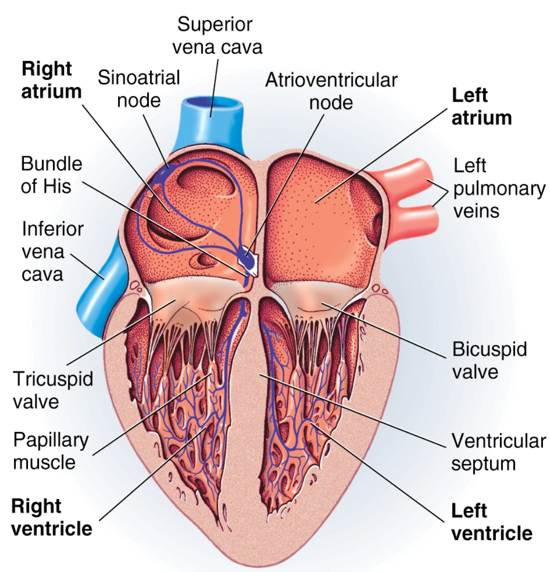
Cardiac Mechanics

Bioengineering/Physiology 6000

The Heart

- Structure
  - Macro and micro
- Function
- Cells
  - Pacemaker
  - Conduction system
  - Contractile myocytes
- Electrophysiology
  - Action potentials
  - Cell to cell coupling
- Mechanics
  - EC coupling
  - Cardiac cycle



Average Hemodynamic Values

Variable	Cow	Man	Dog	Rabbit	Rat	
Weight (kg)	414	70	20	4	0.6	690
Cardiac Output (ml/sec)	680	110	42	5.2	1.2	560
Heart rate (min-1)	71	76	99	288	349	.2 (5)
Stroke Volume (ml)	570	87	25	1.1	0.21	2700
Velocity in ascending aorta		16	18	32	22	.7 (1.4)

Cardiovascular Physiology
By William R. Milnor

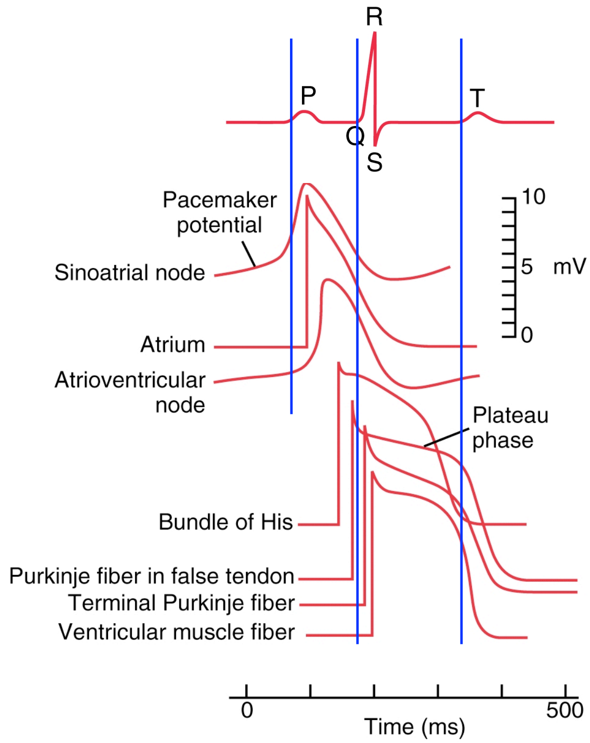
Hummingbird Physiology (What we need to explain)

- Heart is 20% of body volume (largest of any animal), 2-3% of body mass
- Heart rate varies from 30 (deep rest), 500 (while perching), to 1200 (during high speed chases)
- Highest known mass-specific metabolic rates among vertebrate homeotherms (100 times greater than elephant)
- Eats .5-8 times body weight per day
- Respiratory rate of 250 at rest
- Dives produce 7-10 G at speeds of up to 100 kph.

R.K. Suarez, Hummingbird flight: Sustaining the highest mass-specific metabolic rates among vertebrates. Cellular and Molecular Life Sciences (CMLS) 48(6), 1992.

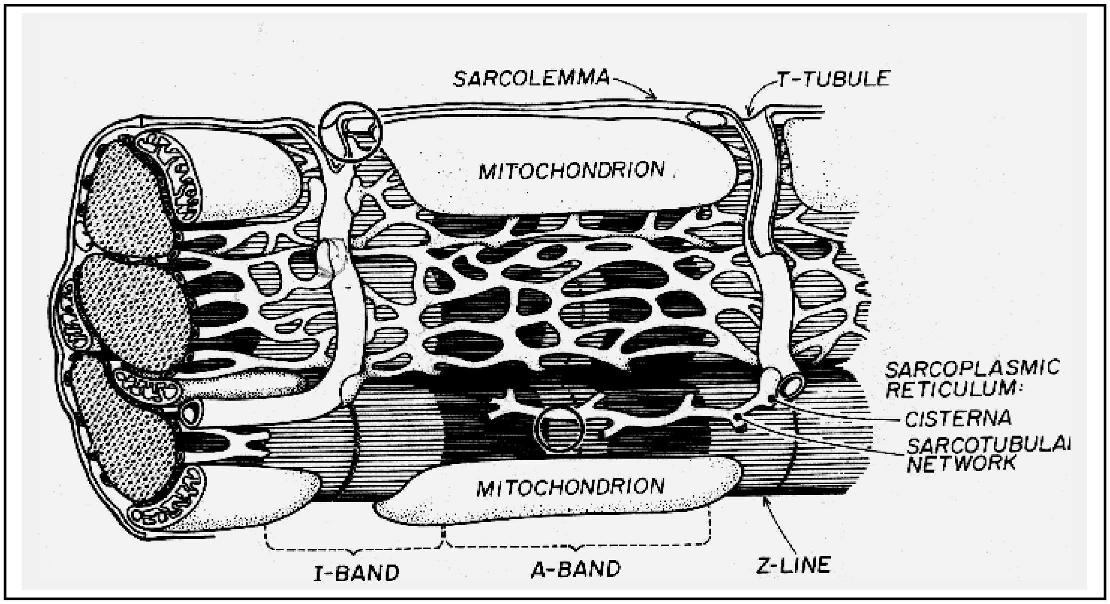
Electrophysiology Review

- Pacemaker cells
  - Neurogenic vs. myogenic
  - SA Node
  - AV Node
  - Purkinje Fibers
- Conduction system
- Ventricular myocytes
- The Electrocardiogram (ECG)



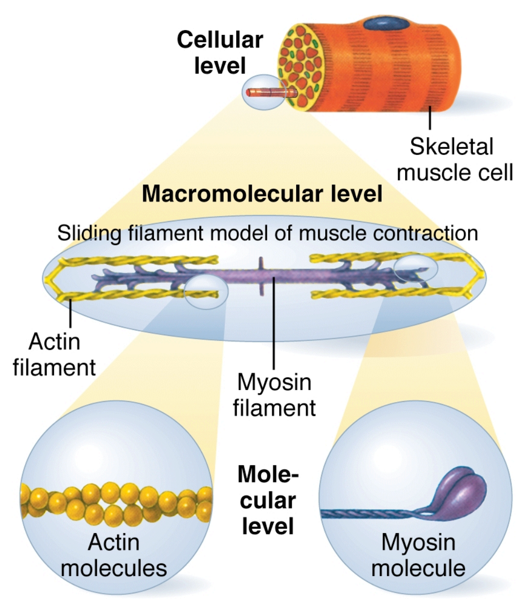
Excitation-Contraction Coupling (ECC)

