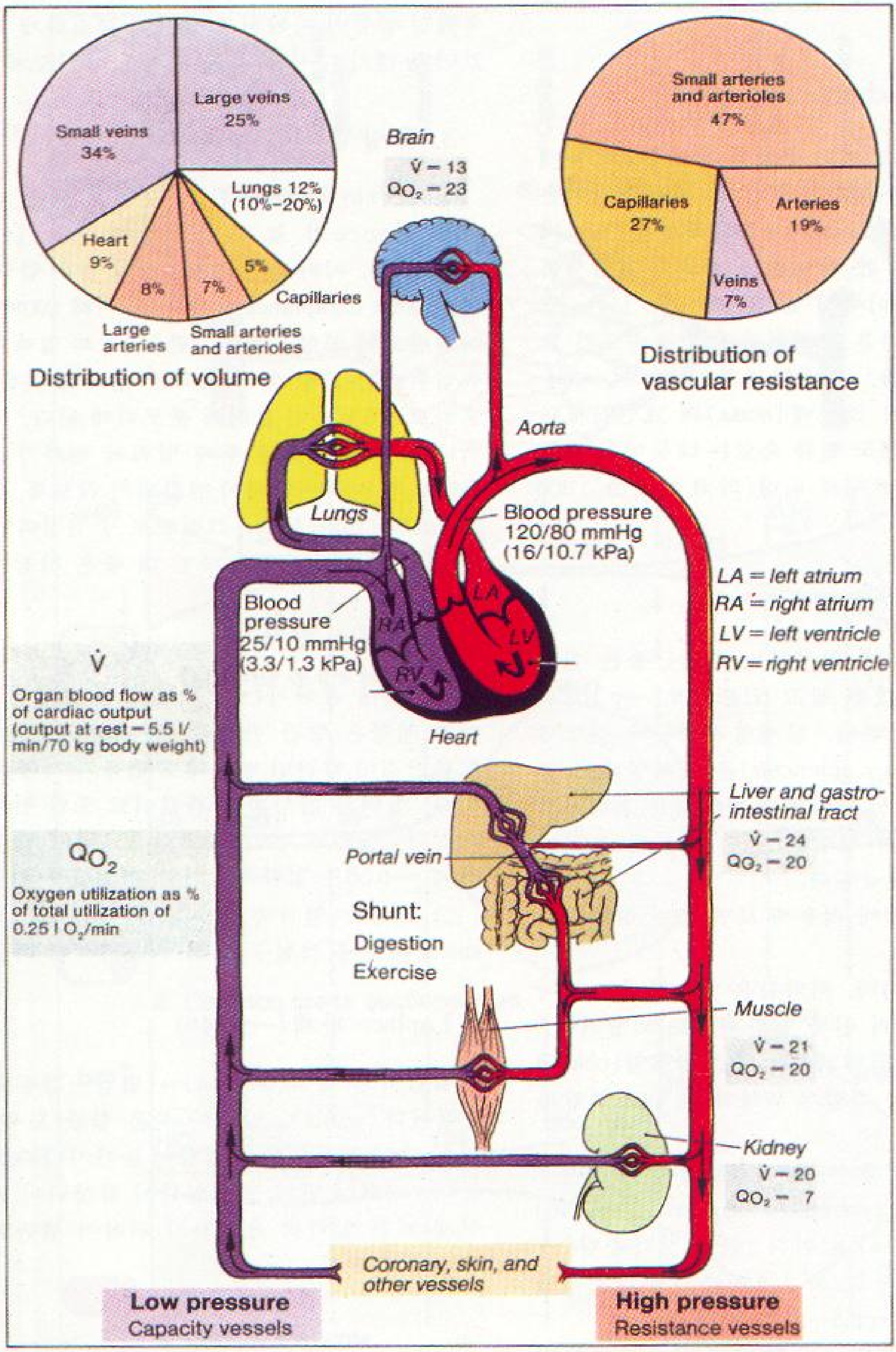
The Heart & Circulation (I)

(Ch. 1. Modeling and Simulation in Medicine and the Life Sciences)

