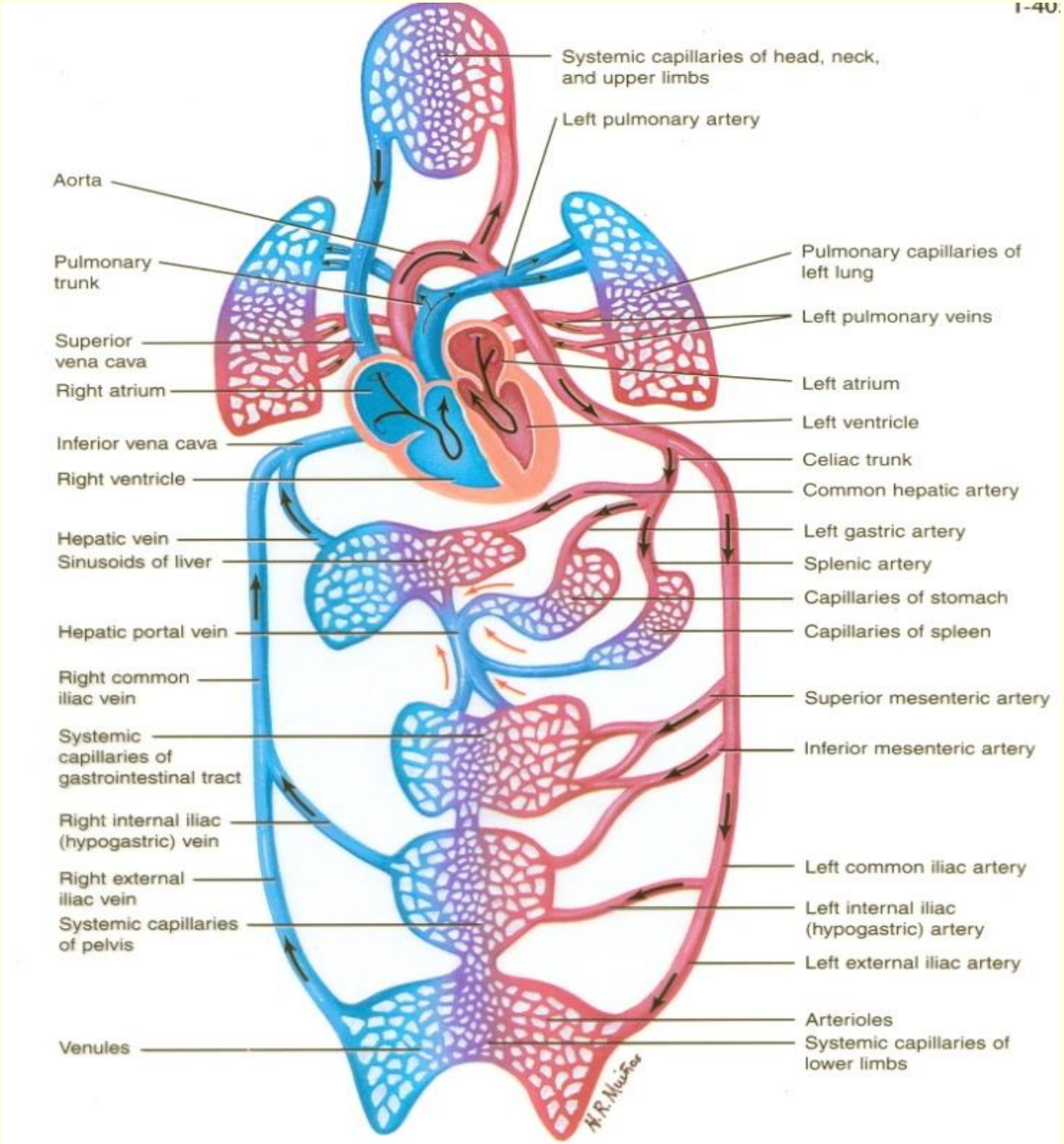
Cardiac Muscle Physiology

Faisal Mohammed, MD, PhD

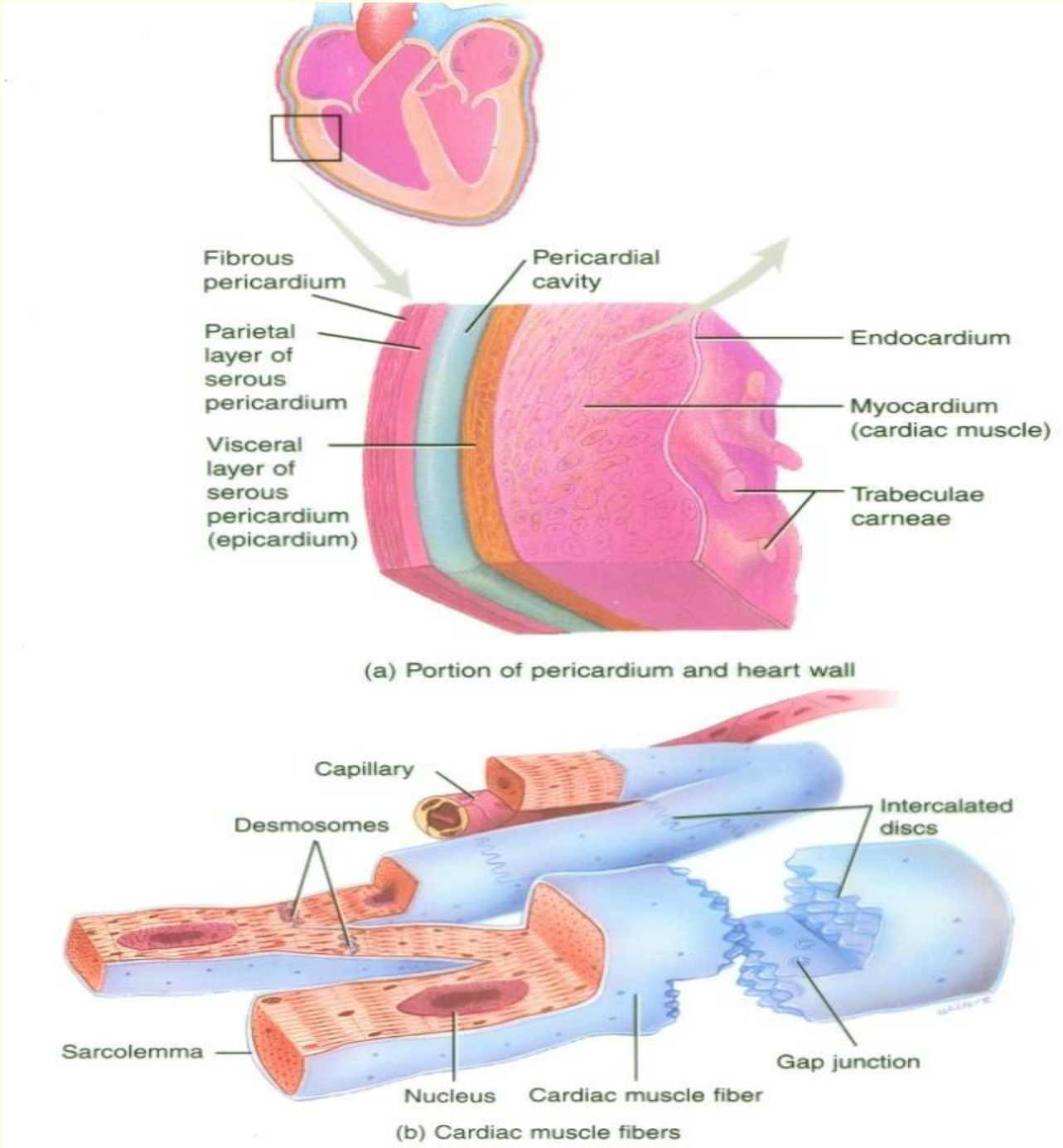
Objectives:

By The end of this lecture students should be able to:

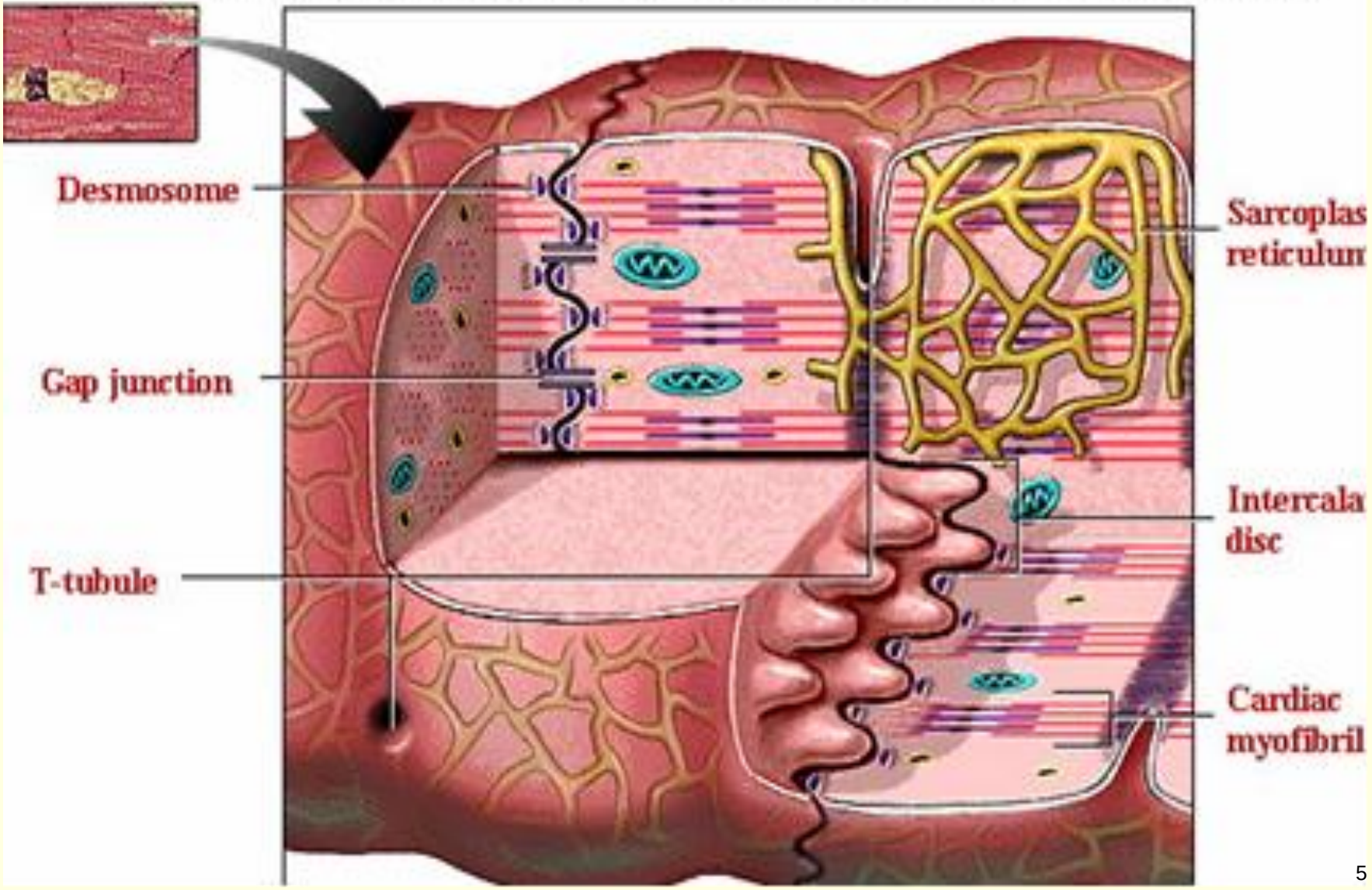
- Distinguish the cardiac muscle cell microstructure
- Describe cardiac muscle action potential
- Point out the functional importance of the action potential
- Follow the cardiac muscle mechanism of contraction
- Delineate cardiac muscle energy sources
- Outline the intracellular calcium homeostasis
- Explain the relationship between muscle length and tension of cardiac muscle (Frank-Starling law of the heart)