Structure-Function Relationship



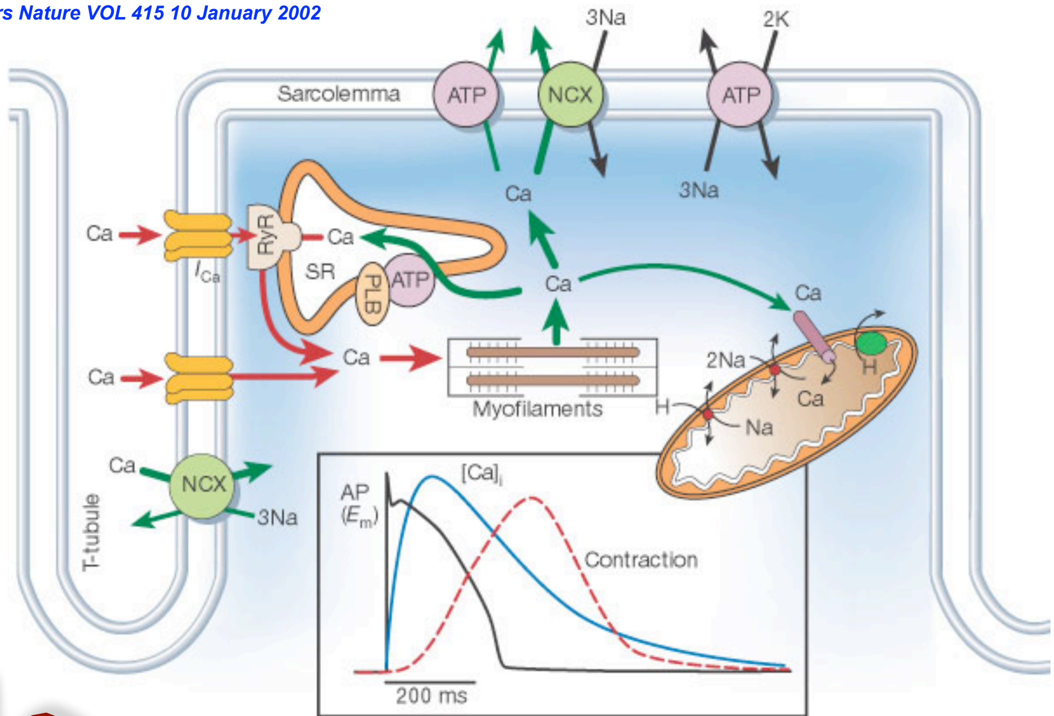
EC Coupling

- Action potential causes influx of Ca^{2+}
- In mammals and birds, this causes release of more Ca^{2+}
- Ca^{2+} interacts with actin/myosin to cause contraction
- Pumps gather up Ca^{2+} or remove it from cell



Calcium-induce Calcium Release

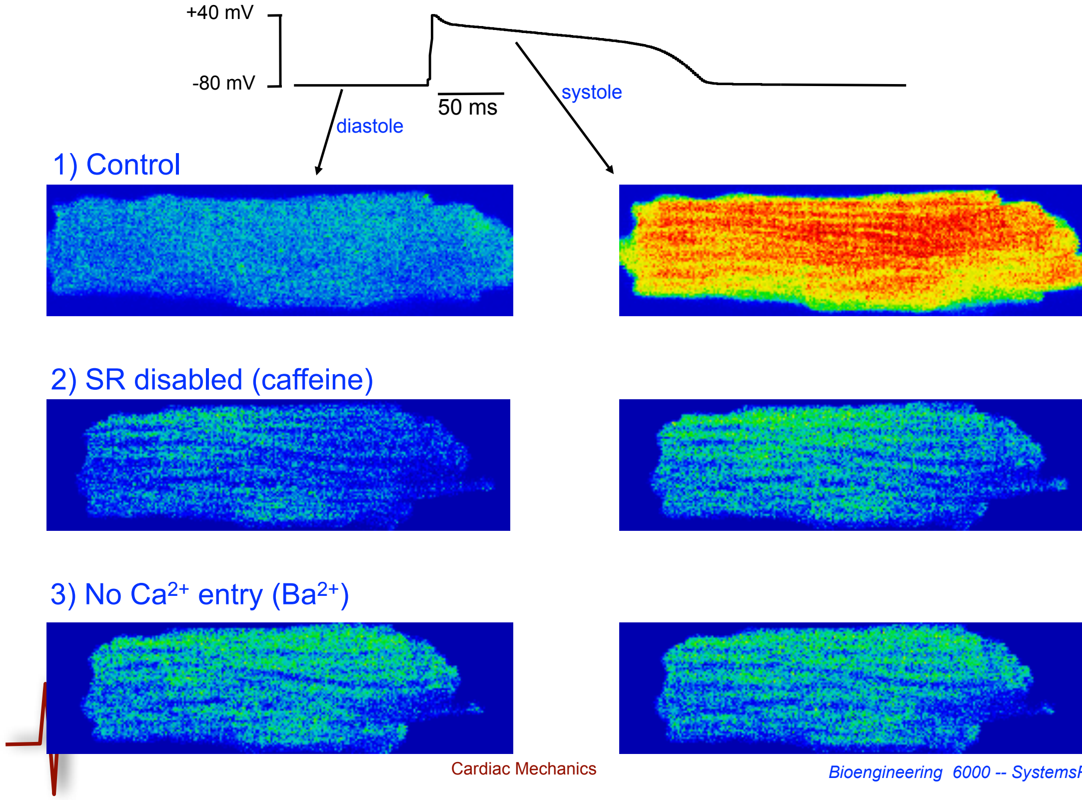
D.M.Bers Nature VOL 415 10 January 2002



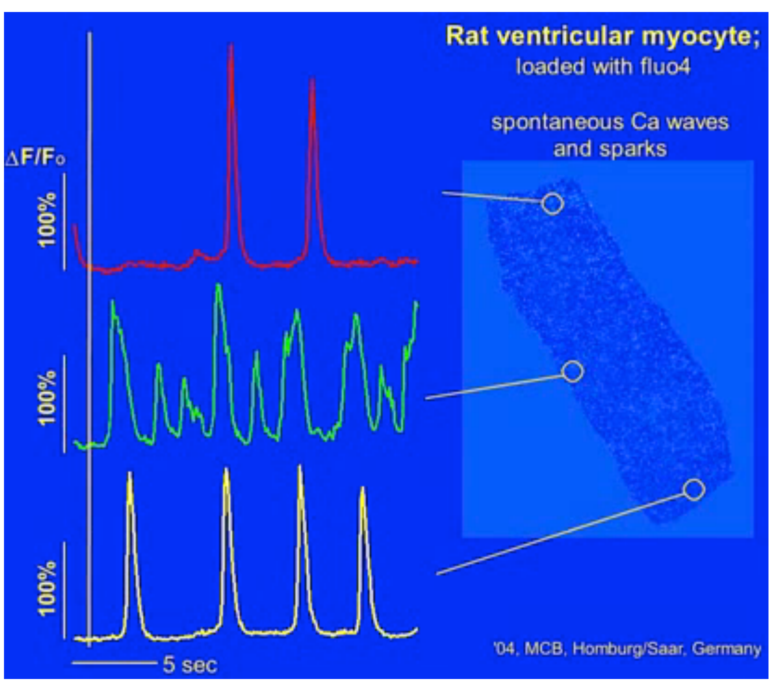
Calcium Measurement

- Calcium-sensitive dye
- Optical recording system
- Stimulate cell and synchronize with optics

