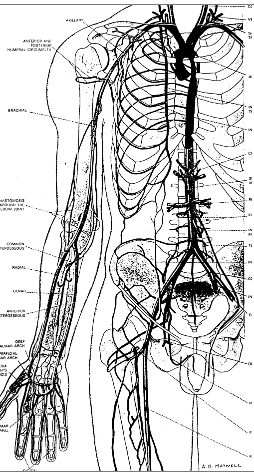
Structure, function and diversity of the vasculature

Steven Marston



The arterial system



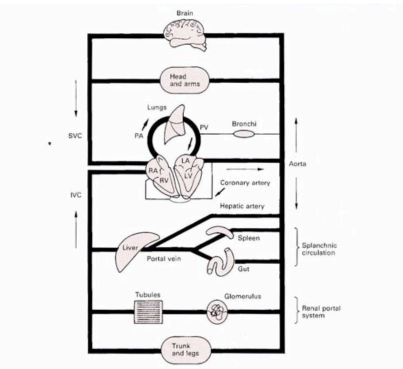
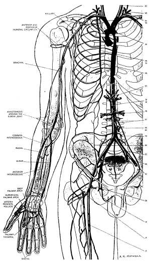
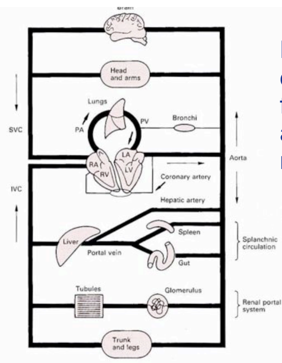


Figure 1.4 Arrangement of the circulation. Systematic and pulmonary circulations are 'in series'. Circulations to indvidual organs are mostly in parallel (e.g. cerebral and coronary circulations) but a few are in series (e.g. liver, renal tubules). Bronchial venous blood drains anomalously into the left rather than the right atrium. PA, PV, pulmonary artery and vein; RA, LA, right and left atrium (an 'atrium' was a Roman hall); RV, LV, right and left ventricle; SVC, IVC, superior and inferior vena cava





Functions of CVS

Rapid convective transport of oxygen, glucose, amino acids, fatty acids etc. to the tissues and rapid washout of metabolic waste products

Part of the Cardiovascular control system.

Distribution of hormones, temperature regulation

Cardiac output: L and R ventricle pump equal volumes of blood simultaneously - needed for continuity

Resting adult **stroke volume** ~ 70 - 80 cm^3 and **heart rate** ~ 65 - 75 beats min^{-1} giving a cardiac output ~ 5 l min^{-1}.

On **exercise,** oxygen demand from muscle can rise 10x and cardiac output can rise 5x by increasing stroke volume and heart rate

Distribution of cardiac output at rest

Total output of **R heart -----> lungs**

L. heart	% O2 consumption	% of C.O.
Liver + GI	30	24
Kidney	6	20
Brain	18	13
Heart	10	4
Skeletal muscle	20	20
Skin		9

2

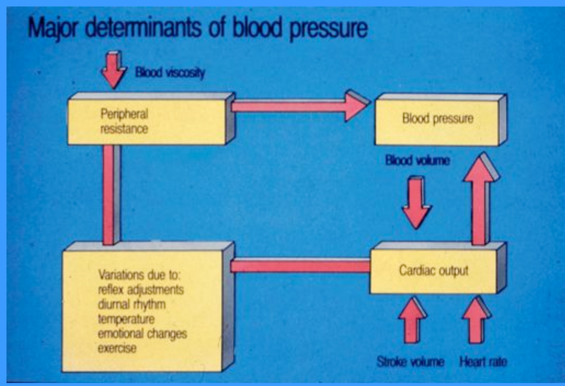
Exercise: Up to 80% of C.O. can flow to the skeletal muscles. There is a fall in visceral blood flow but no change to brain blood flow.

Pressures and flows in blood vessels

Systole Contraction of the L. ventricle raises pressure to above that of the aorta (~1.5 x 10^4Pa (120 mm Hg))

Diastole Heart fills from venous system (pressure is very small).

