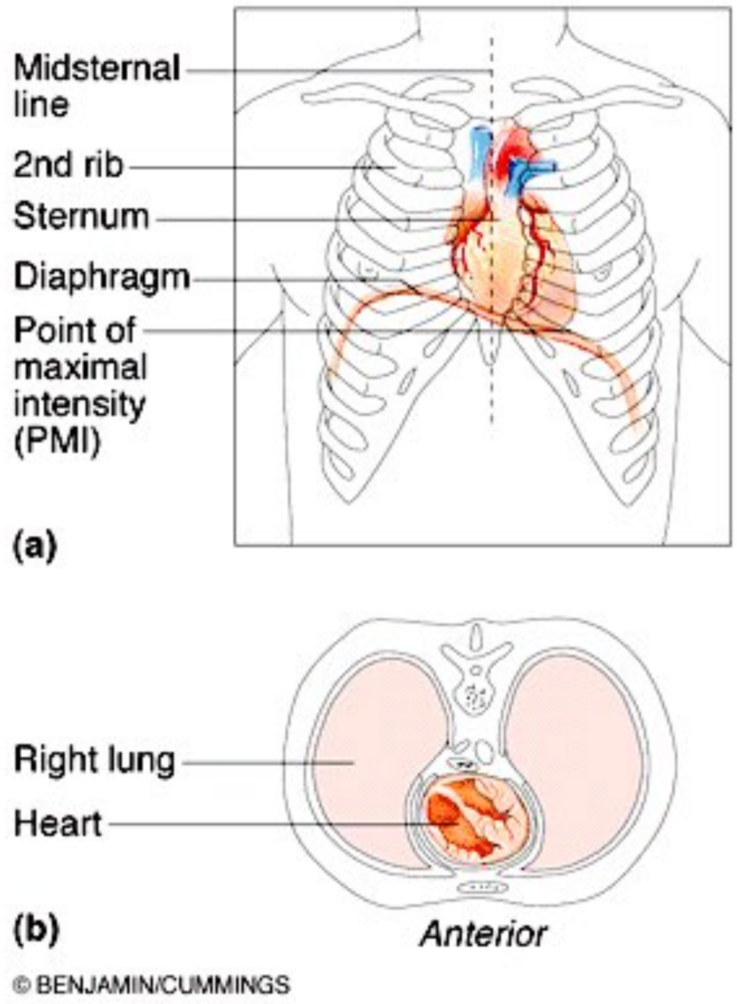
Cardiac Biomechanics

- Anatomy, electrical activity and mechanical activity of the heart
- Biomechanics of cardiac muscle
  - force-length relation
  - force-velocity relation
- Pressure-volume relation
- «The cardiac pump function graph»
- Work and energy

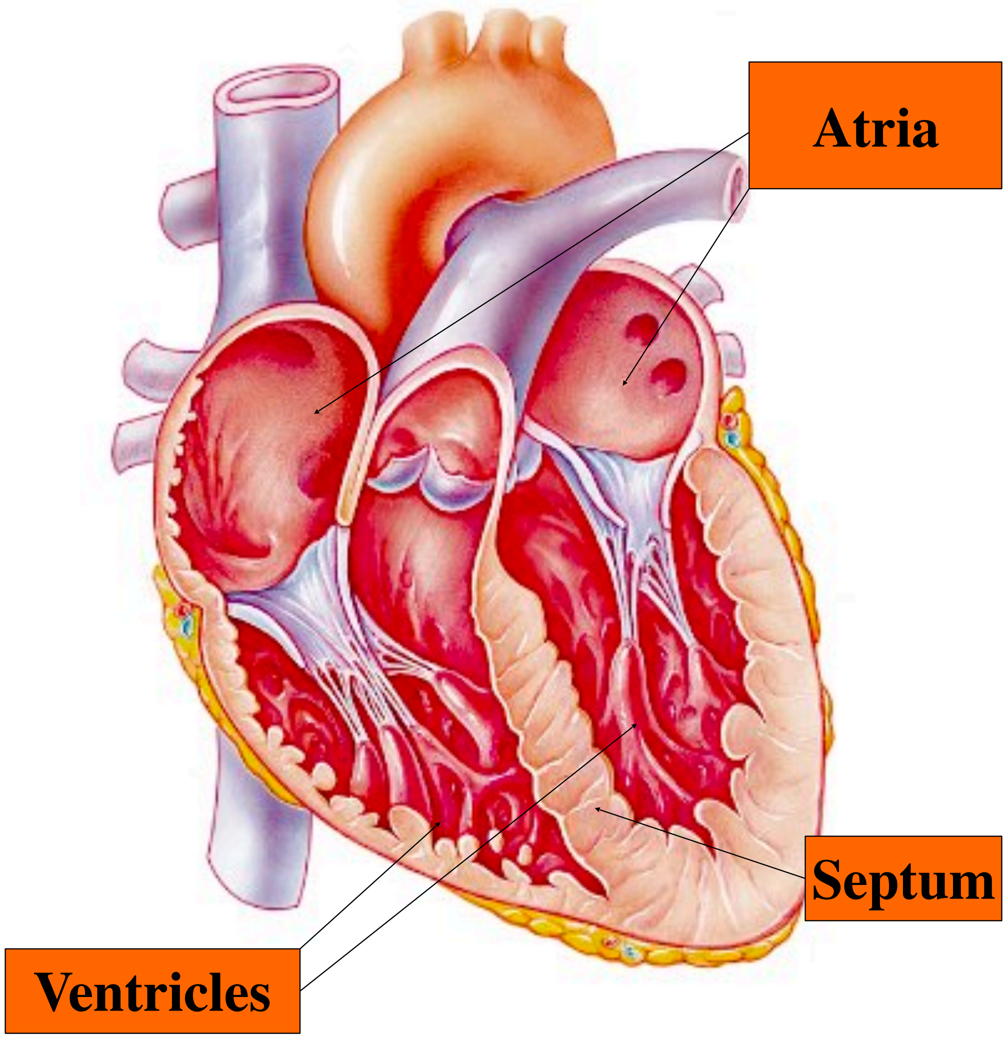
Heart Size, Location and Position

- The heart is about the size of a fist
- It weighs between 250 - 350 grams
- Located in the medial cavity of the thorax, the mediastinum
- It extends from the 2nd rib to 5th intercostal space
- Rests on the superior surface of diaphram



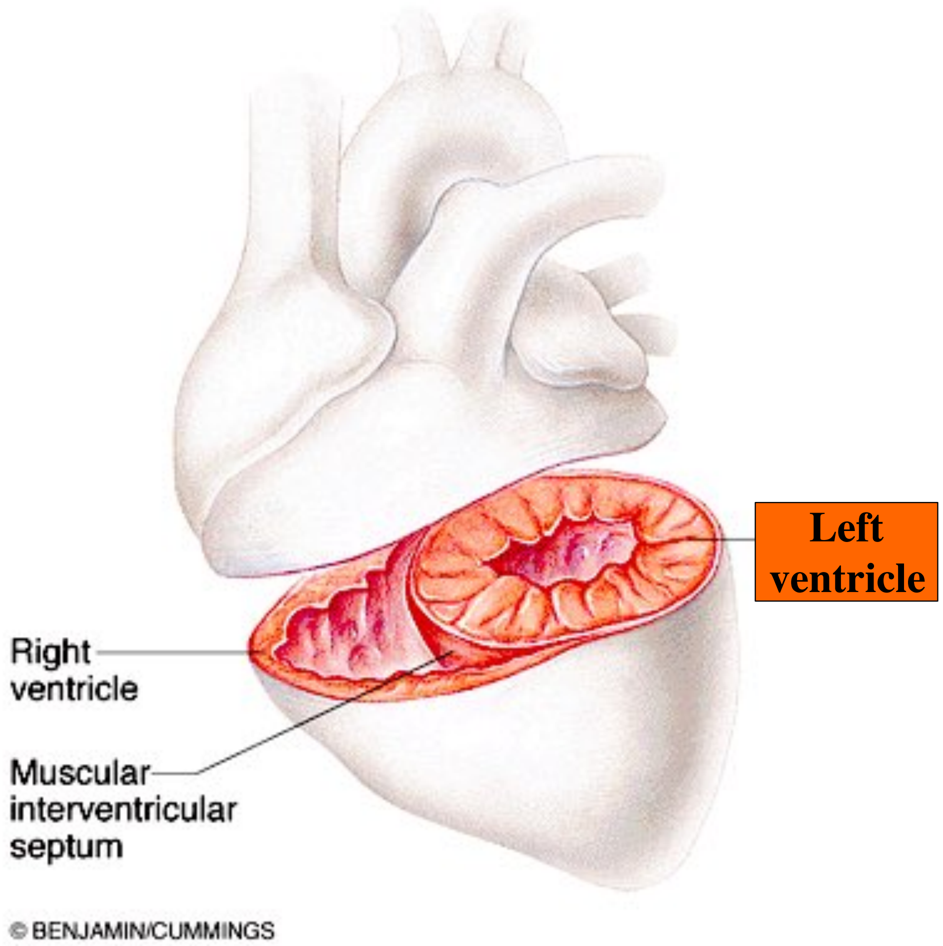
Chambers and Great Vessels

- The heart has four chambers
  - Two superior atria
  - Two inferior ventricles
- The longitudinal wall separating the chambers is called the
  - Interartial septum
    - Between atria
  - Interventricular septum
    - Between ventricles



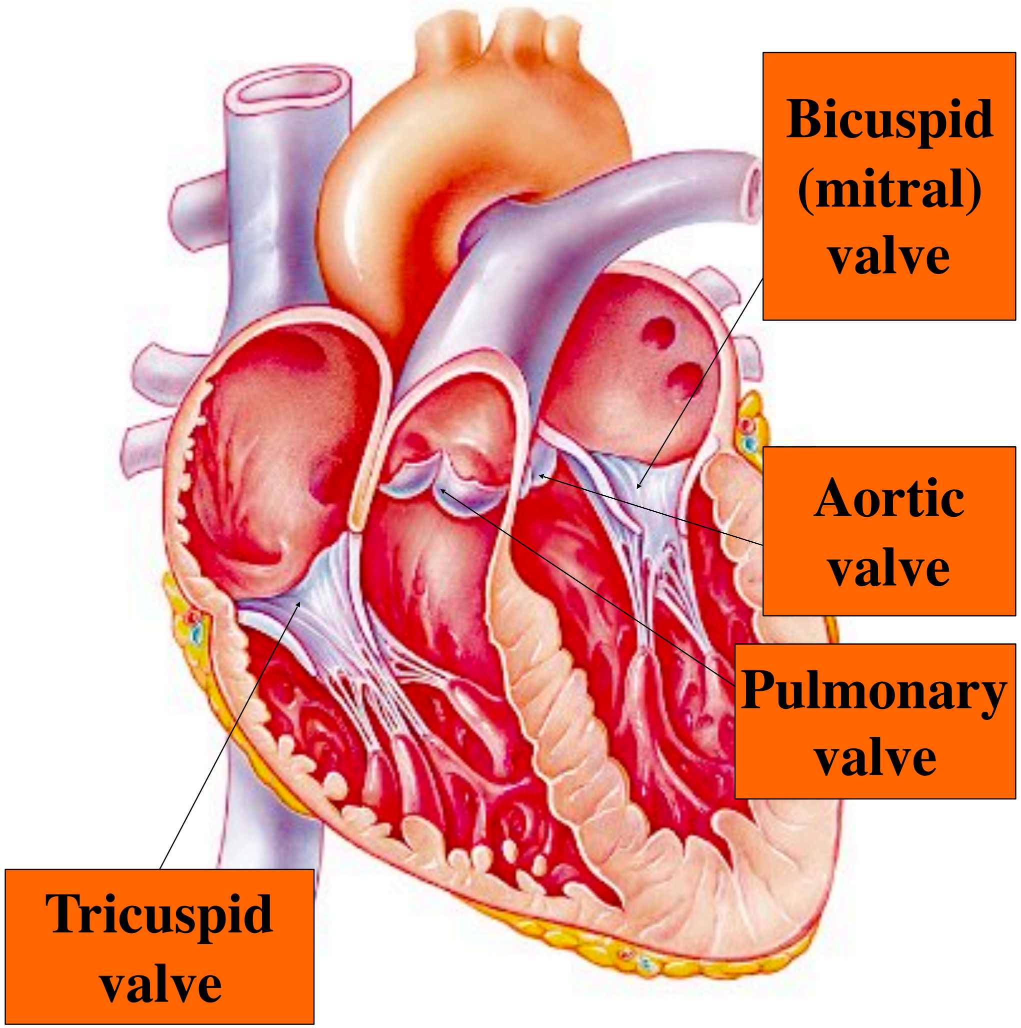
Ventricles: Discharging Chambers

- The difference in system work load is revealed in the comparative anatomy of the two ventricles
- The walls of the left ventricle are three times as thick as those of the right ventricle



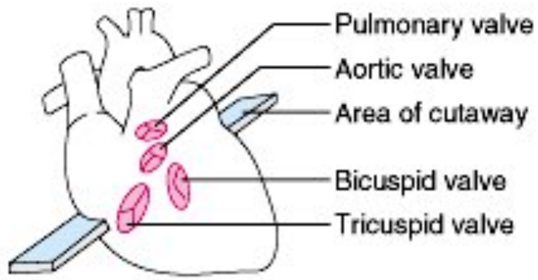
Heart Valves

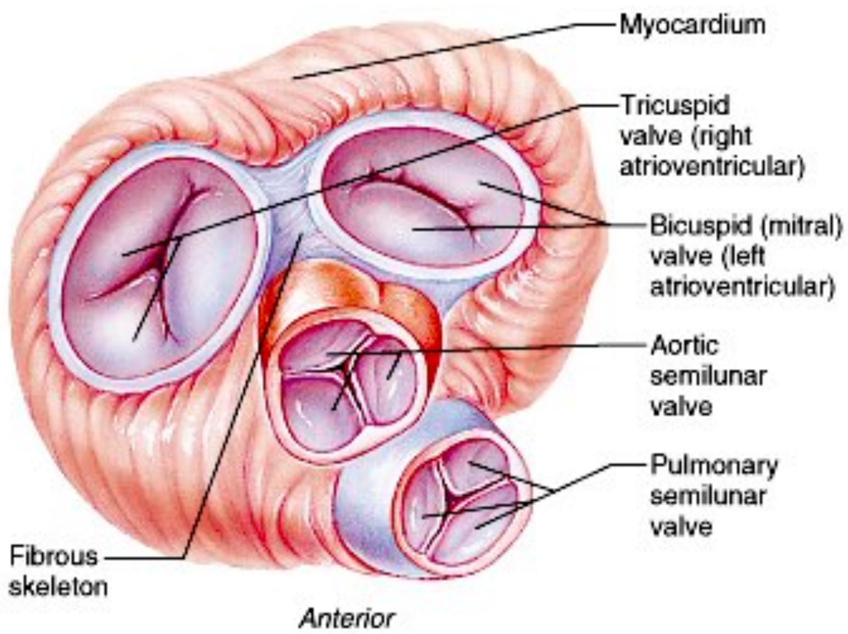
- Heart valves are positioned between the atria and the ventricles and between the ventricles and the large arteries that leave the heart
- Valves open and close in response to differences in blood pressure



Heart Valves

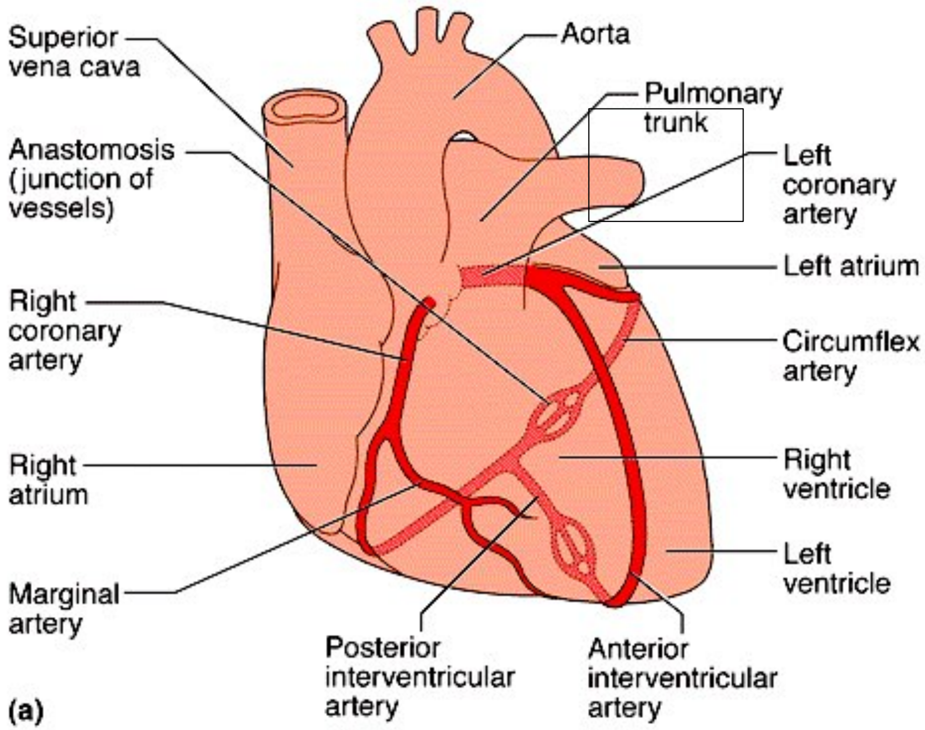
- The valves of the heart allow for the blood to flow in only one direction
- Note: View of the heart with the superior atria removed





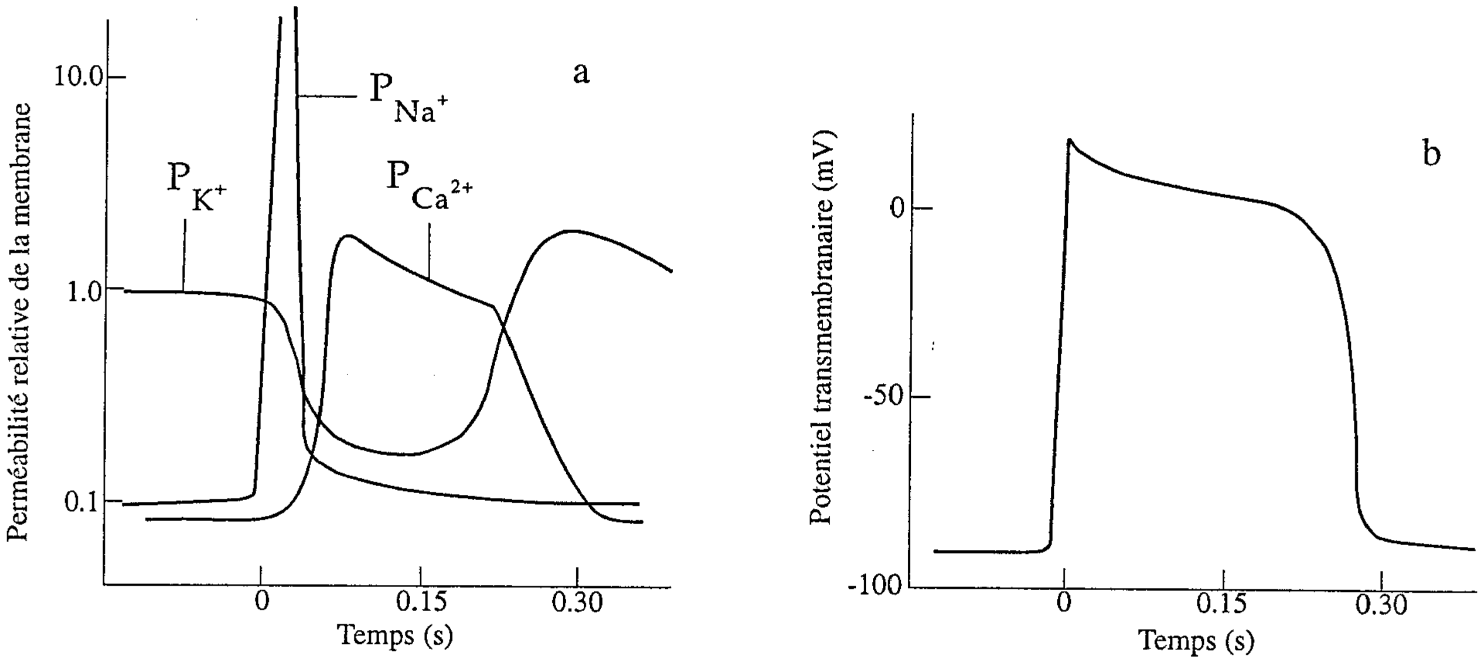
Coronary Circulation

- The coronary circulation, the functional blood supply of the heart, is the shortest circulation in the body
- The arterial supply of the coronary circulation is provided by the right and left coronary arteries