EC Coupling and Ca^{2+}



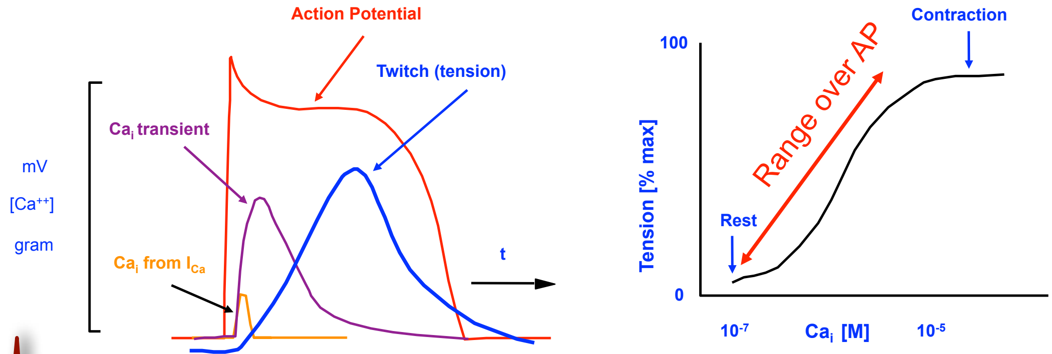
Ca^{+2} Measurements



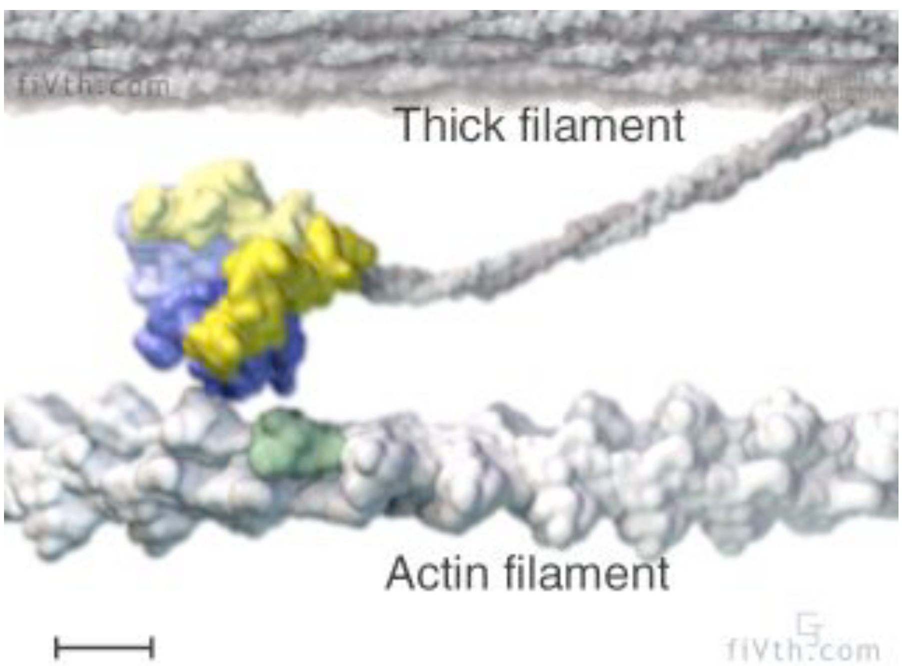
http://www.youtube.com/watch?v=x3s2L2rvNLM

CICR Summary

- Calcium causes contraction
- Calcium is stored in the sarcoplasmic reticulum (SR)
- A small increase of Ca in the vicinity of the SR causes a much larger release of Ca from the SR.
- Contraction can be graded