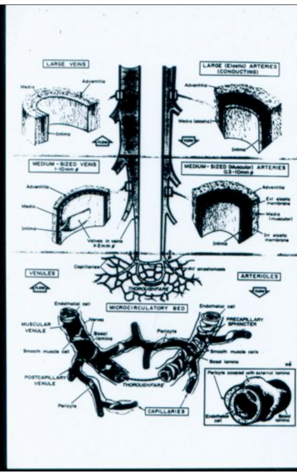
Aortic pressure falls only to about 1.2 x 10^4Pa (70-80 mm Hg), because of the high hydraulic impedance of the circulation



Blood flow = ΔP / R, where ΔP is the pressure difference between the arterial and venous sides of the heart (or an organ), and R is the hydraulic resistance

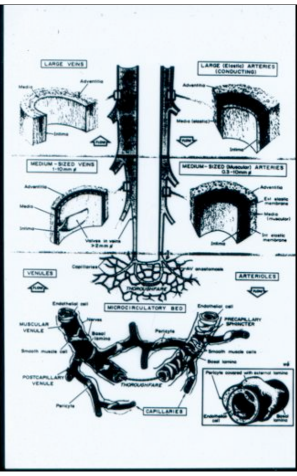
Resistance of the systemic circulation **(peripheral resistance)** ~ 0.02 mmHg cm^{-3} min^{-1}.

Pulmonary vascular resistance ~ 0.003 mmHg cm^{-3} min^{-1}, the R ventricle producing a much lower pressure (25/10 mm Hg) compared with the L ventricle



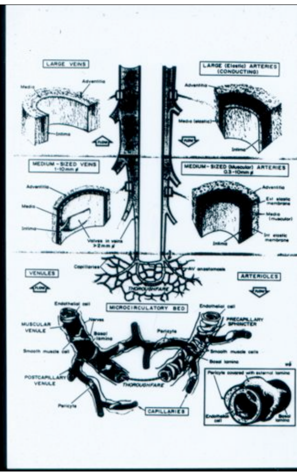
- Functions of large arteries

- Windkessel effect: High compliance, low impedance, reducing afterload on the heart, permitting diastolic flow
- Barorecptor function
- Contractile properties of large arteries on wounding

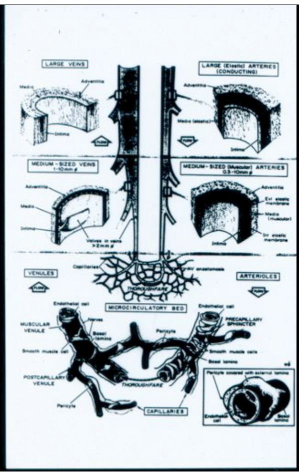


- Functions of larger veins

- Capacitance properties
- Valves; rectification of flow, maintenance of cardiac filling
- Collapsibility, the muscle pump



- Arterioles are the main resistance vessels



- Oxygen, glucose, Co2 etc. exchange takes place in the capillary bed
- Perfusion pressure is maintained at about 20mm Hg

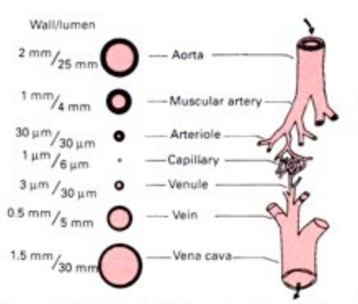


Figure 1.8 Thickness of the wall relative to the diameter of the lumen in different blood vessel. The ratio varies, however, with blood pressure and vascular tone. The large-vessel dimensions are for man. (Sources as for Table 1.3)

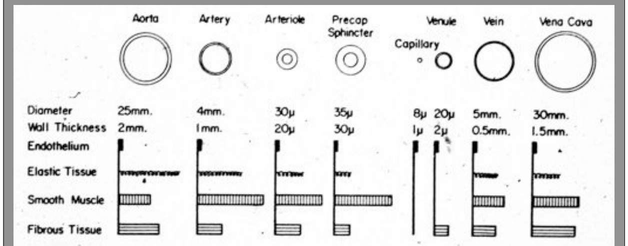


Fig. 1-1. Internal diameter, wall thickness, and relative amounts of the principal components of the vessel walls of the various blood vessels that compose the circulatory system. Cross sections of the vessels are not drawn to scale because of the huge range from aorta and venae cavae to capillary. (Redrawn from Burton, A. C.: Physiol. Rev. 34:619, 1954.)