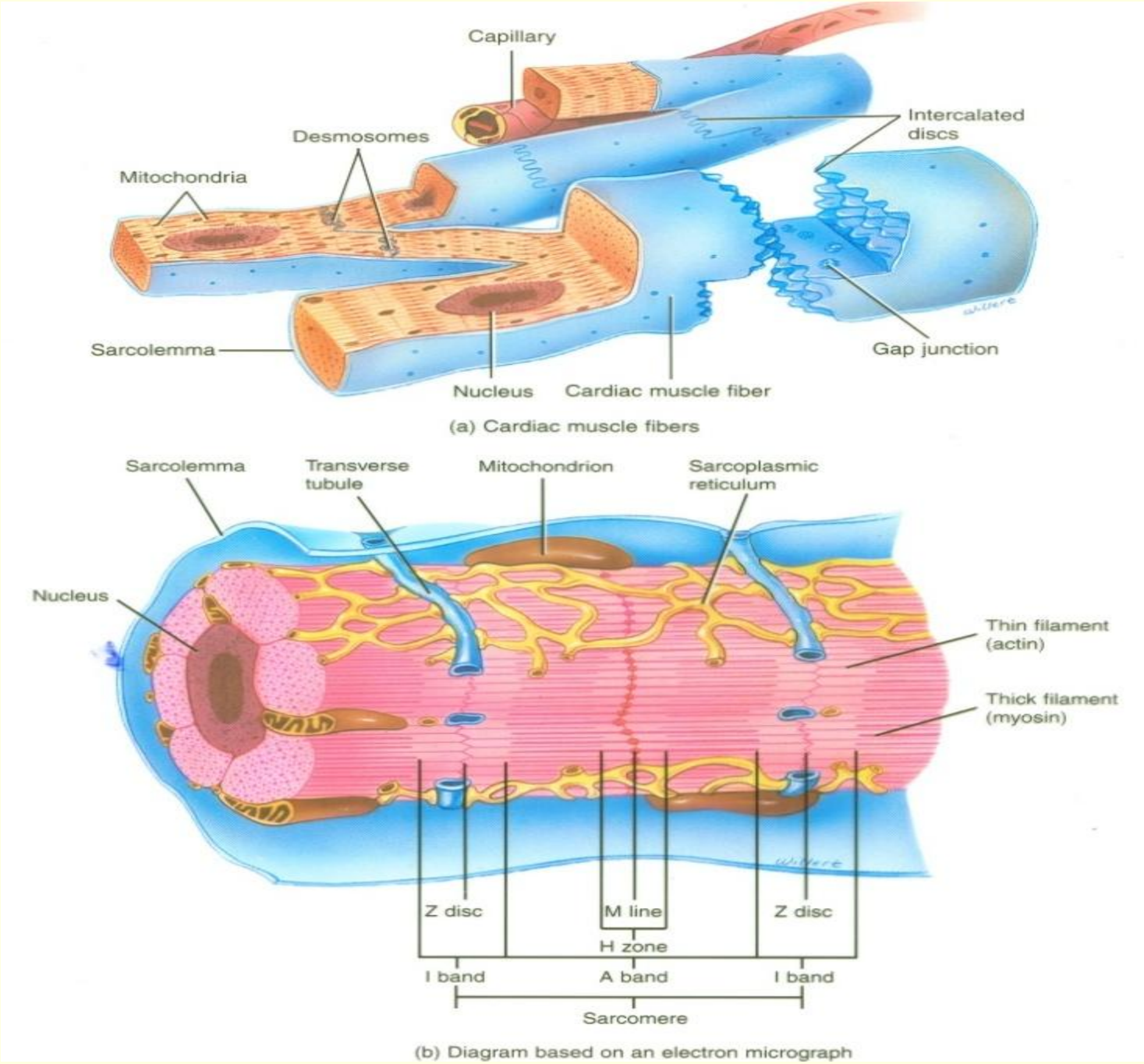


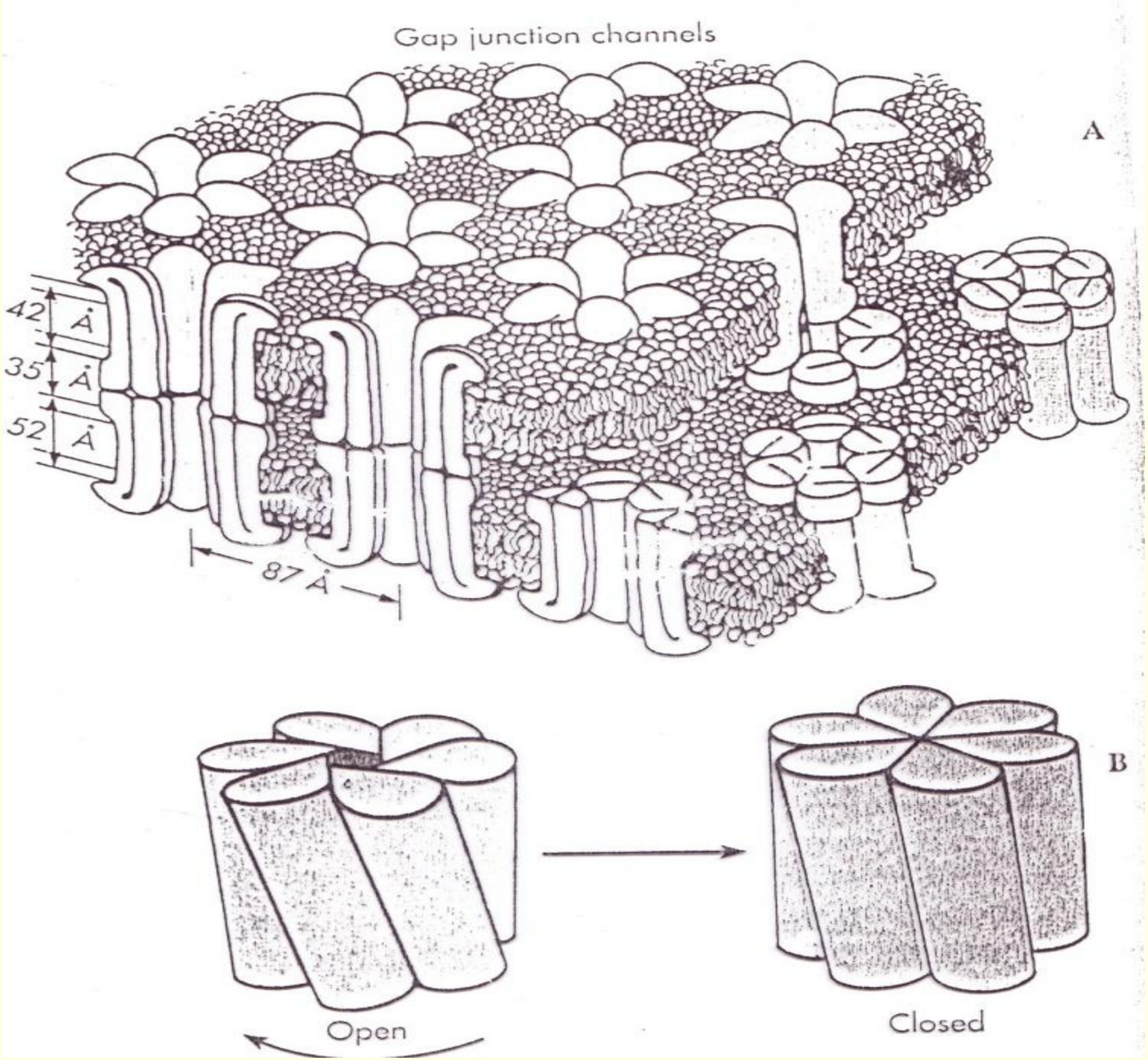
General plan of circulation


Fibrous pericardium
Pericardial cavity
Parietal layer of serous pericardium
Endocardium
Myocardium (cardiac muscle)
Visceral layer of serous pericardium (epicardium)
Trabeculae carneae
(a) Portion of pericardium and heart wall
Capillary
Desmosomes
Intercalated discs
Sarcolemma
Nucleus
Cardiac muscle fiber
Gap junction
(b) Cardiac muscle fibers

MAGNIFIED VIEW OF CARDIAC MUSCLE CELLS



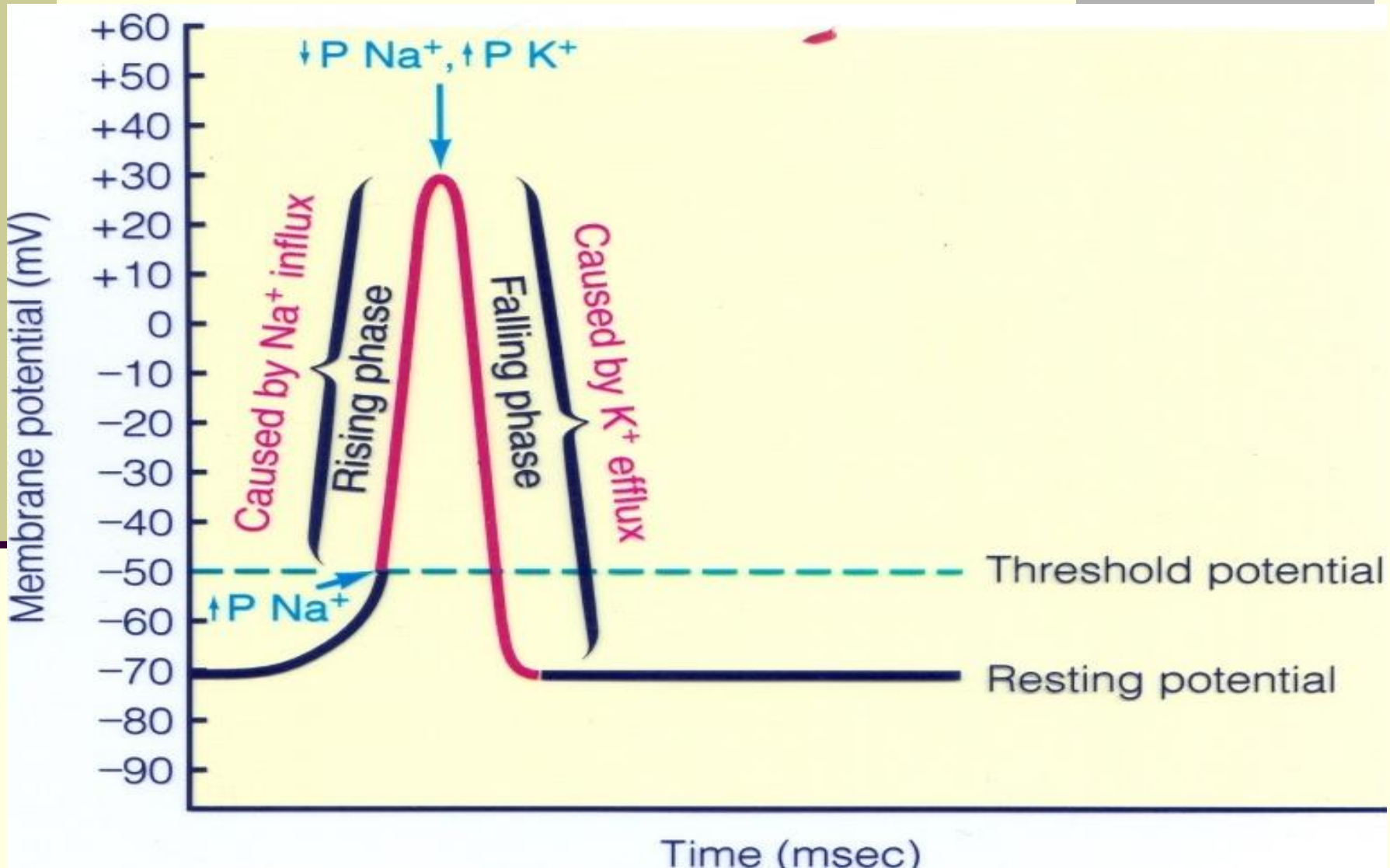

Capillary
Intercalated discs
Desmosomes
Mitochondria
Sarcolemma
Nucleus
Cardiac muscle fiber
Gap junction
(a) Cardiac muscle fibers
Sarcolemma
Transverse tubule
Mitochondrion
Sarcoplasmic reticulum
Nucleus
Thin filament (actin)
Thick filament (myosin)
Z disc
M line
Z disc
H zone
I band
A band
I band
Sarcomere
(b) Diagram based on an electron micrograph

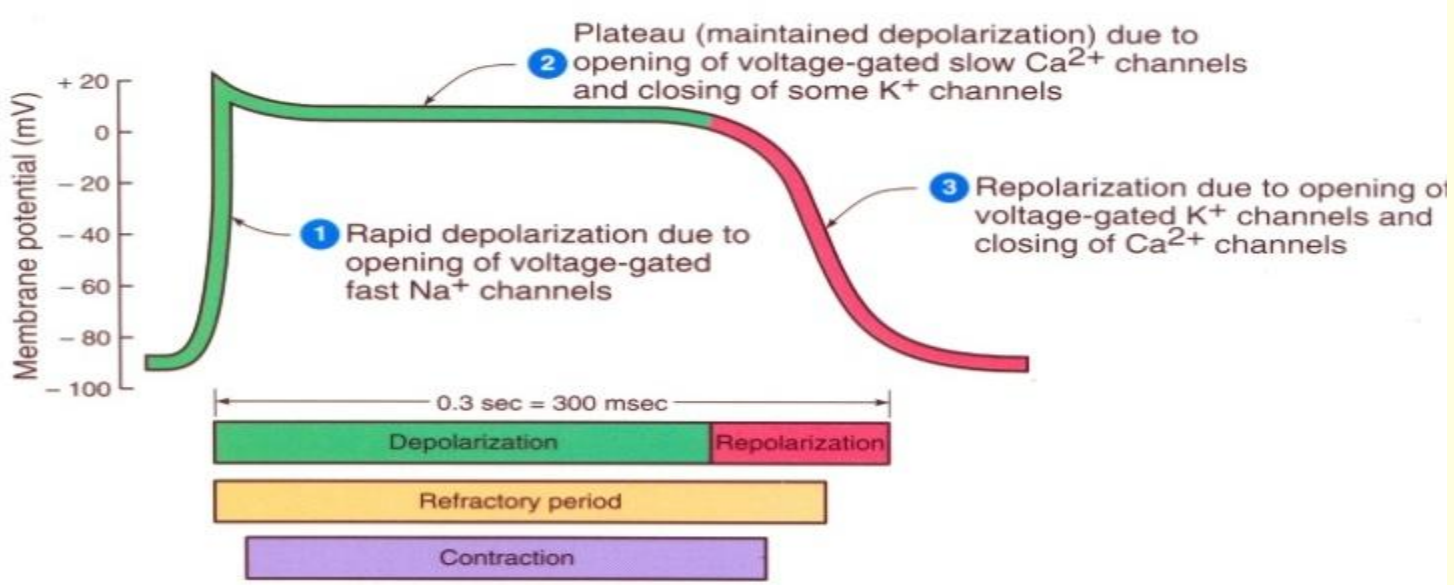

Gap junction channels
A
42 Å
35 Å
52 Å
87 Å
B
Open
Closed

Cardiac Muscle Vs Skeletal Muscle

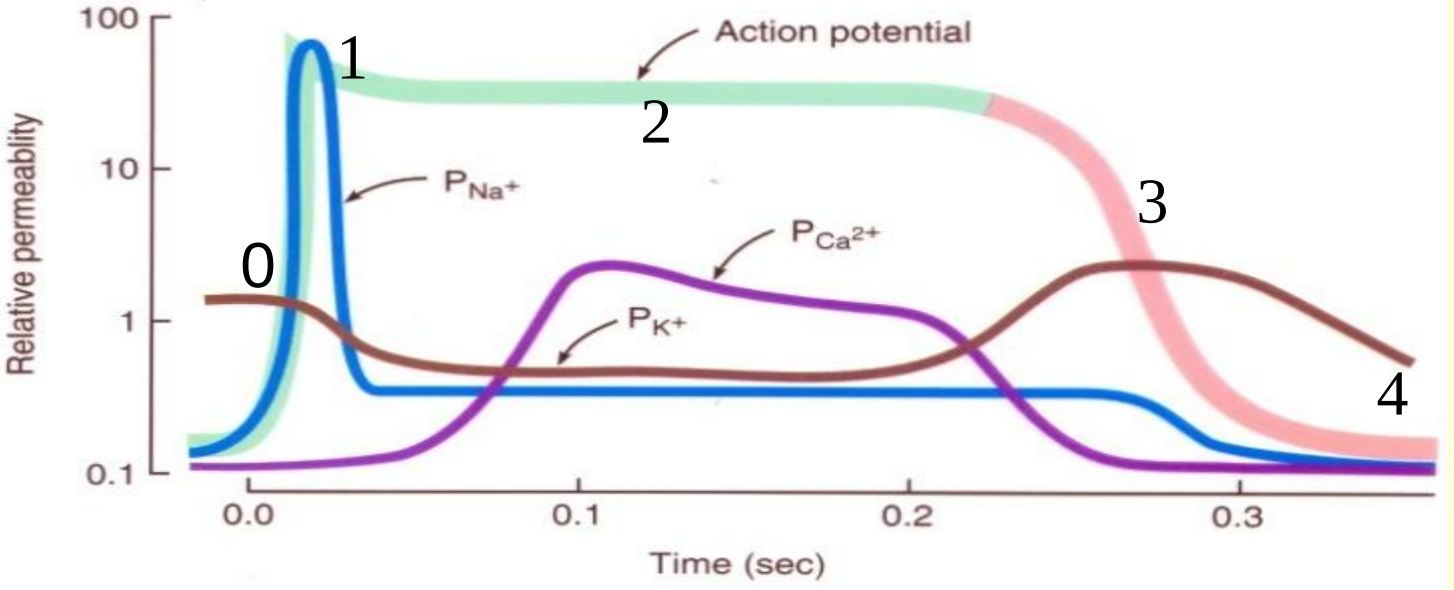
- Syncytium structure
- Gap Junction (electrical coupling) low resistance area
- Poorly developed Sarcoplasmic reticulum (SR)
- Transverse (T)Tubule on Z-line (i.e.One T-tubule per sarcomere)
- Rich in mitochondria
- Low in nuclei