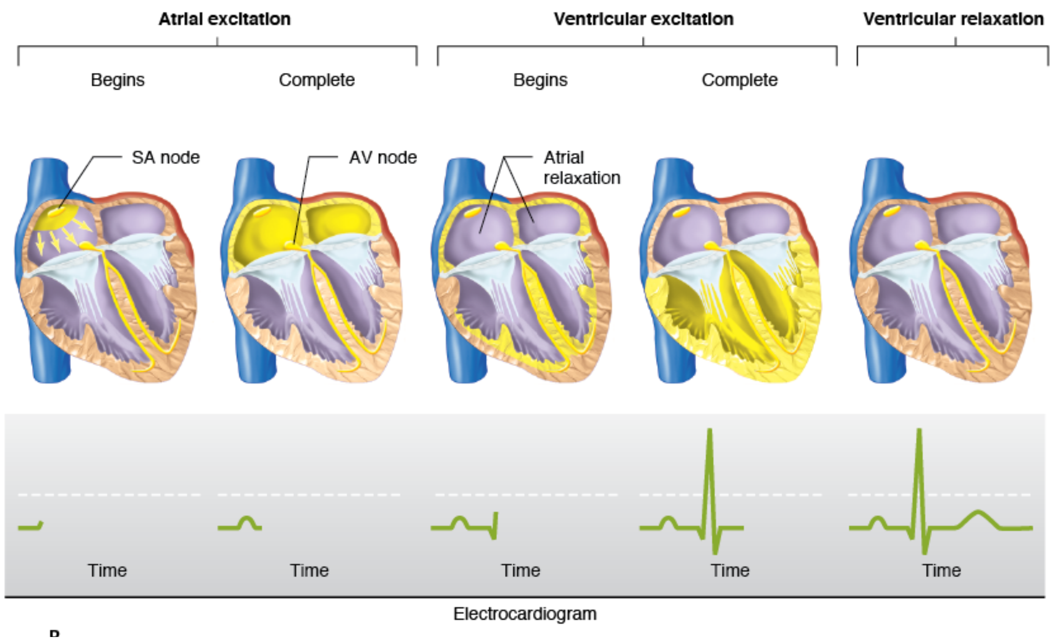


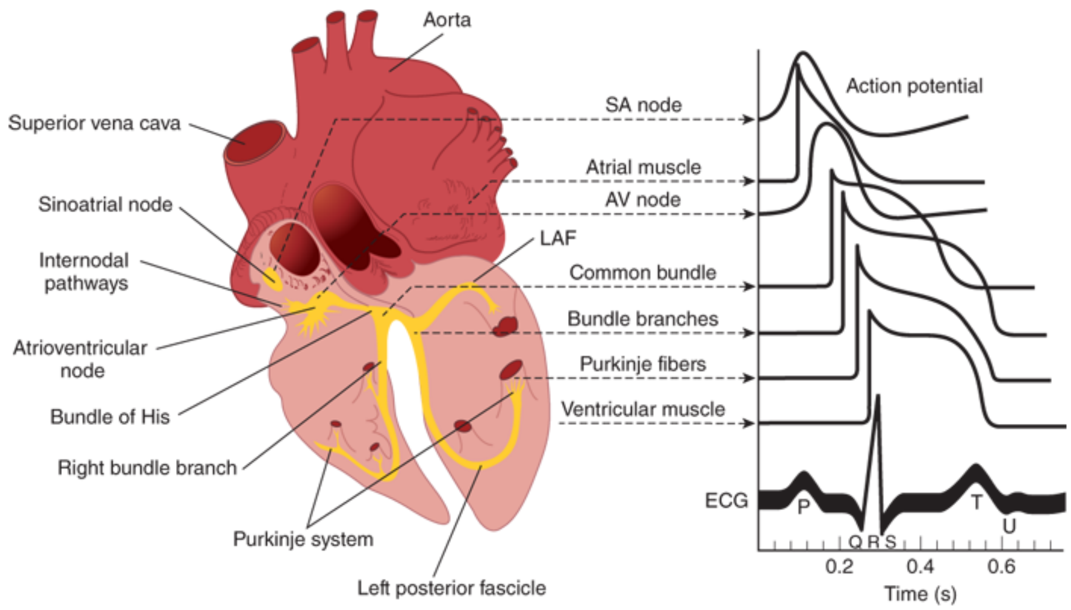
(a)

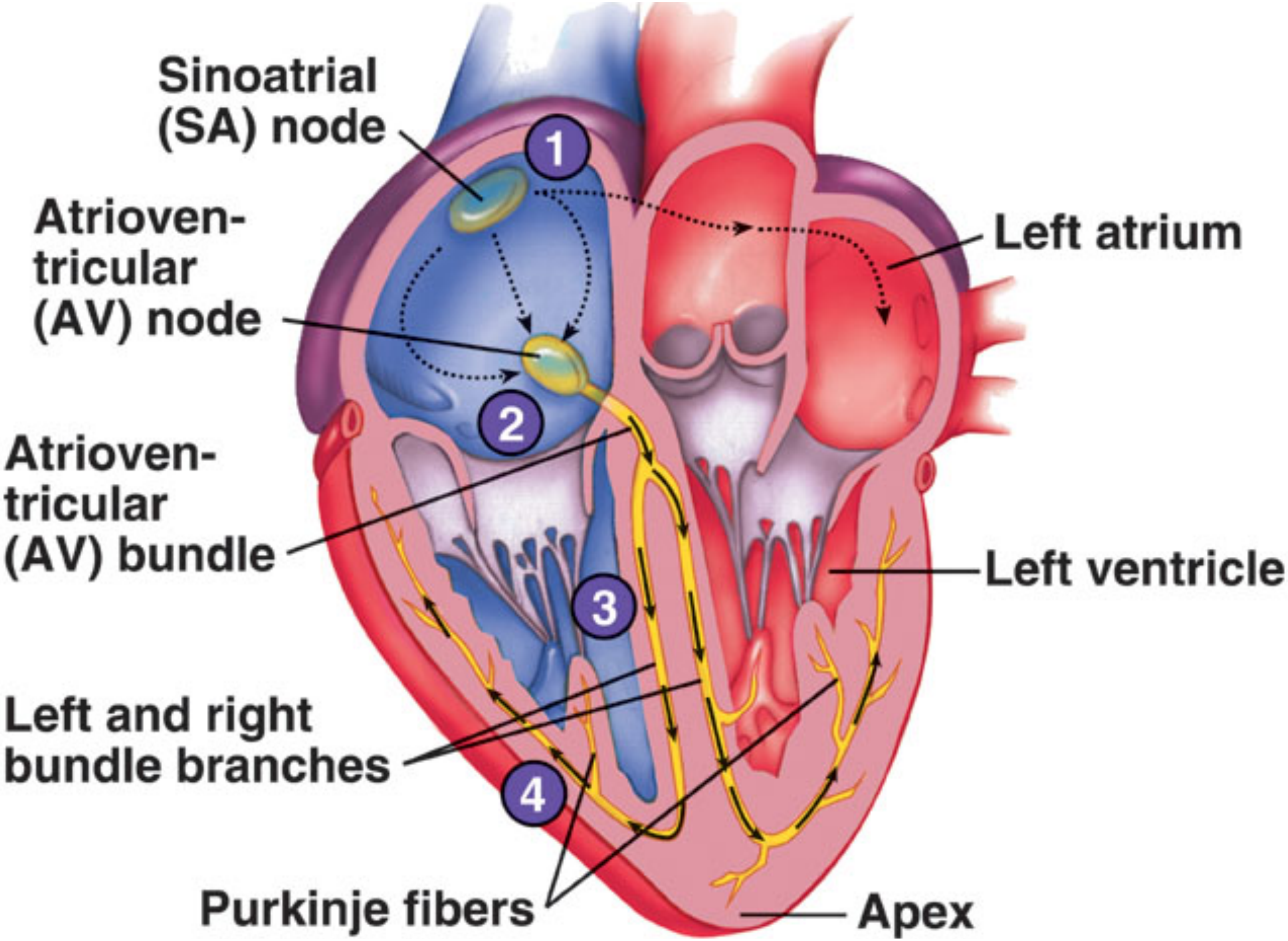
Electrical activity of the heart

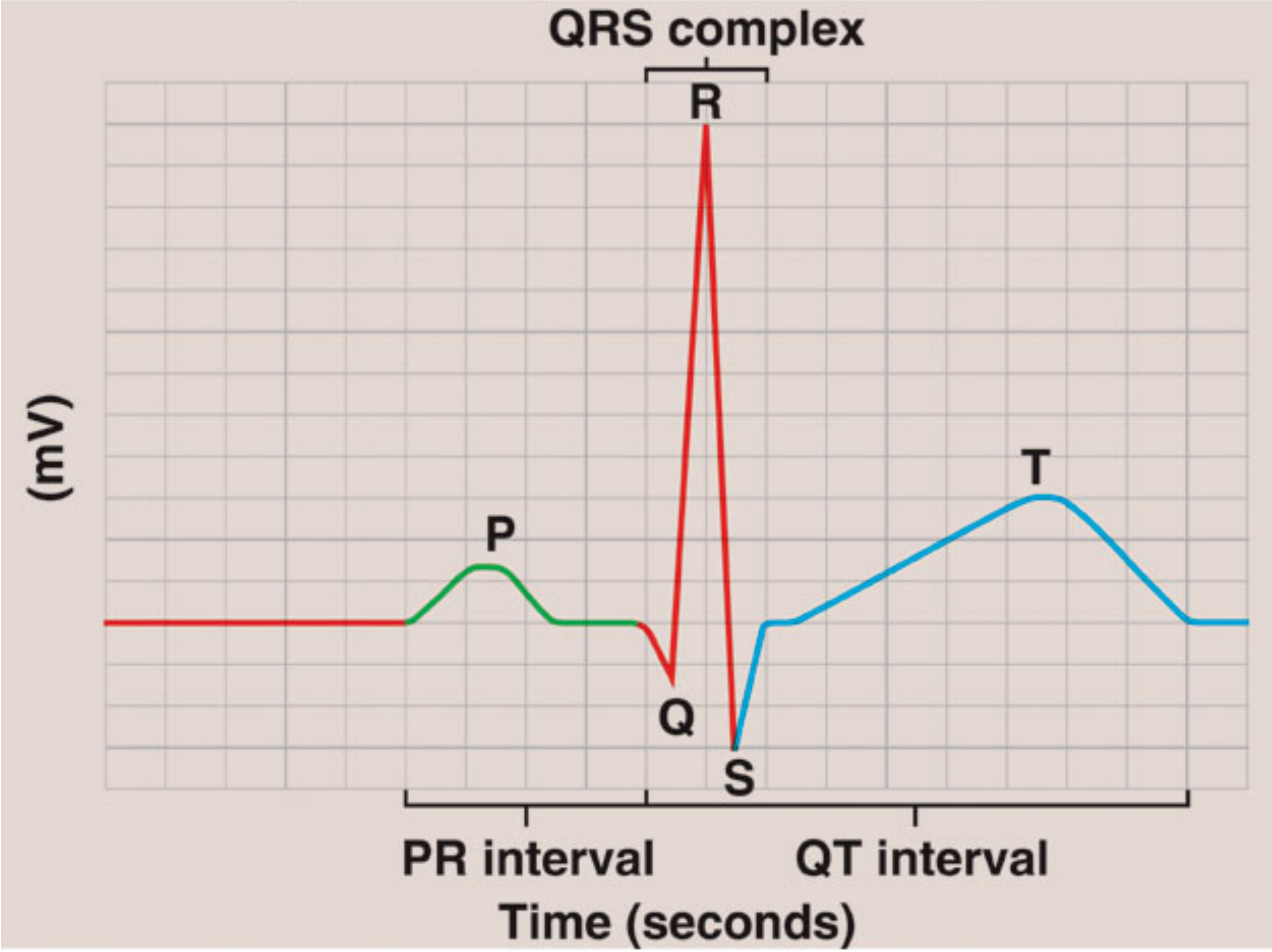


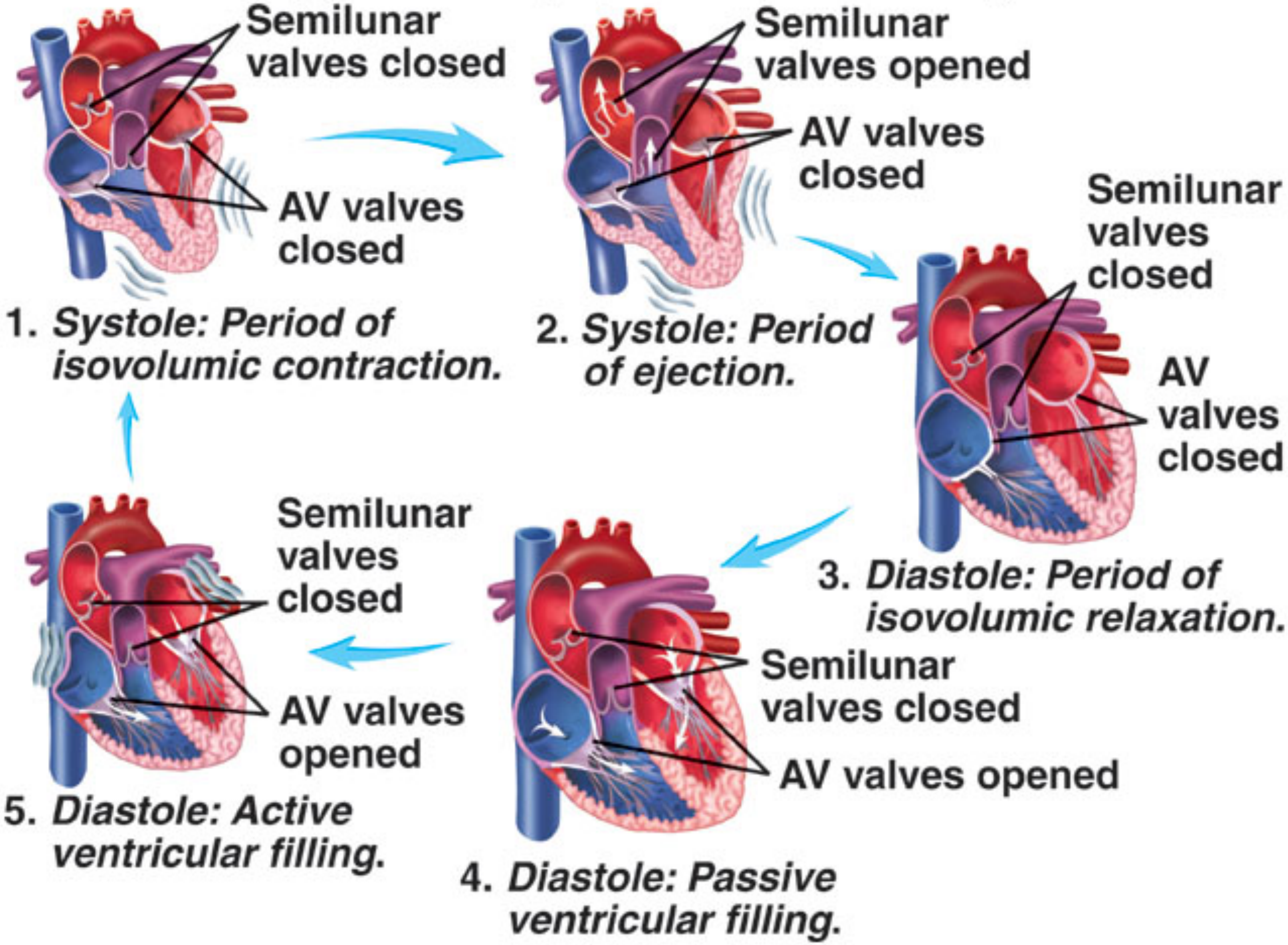
Electrical activity of the heart

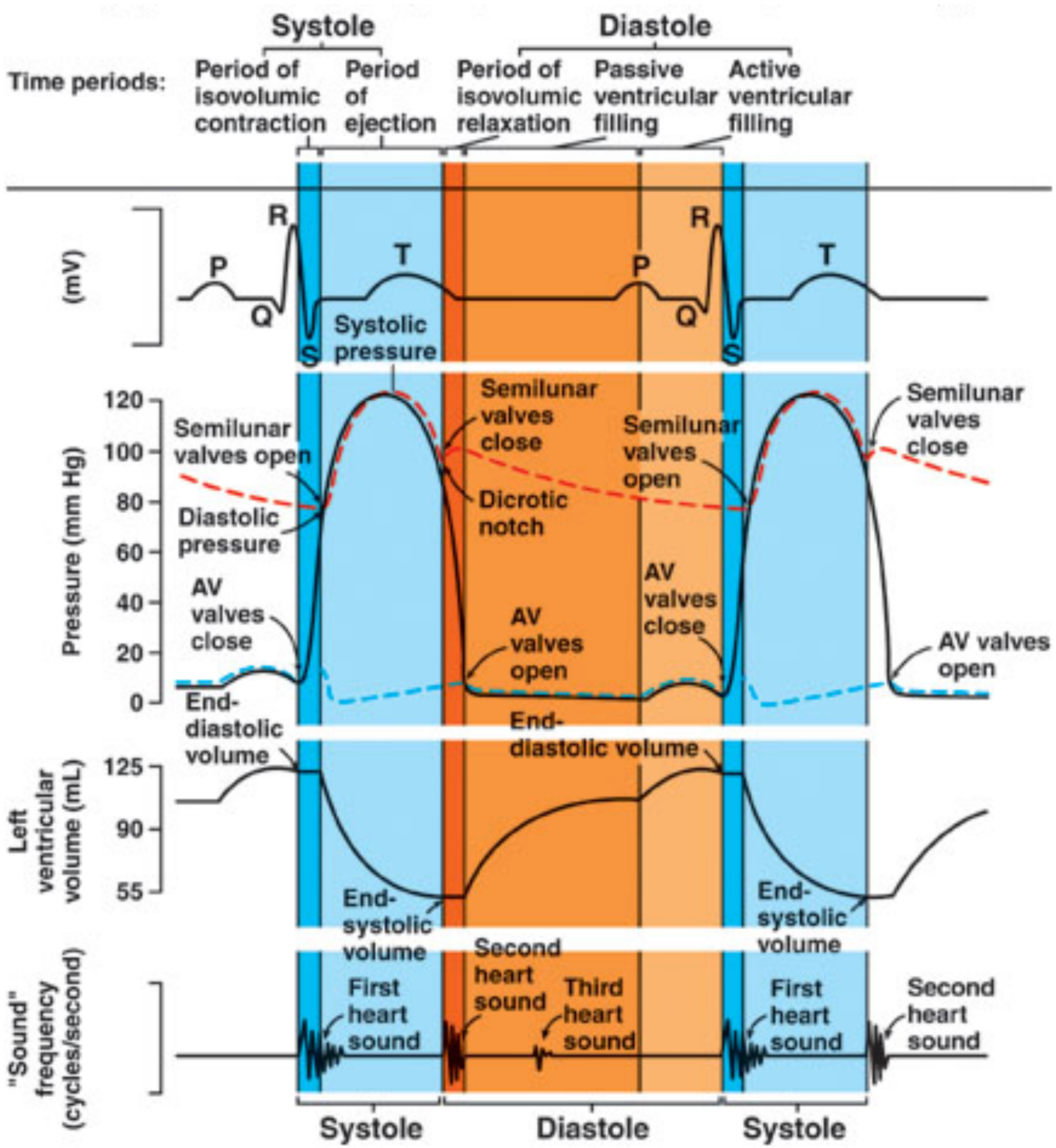




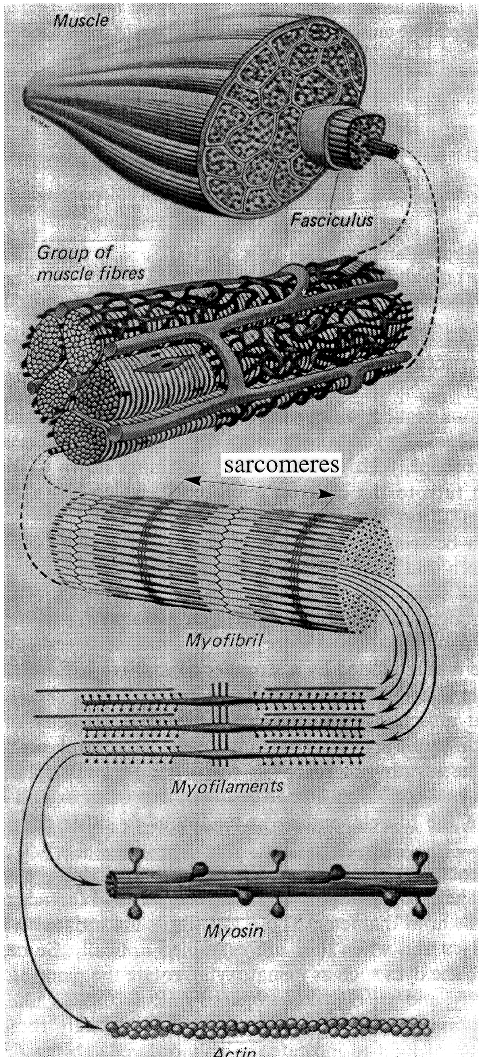

Sinoatrial
(SA) node
Atrioven-
tricular
(AV) node
Atrioven-
tricular
(AV) bundle
Left and right
bundle branches
Purkinje fibers
Left atrium
Left ventricle
Apex
1
2
3
4

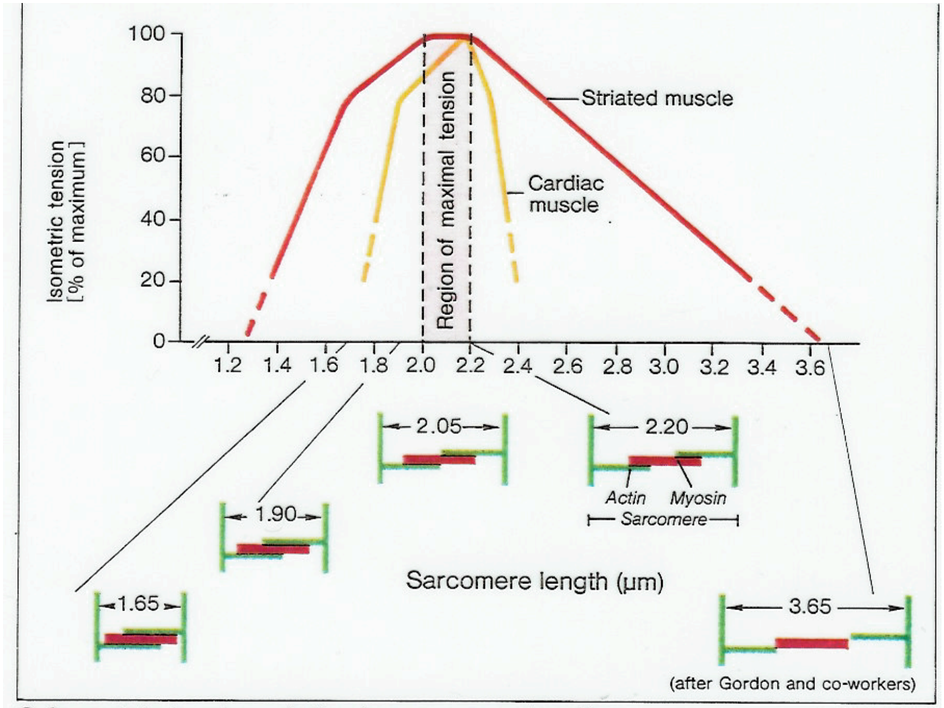

QRS complex
R
P
T
Q
S
(mV)
PR interval
QT interval
Time (seconds)


Semilunar valves closed
AV valves closed
1. Systole: Period of isovolumic contraction.
Semilunar valves opened
AV valves closed
2. Systole: Period of ejection.
Semilunar valves closed
AV valves closed
3. Diastole: Period of isovolumic relaxation.
Semilunar valves closed
AV valves opened
4. Diastole: Passive ventricular filling.
Semilunar valves closed
AV valves opened
5. Diastole: Active ventricular filling.