Peripheral resistance increases dramatically as vessel diameter decreases

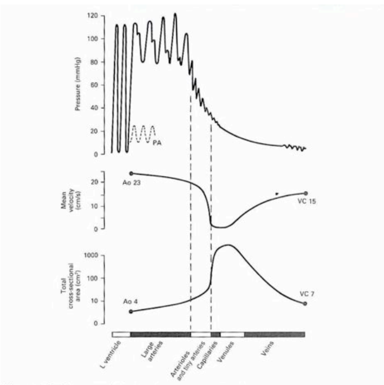
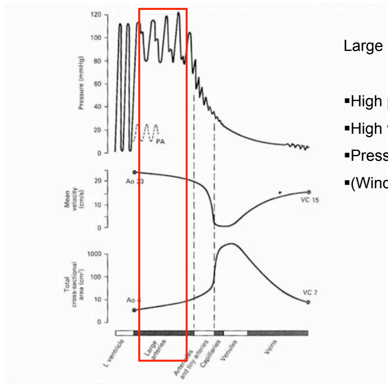


Figure 1.6 Blood pressure and velocity in the systemic circulation of a resting adult. The abscissa is distance along the vessels. The greatest fall in pressure occurs across arterioles and the tiniest arteries, of diameter 100–500 µm. Velocity is the cardiac output divided by total cross-sectional area of the vascular bed at that point. Pressure in the pulmonary artery is shown as a dotted line. Ao, human aorta; VC, human vena cava



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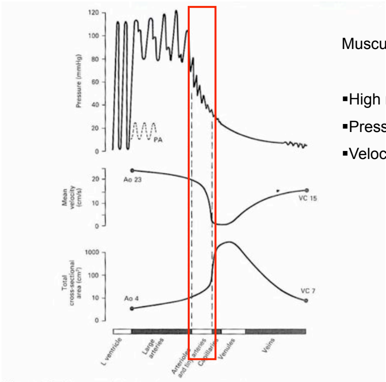
Large elastic arteries

- High pressure
- High velocity
- Pressure damping
- (Windkessel)



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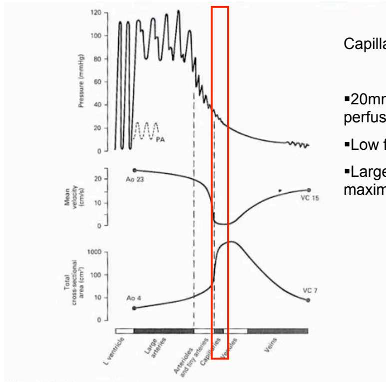
Muscular arterioles

- High resistance
- Pressure drop
- Velocity drop



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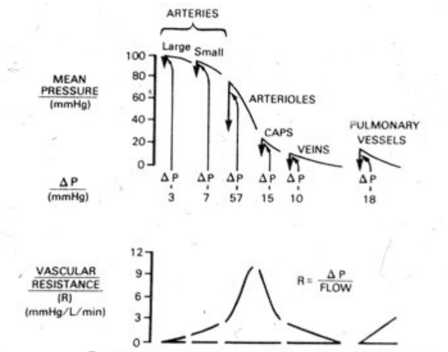
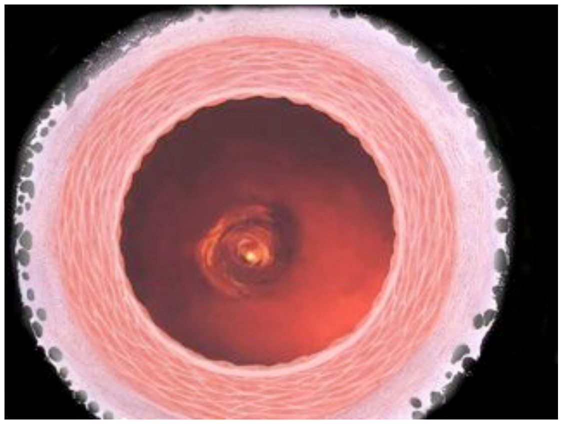
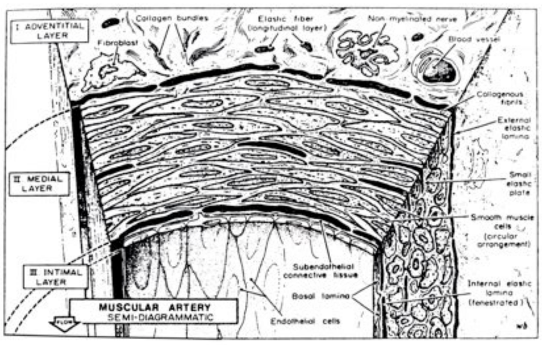
Capillaries