Permeability Changes and Ionic Fluxes During an Action Potential (skeletal Muscle)



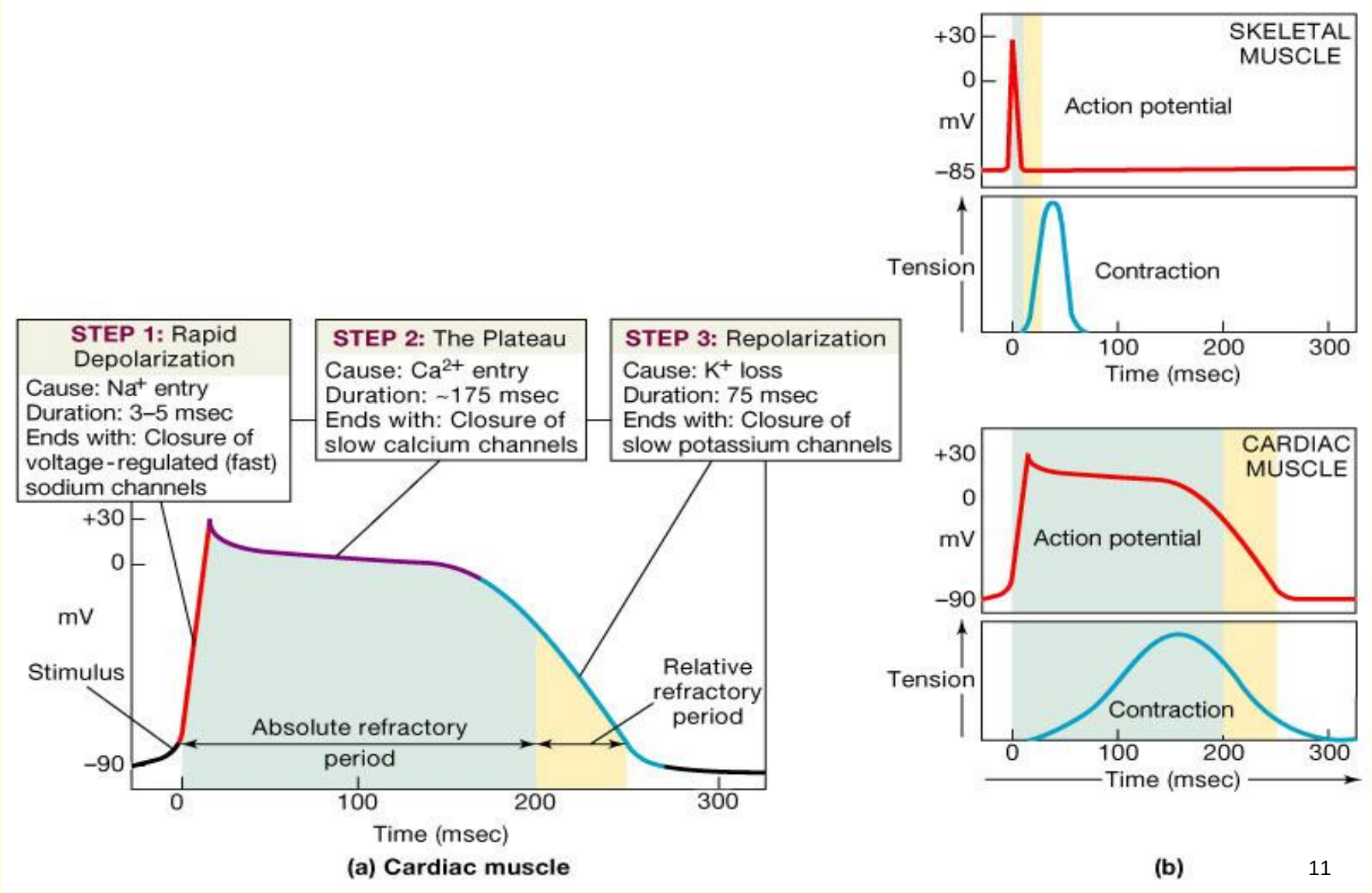


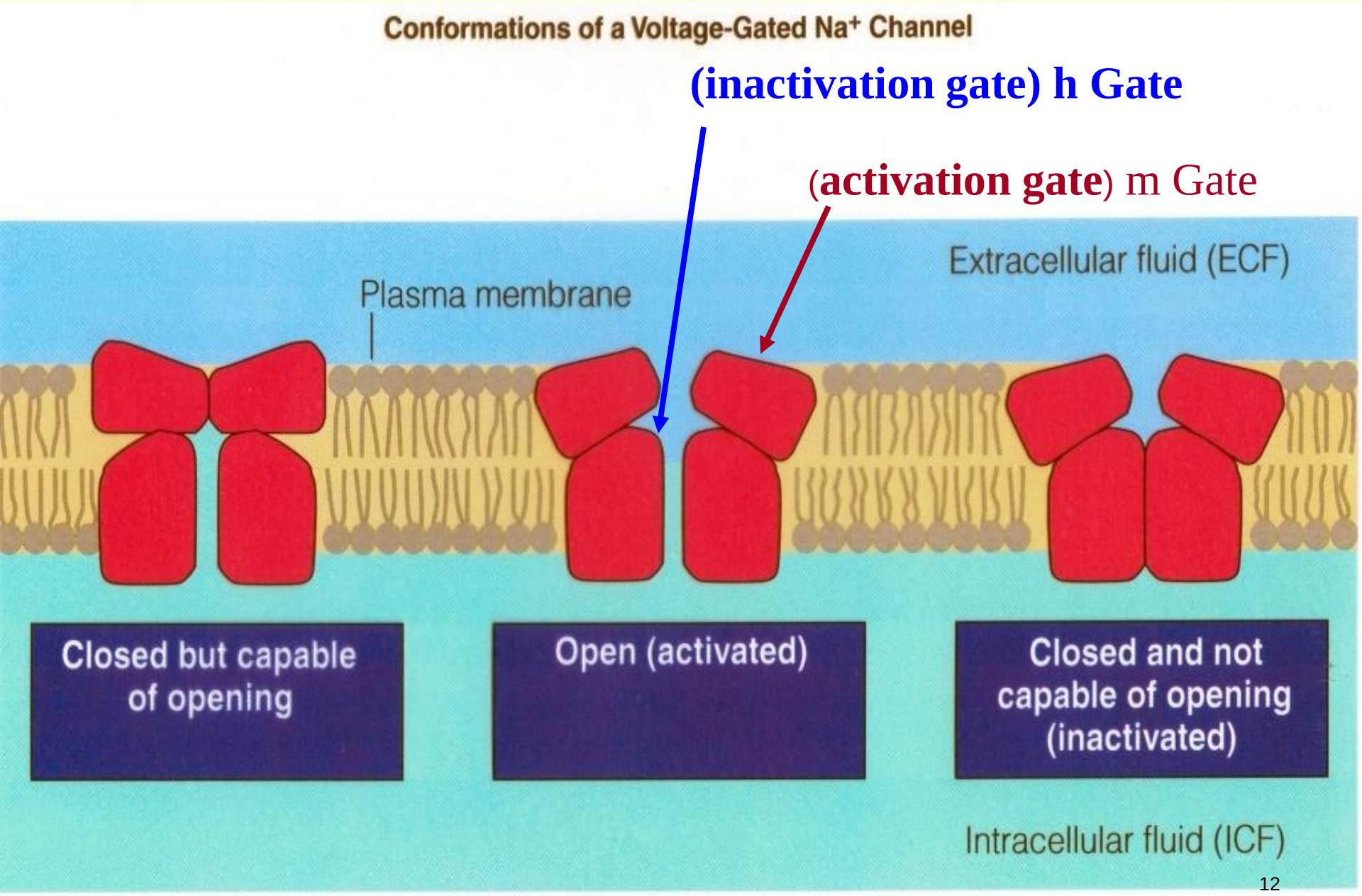
(a) Action potential, refractory period, and contraction

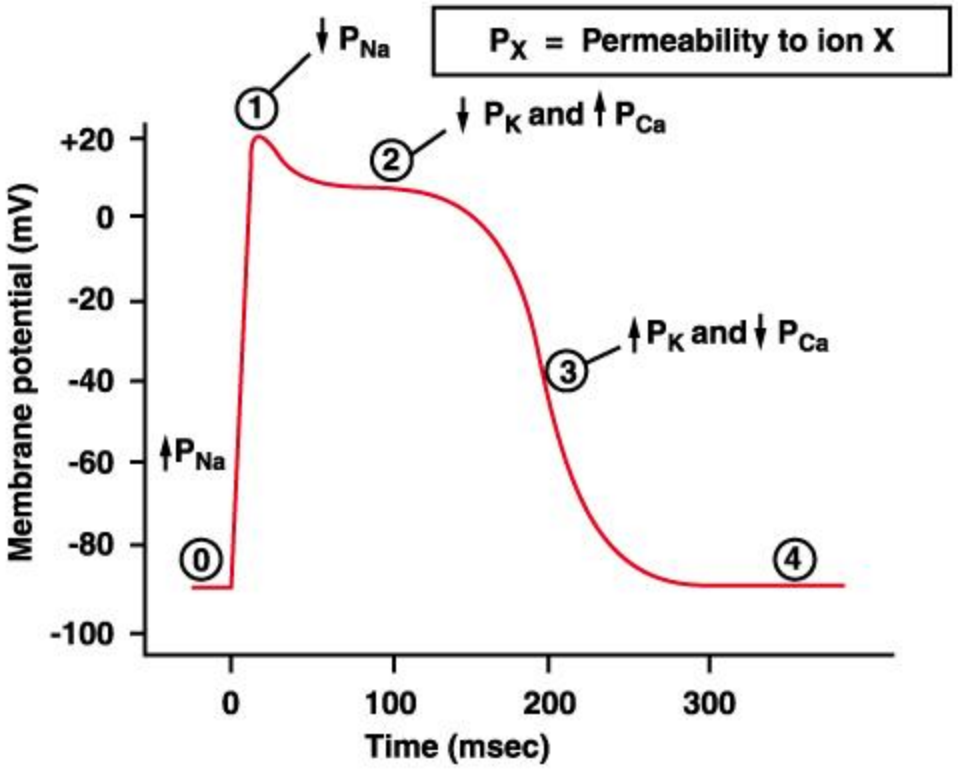


(b) Membrane permeability (P) changes

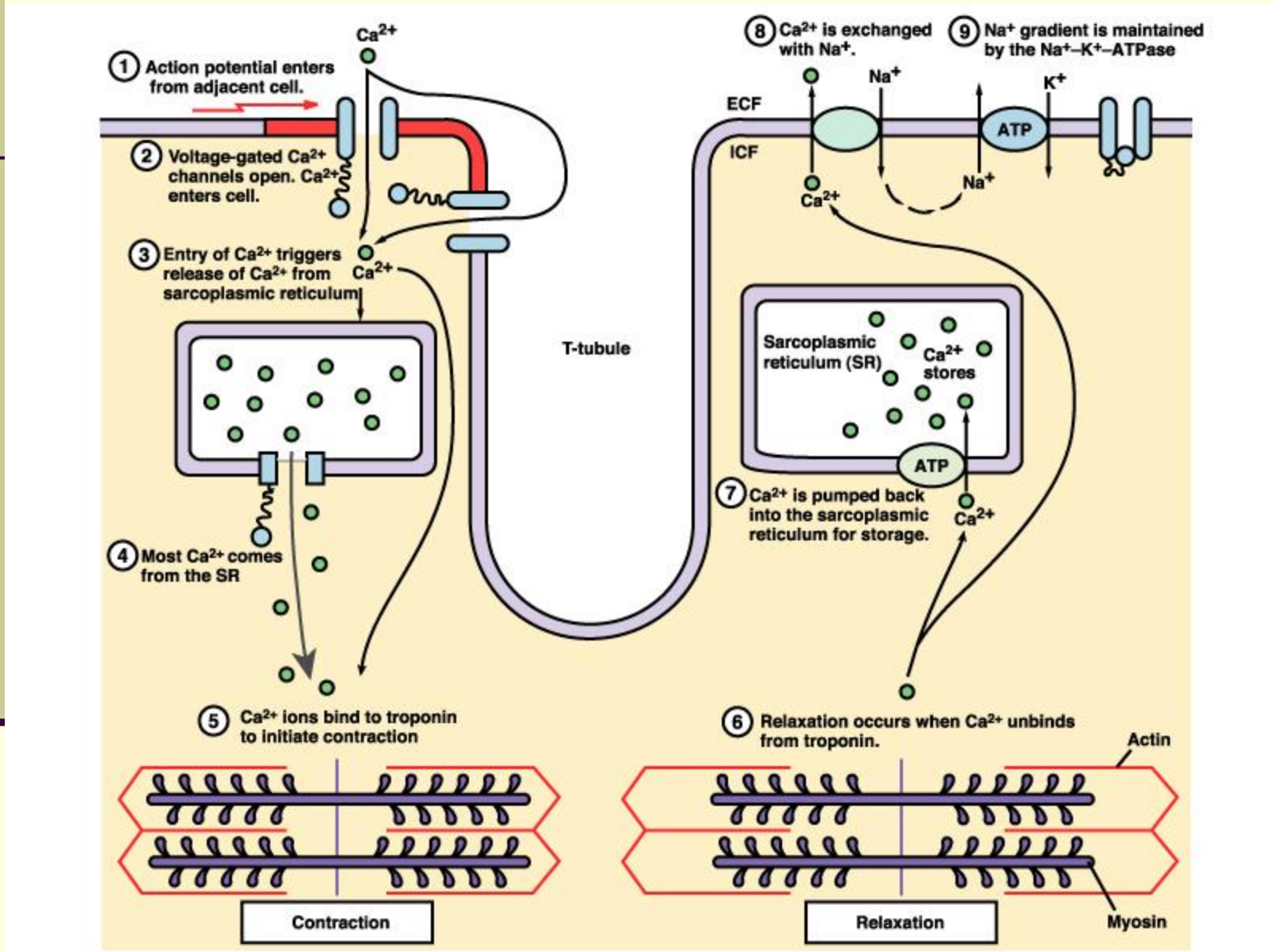
The Action Potential in Skeletal and Cardiac Muscle