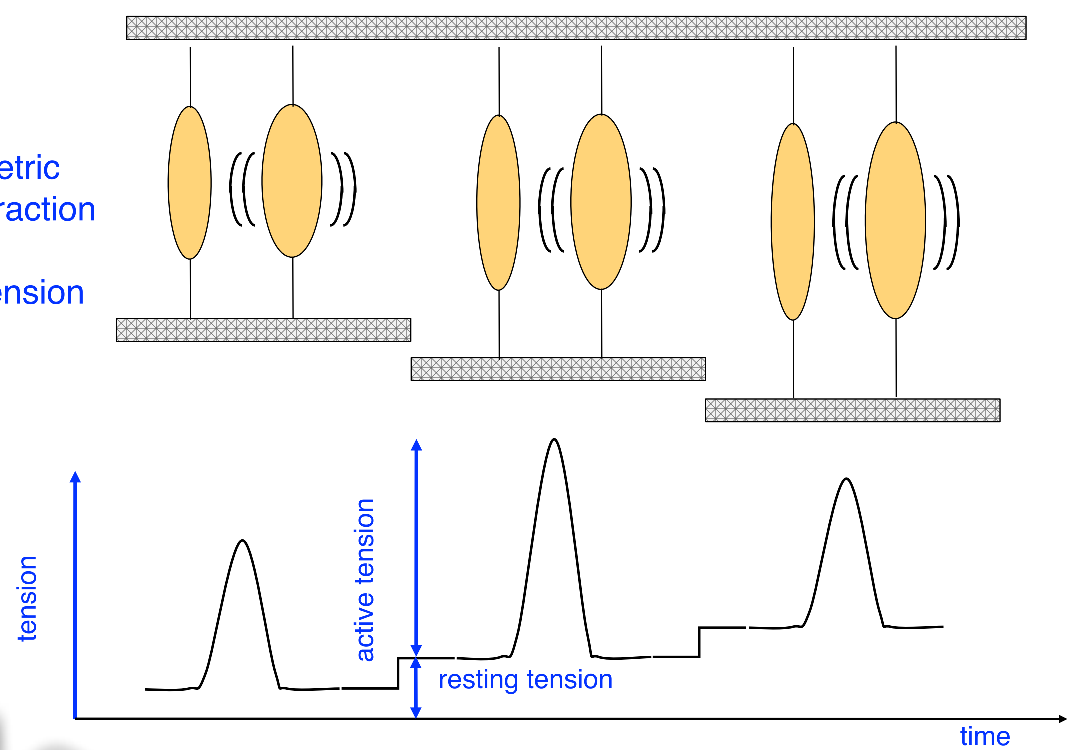
Contractile Proteins



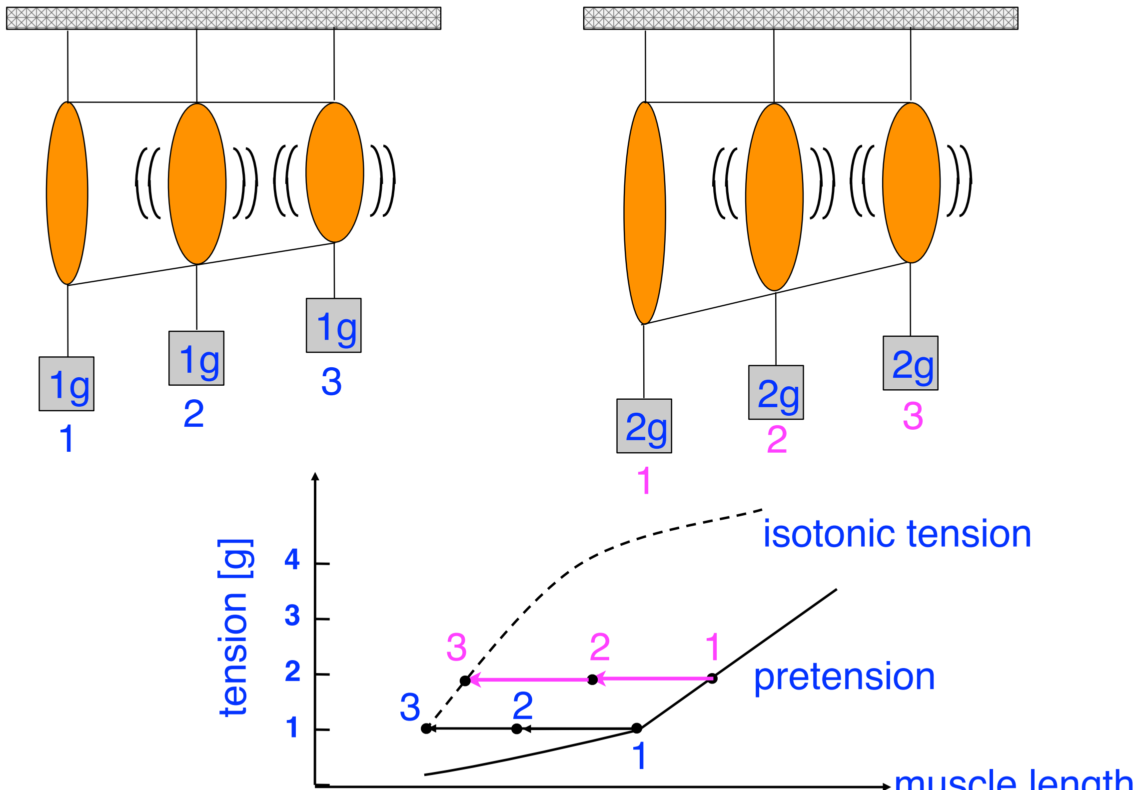
Pretension, Frank-Starling, and Control of Contraction

Pretension of Muscle (Explain?)

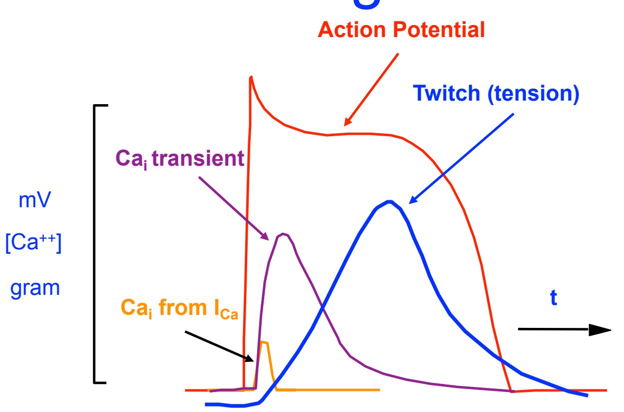
Isometric Contraction with Pretension

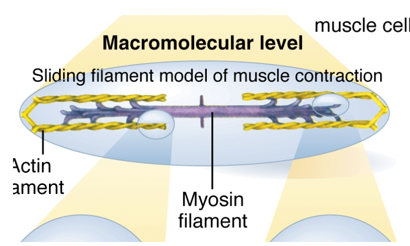


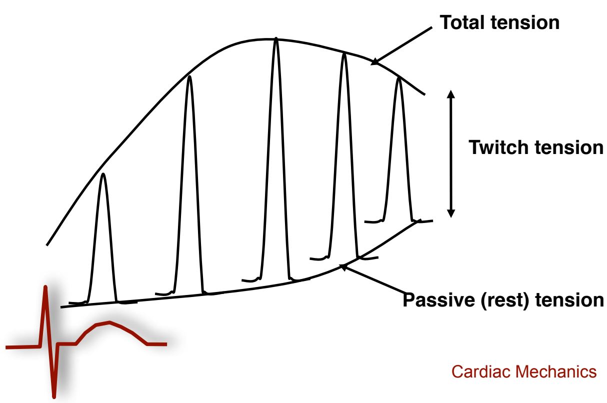
Isotonic Contraction and Preload

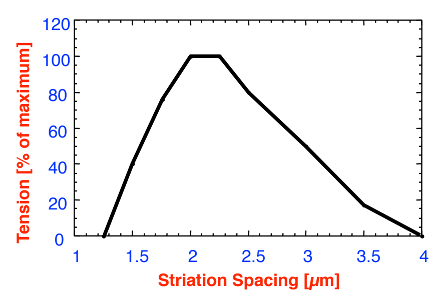


Intrinsic Regulation of Cellular Contraction





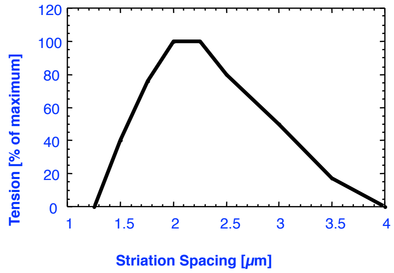




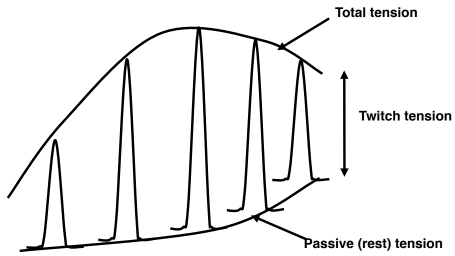
- Spacing in contractile elements
  - Determines contractility
  - Adjusted passively

Frank Starling Mechanism

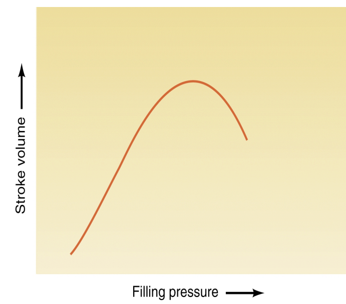
Cell Level



Muscle Level

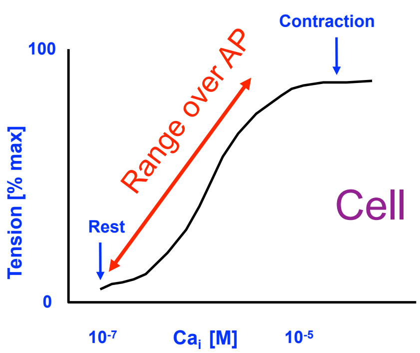


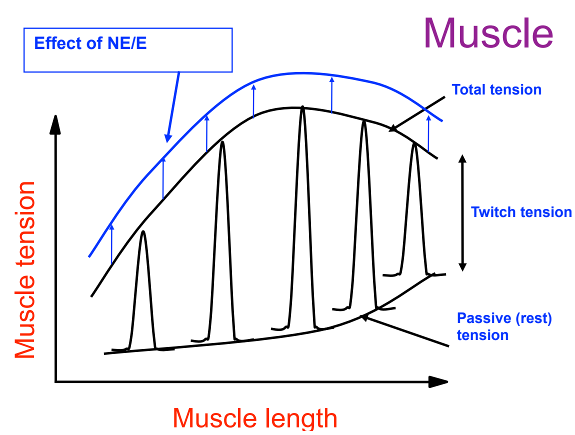
Whole Heart Level

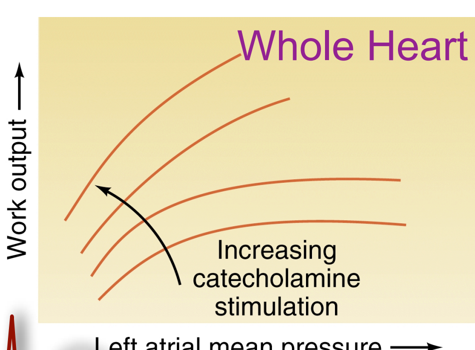


- Increased pretension can increase contraction
- Cell: striation spacing
- Muscle: pretension
- Heart: Increased filling produces increased output
- Does not require neural input