Systole
Diastole
Time periods:
Period of isovolumic contraction
Period of ejection
Period of isovolumic relaxation
Passive ventricular filling
Active ventricular filling
(mV)
P
Q
R
S
T
Systolic pressure
Pressure (mm Hg)
120
100
80
60
40
20
0
Semilunar valves open
Diastolic pressure
AV valves close
Semilunar valves close
Dicrotic notch
AV valves open
End-diastolic volume
Left ventricular volume (mL)
125
90
55
End-systolic volume
"Sound" frequency (cycles/second)
First heart sound
Second heart sound
Third heart sound
Systole
Diastole
Systole

Muscle biomechanics

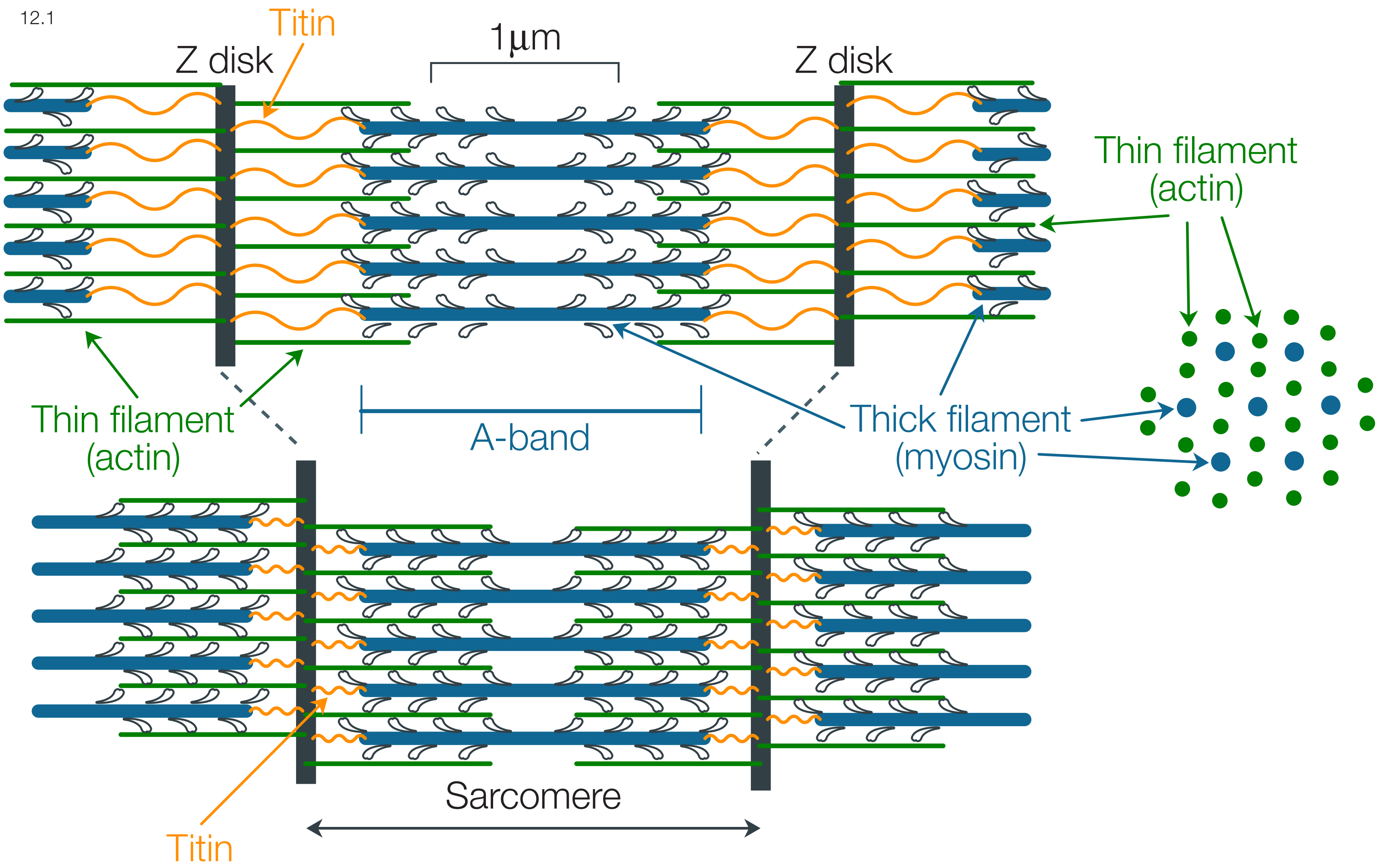




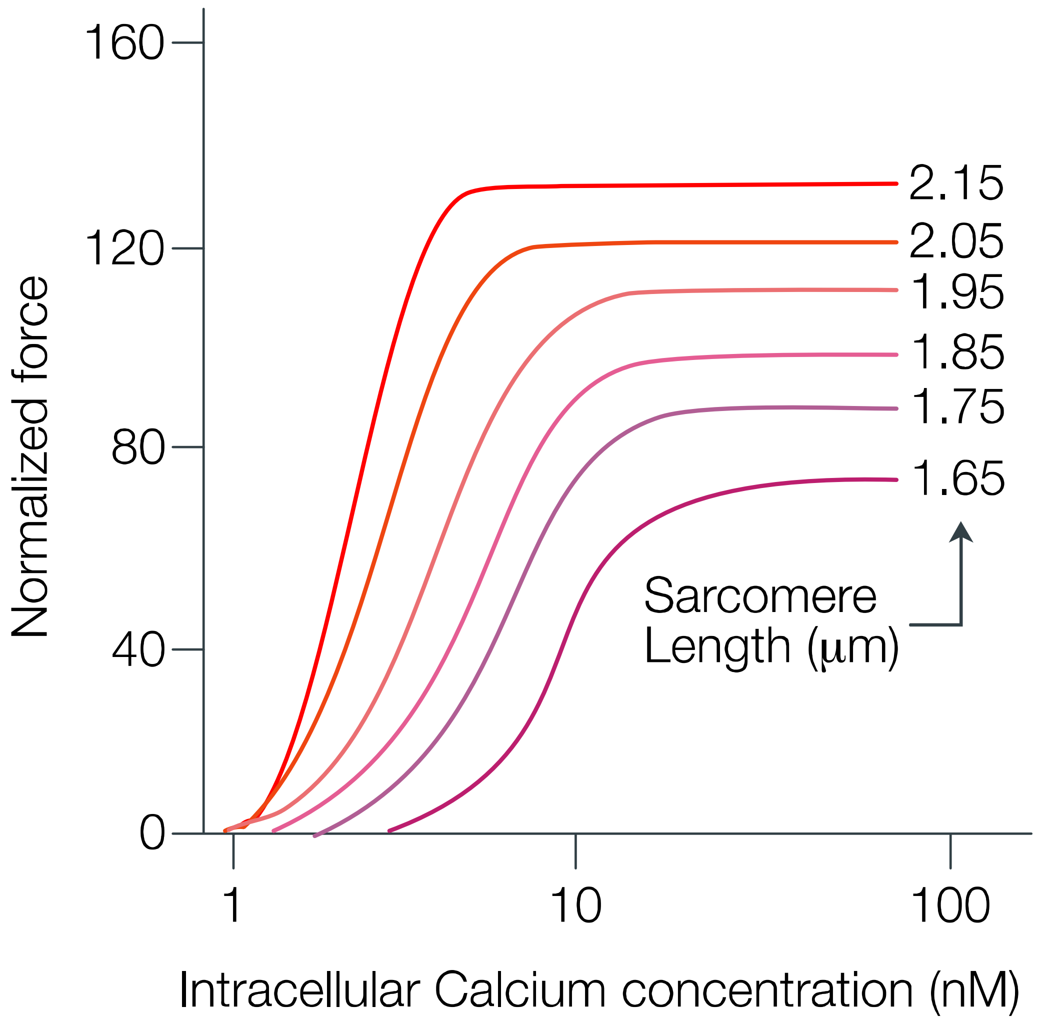
C. Isometric tension relative to sarcomere length

The sarcomere

12.1

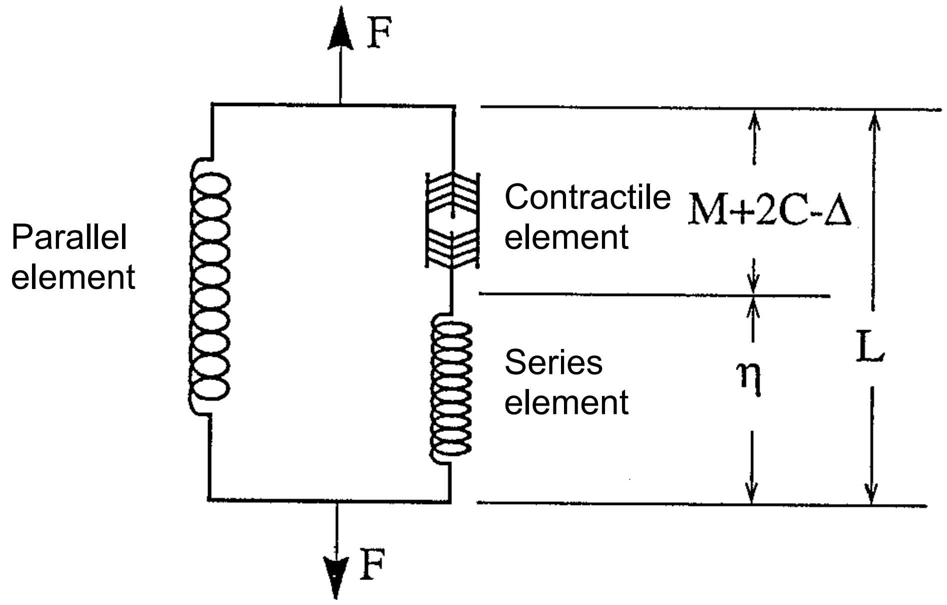


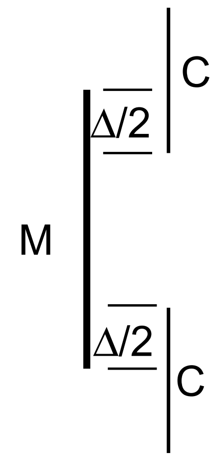
Force vs. [Ca^{2+}] and length of sarcomere