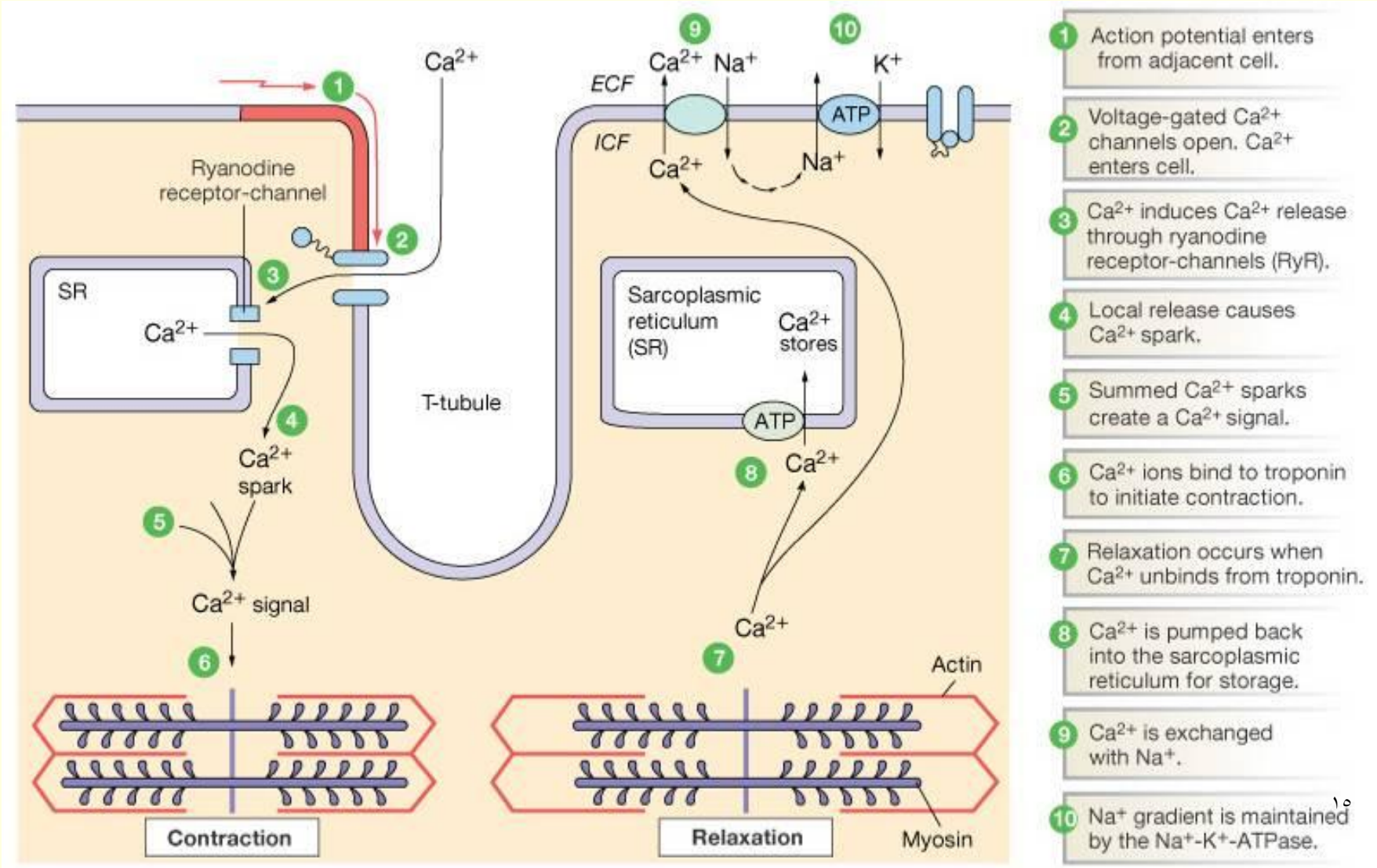

Conformations of a Voltage-Gated Na+ Channel
(inactivation gate) h Gate
(activation gate) m Gate
Extracellular fluid (ECF)
Plasma membrane
Closed but capable of opening
Open (activated)
Closed and not capable of opening (inactivated)
Intracellular fluid (ICF)



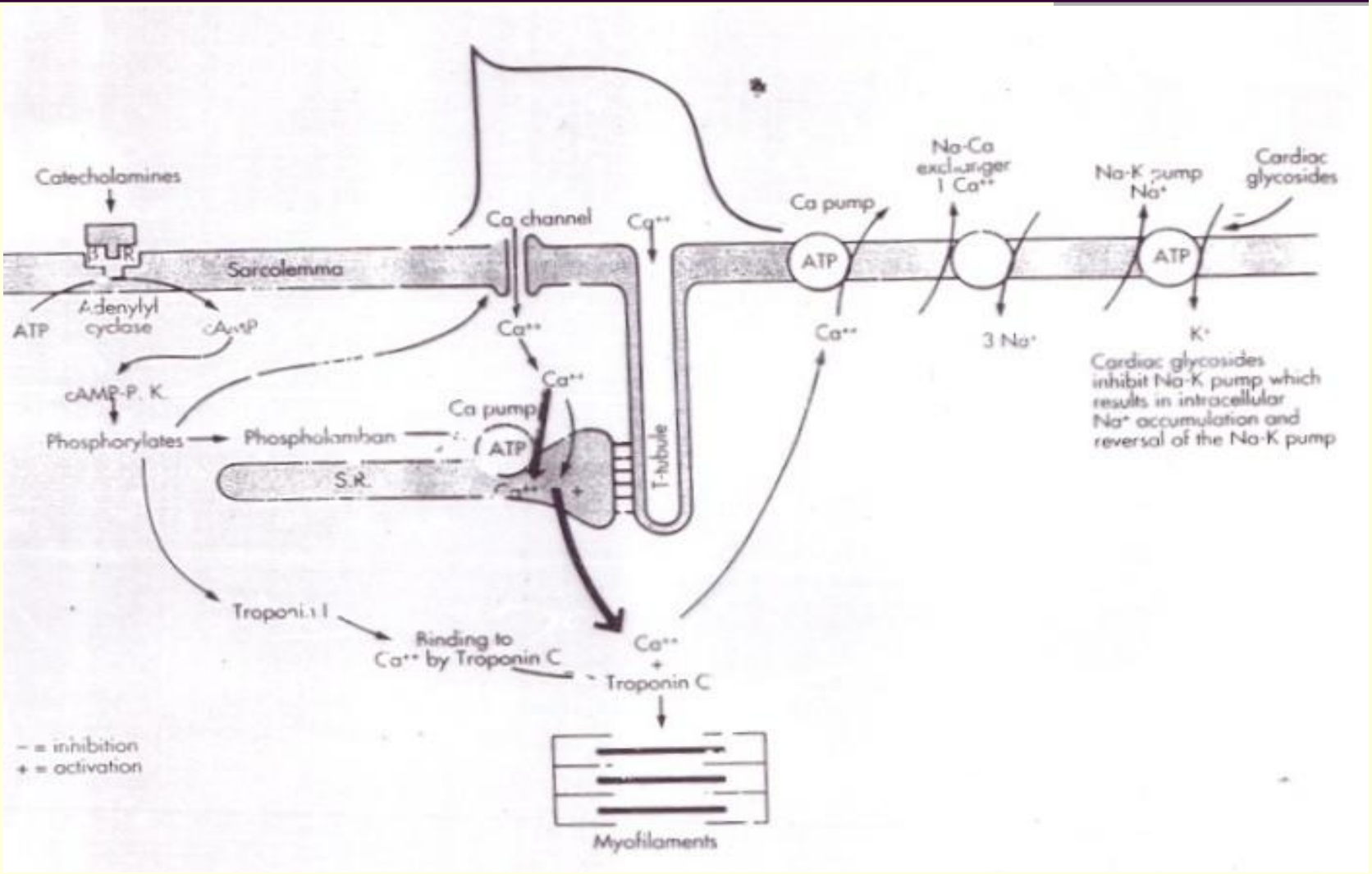
Phase	Membrane channels
0	Na^+ channels open
1	Na^+ channels close
2	Ca^{2+} channels open; fast K^+ channels close
3	Ca^{2+} channels close; slow K^+ channels open
4	Resting potential


1 Action potential enters from adjacent cell.
2 Voltage-gated Ca2+ channels open. Ca2+ enters cell.
3 Entry of Ca2+ triggers release of Ca2+ from sarcoplasmic reticulum
4 Most Ca2+ comes from the SR
5 Ca2+ ions bind to troponin to initiate contraction
6 Relaxation occurs when Ca2+ unbinds from troponin.
7 Ca2+ is pumped back into the sarcoplasmic reticulum for storage.
8 Ca2+ is exchanged with Na+.
9 Na+ gradient is maintained by the Na+–K+–ATPase
T-tubule
ECF
ICF
ATP
Sarcoplasmic reticulum (SR)
Ca2+ stores
Actin
Myosin
Contraction
Relaxation

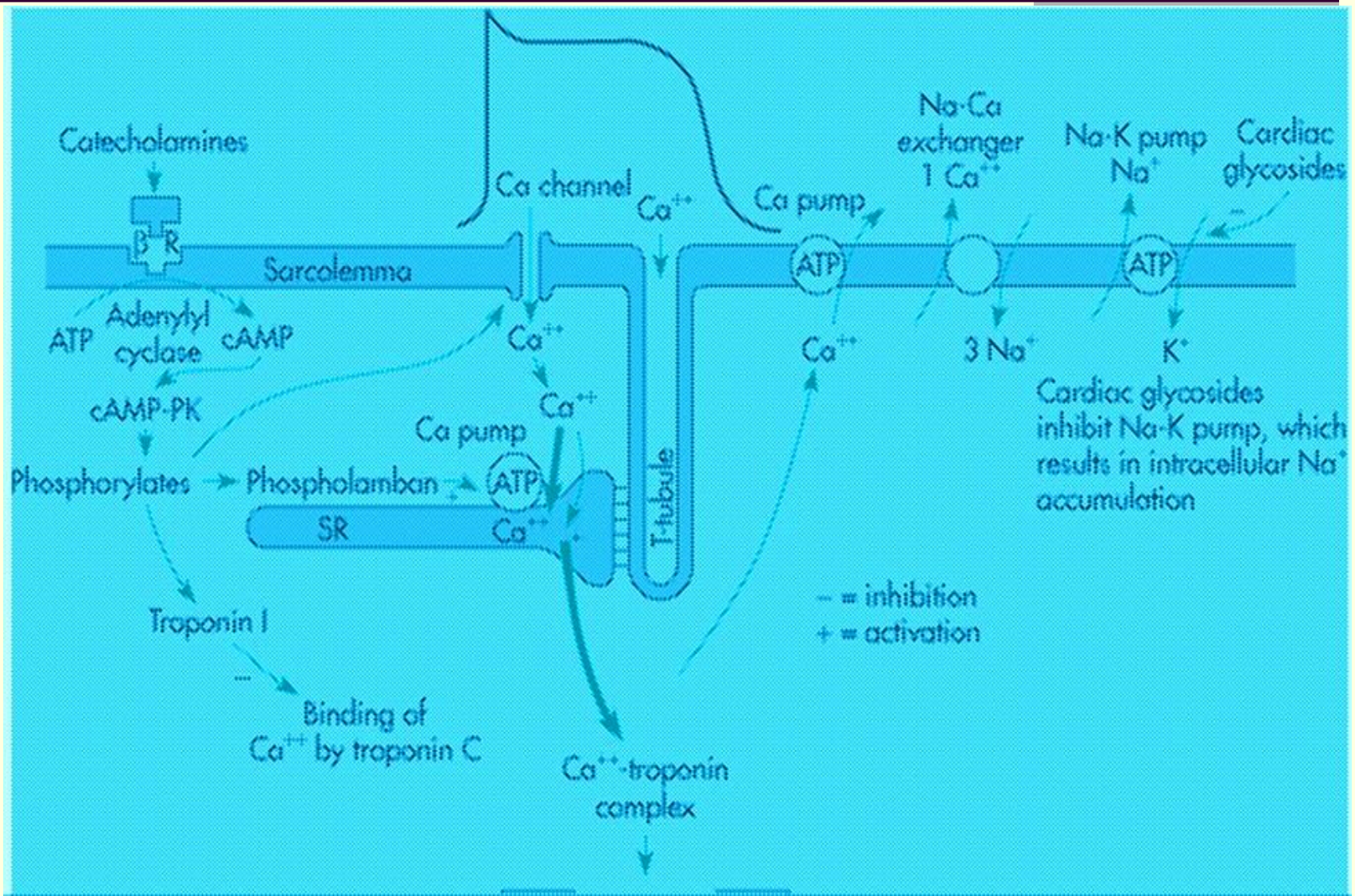
Mechanism of Cardiac Muscle Excitation, Contraction & Relaxation