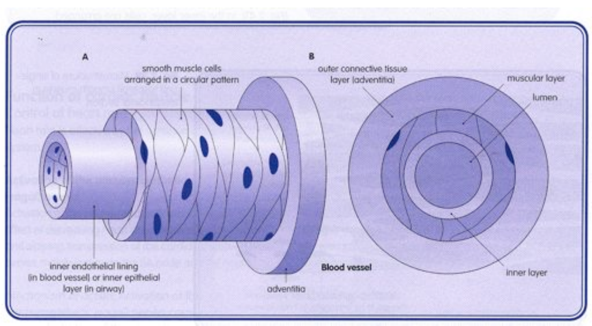
- 20mm tissue perfusion pressure
- Low flow rate
- Large area maximises exchange



Top, Vascular resistances in different segments of the circulation. The pressure fall (Δ*P*) is shown in different parts of the circulation and is least in the aorta and the greatest at the arteriolar level. *Center*, If the Δ*P* values are divided by the cardiac output (5 liters/min) which will be constant through all the segments, the vascular resistance of the different segments (*bottom*) can be estimated. As expected, it is least in the aorta and highest in the arterioles.







Section across arteriole wall

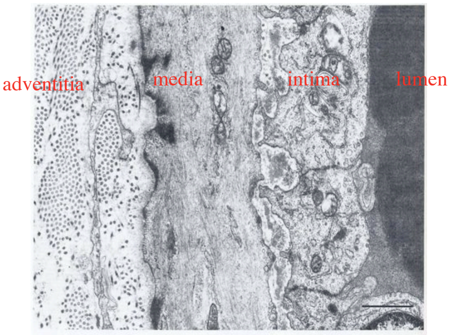
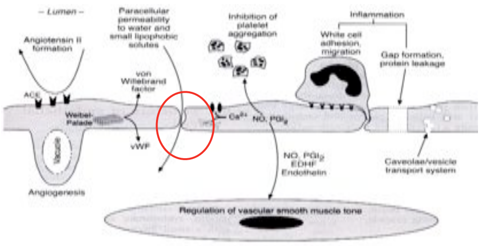


Figure 1-4. Transverse section of an arteriole in the wall of the colon of a pig. In the middle is a muscle cell in longitudinal section. To the right are red blood cells (in the lumen of the vessel) adjacent to a layer of endothelial cells (intima). To the left is the adventitia with many collagen fibrils and a fibroblast process. Between the endothelium and the muscle cells are elastic fibers and collagen, and processes from the two cell types project towards each other. The muscle cell displays mitochondria, sarcoplasmic reticulum, caveolae, dense bands, and myofilaments. Characteristically, the dense bands are more numerous and more extensive on the membrane at the abluminal side of the cell than on the lumenal side, an arrangement that is found when muscle cells are coiled around the lumen of a vessel of small caliber. Calibration bar: 1 µm.

Figure 1 Structure of a normal large artery. A large artery consists of three morphologically distinct layers. The intima, the innermost layer, is bounded by a monolayer of endothelial cells on the luminal side and a sheet of elastic fibres, the internal elastic lamina, on the peripheral side. The normal intima is a very thin region (size exaggerated in this figure) and consists of extracellular connective tissue matrix, primarily proteoglycans and collagen. The media, the middle layer, consists of SMCs. The adventitia, the outer layer, consists of connective tissues with interspersed fibroblasts and SMCs.