Extrinsic Regulation of Contractility



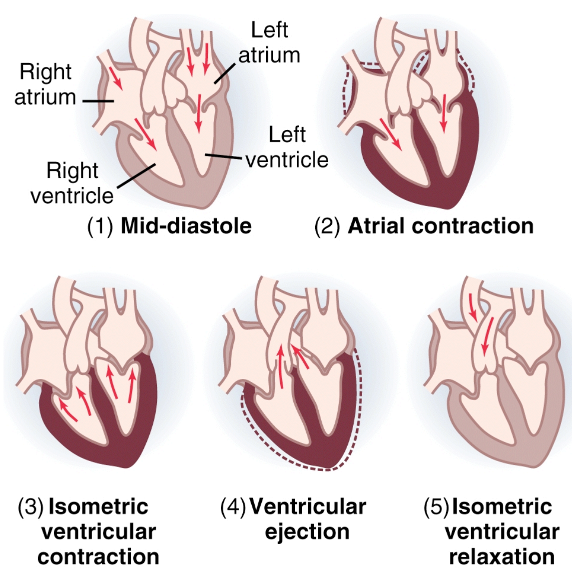


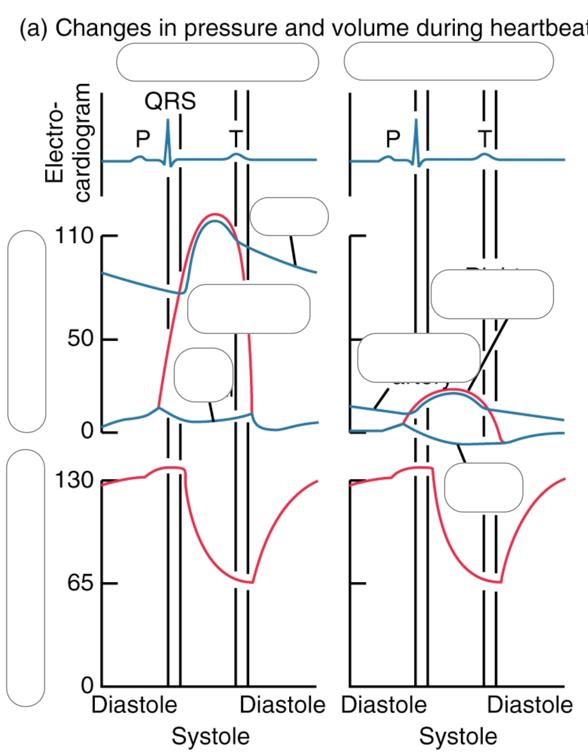


- Free [Ca]i is key component
- Positive inotropic agents:
  - epinephrine: stimulate β receptors and increase Ca influx and uptake (load SR)
- Negative inotropic agents:
  - ACh: acts mostly on atria to shorten AP and reduce [Ca]i
  - Acidosis