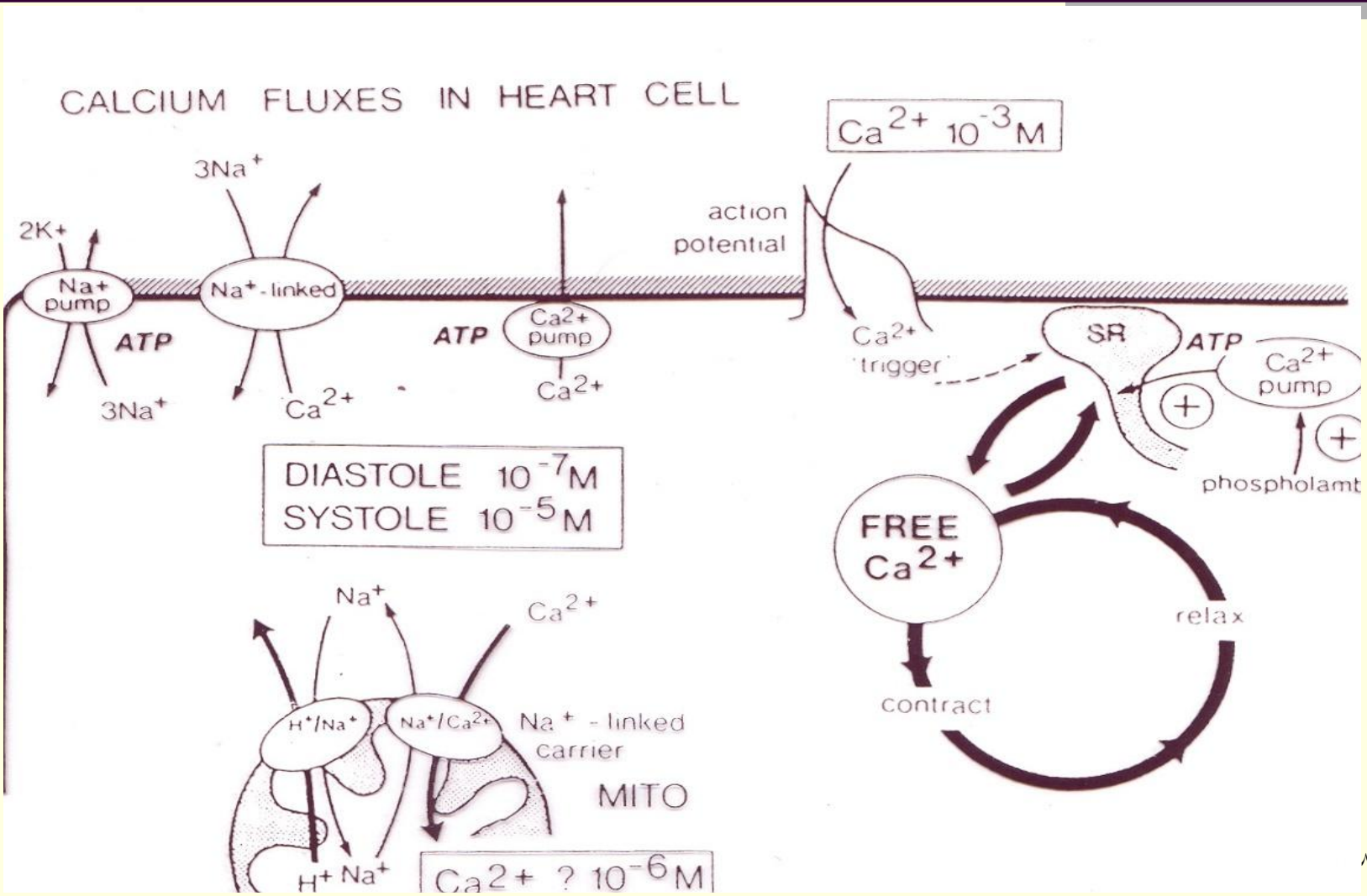
Intracellular Calcium Homeostasis…1



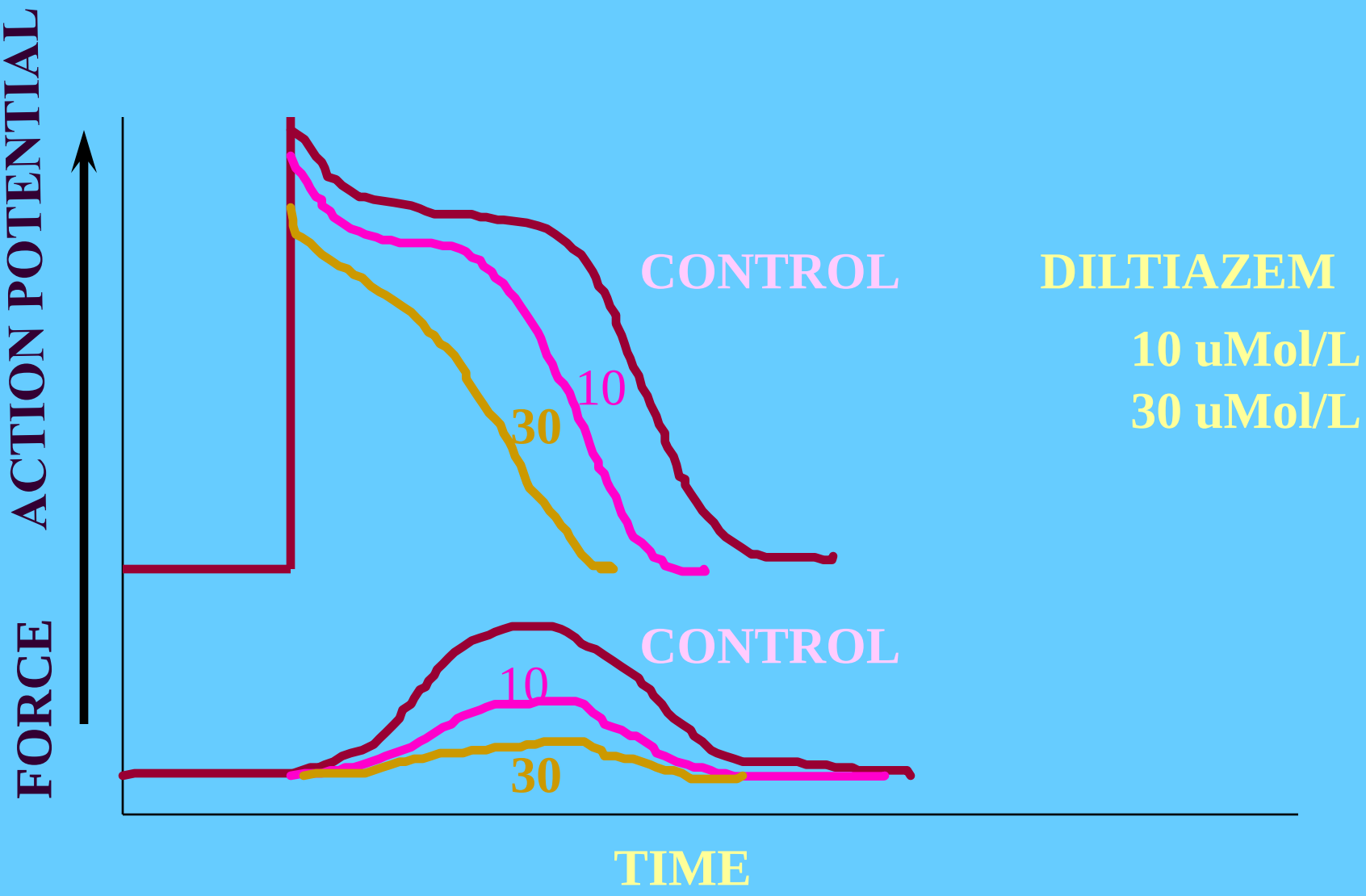
Intracellular Calcium Homeostasis…1



Intracellular Calcium Homeostasis…2

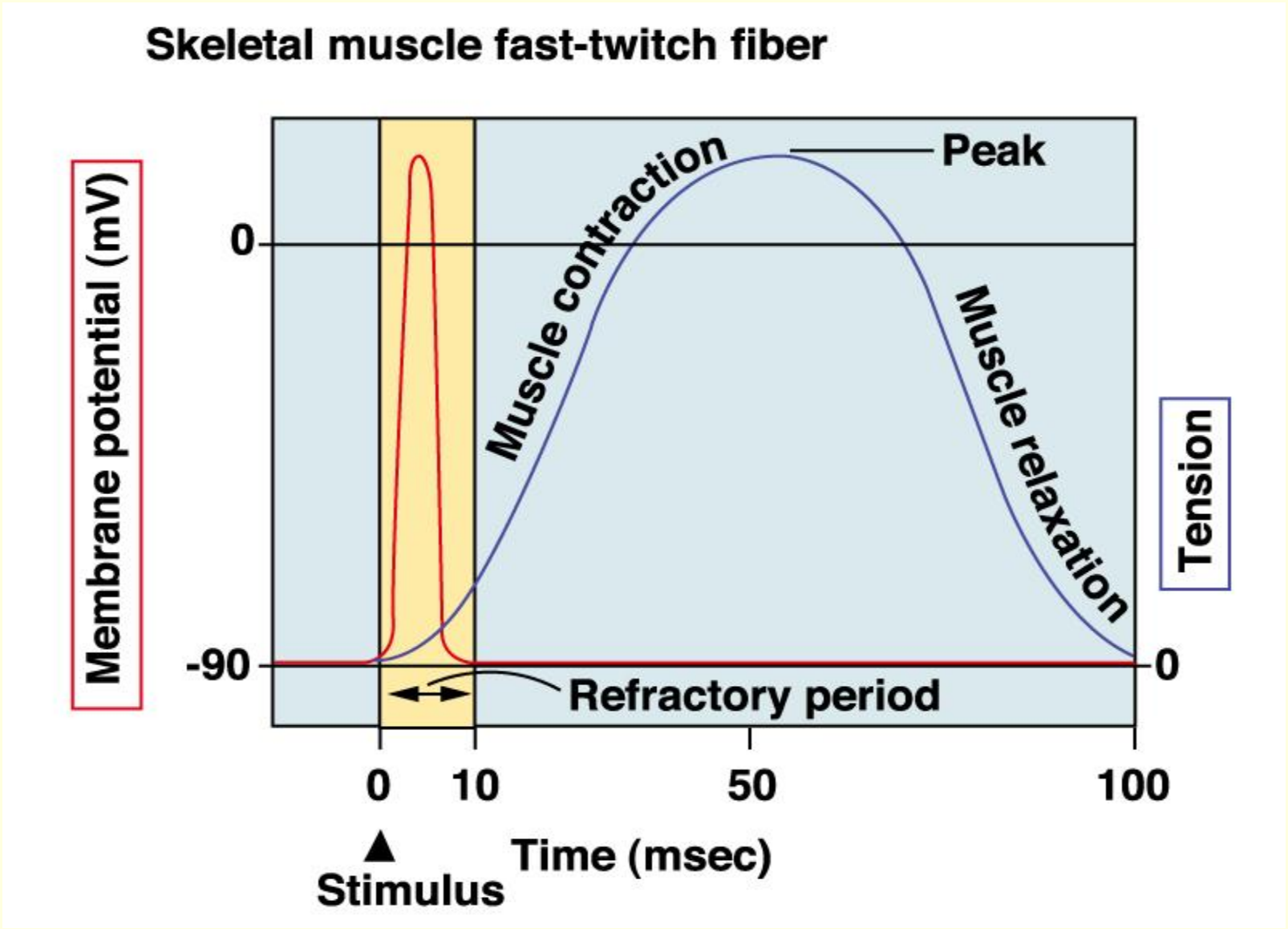


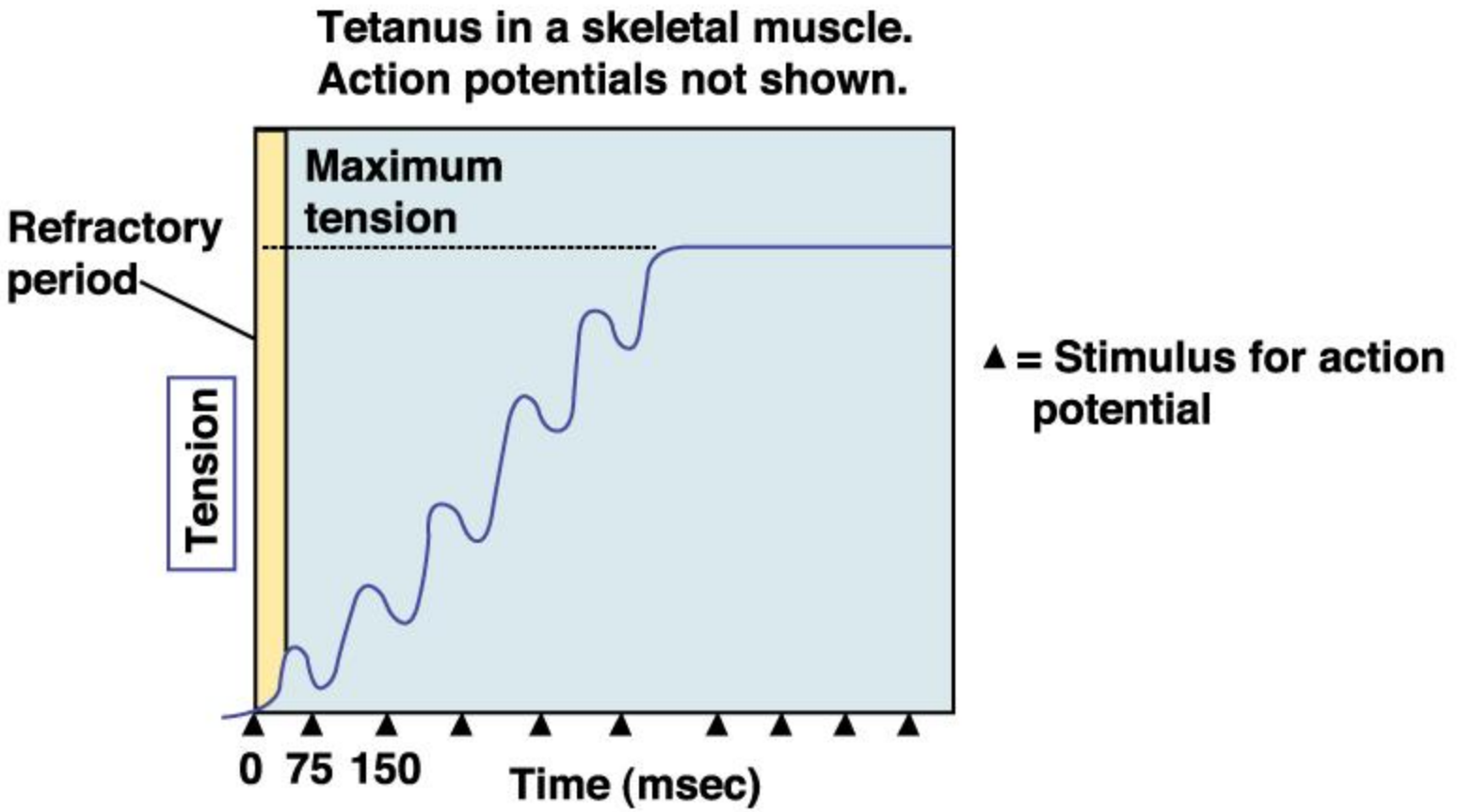
EFFECTS OF Ca++ CHANNEL BLOCKERS AND THE CARDIAC CELL ACTION POTENTIAL

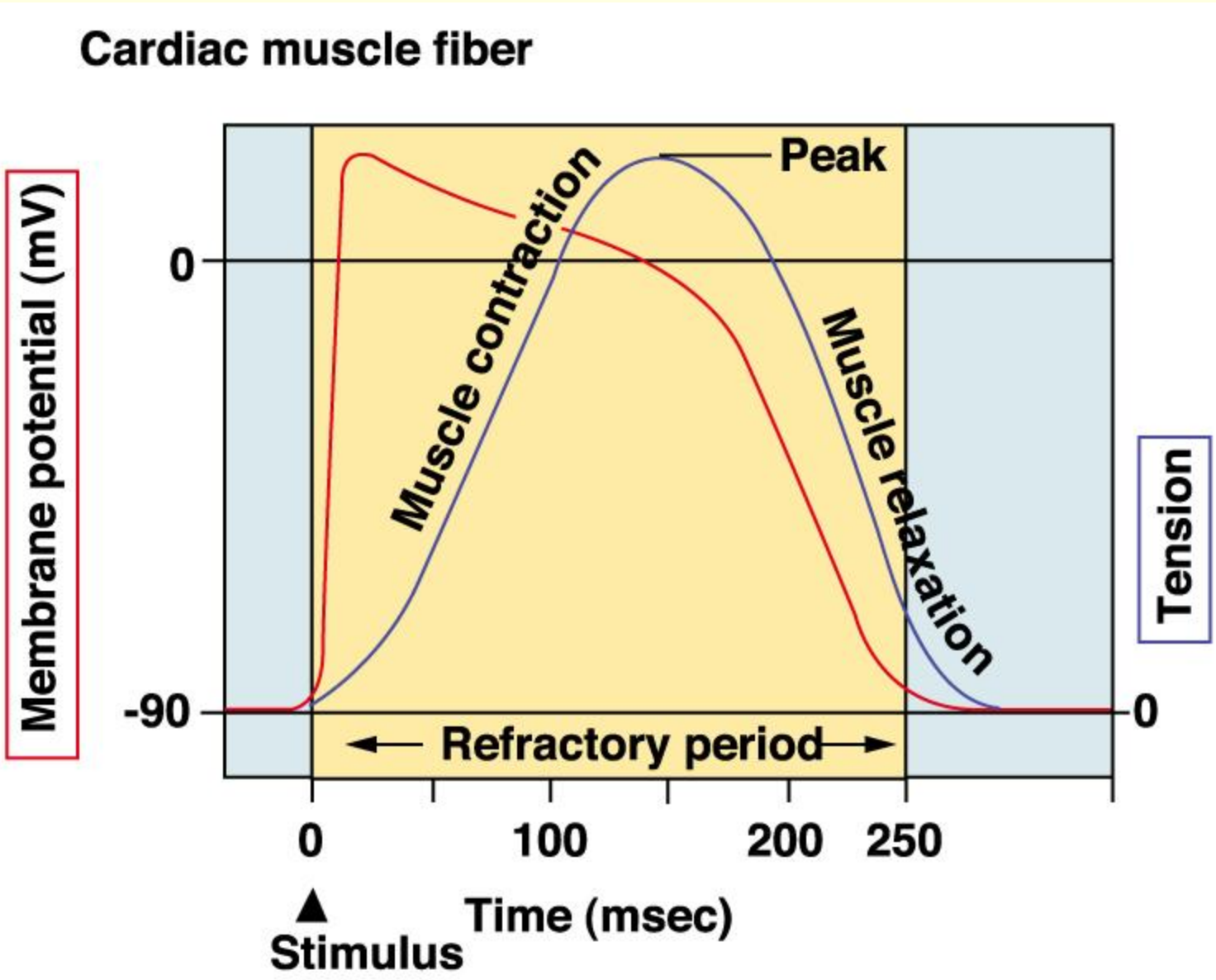


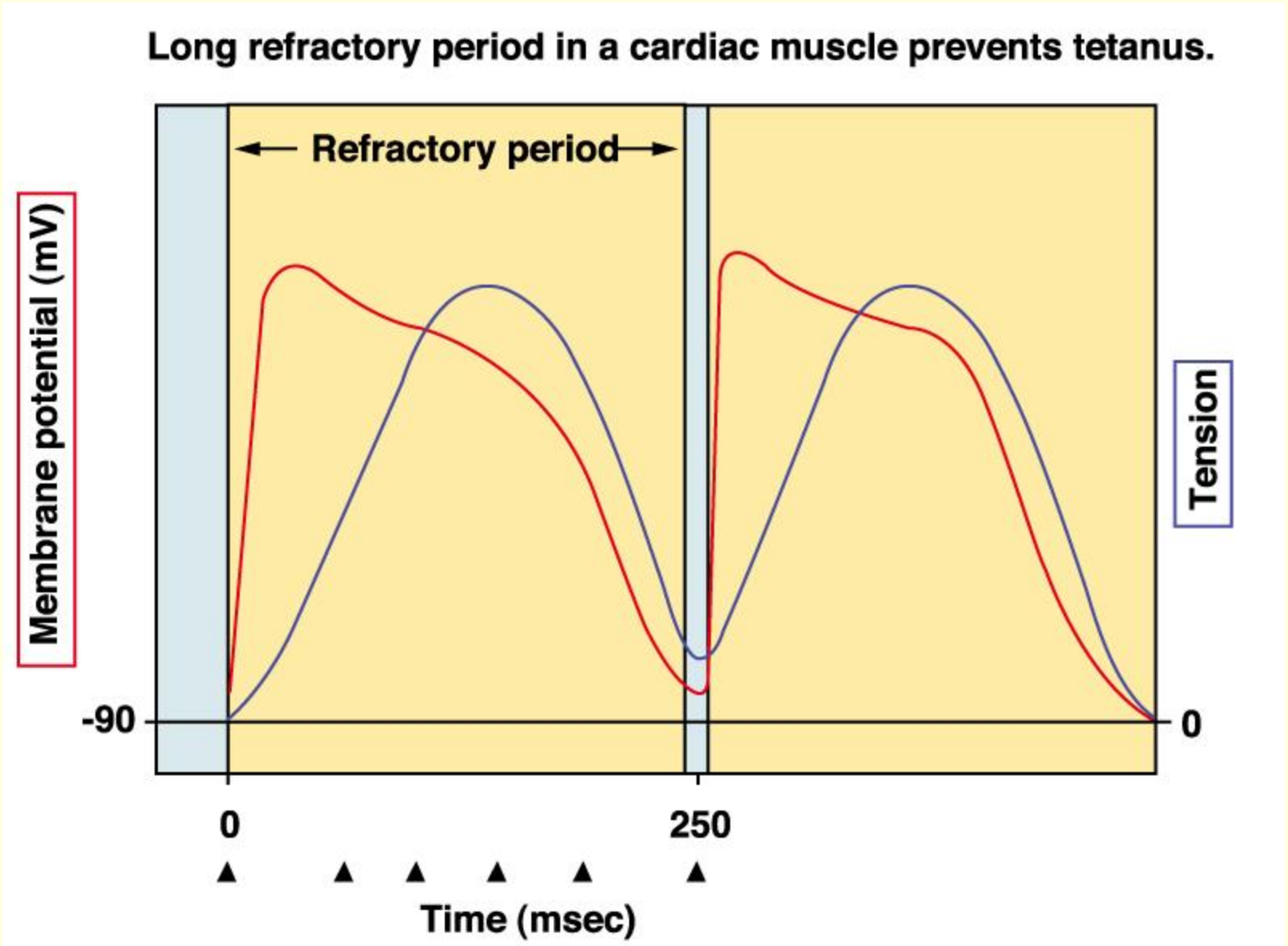
Cardiac Muscle action potential Vs. Skeletal Muscle