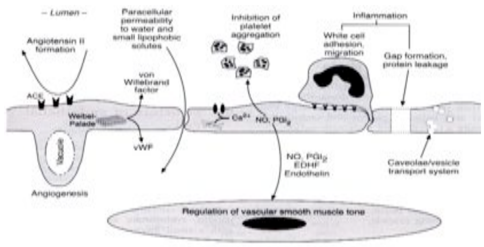
A single layer of endothelial cells lines all blood vessels



Functions of endothelial cells

1 Permeability and its regulation

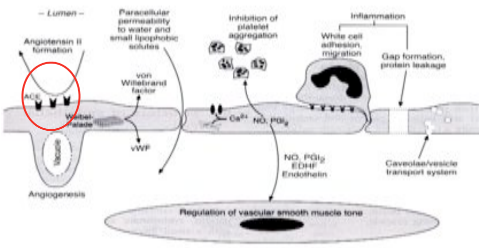
The primary role of the endothelium is to form a selective, adjustably porous membrane



Functions of endothelial cells

2 Local vascular control

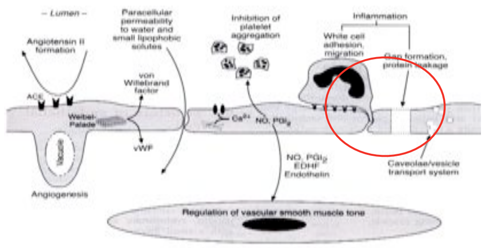
Endothelial cells sense shear stress which elicits local flow-regulating responses via release of vaso active agents



Functions of endothelial cells

3 Enzyme action on plasma

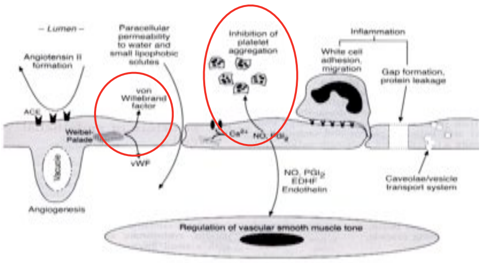
Angiotensin converting enzyme and carbonic anhydrase are located on the surface of endothelial cells



Functions of endothelial cells

4 Defence against pathogens

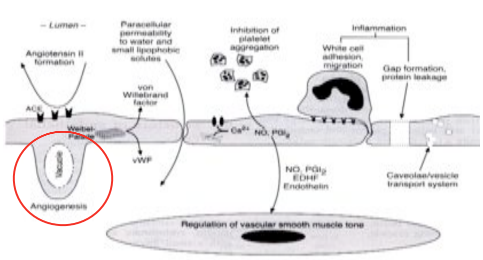
Venule endothelium plays a very active role in the inflammatory response to pathogens



Functions of endothelial cells

5 Antihaemostatic and haemostatic roles

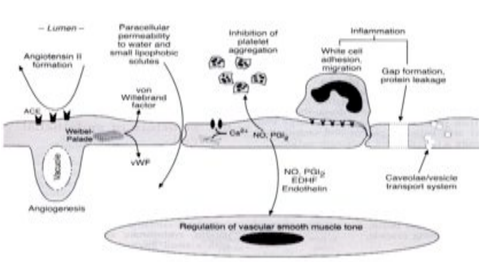
NO and prostaglandin inhibit aggregation and clotting. Von Willebrand factor promotes it.