1.1 Plan of the Circulation

- Function of the heart?
- Figure 1.1: The left heart receives blood that is rich in O2 and pumps this blood into the systemic arteries, systemic capillaries, O2-CO2 exchange, systemic veins, right heart, pulmonary arteries, pulmonary capillaries, CO2-O2 exchange, pulmonary veins.
- A complete cycle of circulation
- The average time required for a red blood cell to complete the circuit is about 1 min.
- Notice the similarities in systemic circulation and pulmonary circulation



A. Cardiovascular system

1.2 Volume, Flow, and Pressure

- Three physical variables to describe the circulation

- **Volume (V)**
- Volume of the blood = measure of the amount of blood in any part of the circulation
- Volume is measured in liters (1 liter = 1000 cm^3)
- Symbol for volume = V
- Total blood volume ~ 5 liters

- **Flow (Q)**
- Volume of blood per unit time passing a point in the circulation.
- Flow is measured in liters/min
- Its symbol is Q
- Cardiac Output (CO) = volume of blood pumped per unit time by either side of the heart
- Cardiac Output = Stroke Volume (volume of blood pumped per beat) X Heart Rate (number of beats per unit time)

- **Pressure (P)**
- Force per unit area, expressed using P
- Unit is in the height of a column of mercury, mmHg (millimeters of mercury)
- Difference in pressure produces observable effects. Needs a reference pressure.

1.3 Resistance and Compliance Vessels

- Blood vessel in Fig. 1.2
- Volume (V), inflow (Q1 at P1), outflow (Q2 at P2).
- If in steady state (none of quantities change in time), then Q1=Q2=Q
- Relationship of Q, P1, P2, and V
- Two separate properties of the blood vessel; resistance and compliance

- If the vessel is rigid, so that volume is known and constant
- Q=(P1-P2)/R   R=resistance of the vessel
- If a vessel satisfies this equation, we call it a resistance vessel

- Now if the vessel is elastic and it has no resistance to blood flow, then the pressure at the two ends are equal, P1=P2=P
- Then V=CP C=compliance of the vessel
- If we consider a nonzero residual volume of the vessel at zero pressure (Vd)
- Then V=Vd+CP
- The vessel satisfying these equations is called a compliance vessel

- Shortcomings of this model
  i) A real vessel has both properties at the same time.
  ii) Only assumed linear relationships

- Large arteries and veins are mostly compliance vessels since only small pressure differences are needed to drive the cardiac output through the vessels.
- Main resistance vessels are the smallest arteries (arterioles) since volume changes are less important, but pressure drops are significant.
- Is linear approximation good between flow and pressure? In fact, tissues exhibit reasonably constant values of R under conditions where the diameters of their blood vessels remain constant.
- R could change by a stimulus that results in contraction or relaxation of the smooth muscles in the walls of the arteroles.
- Same for the compliance vessel.

1.4 The Heart as a Pair of Pumps

- A pump is a device that can accept fluid at low pressure (P1) and transfer it to a region where the pressure is high (P2>P1)
- Consider the left side of the heart (Fig. 1.3)
- To characterize the pump, we need to express Q in terms of P1 and P2
- At diastole, P1=Psv=5mmHg
- At systole, P2=Psa=100mmHg

- Model the ventricle as a compliance vessel, thus
- V(t)=Vd + C(t)P(t)
- C(t)=a given function with the qualitative character in Fig. 1.4
- C(t) takes on a small value Csystole when the ventricle is contracting and a much larger value Cdiastole when the ventricle is relaxed.

- Vd is independent of time
- A pressure-volume diagram of the cardiac cycle in Fig. 1.5
- Maximum volume obtained by the ventricle at end-diastole is $Ved=Vd+CdiastolePv$
- Minimum volume achieved at end-systole $Ves=Vd+CsystolePa$
- Stroke volume, $Vstroke=Ved-Ves=CdiastolePv-CsystolePa$
- If $Csystole=0$, $Vstoroke=CdiastolePv$
- If F is the heart rate (beats per minute), $Q=FVstroke=FCdiastolePv$.
- Define $K=FCdiastole$. K is called the pump coefficient of the ventricle.
- For the right and left cardiac output, $Q_R=K_RPsv$, $Q_L=K_LPpv$
- In this section, let's assume the pressure outside the heart is zero (atmosphere)