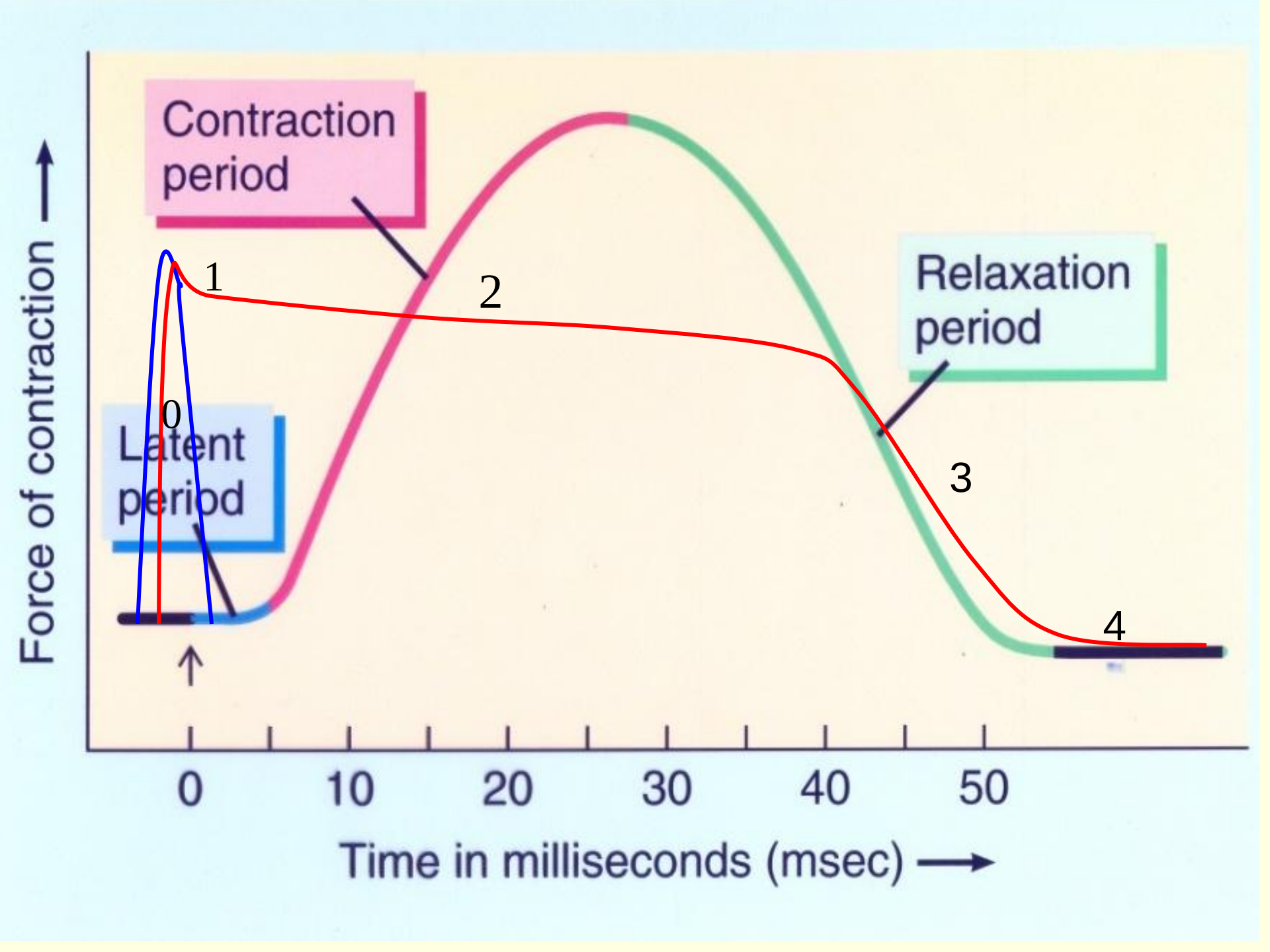
- Phase 0 –Depolarization phase (Na^+ influx)
- Phase 1 partial repolarization (Not in skeletal)
- Phase 2 Plateau (depolarization not in skeletal) slow calcium channels
- Phase 3 fast repolarization phase (K^+ efflux
- Phase 4 resting membrane potential


Skeletal muscle fast-twitch fiber
Membrane potential (mV)
0
-90
Muscle contraction
Peak
Muscle relaxation
Tension
0
Refractory period
0
10
50
100
Stimulus
Time (msec)