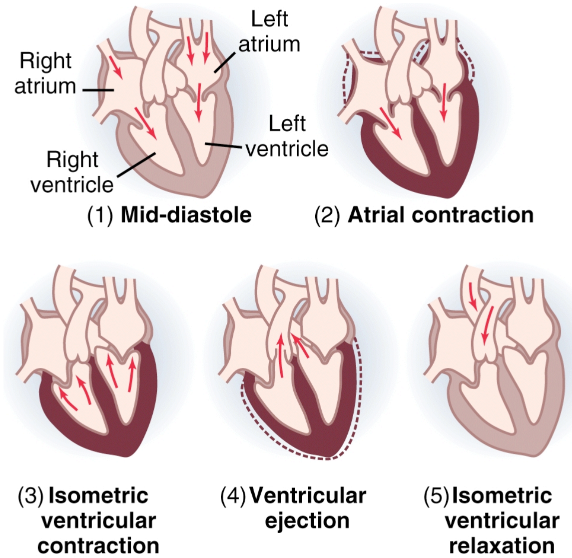
The Cardiac Cycle and Afterload

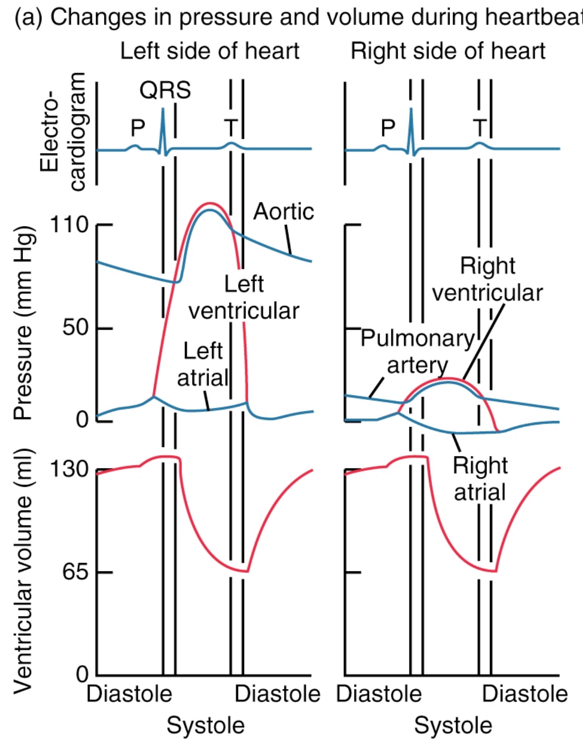
Cardiac Cycle





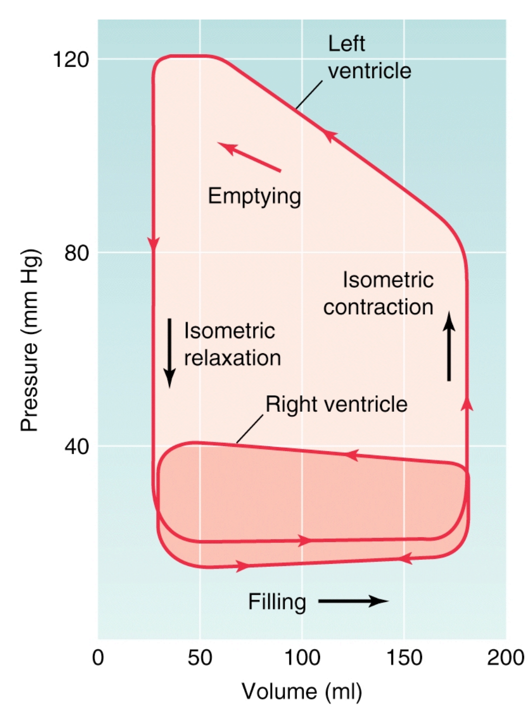
Cardiac Cycle



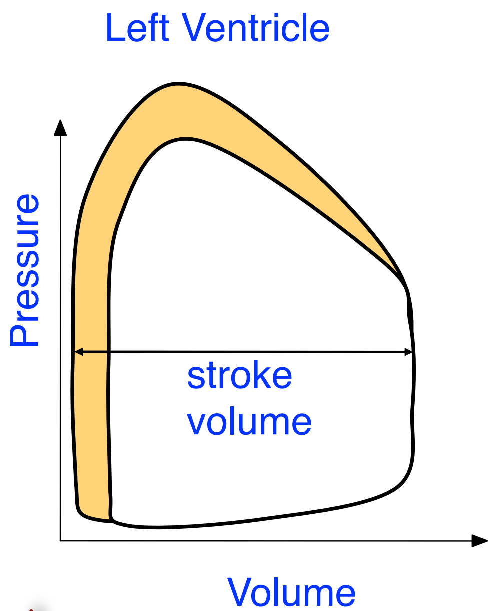


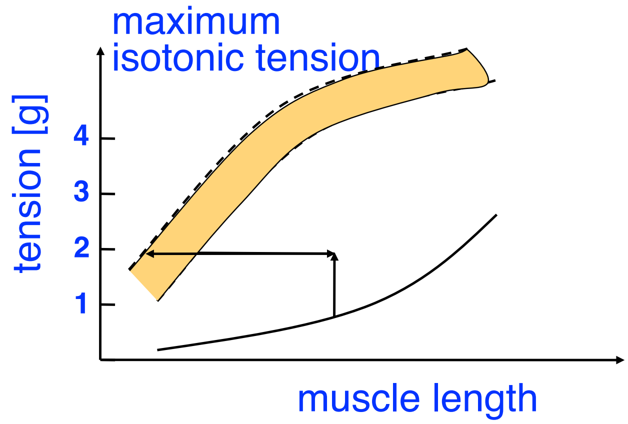
Work of the Heart

- Work = Pressure * Volume (force * distance)
- Cardiac cycle as PV diagram
- Efficiency
  - Convert work to O_2 consumption
  - Compare to total O_2 consumption
  - 10--15% efficient