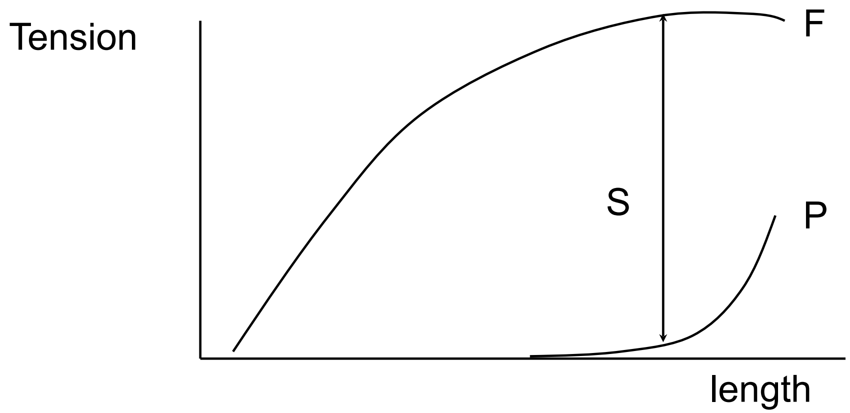


12.2

Hill's model





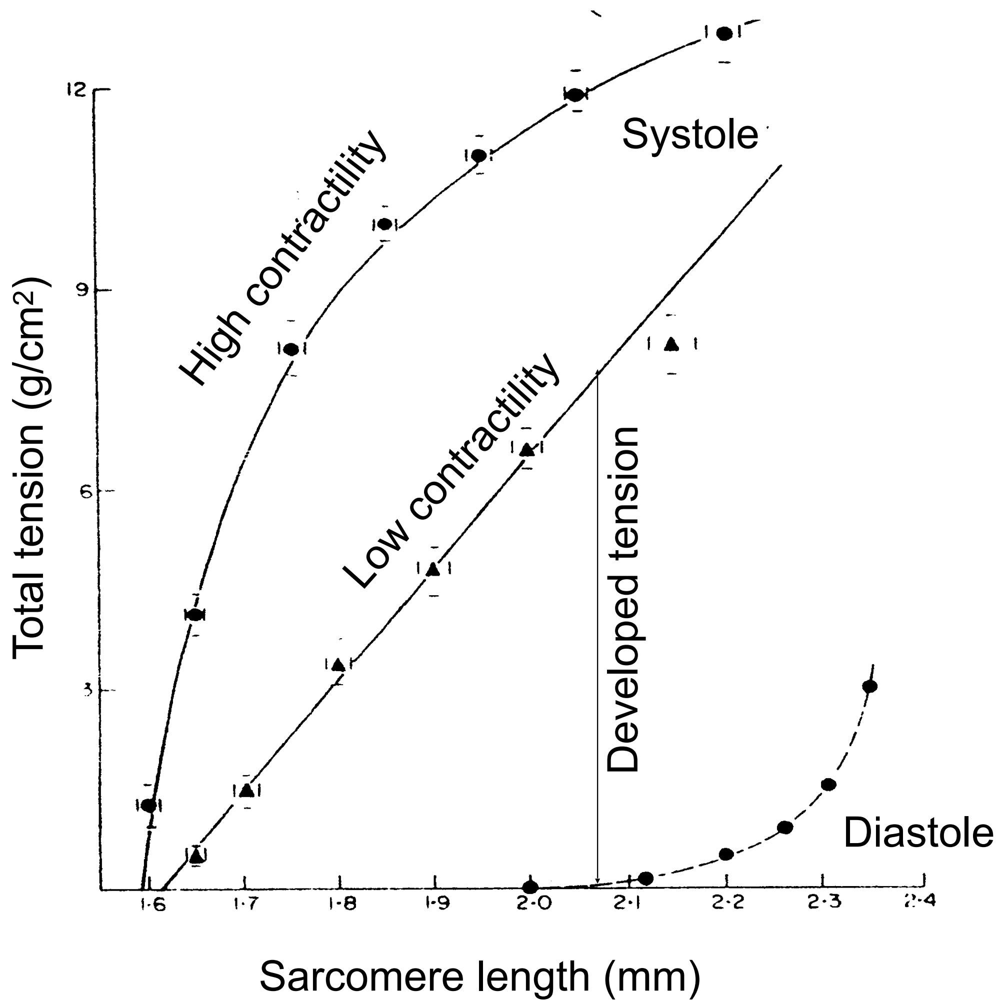


$$F = P(L) + S(\eta)$$

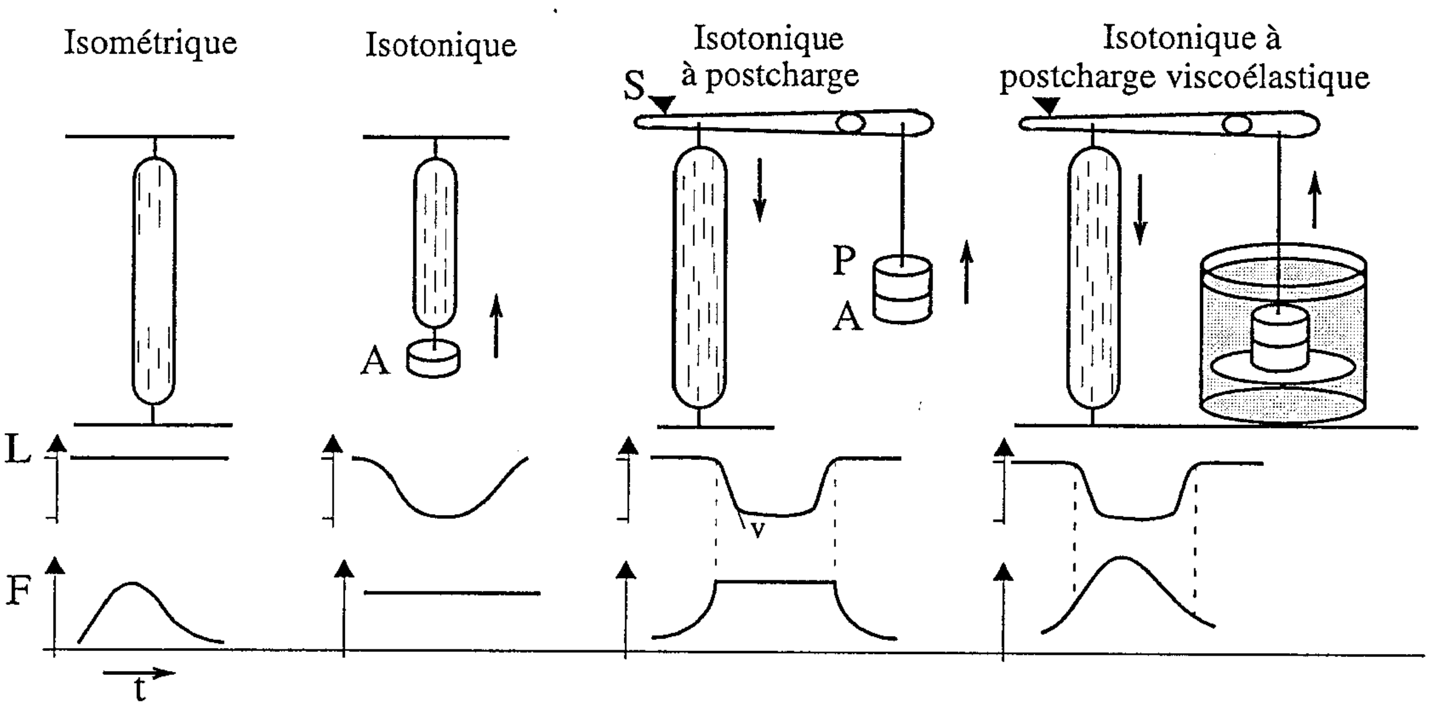
$$L = M + 2C - \Delta + \eta$$

$$\frac{dL}{dt} = -\frac{d\Delta}{dt} + \frac{d\eta}{dt}$$

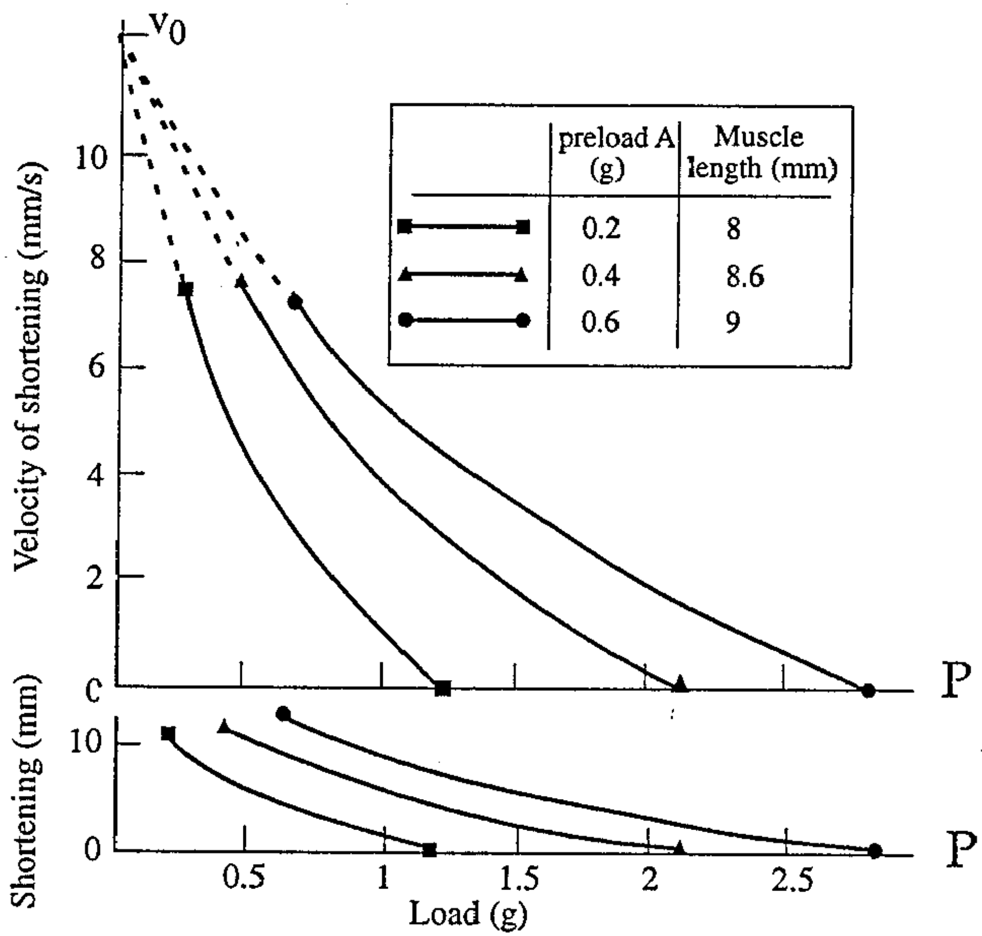
Force-length relation



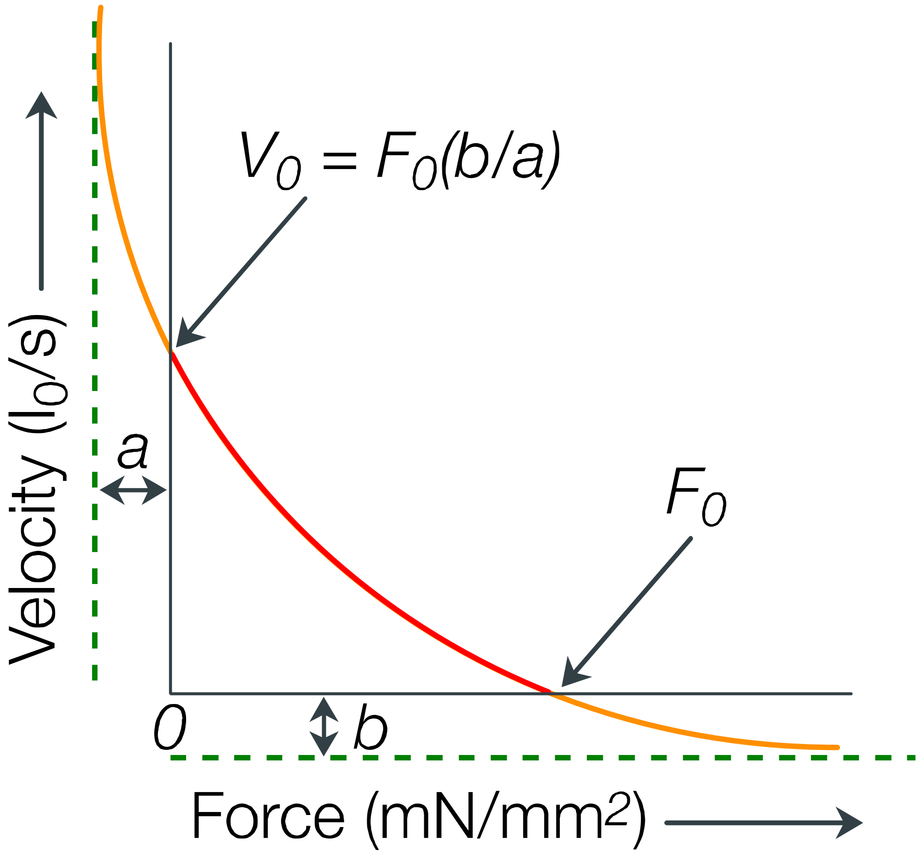
Cardiac muscle biomechanics



Effect of preload on length and velocity of contraction



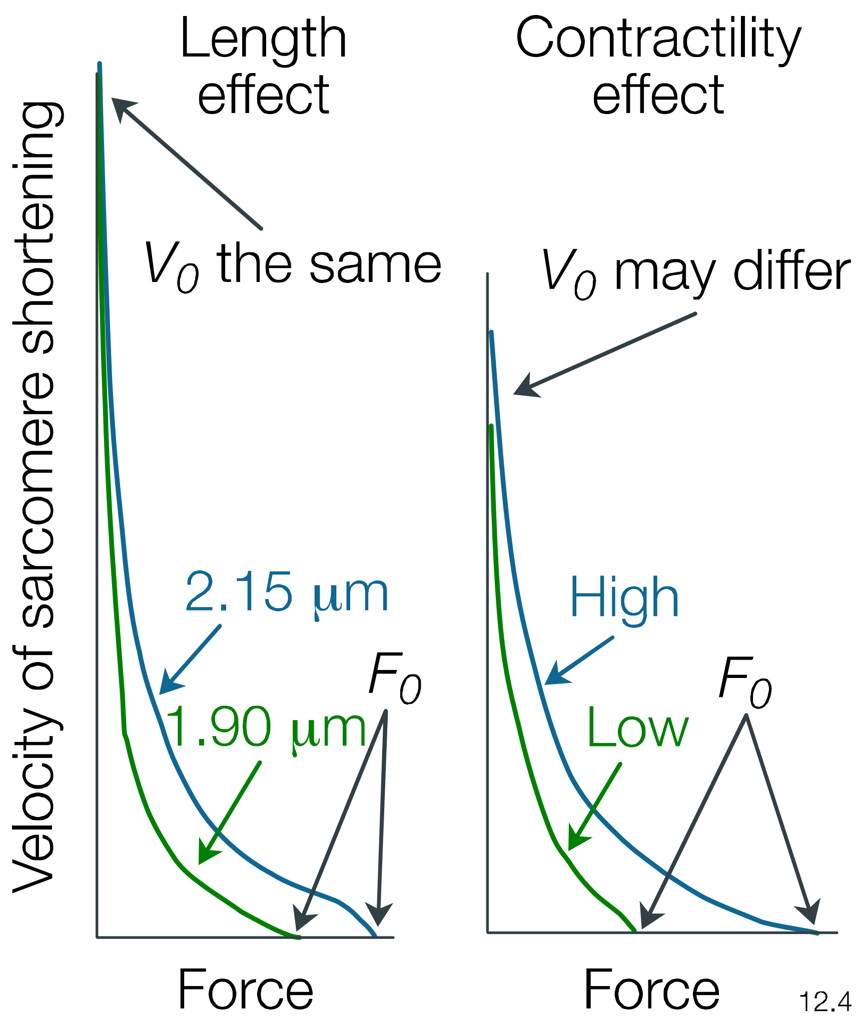
Force-velocity relation



Hill's model:

$(F+a)(v+b)=b(F_0+a)$

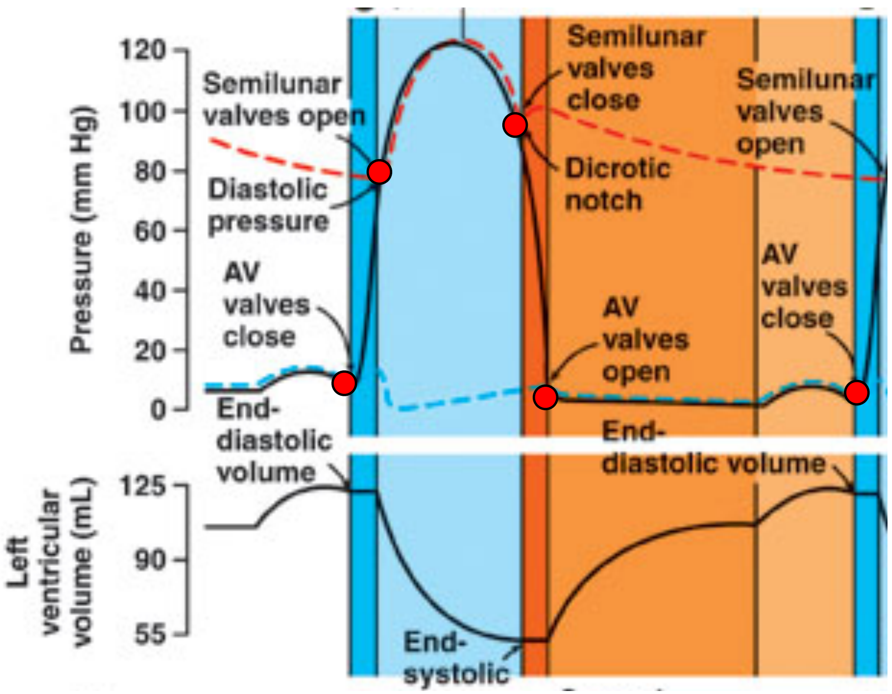
Force-velocity relation

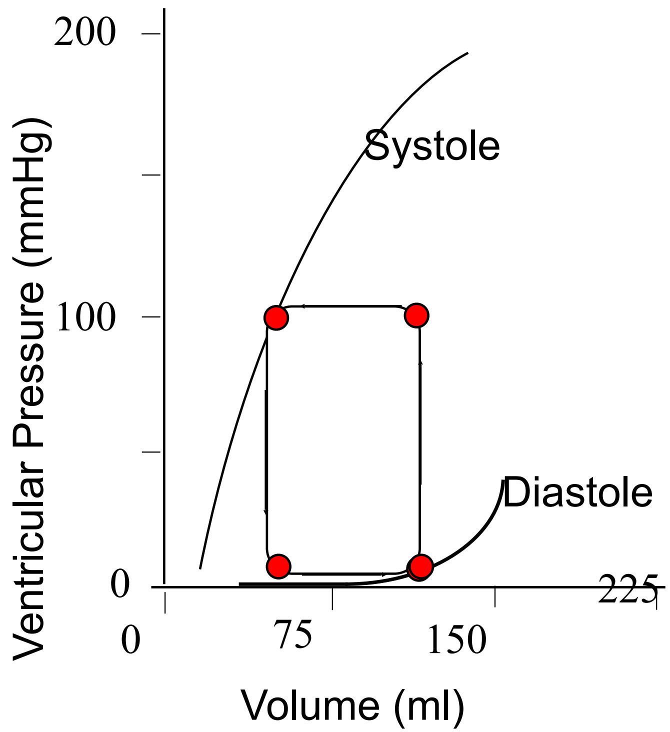


12.4

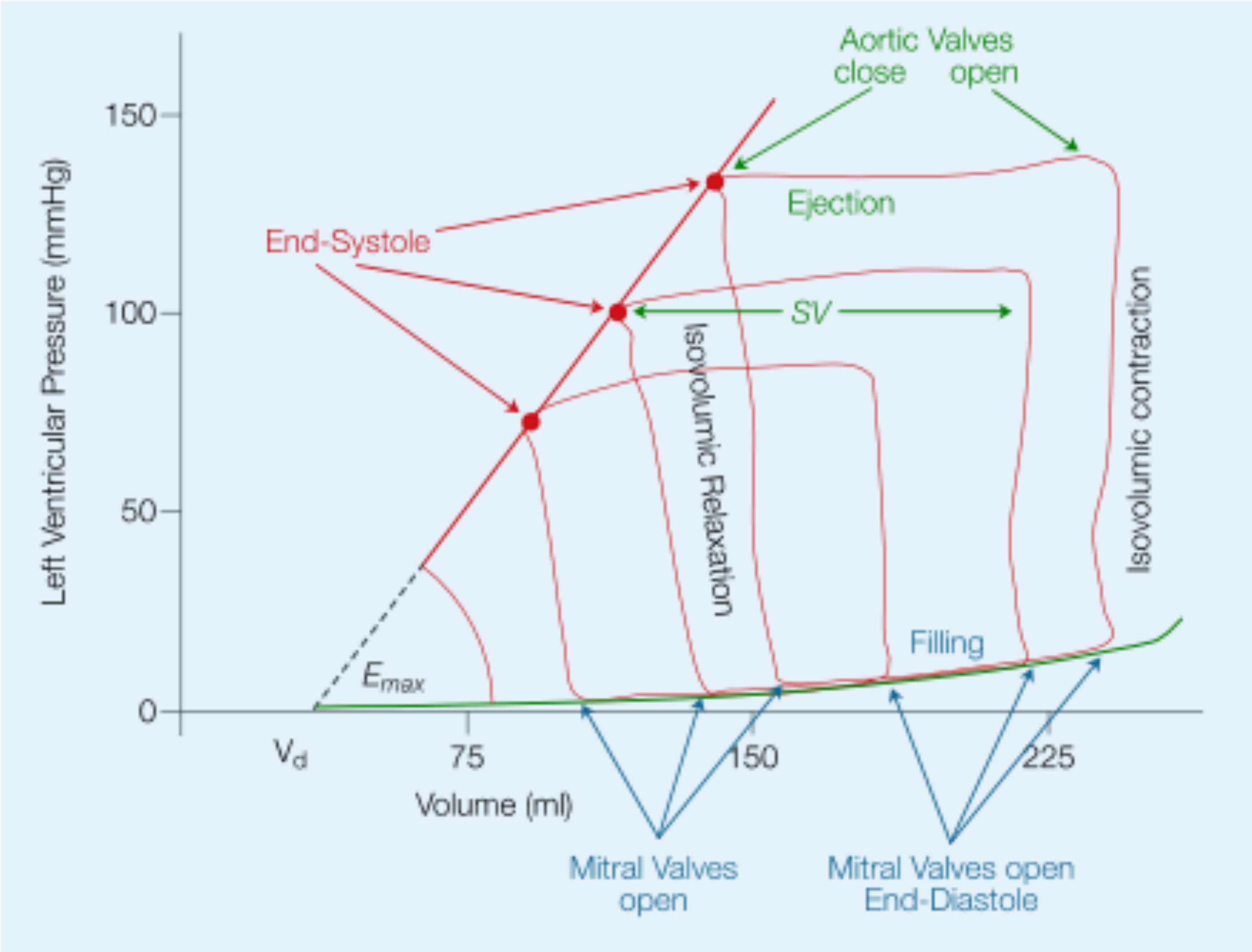
Pressure-Volume relation

Pressure-Volume relation

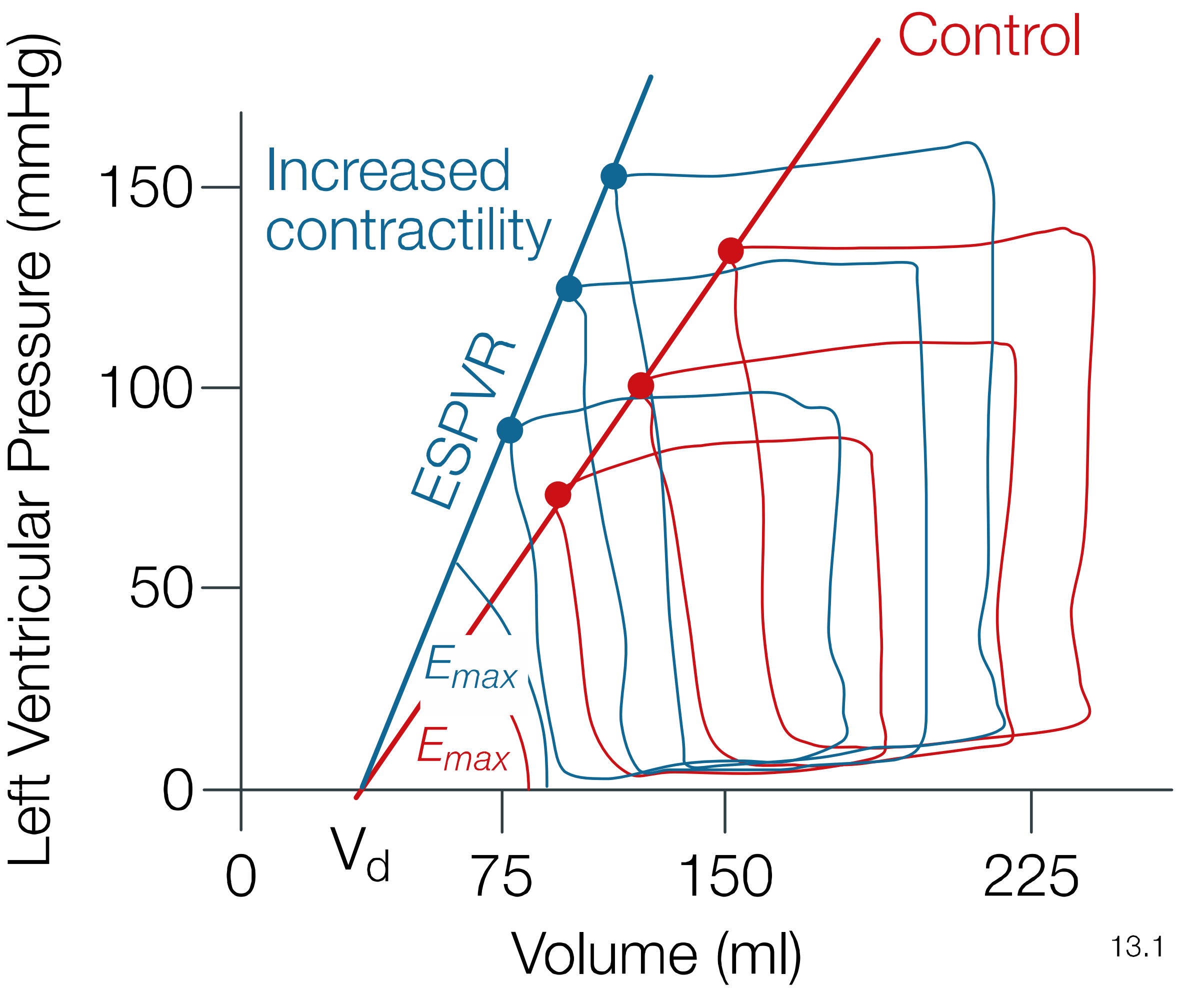




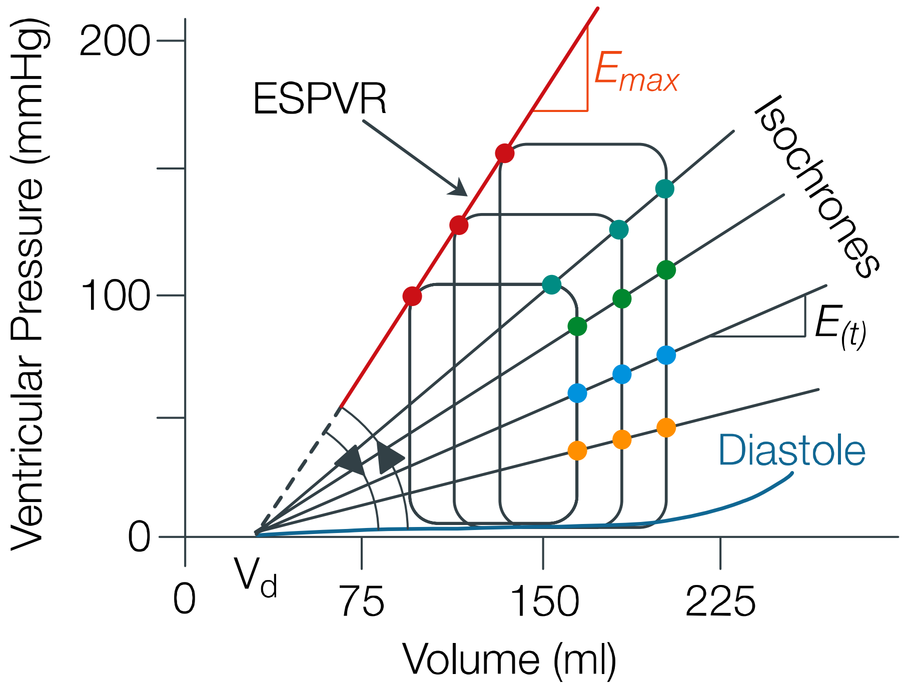
The cardiac cycle in P-V

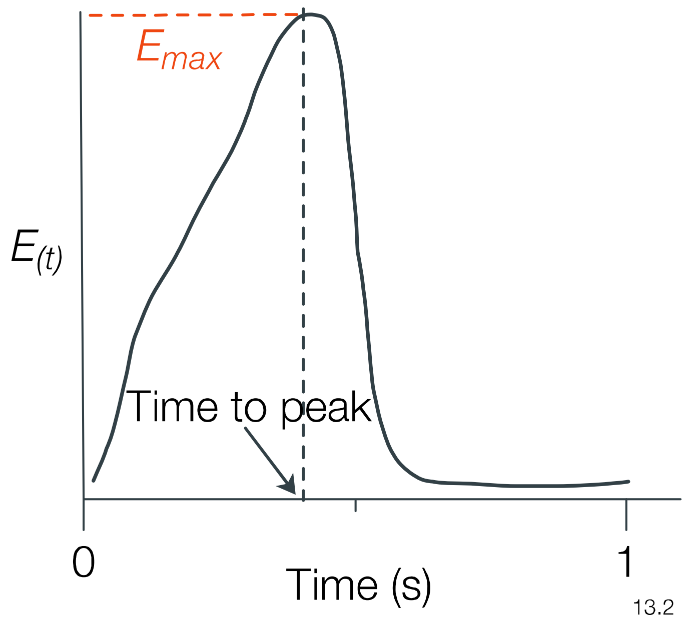


The cardiac cycle in P-V



Linearized pressure-volume relation

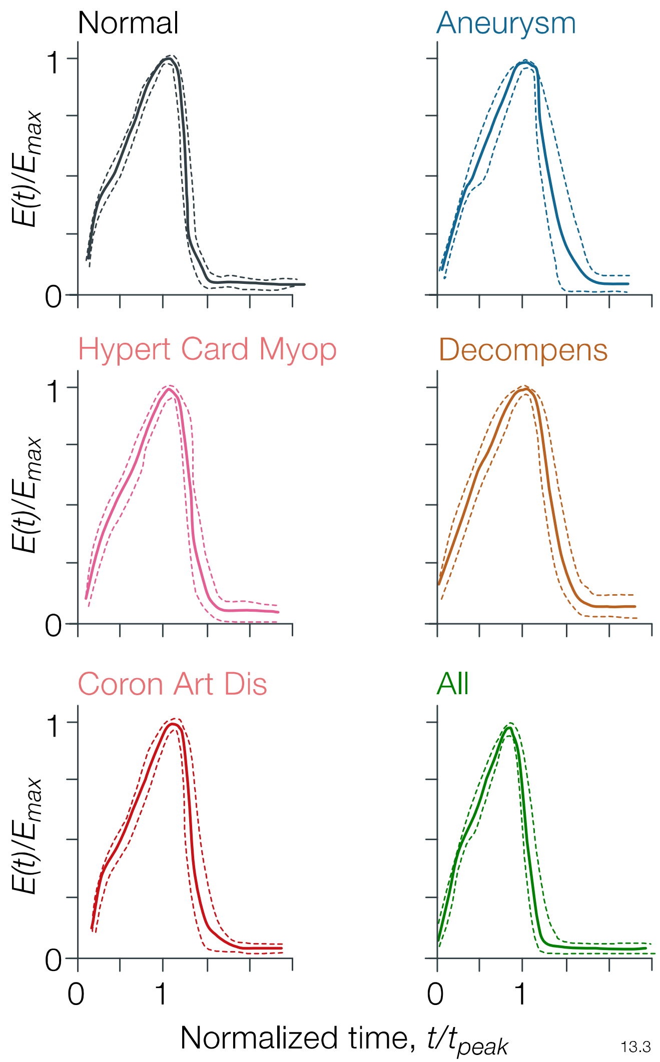




13.2

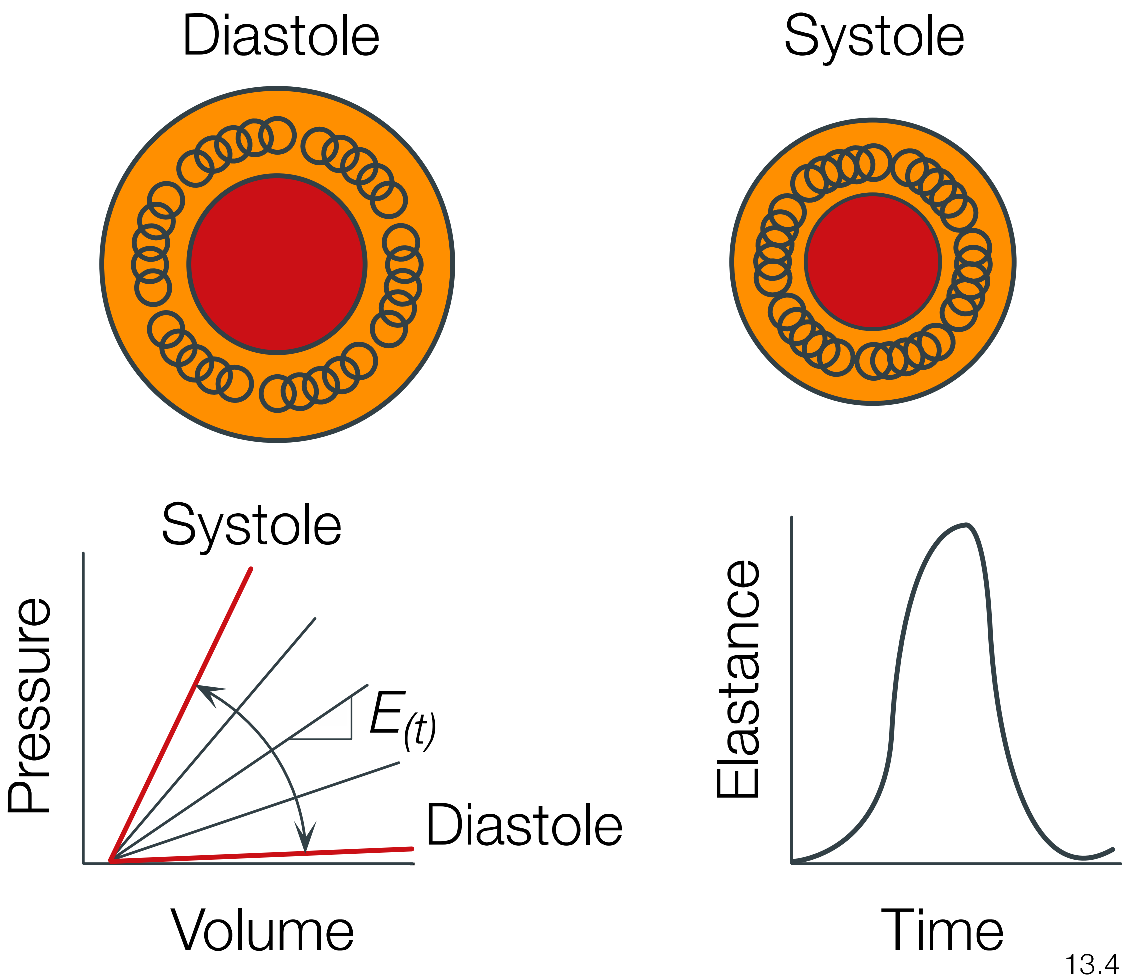
$$E(t) = \frac{P(t)}{V(t) - V_d}$$

Universality and uniqueness of the normalized E(t) curve



13.3

The varying elastance concept



13.4

Otto Frank’s experiment (1899)

wird, soweit er als potentielle Energie auftritt.

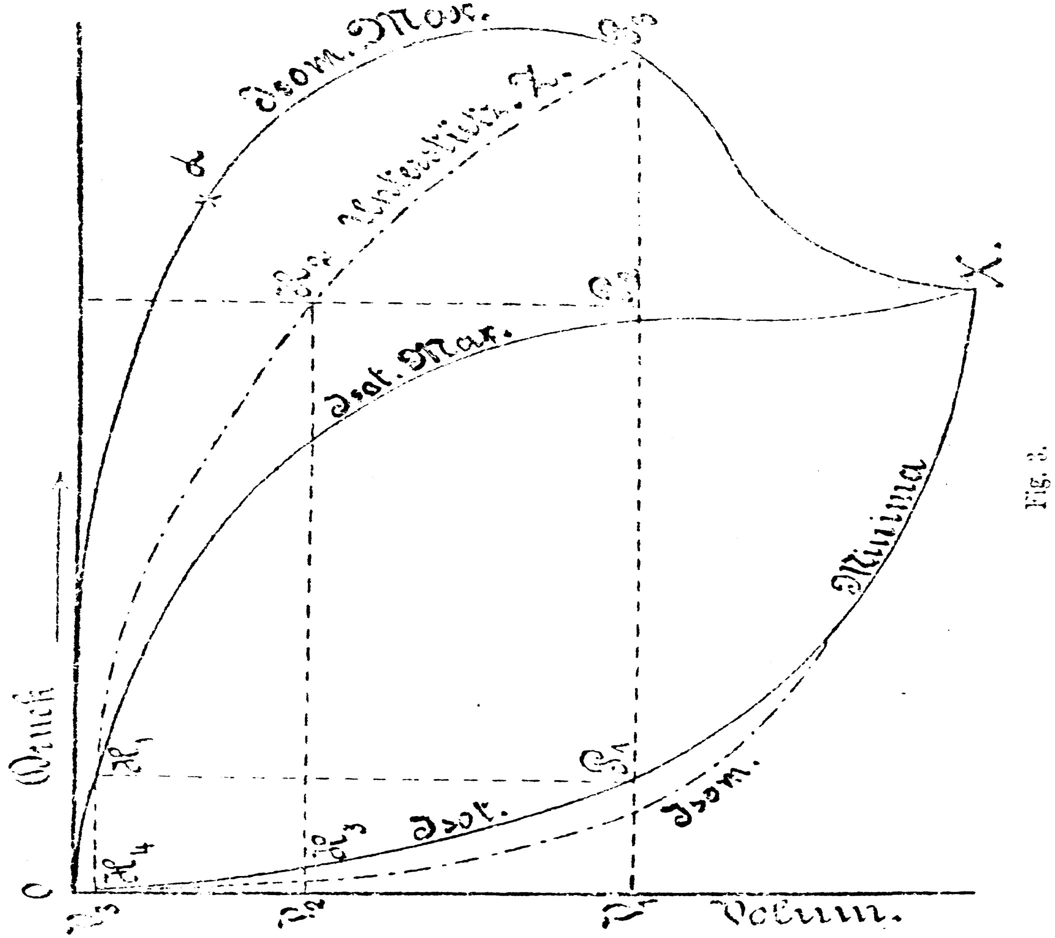
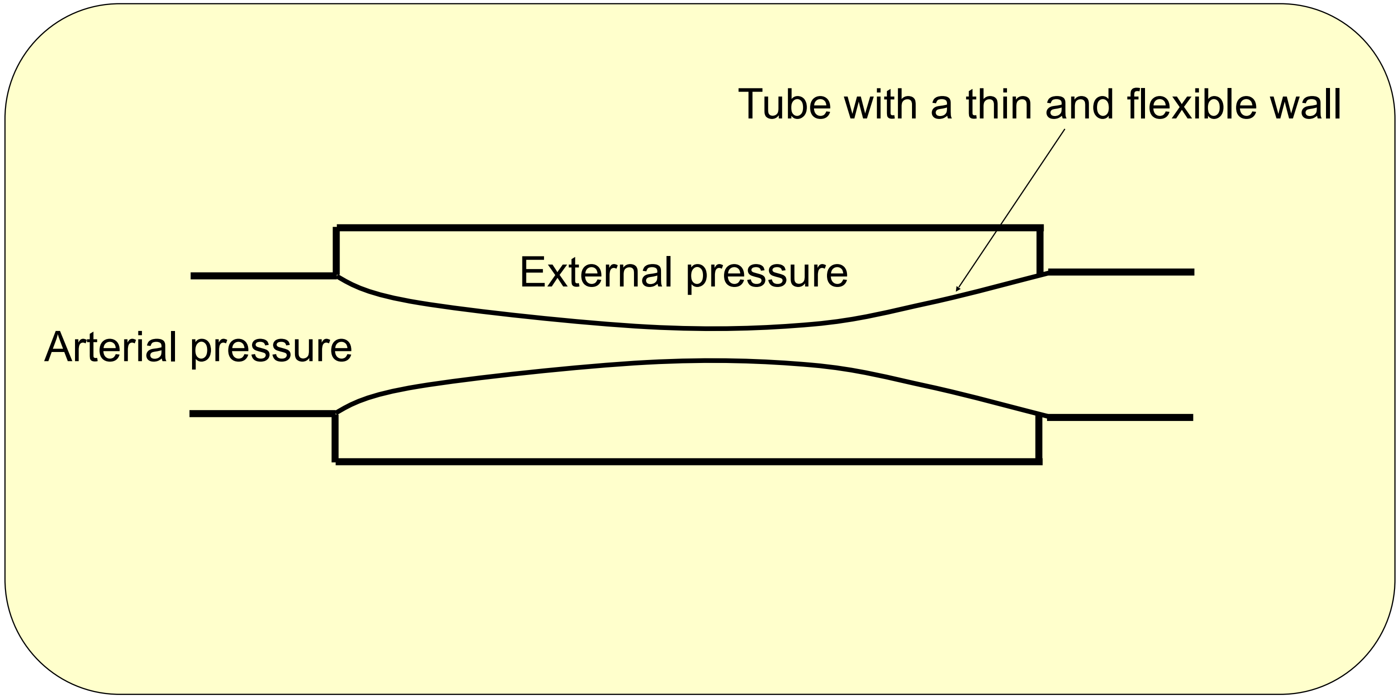


Fig. 3.

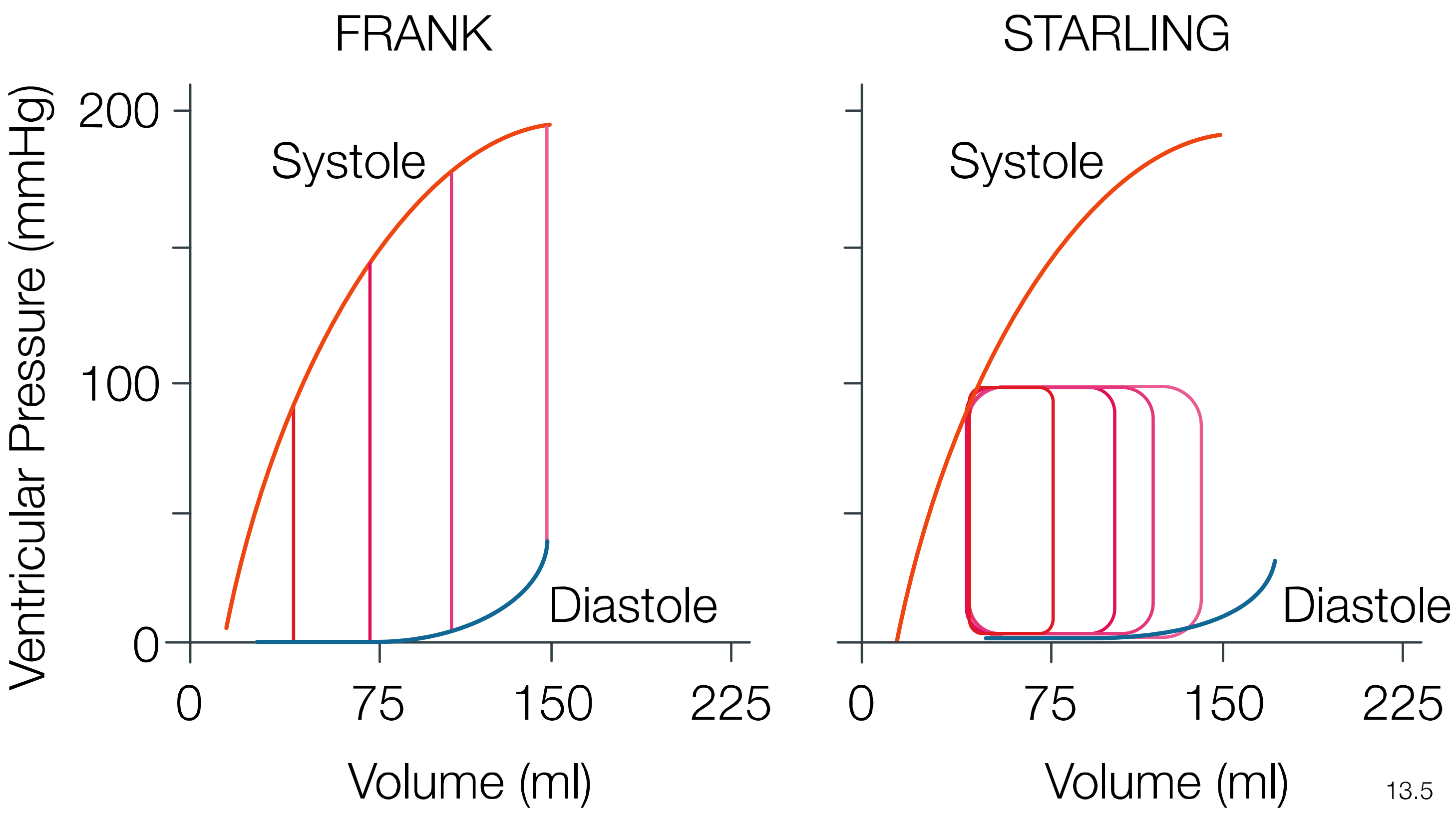
In diesem Schema stellen sich die idealen isometrischen Zu-

The Starling ‘resistor’



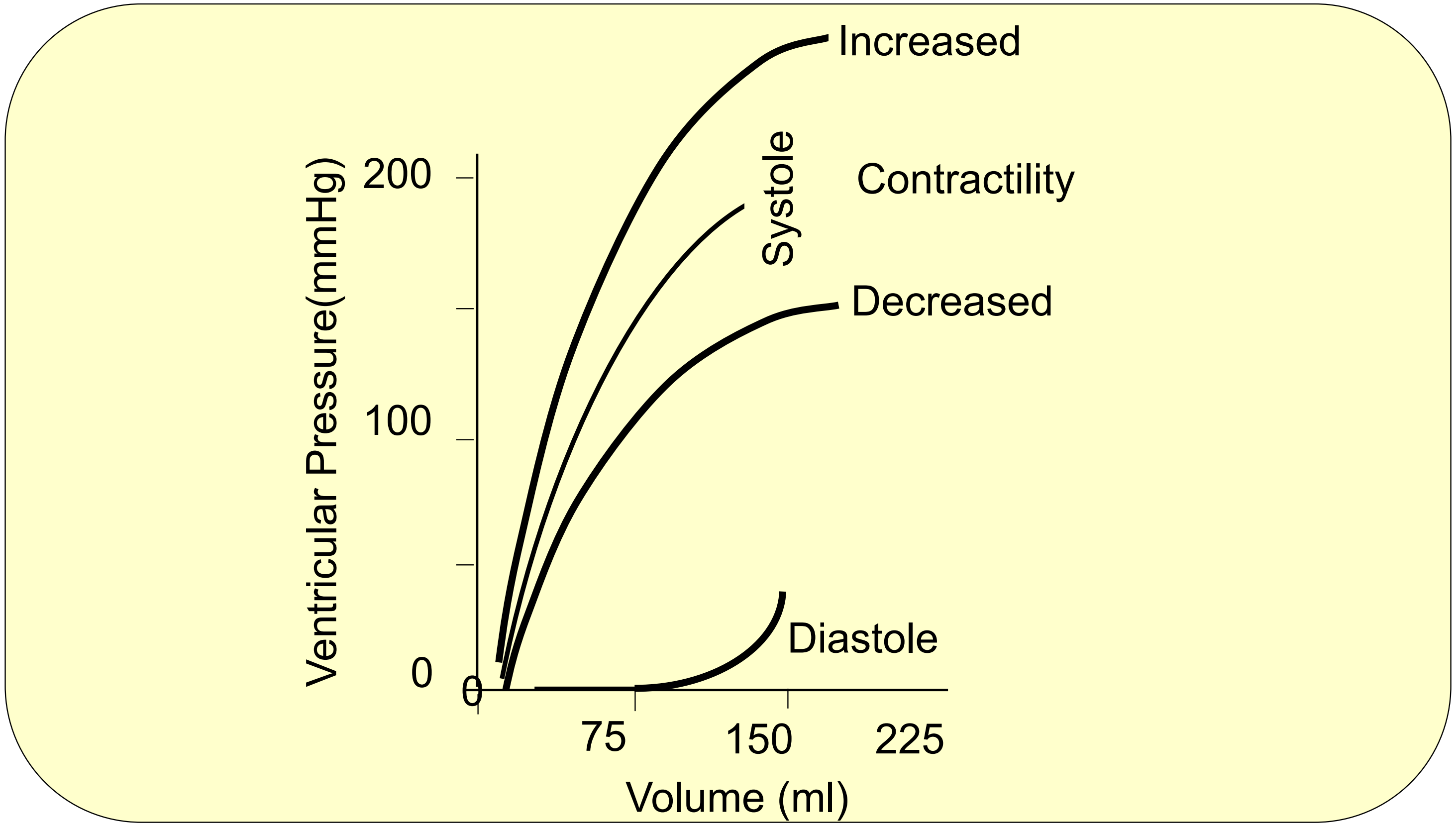
The Starling resistor keeps the pressure constant

Frank-Starling law

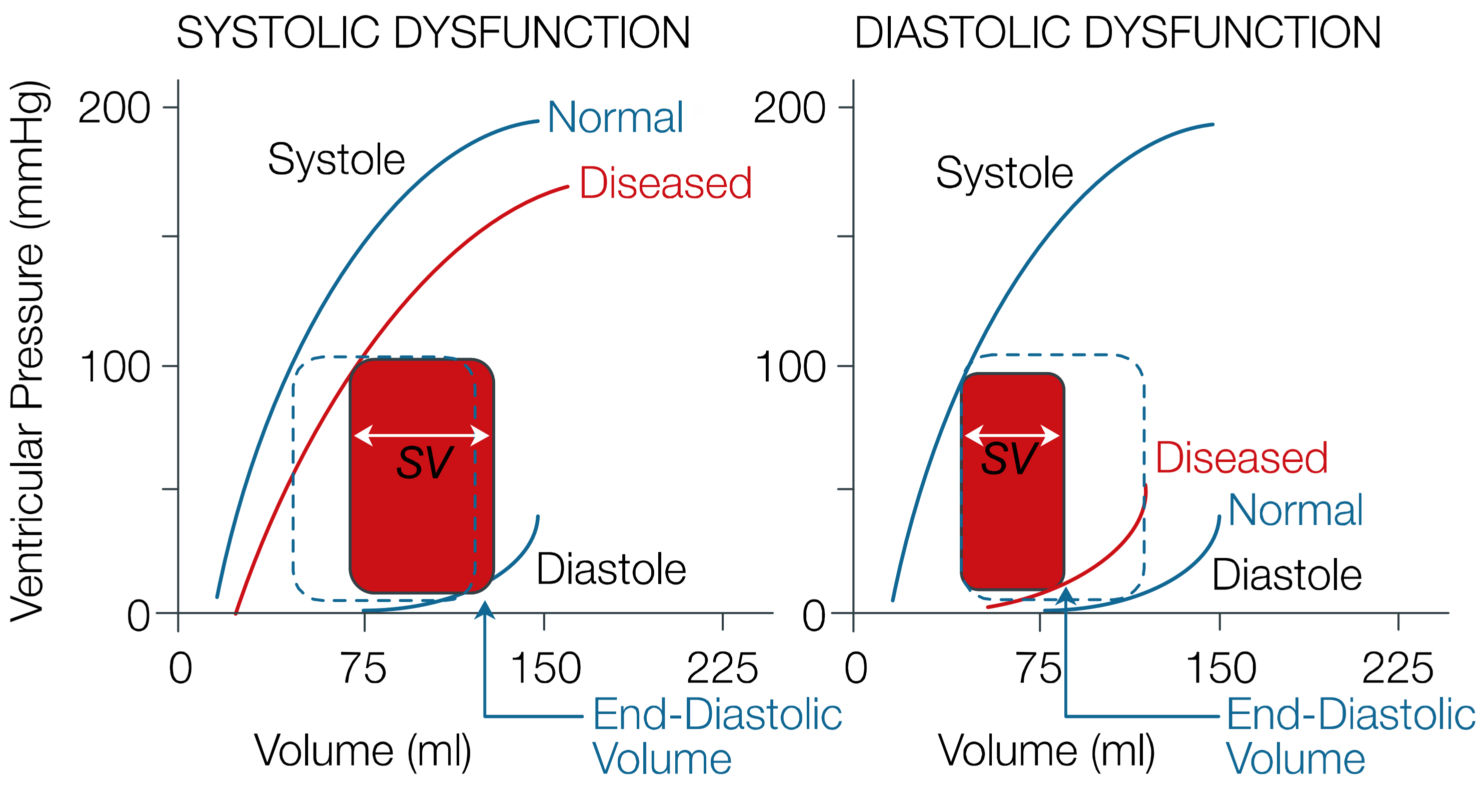


13.5

The slope of the end-systolic pressure volume relation is a measure of contractility