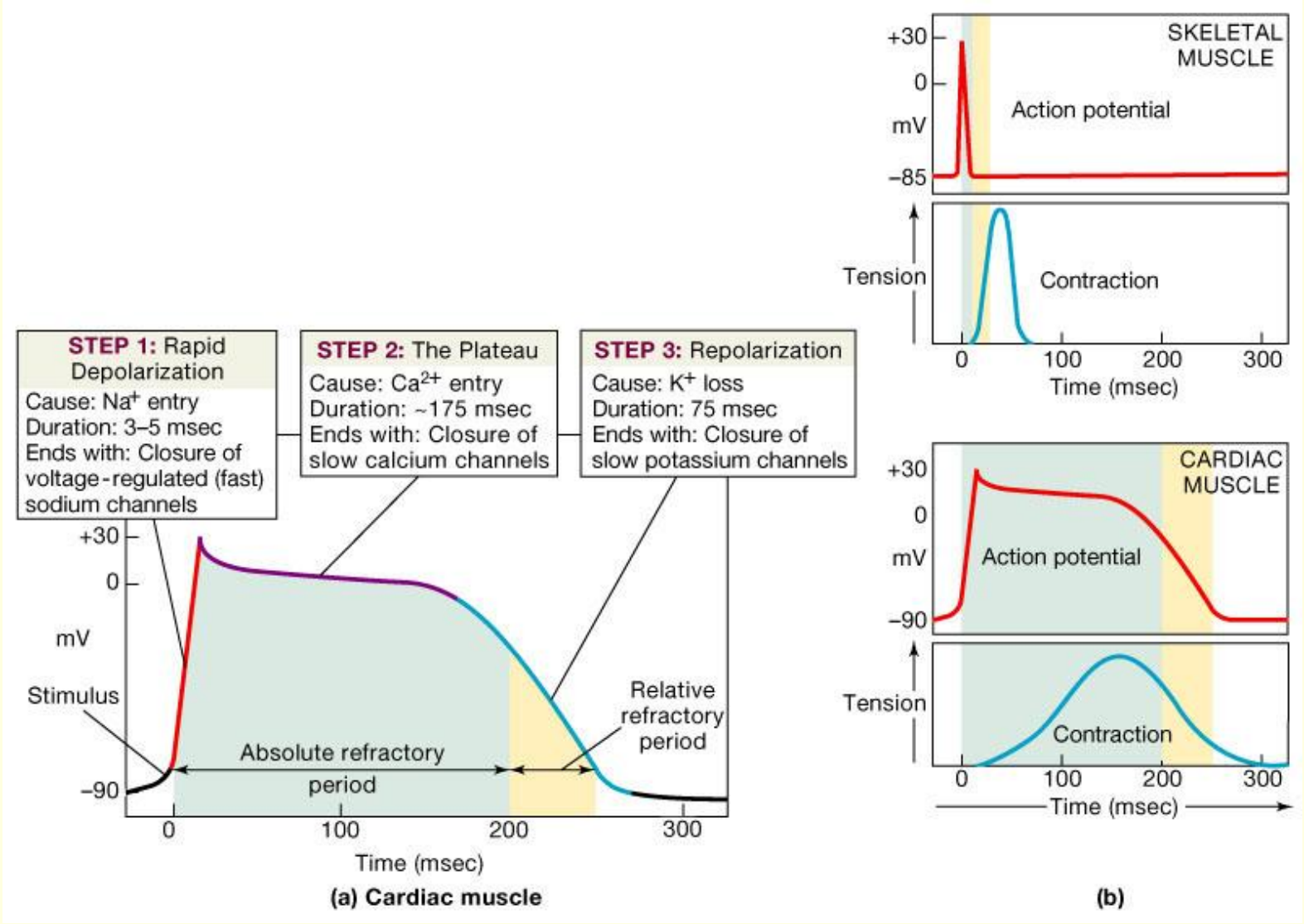

Tetanus in a skeletal muscle.
Action potentials not shown.
Maximum tension
Refractory period
Tension
▲ = Stimulus for action potential
0 75 150
Time (msec)

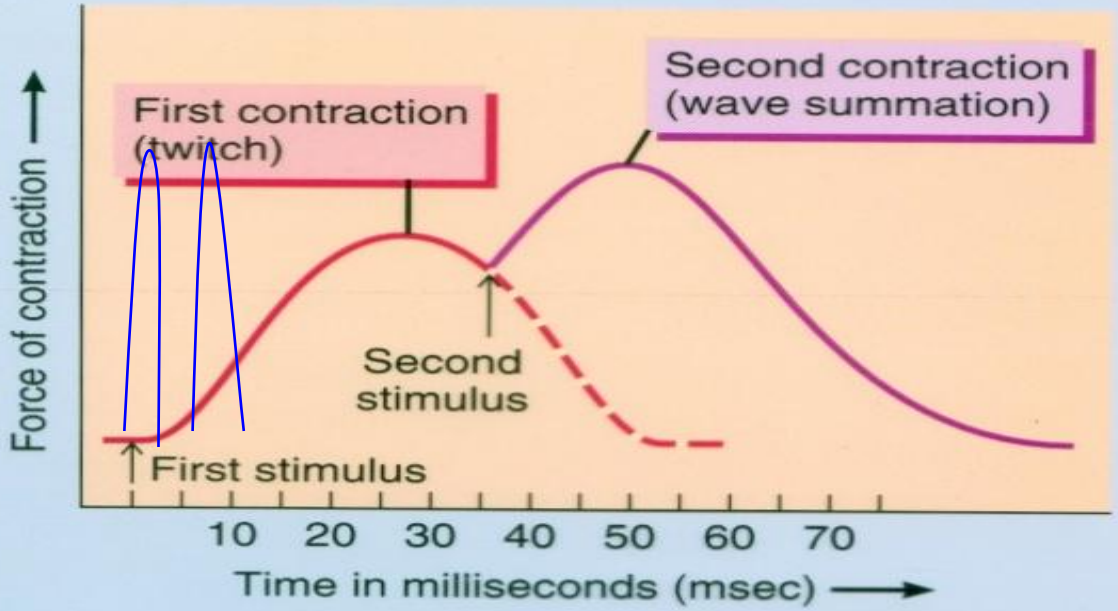

Cardiac muscle fiber
Membrane potential (mV)
0
-90
Peak
Muscle contraction
Muscle relaxation
Tension
0
Refractory period
0
100
200
250
Time (msec)
Stimulus


Long refractory period in a cardiac muscle prevents tetanus.
Refractory period
Membrane potential (mV)
Tension
-90
0
0
250
Time (msec)

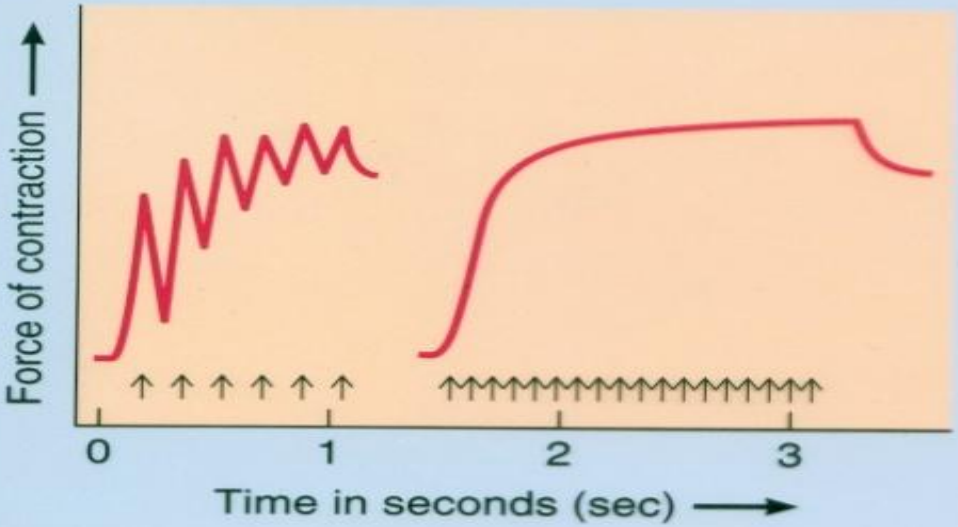

Contraction period
Relaxation period
Latent period
1
2
3
4
0
Force of contraction
0
10
20
30
40
50
Time in milliseconds (msec)