Functions of endothelial cells

6 Angiogenesis

The development of new blood vessels is initiated by endothelial cells

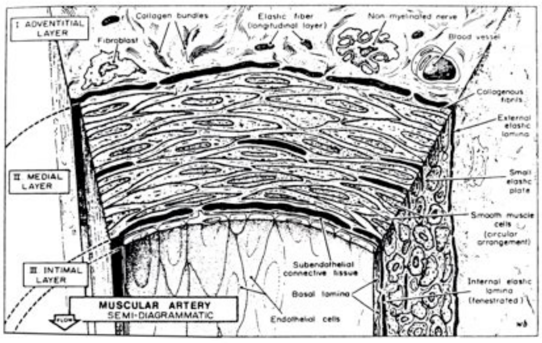


Functions of endothelial cells

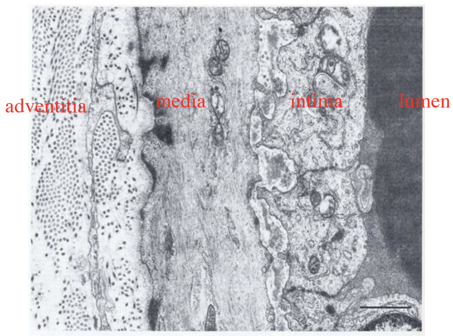
7 Atherogenesis

Changes in the endothelial cell function are important in the development of atheromatous plaques

Diagram of a small muscular artery



Section across arteriole wall



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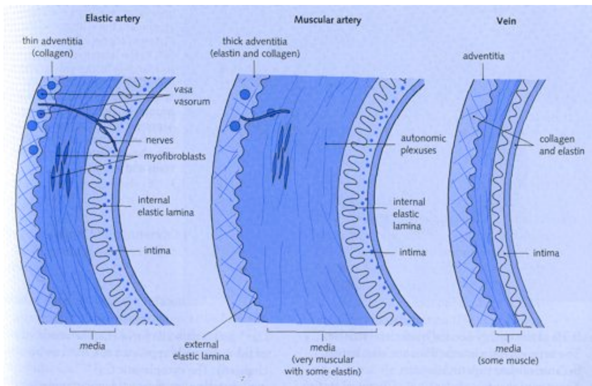

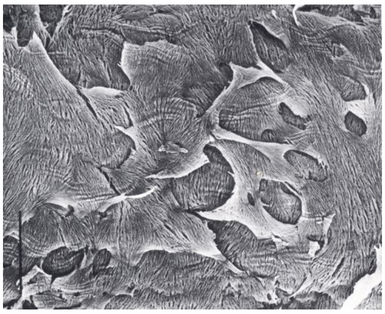

Smooth muscle cells surrounding the aorta

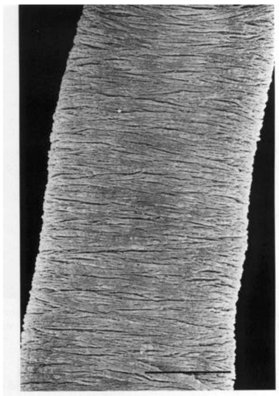

Figure 12-6. Guinea pig muscular artery about 100 µm in diameter. The media consists of a parallel array of circular muscle fibers. Bar: 50 µm.

Figure 12-7. Branching point of the guinea pig mesenteric artery. Note the disordered arrangement of smooth muscle fibers. Bar: 50 µm.

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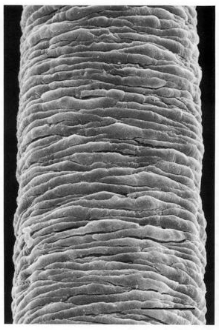

Figure 12-8. Subarachnoidal muscular arteriole of the rat. Muscle fibers are fusiform with tapered ends. They are tightly apposed to each other and are circularly oriented. Bar: 20 µm.

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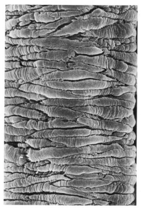

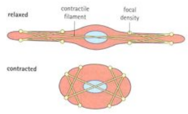

Smooth muscle cell contraction leads to vasoconstriction of an arteriole

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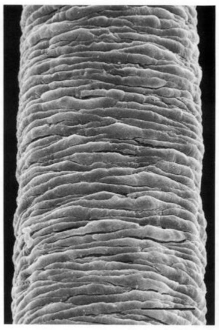

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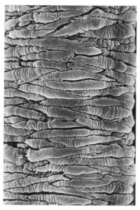
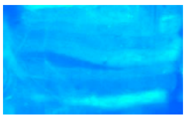
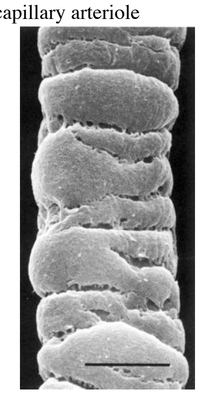