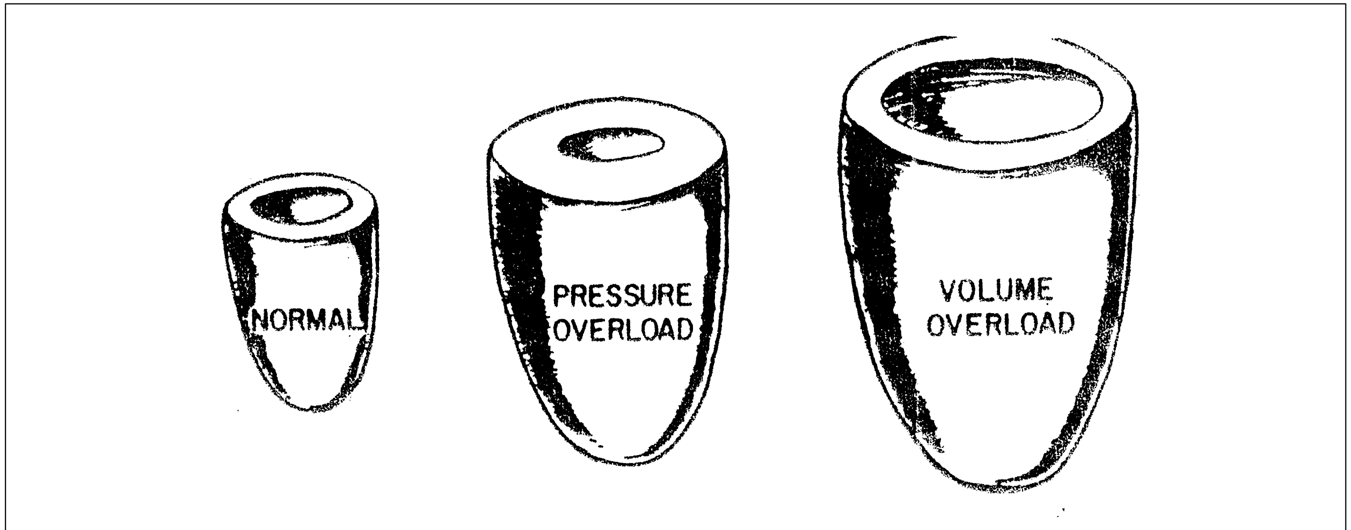


Systolic and Diastolic Dysfunction



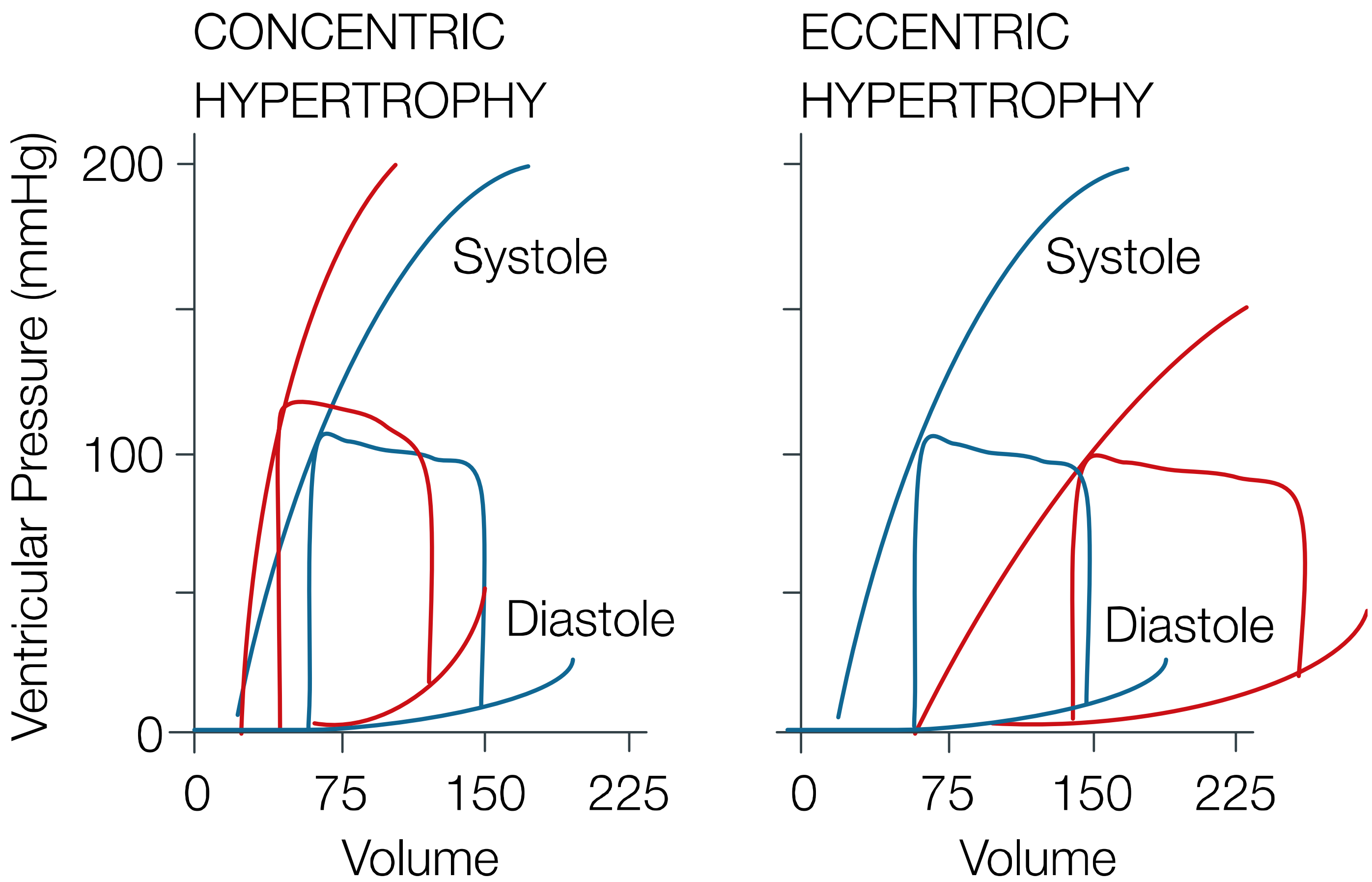
13.6

Concentric and eccentric hypertrophy



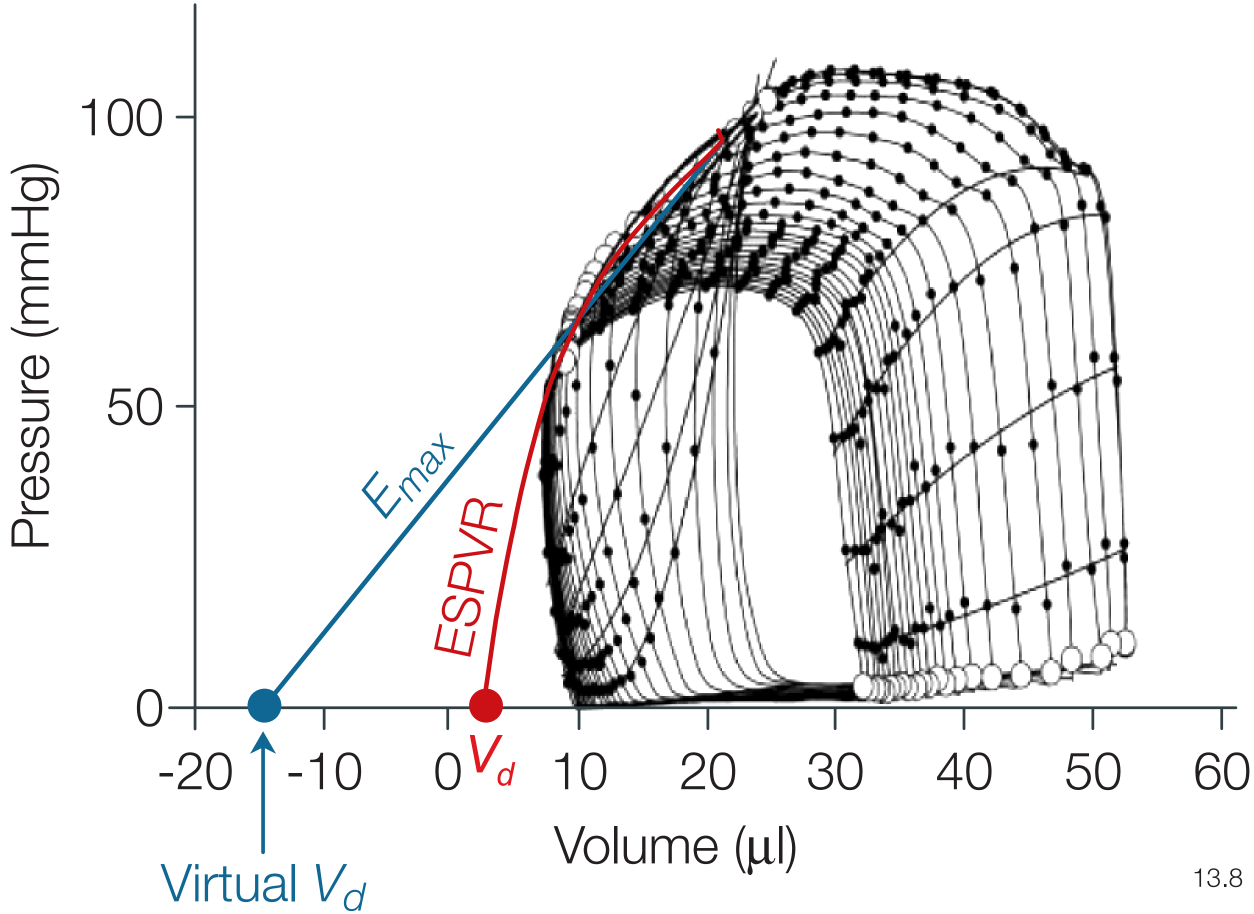
LV Pressure (mmHg)	117/10	226/23	138/23
LVMI (g/m^2)	71	206	196
LV wall thicknmess (mm)	8.2	15	11
h/R	0.34	0.56	0.33
stress (10^3 dynes/cm^2)			
peak	151	161	175
end siastolic	17	23	41

Pressure-volume relations in severe concentric hypertrophy (left) and severe dilatation (right)