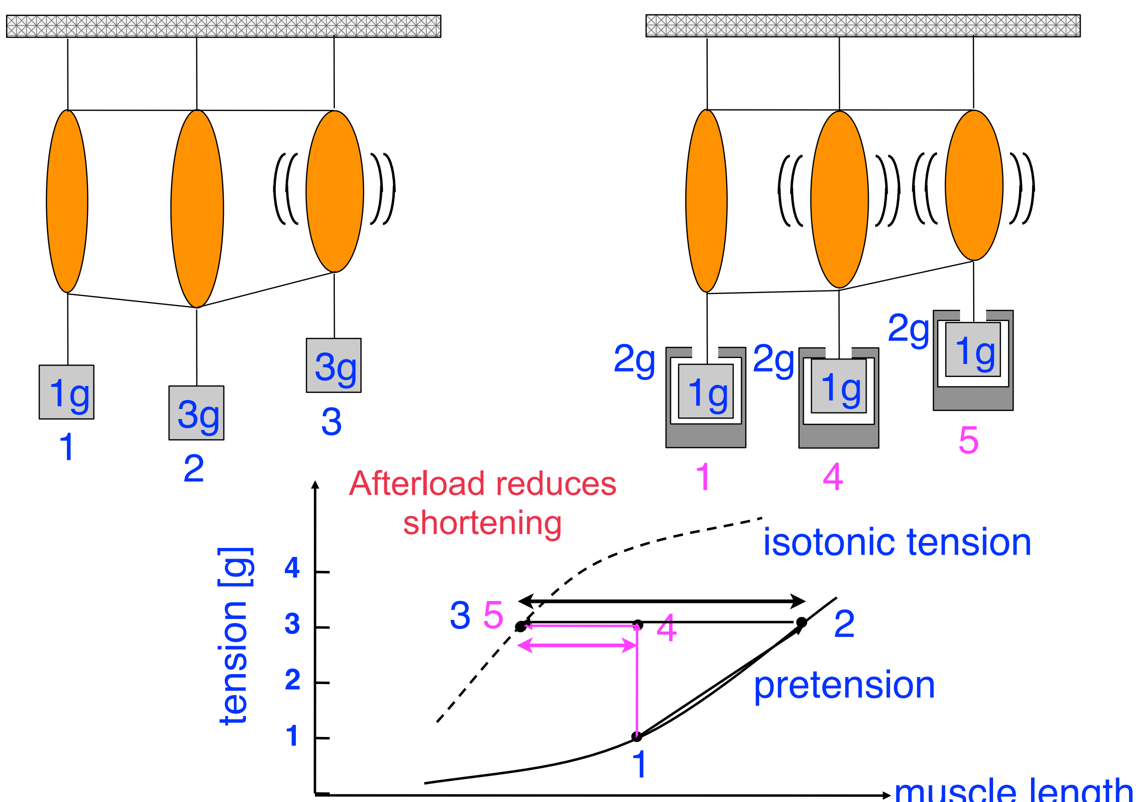
Effect of E/NE on Contraction



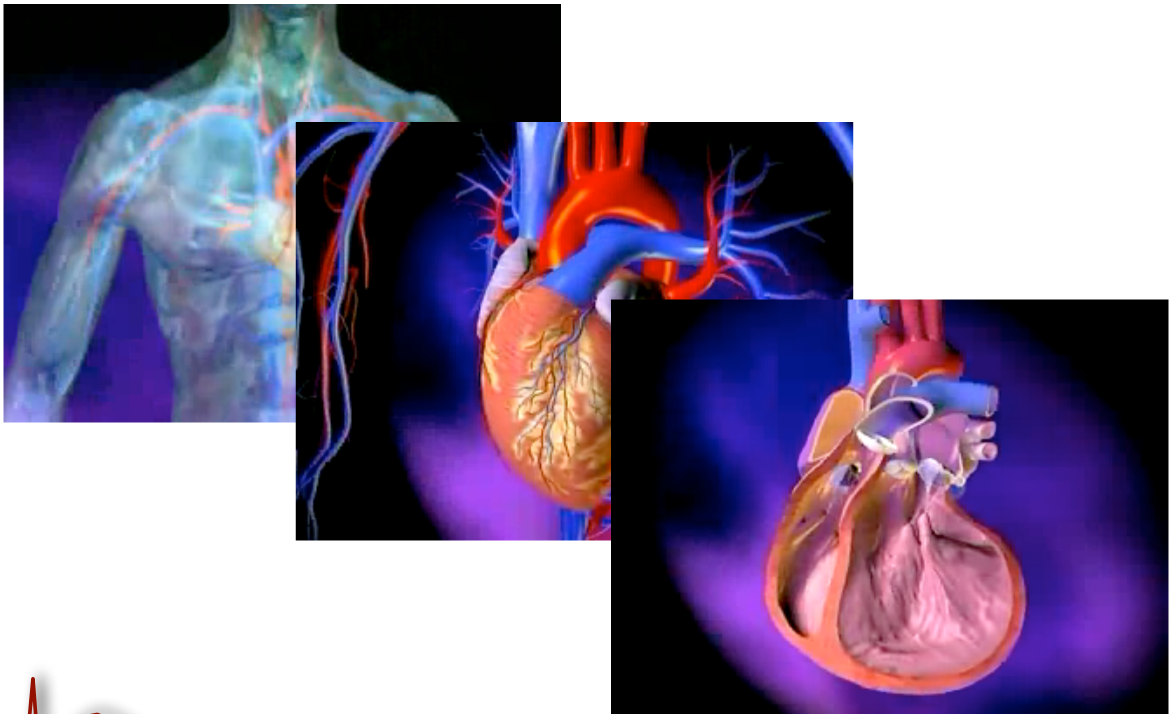


- constant pretension
- reduced end-systolic volume
- increased stroke volume

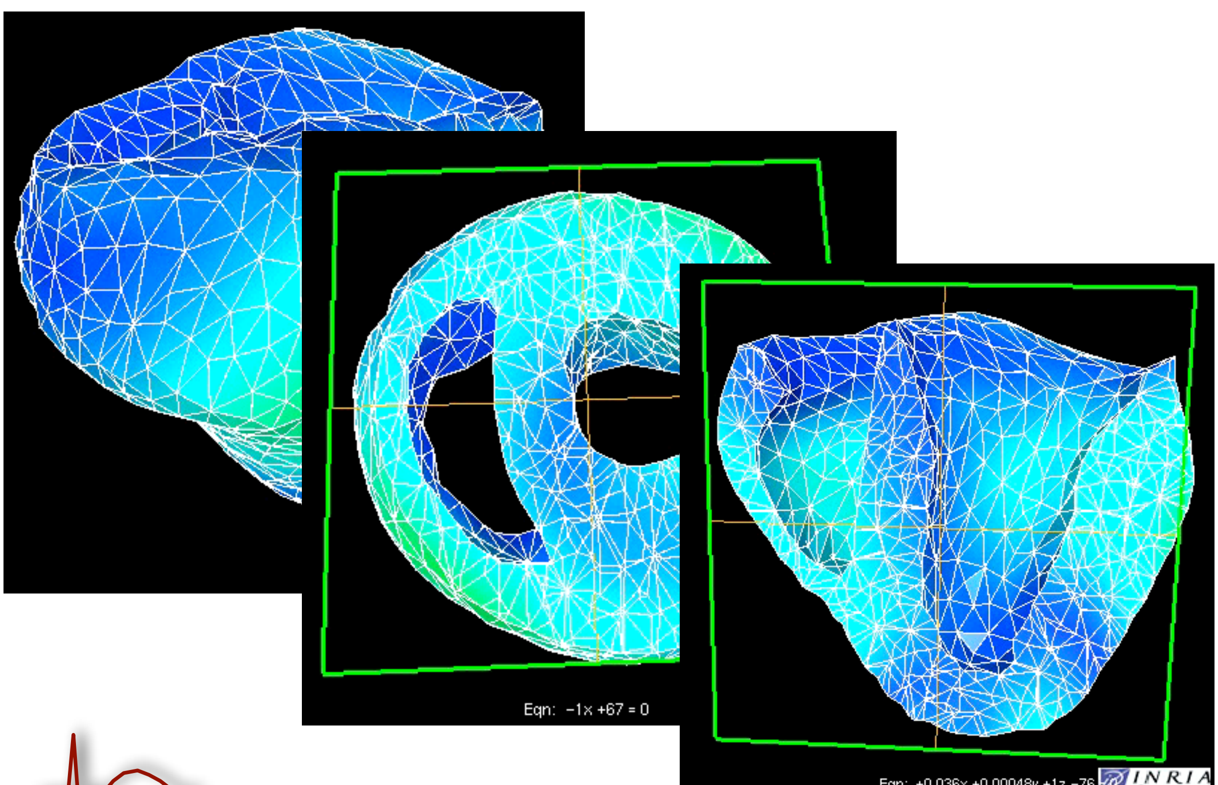
Isotonic Contraction and Afterload



Contraction at the Whole Heart



Whole Heart Simulation



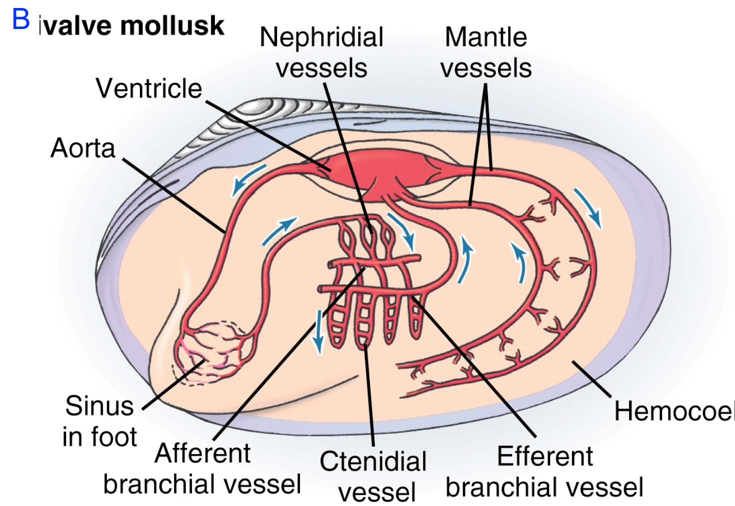
Animal Hearts

Animal Hearts

- Air-breathing vs. water breathing vs. fetal
- Open Systems
- Separate left and right hearts
  - Higher pressure good for rapid transport but require lymphatic system
  - Lower pressure (e.g., pulmonary) does not require lymphatics and stays drier
  - Both sides must have equal flow
- Shared ventricles
  - Shunts from pulmonary to systemic (P->S)
  - Allows adjustment of flow through lungs/gills
  - Flows to both parts of circulation are not equal but pressures are

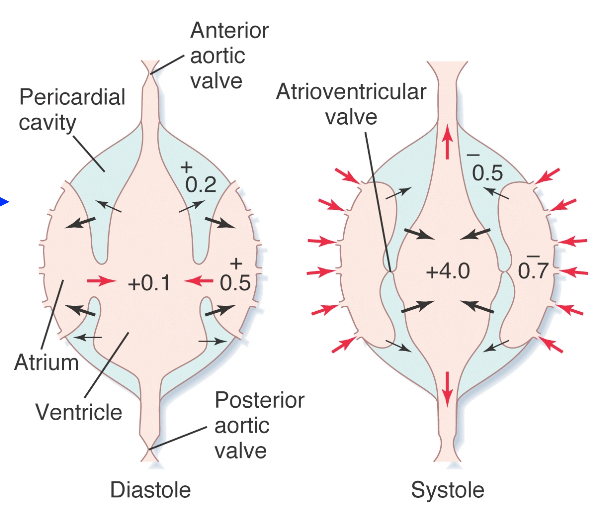
Open Systems

- Blood empties into body space
- Bathes tissues directly, blood in small chambers
- Low pressure system (4-10 mm Hg)
- Typically limited regulation and low oxygen transport (with exceptions)
- Insects bypass lungs and transport oxygen directly so open circulation does not carry oxygen

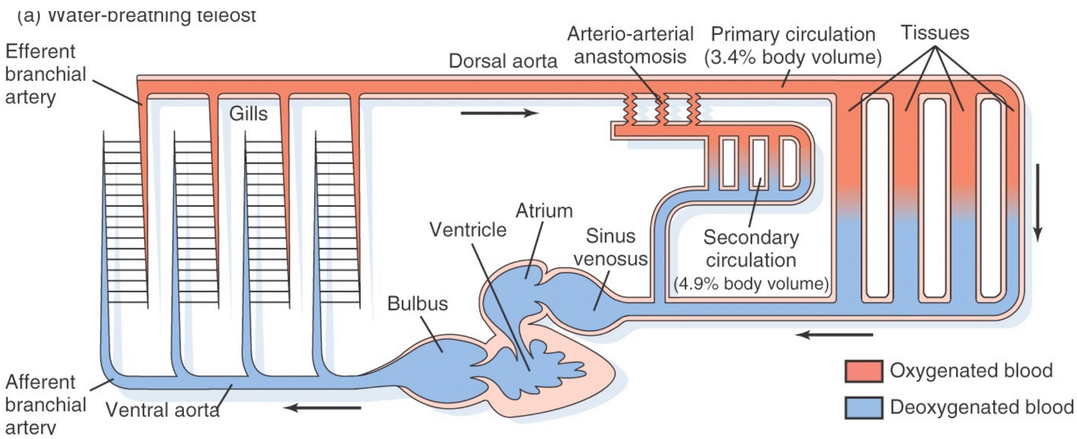


Rigid Pericardium

- Compliant
  - Minimal constraint
  - Lubrication
- Non-compliant
  - contraction of one chamber assists filling the other