Smooth muscle cell contraction leads to vasoconstriction of an arteriole

Precapillary arteriole



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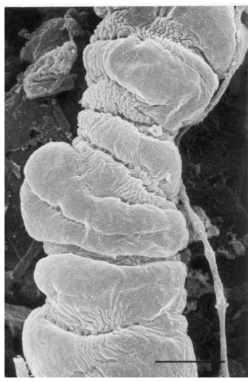

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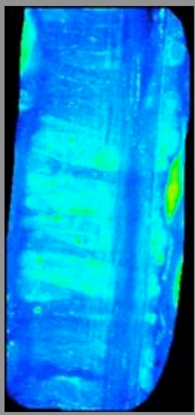
AVI movie 3. Ca^{2+} waves and contractions of individual vascular smooth muscle cells with Fluo-4 with the focal plane located in the middle of the blood vessel. It demonstrates the changes in diameter of the terminal arteriole in the area of a contracting cell.

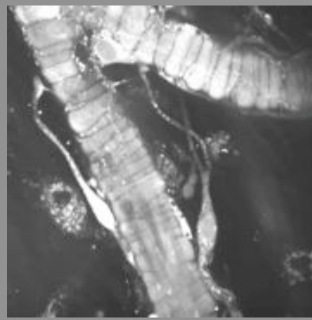
Burdyga T, Shmygol A, Eisner DA, Wray S. A new technique for simultaneous and in situ measurements of Ca2+ signals in arteriolar smooth muscle and endothelial cells. Cell Calcium. 2003

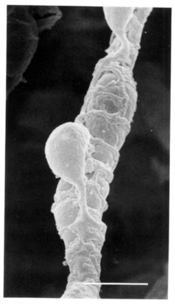
Jul;34(1):27-33.



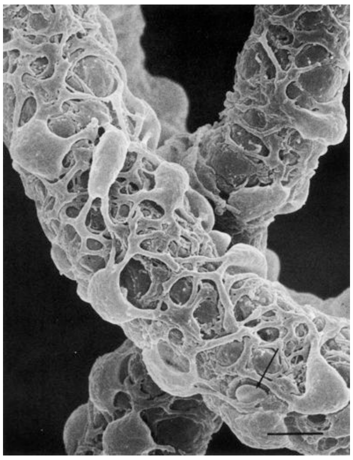
An animation showing Z-stepping through a region of Fluo-4 loaded rat ureter, taken from top to bottom at 2 µm steps. The monolayer of circumferentially running smooth muscle cells, and then rows of endothelial cells running parallel to the blood vessel can be seen.

Burdyga T, Shmygol A, Eisner DA, Wray S. A new technique for simultaneous and in situ measurements of Ca2+ signals in arteriolar smooth muscle and endothelial cells. Cell Calcium. 2003Jul;34(1): 27-33.

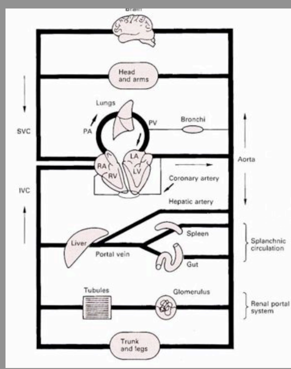




Capillary

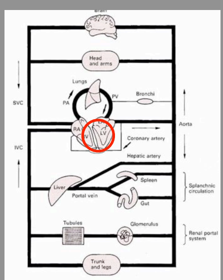


Venule



Regional circulations

- Heart
- Skeletal muscle
- Skin
- Brain
- Lungs



Flow ranges from 70-80 ml/min/100g during basal cardiac output to 300-400ml/min/100g during maximal cardiac work.

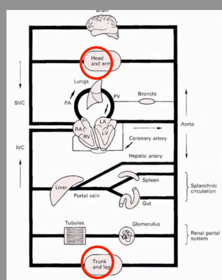
Table 15.1 Summary of coronary circulation

Special tasks
- Maintain a high basal oxygen supply.
- Oxygen supply must keep pace with cardiac work

Structural adaptation
- High capillary density, short diffusion path

Functional adaptation
- High oxygen extraction (>60%)
- Metabolic vasodilatation dominates control

Special problems
- Functional end-arteries, so risk of infarction and angina
- Mechanical interferencing during systole



Flow ranges from 15 ml/min/100g in resting postural muscle to 3-5 ml/min/100g in resting phasic muscle but increases to > 100-200 ml/min/100g during exercise.