13.7

The end systolic pressure-volume relation has an apparently negative V_d



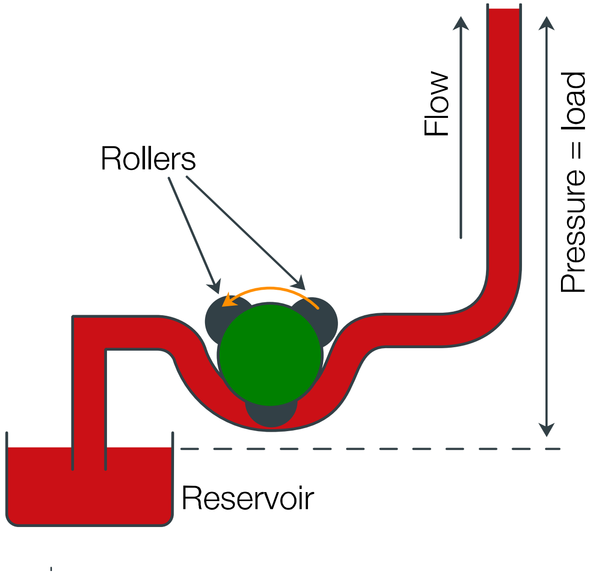
13.8

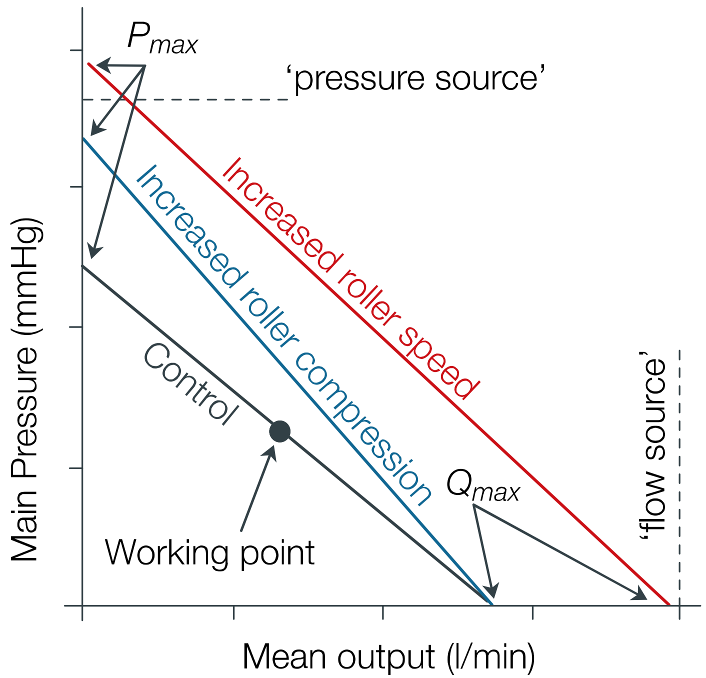
The Pressure Flow Relation

or

The Pump Function Graph

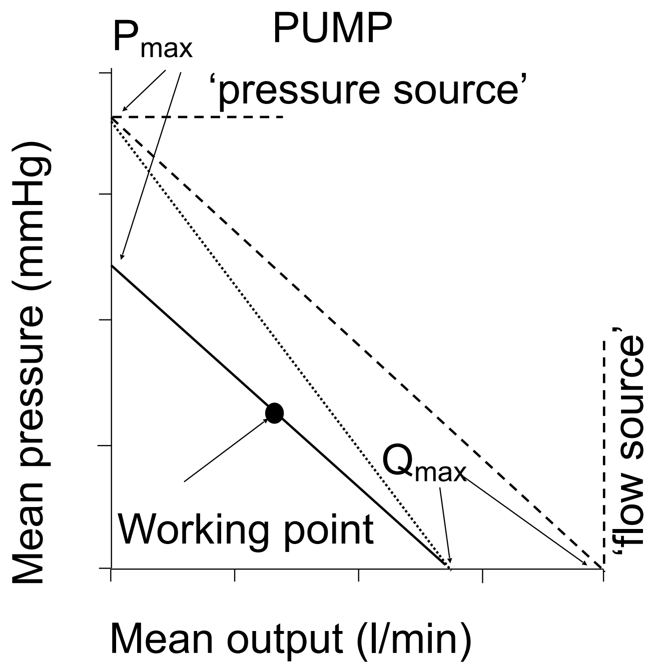
The pump function graph

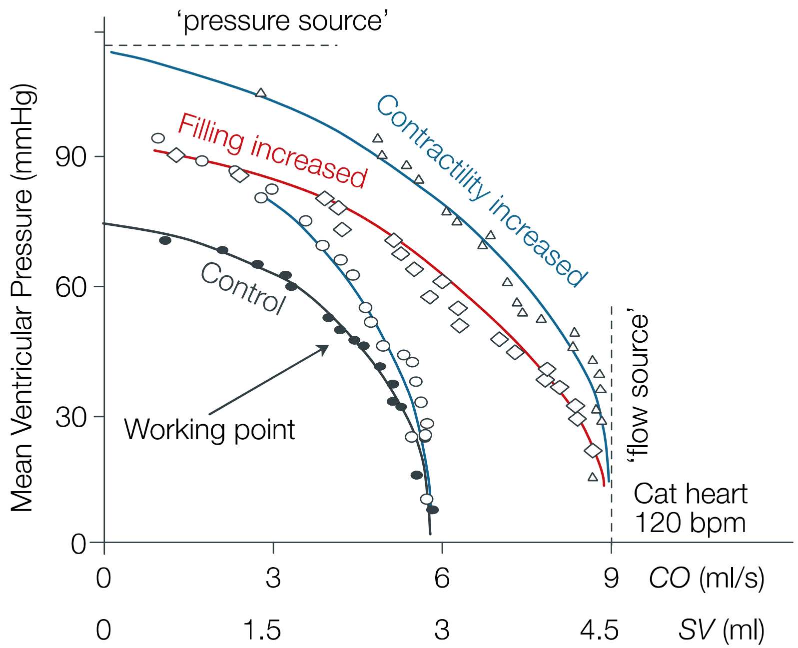




14.1

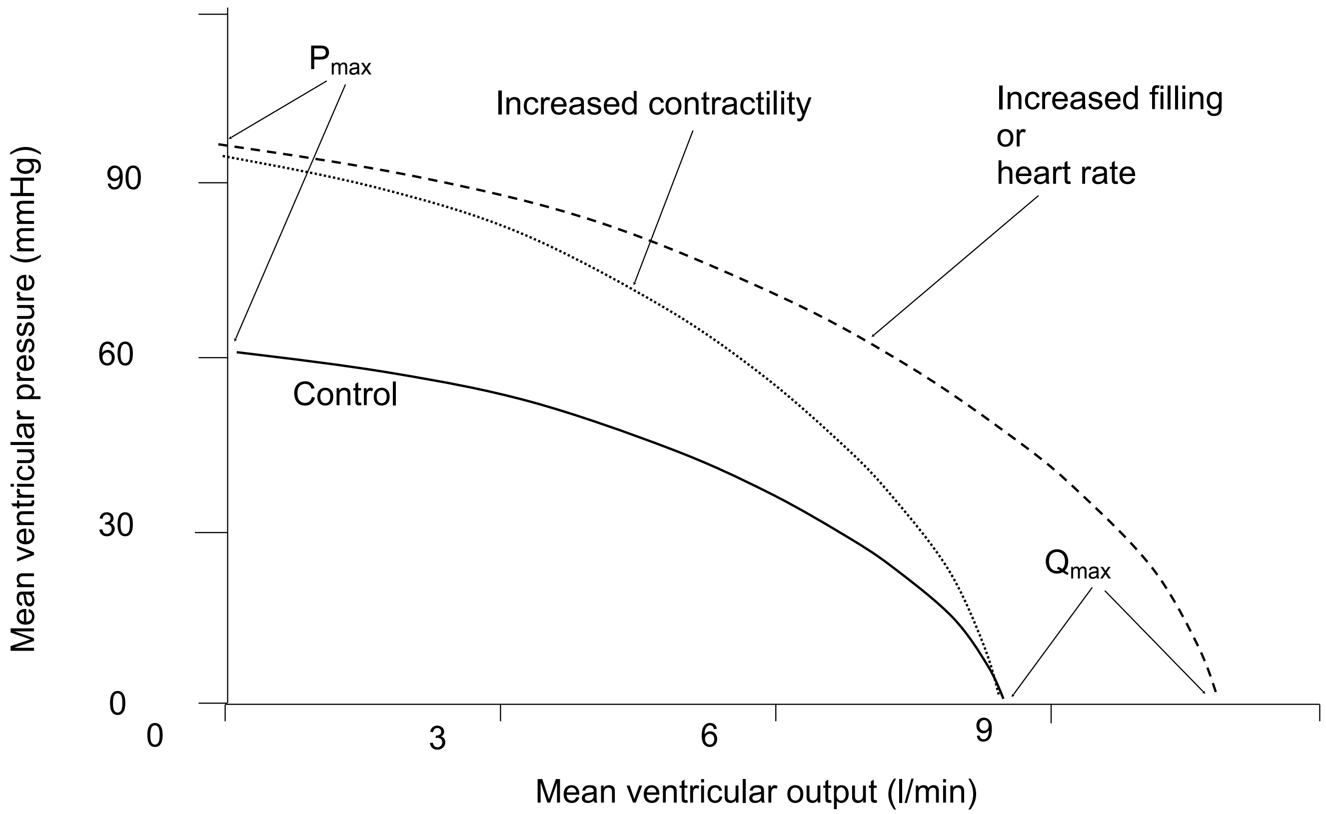
The pump function graph



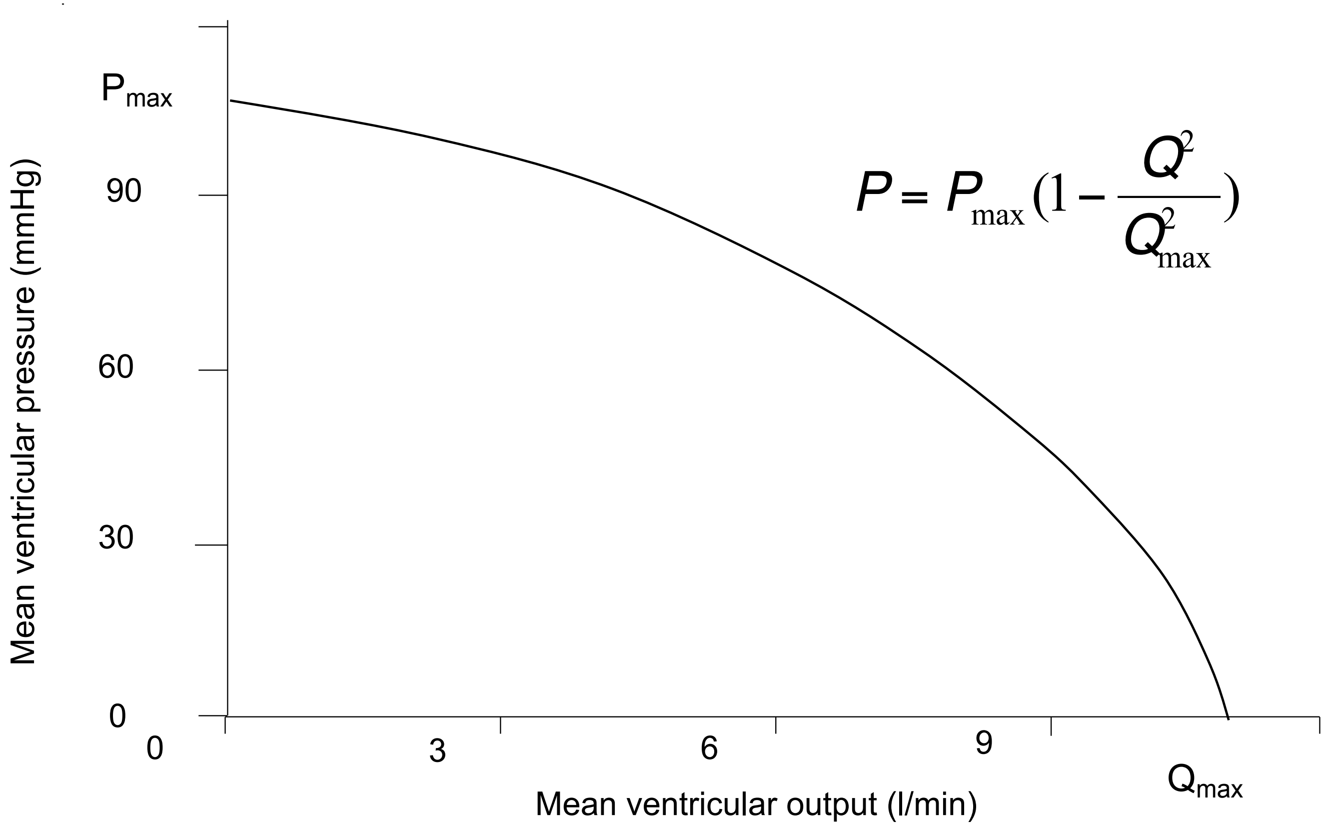


14.2

Pump function graphs of the isolated cat heart

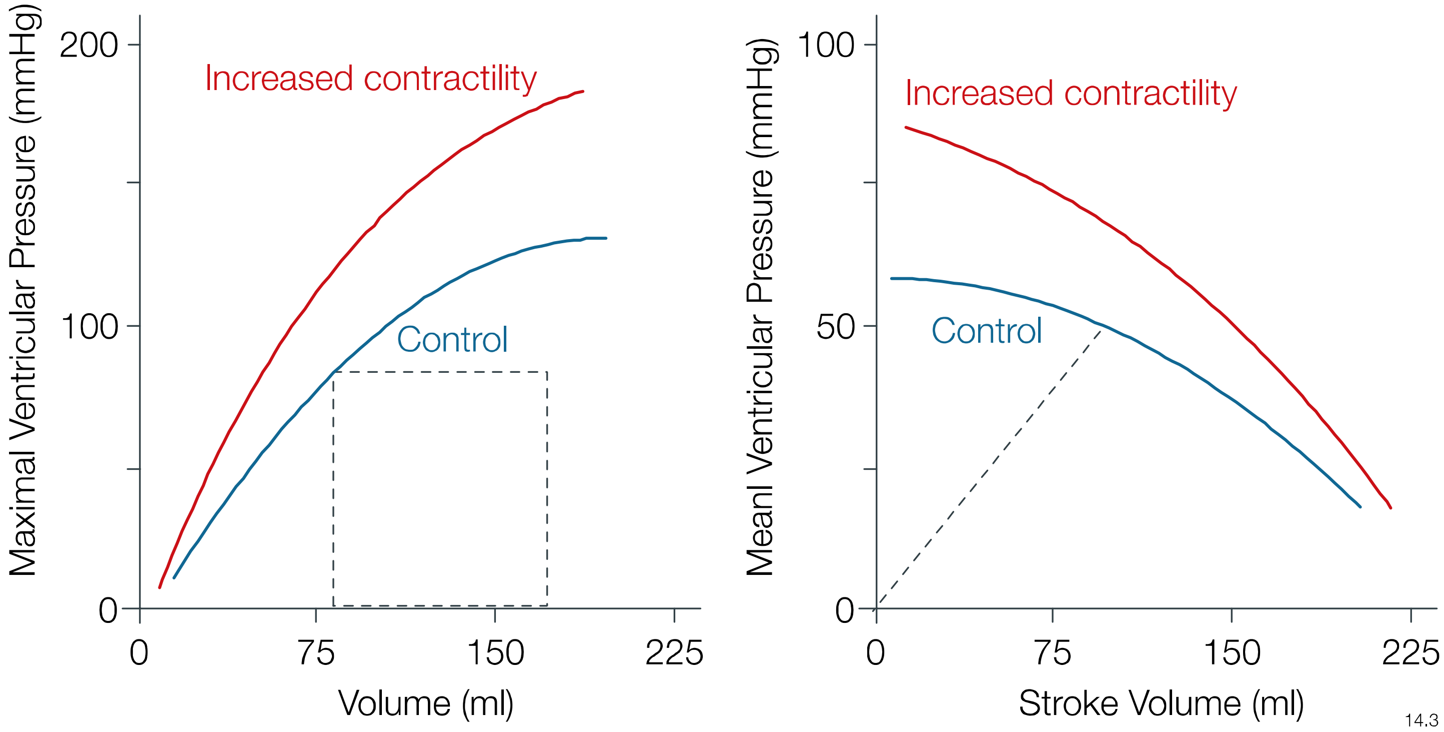


Pump function graph equation



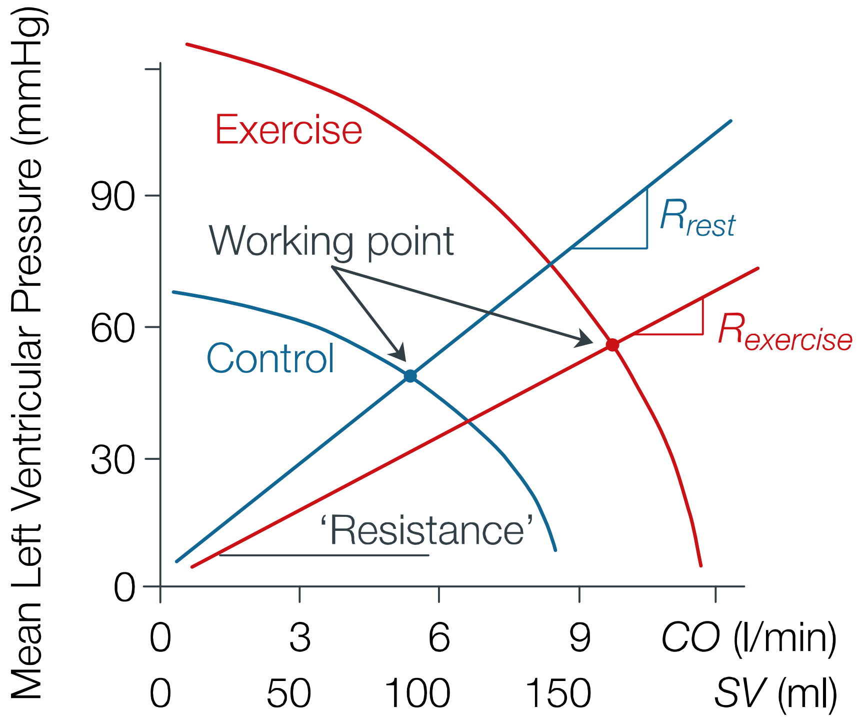
$$P = P_{\max}\left(1 - \frac{Q^2}{Q_{\max}^2}\right)$$

Pump function graph and end-systolic pressure-volume relation



Note difference in vertical scale

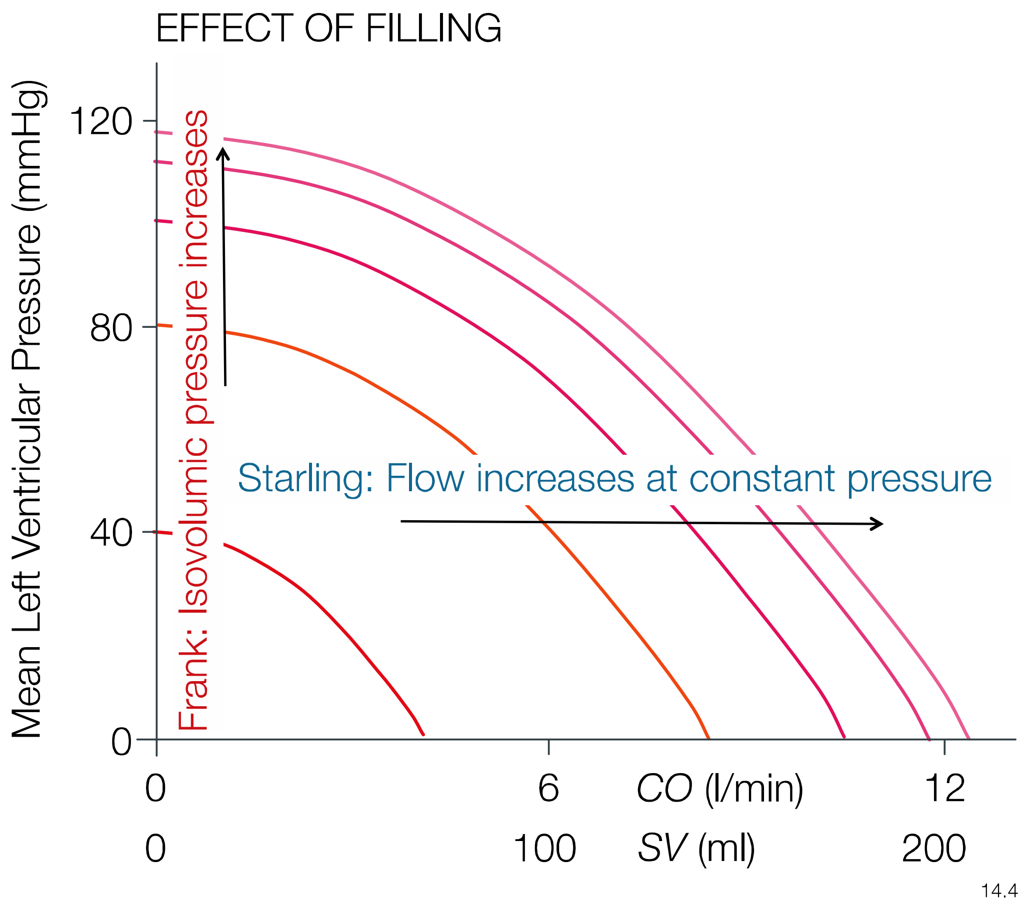
Pump function in exercise



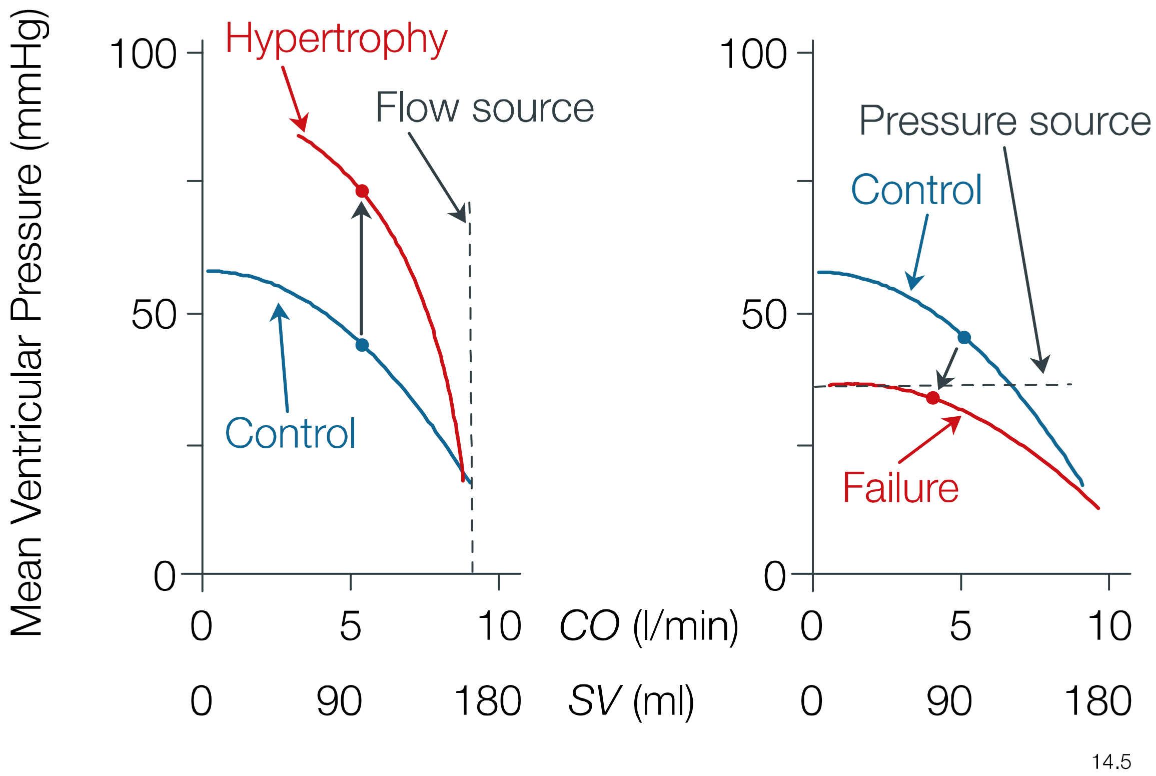
14.7

DURING EXERCISE vascular resistance decreases and the slope of the pump function graph increases. The cardiac output increases strongly with a limited increase in pressure.

The cardiac pump function graph is a generalized description of the Frank-Starling mechanism

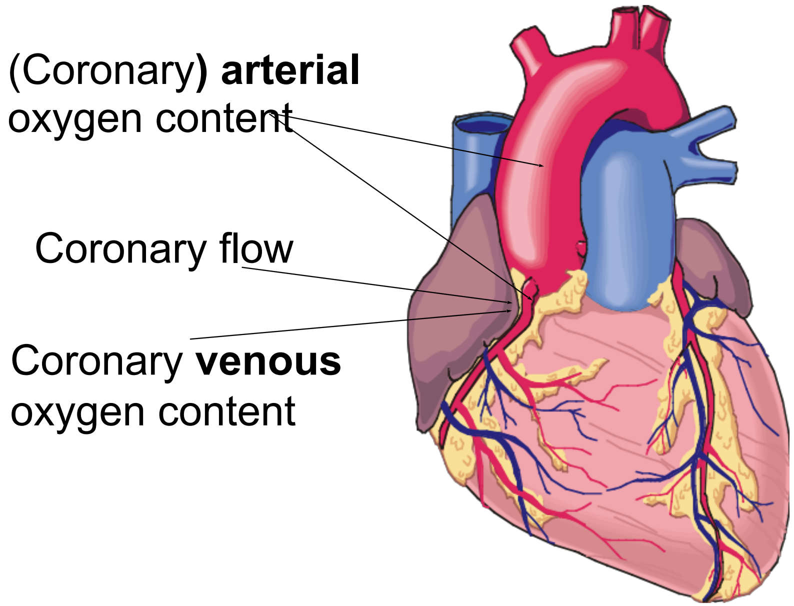


THE PUMP FUNCTION GRAPH in hypertrophy and failure



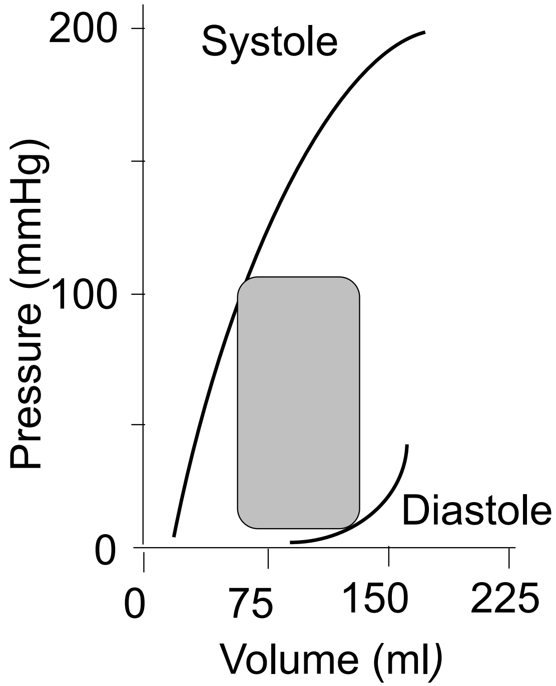
Work and Power

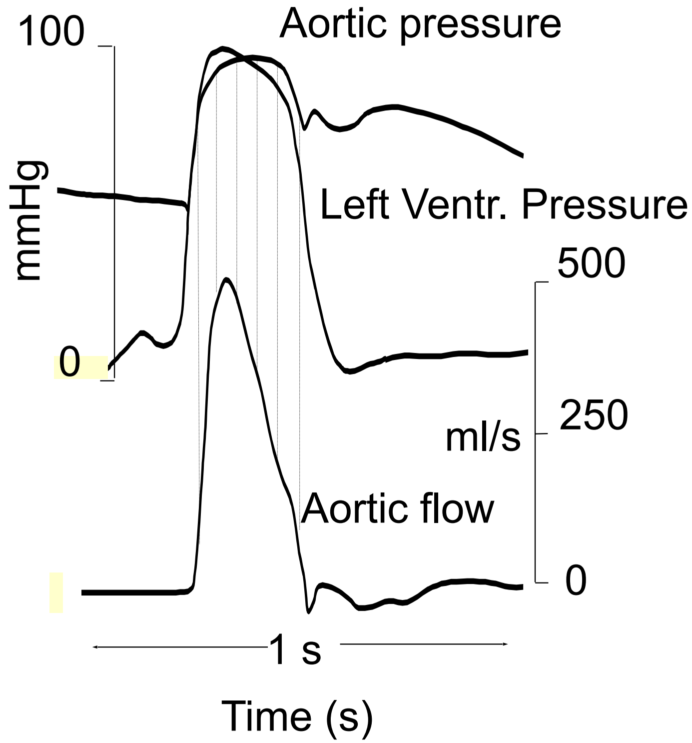
Measurement of cardiac oxygen consumption



For carbohydrate and fat metabolism
1 ml $O_2 \approx$ 20 Joule or 1 ml O_2/min $\approx$ 0.33 Watt