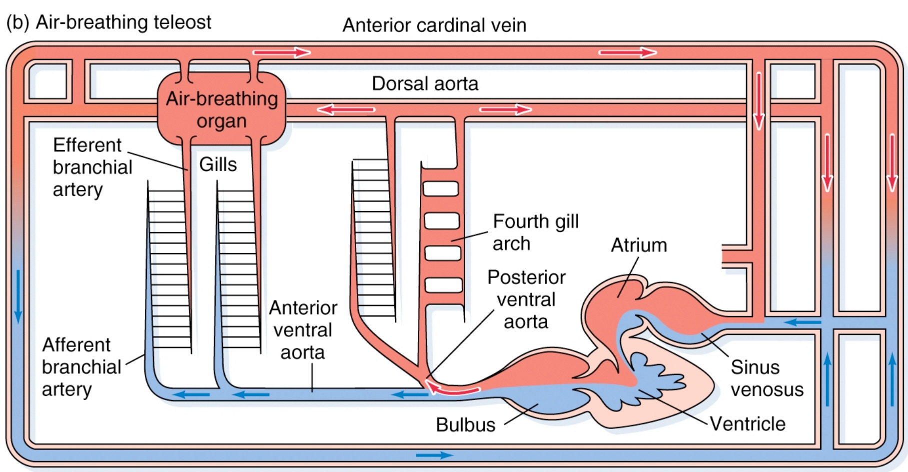


Water Breathing Fishes



- 4-chambered, sequential heart with valves
- Gills perform gas exchange and also ion balance (like kidneys in mammals)
- Gill circulation under higher pressure than systemic circulation

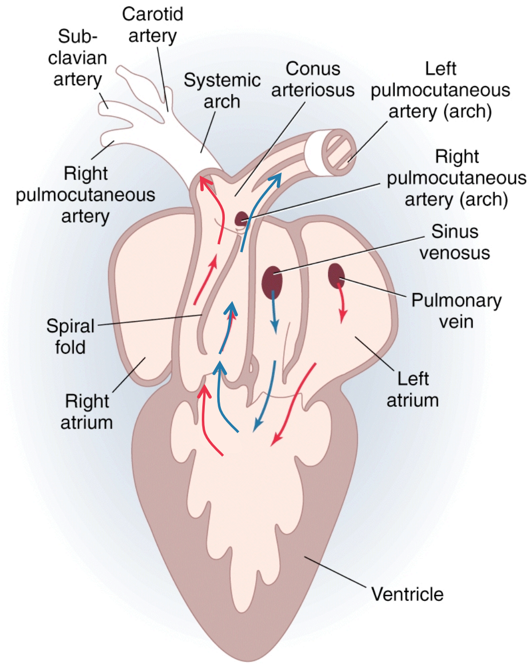
Air Breathing Fishes



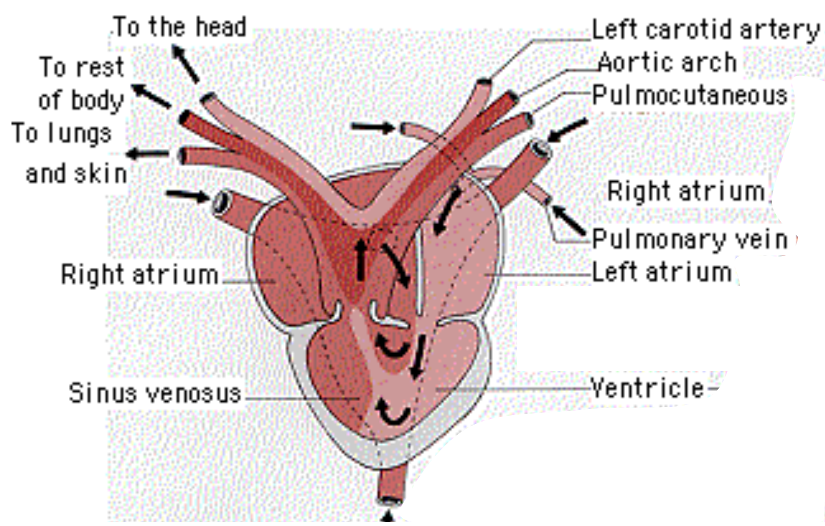
- Gills and vascularized air sac both provide O_2; gills used for CO_2 and ion balance
- Blood directed to different parts of system by the heart, also between gills and air-breathing organs

Amphibians (e.g., Frog)

- Shared ventricle but blood separated
  - Spiral fold
  - Initial flow through pulmonary because of reduced pressure
  - Resistance to flow varies with breathing (inhale reduces resistance)



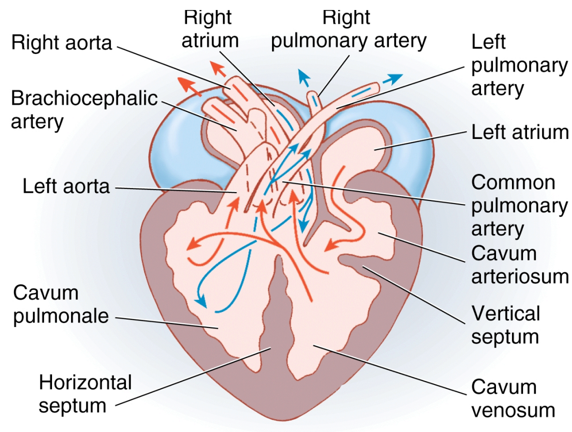
Frog II



- Partial mixing of systemic blood flow
  - Cerebral flow oxygenated, systemic mixed
- http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/A/AnimalHearts.html

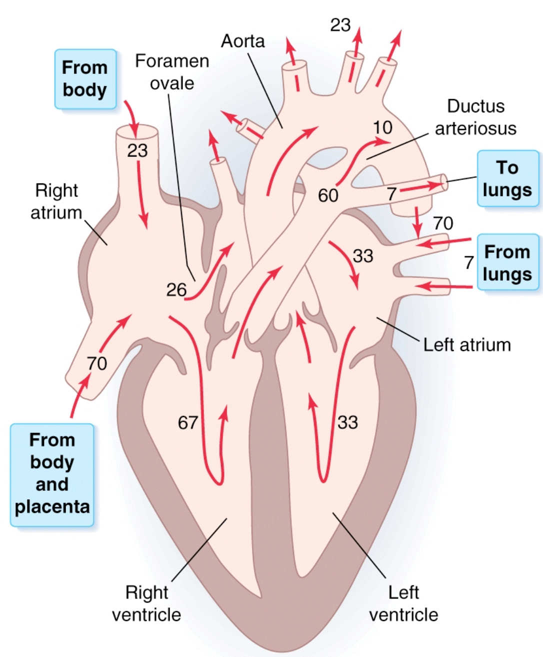
Reptiles (non crocodilian)

- Partial separation of single ventricle by 2 septa
- In ventricular systole, flow determined by relative resistances of pulmonary and system, e.g., breathing, diving
- Pressure differences in arteries also directs flow: lower pressure value opens first
-



Fetal Heart

- Lungs collapsed so minimal pulmonary flow
- Oxygenated blood comes from placenta and some passes through foramen ovale to left atrium
- Rest of returning blood goes from RV and most through Ductus ateriosus to aorta
- At birth, lungs inflate, flow to them increases, placenta flow gone so systemic resistance increases
- Left side pressure increases, D.A. and F.O close



Numbers are percentage of ventricular output