Table 13.2 Summary of circulation through skeletal muscle

Special tasks
- Delivery of oxygen and nutrients in proportion to exercise intensity
- Contributes to homeostasis of arterial pressure

Structural adaptation
- High capillary density in tonic (postural) muscle

Functional adaptation
- Participates in baroreceptor reflexes
- Metabolic vasodilatation dominant during exercise
- Vasodilator response to adrenaline
- Skeletal muscle pump
- Variable oxygen extraction

Special problems
- Mechanical interference during contraction
- Increased capillary filtration in exercise

Flow in thermoneutral environment 10-20 ml/min/100g

Minimal (cold) flow 1 ml/min/100g
Maximum flow 150-200 ml/min/100g

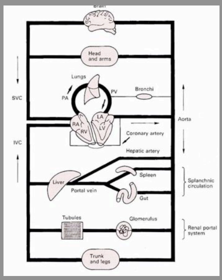


Table 15.3 Summary of cutaneous circulation

- Special tasks
  - Temperature regulation
  - Response to trauma
- Structural adaptation
  - Arteriovenous anastomoses in extremities
- Functional adaptation
  - Sympathetic control dominant and regulated by core temperature receptors
  - Vessel tone also directly sensitive to local temperature
  - Dependent vasoconstriction by local mechanisms
  - Reflex vaso- and venoconstriction in response to hypotensive shock
  - Triple response to cutaneous trauma
- Special problems
  - Compression when weight-bearing; bed sores
  - Hot weather causes local swelling and venodilatation, aggravating postural hypotension

Average flow 55ml/min/100g

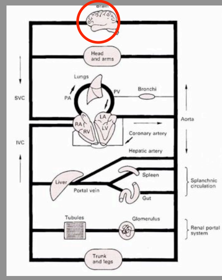


Table 15.4 Summary of cerebral circulation

- Special tasks
  - Maintain oxygen supply to hypoxia-intolerant grey matter
  - Adapt local perfusion to local activity
- Structural adaptation
  - Circle of Willis
  - High capillary density
  - Tight endothelial junctions (blood-brain barrier)
- Functional adaptation
  - High basal blood flow
  - Brain controls heart and peripheral resistance to maintain its pefusion pressure
  - Cerebral vessels 'excused' from baroreflex vasoconstriction
  - Good autoregulation in face of pressure changes; sensitive to P_{CO_2}
  - Local metabolic hyperaemia in response to local cortical activity
  - Blood-brain barrier provides a highly stable neuronal environment
- Special problems
  - Postural syncope if baroreflex impaired
  - Space-occupying lesions lead to bulbar ischaemia

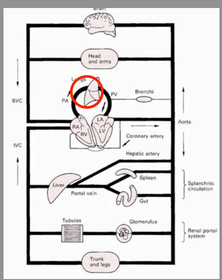


Table 15.5 Summary of pulmonary circulation

- Special tasks
  - Respiratory gas exchange
  - Metabolic conversion of circulating vasoactive substances by endothelium
- Structural adaptation
  - Extremely high capillary density and very short diffusion distance
  - Low vascular resistance, so only modest rises in pulmonary vascular pressure when pulmonary flow (i.e. cardiac output) increases
- Functional adaptation
  - Hypoxic vasoconstriction helps match regional perfusion to regional ventilation
- Special problems
  - Because pulmonary arterial pressure is low, lung apices are poorly perfused in upright subject at rest
  - At extreme cardiac outputs (athletes), residence time in capillary can be 0.3 s or less
  - Chronic hypoxic vasoconstriction can lead to right-sided cardiac failure
  - Very thin capillary–alveolar barrier can become leaky, e.g. mitral stenosis

Diseases of the vasculature involve all three tissue layers

Intima: atherosclerosis

Media: hypertension

Adventitia: aneurism