Calculation of work and power

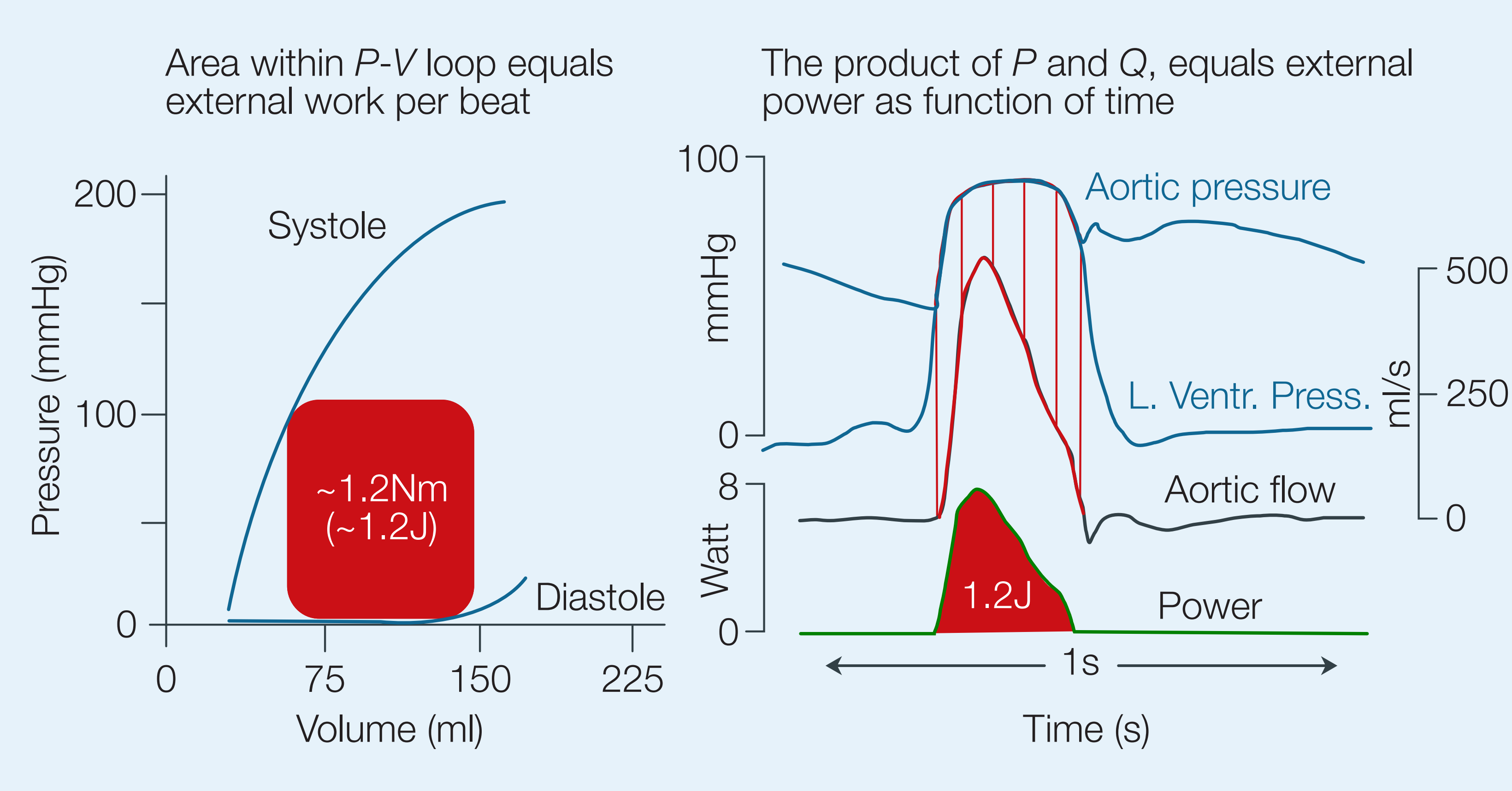




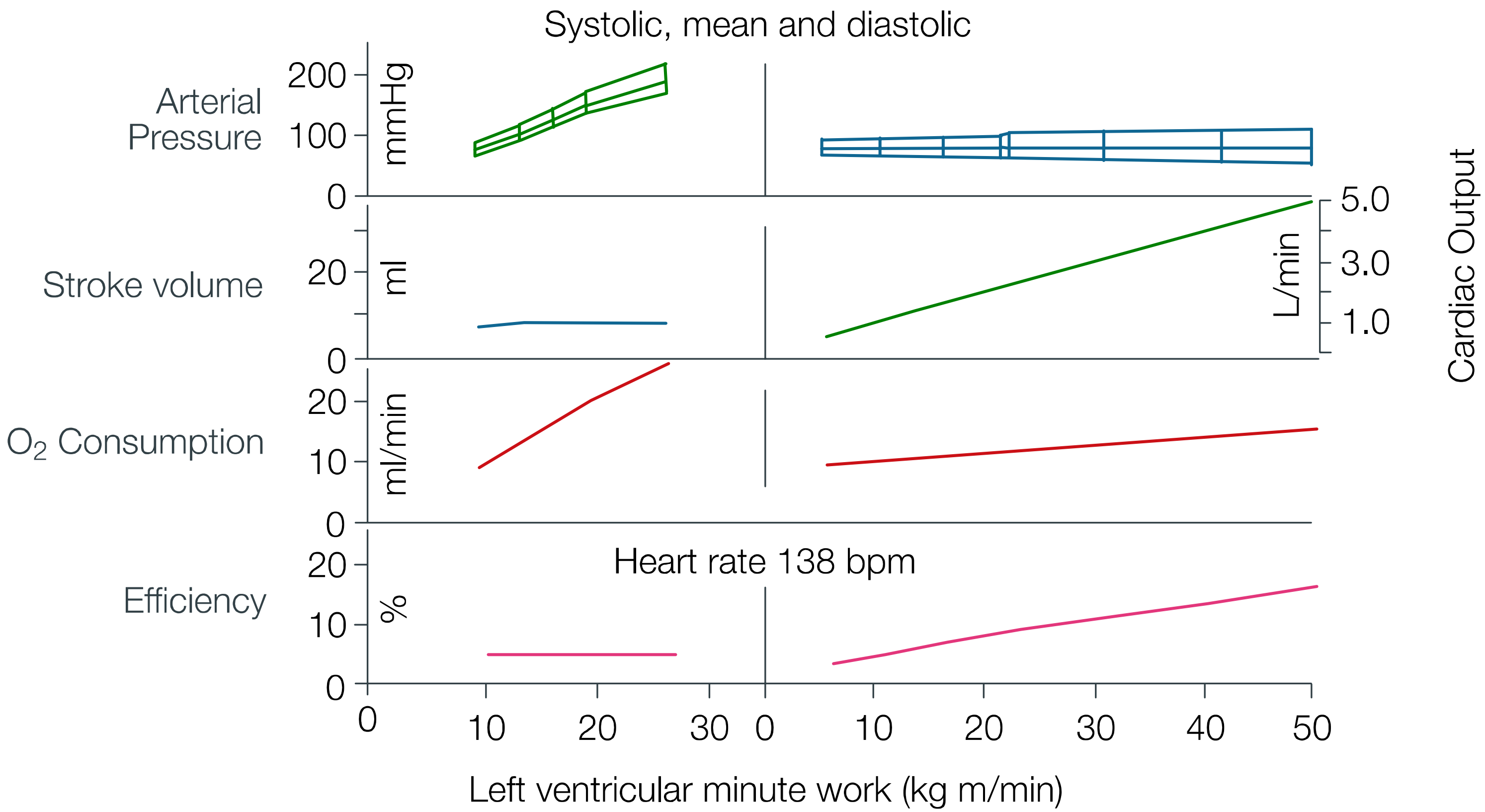
External Work per beat is shaded area

External Power is the product of P and Q, averaged over the heart beat

Calculation of work and power

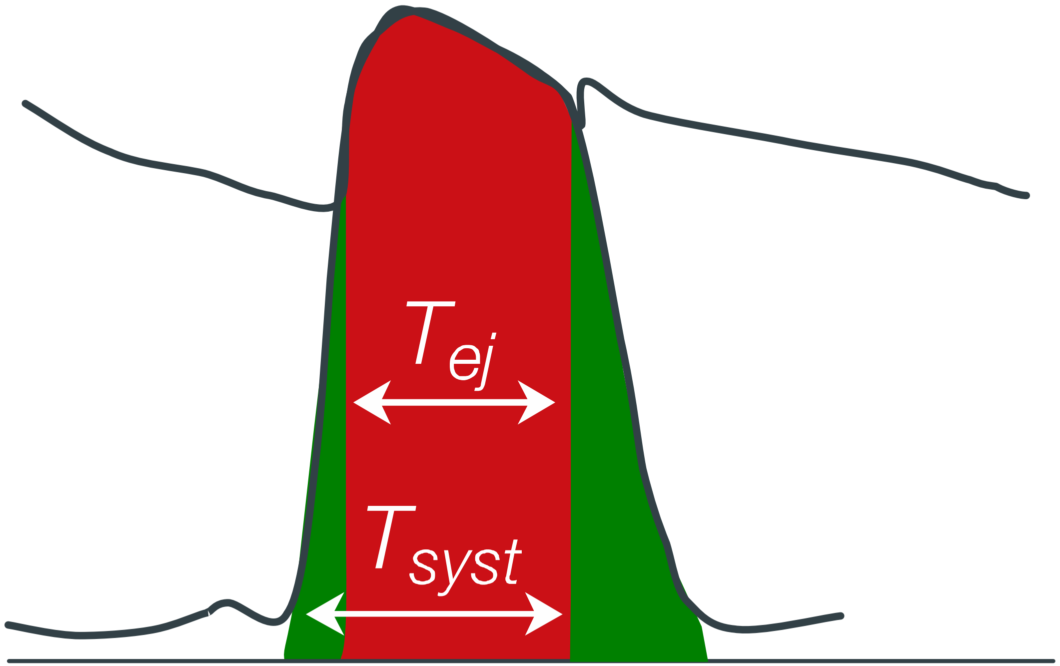


Oxygen consumption is primarily determined by pressure, not by flow or external work



16.1

The Tension Time Index



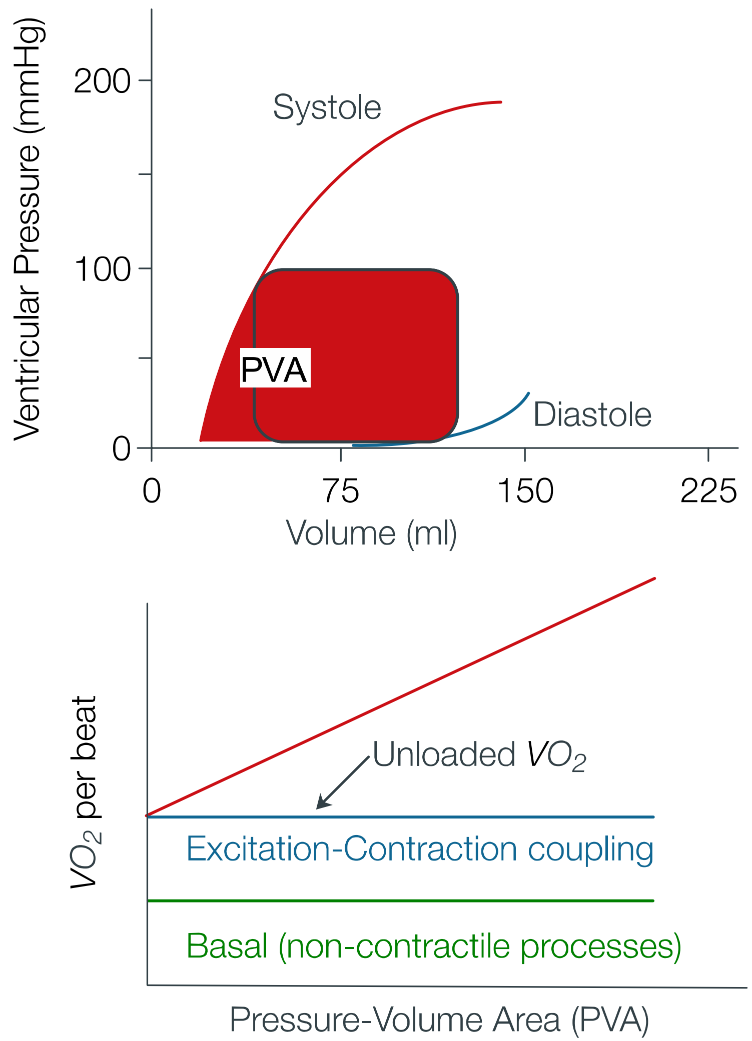
The rate-pressure product

In biochemical and pharmacological studies of the heart
often the rate-pressure product (RPP)
is used to estimate oxygen consumption.

RPP = Heart rate times systolic pressure

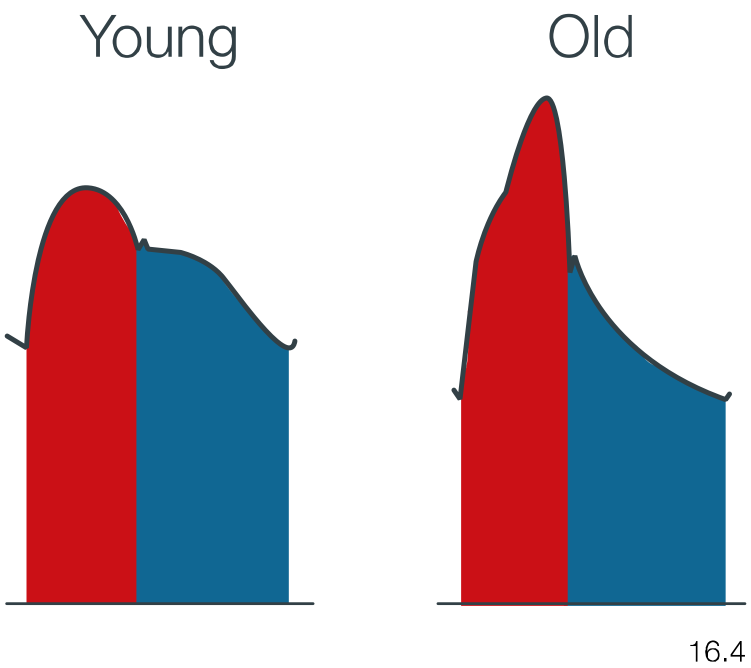
All right in single hearts; be carefull to use it between hearts

The PVA Relates To Cardiac Oxygen Consumption.



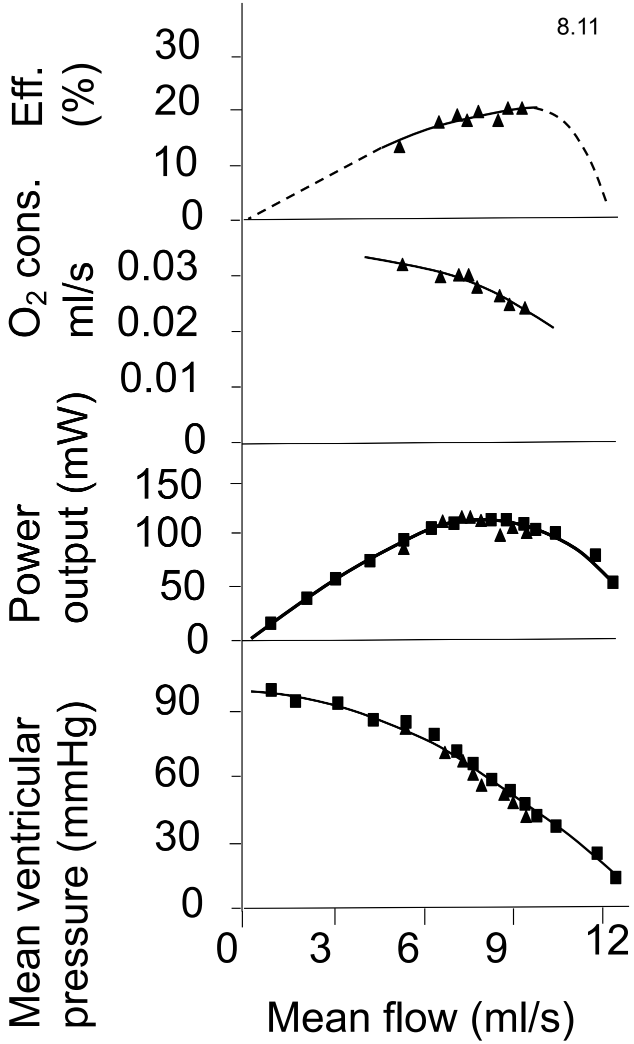
16.3

The Ogyxen Demand And Supply



The ratio may be unfavorably influenced with increasing age

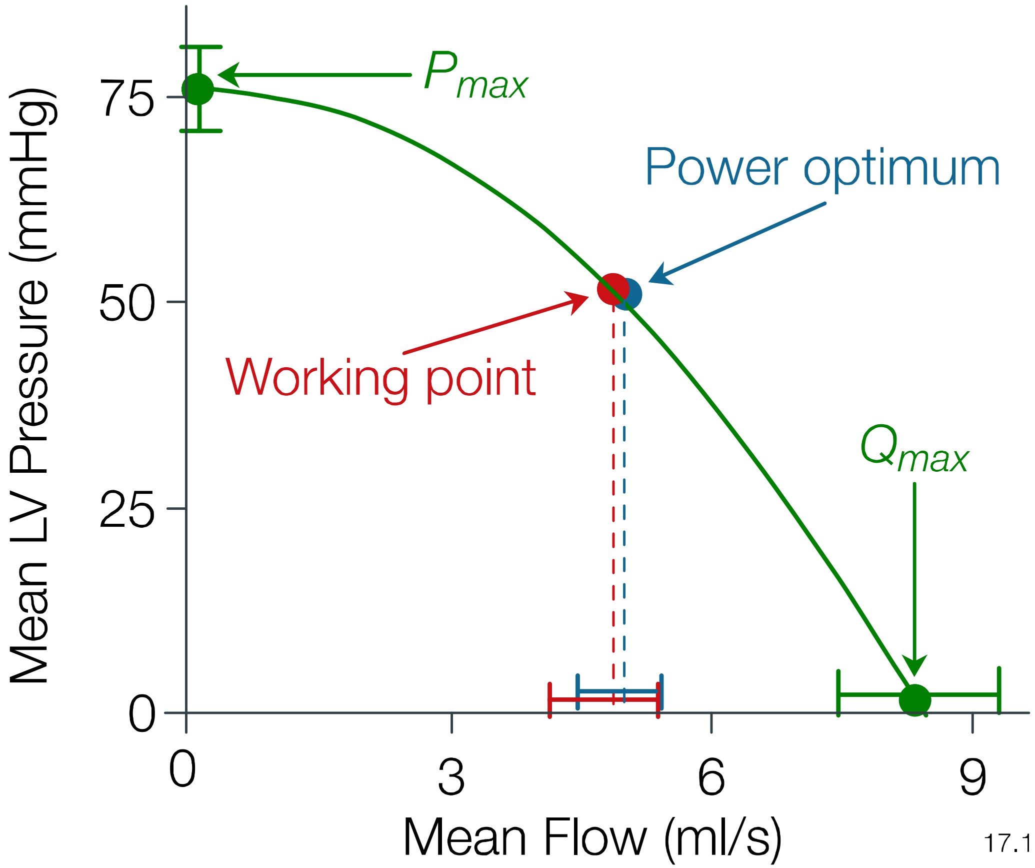
Optimal Power And Efficiency



Calorific equivalent is about 20 J per ml O_2

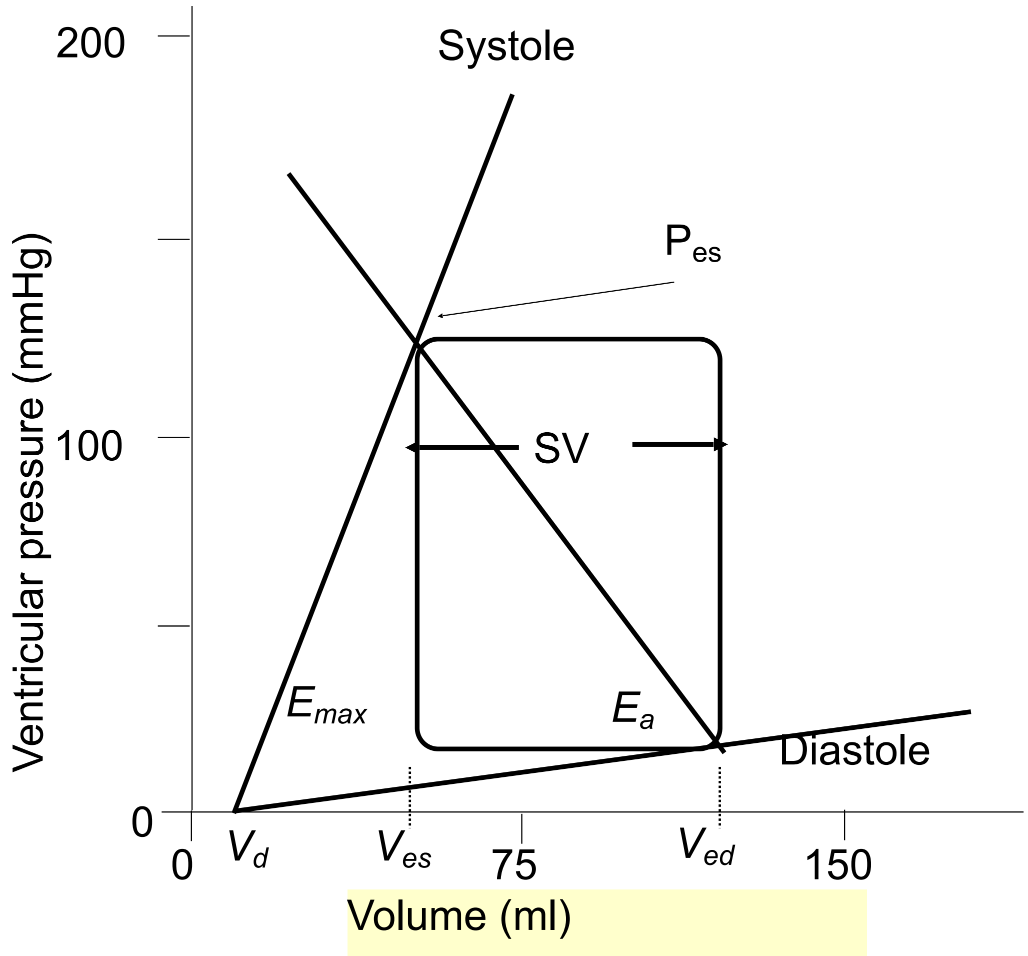
Power ≈ 2 Watt/100gram (human)

The heart pumps at optimal power output

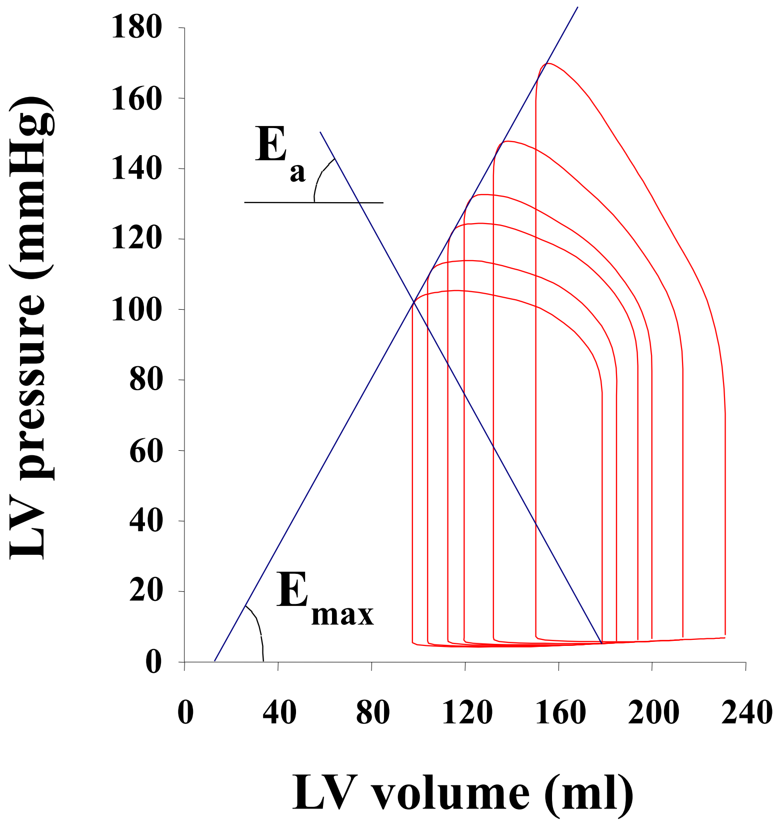


17.1

The concept of E_{max} (ventricular elastance) and E_a (arterial elastance)



Effective arterial elastance E_a



Normal hearts: maximal SW

$$\frac{E_a}{E_{max}} = 1$$

Normal hearts: maximal efficiency

$$\frac{E_a}{E_{max}} = 0.5$$

Dilated hearts

$$\frac{E_a}{E_{max}} >> 1$$