The Action Potential in Skeletal and Cardiac Muscle



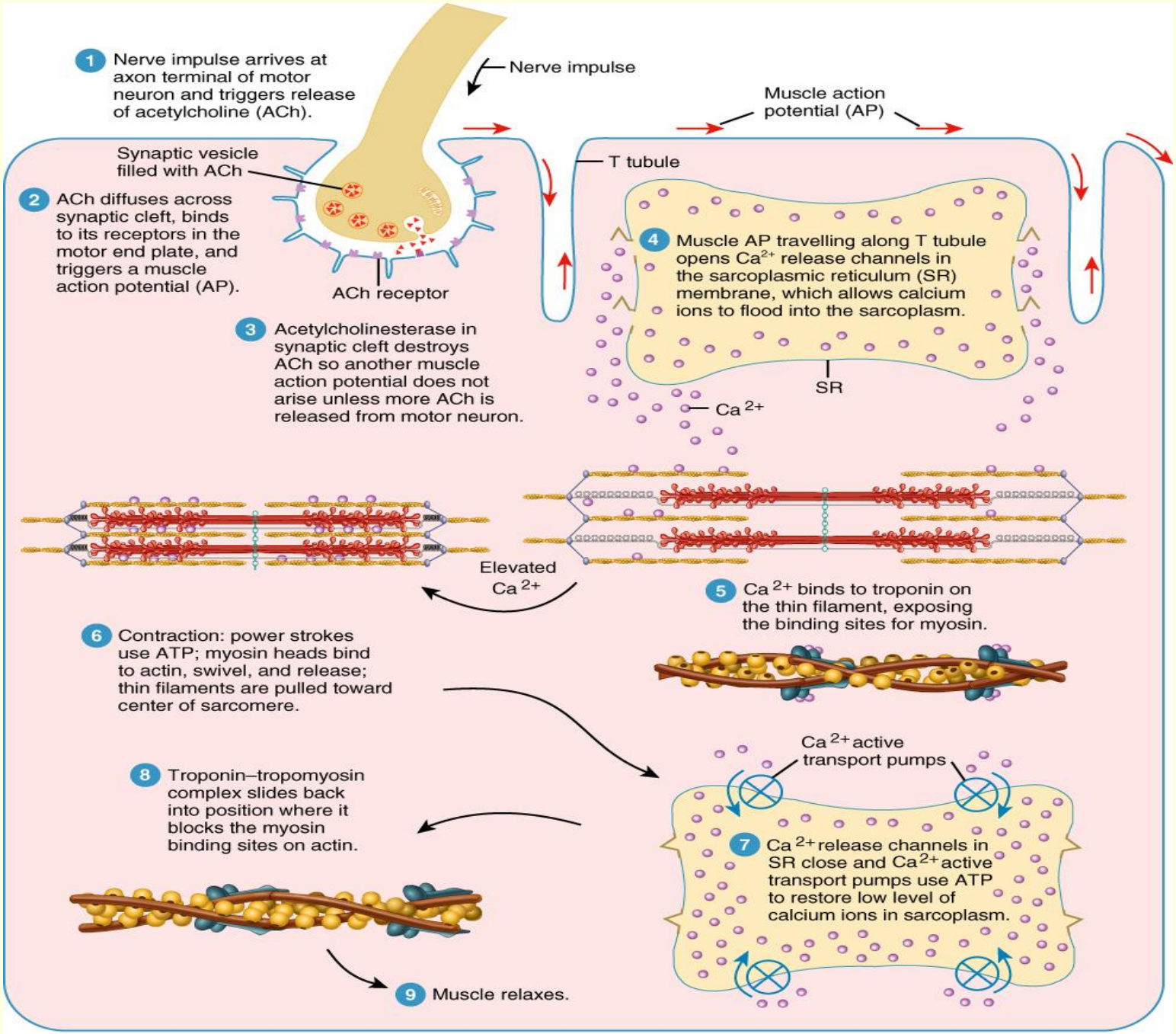


(a) Wave summation

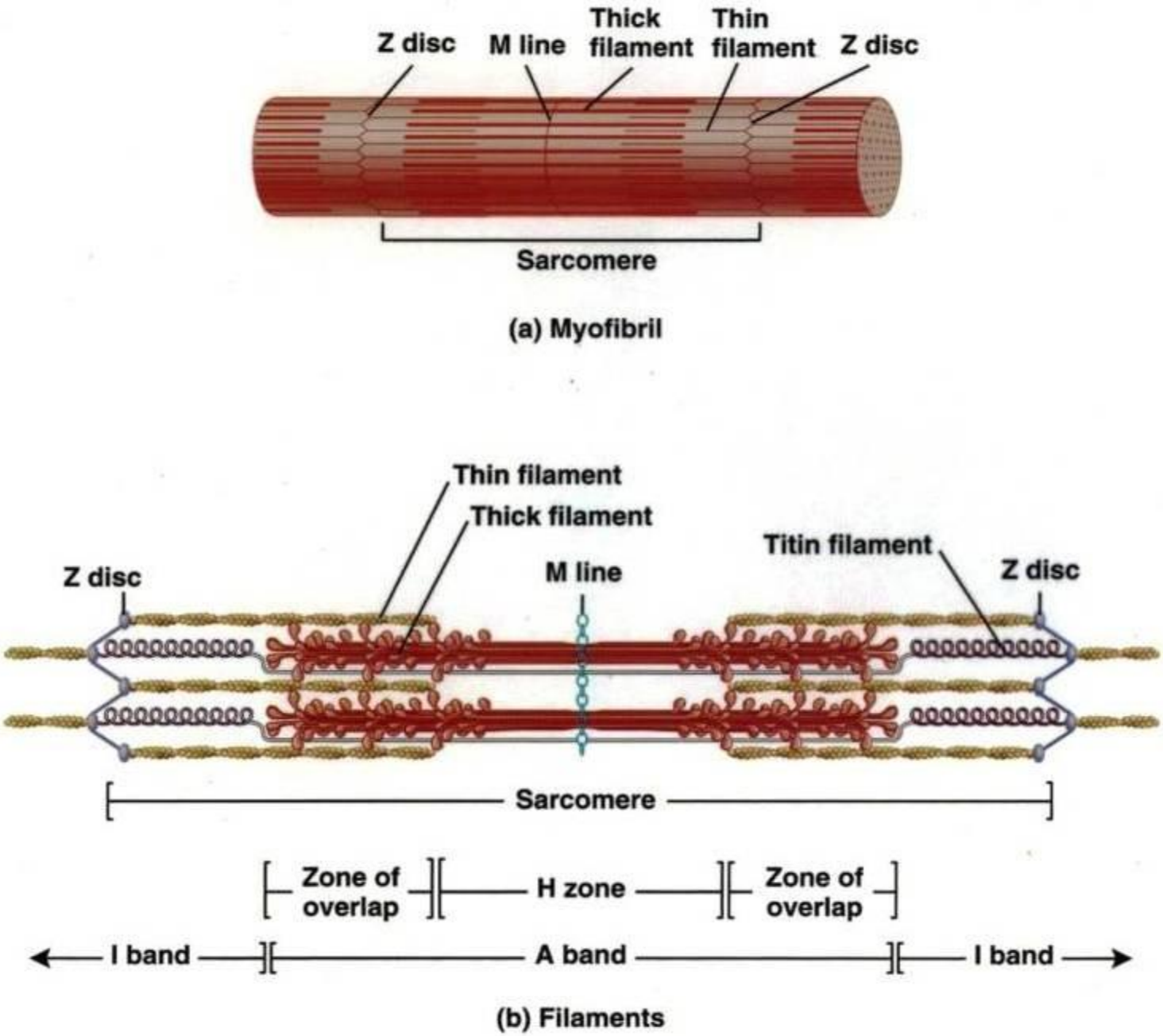


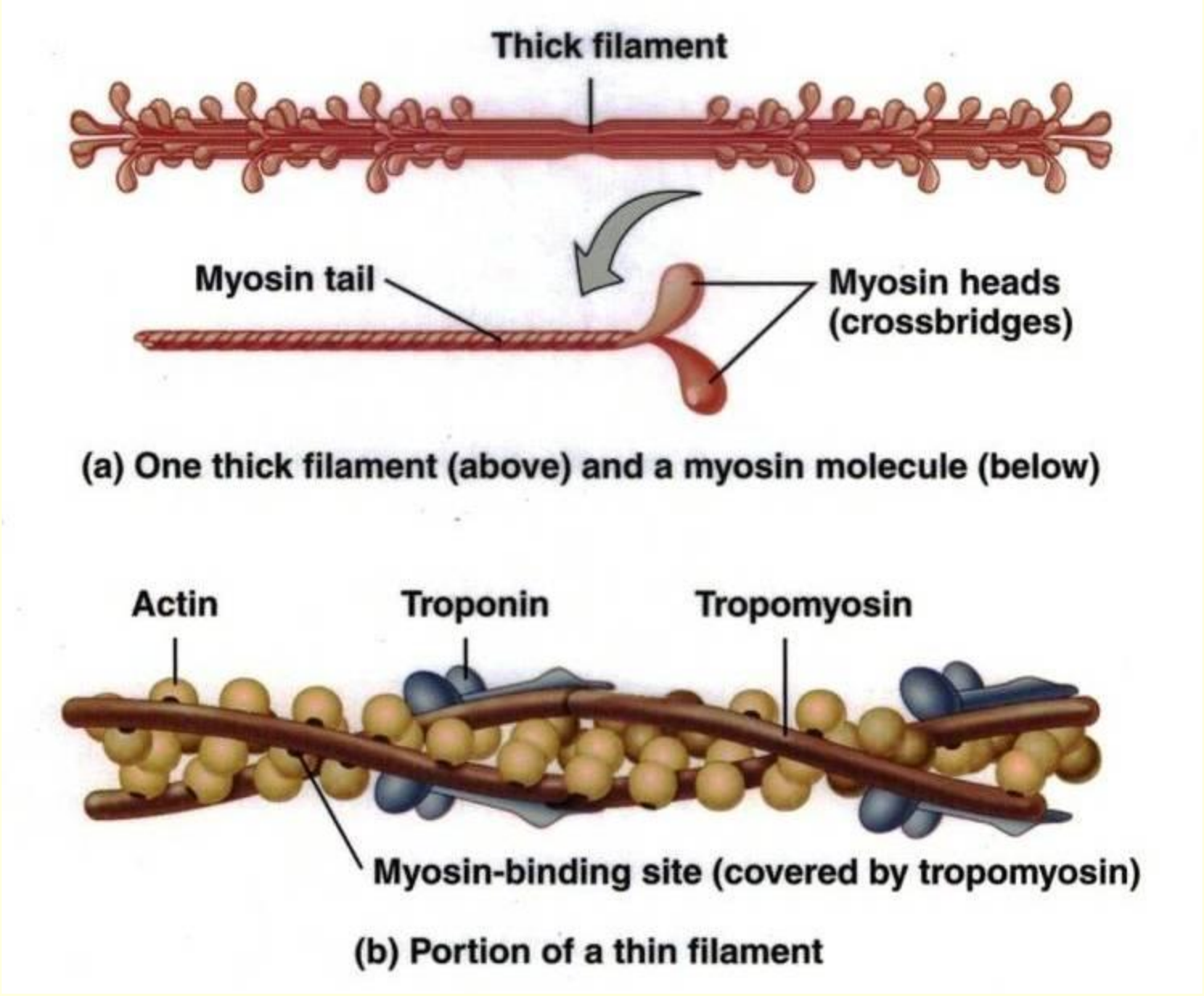
(b) Incomplete tetanus

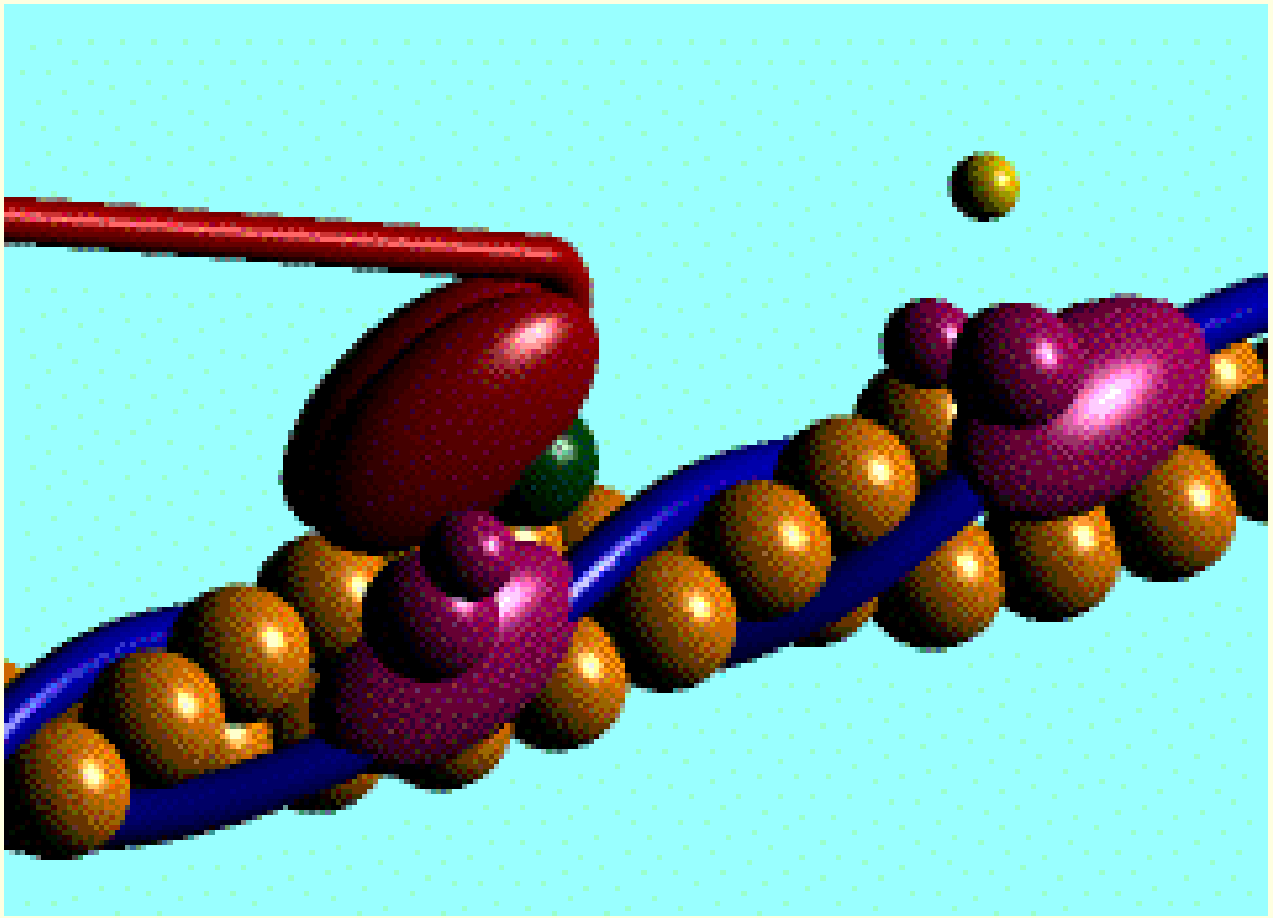
(c) Complete tetanus

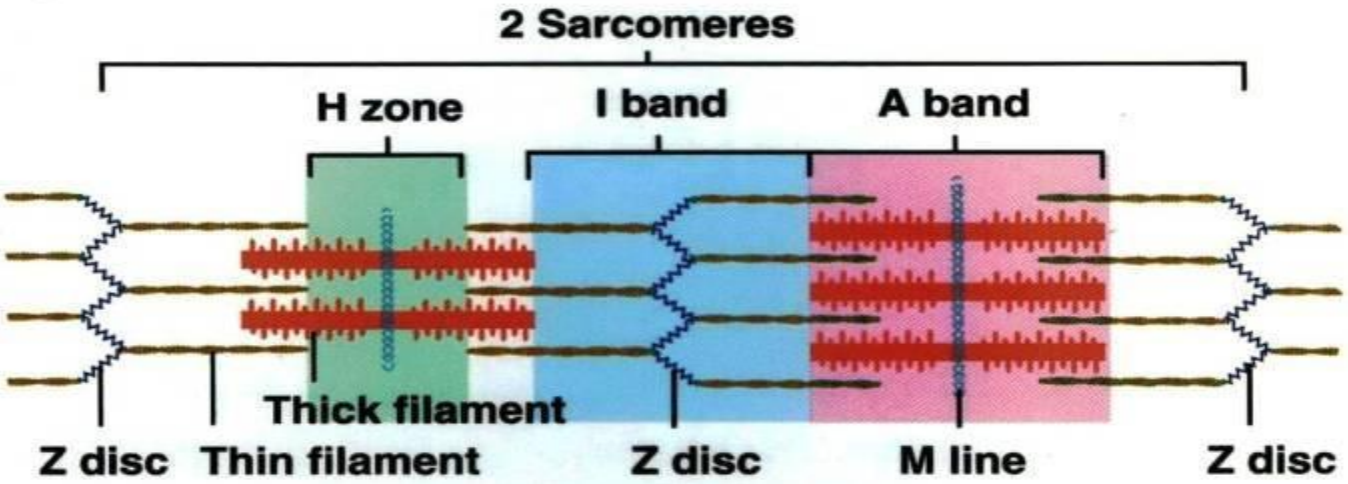

1 Nerve impulse arrives at axon terminal of motor neuron and triggers release of acetylcholine (ACh).
Nerve impulse
Muscle action potential (AP)
Synaptic vesicle filled with ACh
T tubule
2 ACh diffuses across synaptic cleft, binds to its receptors in the motor end plate, and triggers a muscle action potential (AP).
ACh receptor
4 Muscle AP travelling along T tubule opens Ca2+ release channels in the sarcoplasmic reticulum (SR) membrane, which allows calcium ions to flood into the sarcoplasm.
SR
Ca 2+
3 Acetylcholinesterase in synaptic cleft destroys ACh so another muscle action potential does not arise unless more ACh is released from motor neuron.
Elevated Ca 2+
5 Ca 2+ binds to troponin on the thin filament, exposing the binding sites for myosin.
6 Contraction: power strokes use ATP; myosin heads bind to actin, swivel, and release; thin filaments are pulled toward center of sarcomere.
Ca 2+ active transport pumps
8 Troponin–tropomyosin complex slides back into position where it blocks the myosin binding sites on actin.
7 Ca 2+ release channels in SR close and Ca 2+ active transport pumps use ATP to restore low level of calcium ions in sarcoplasm.
9 Muscle relaxes.

10.12

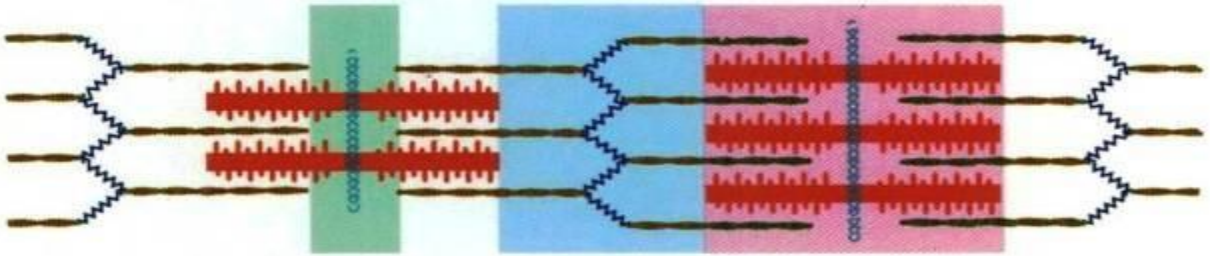

Z disc
M line
Thick filament
Thin filament
Z disc
Sarcomere
(a) Myofibril
Thin filament
Thick filament
Titin filament
Z disc
M line
Z disc
Sarcomere
Zone of overlap
H zone
Zone of overlap
I band
A band
I band
(b) Filaments


Thick filament
Myosin tail
Myosin heads
(crossbridges)
(a) One thick filament (above) and a myosin molecule (below)
Actin
Troponin
Tropomyosin
Myosin-binding site (covered by tropomyosin)
(b) Portion of a thin filament

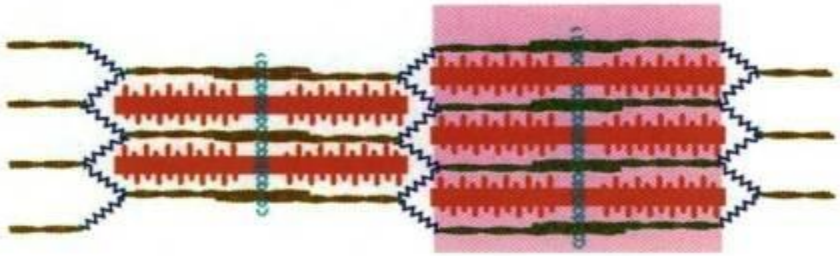




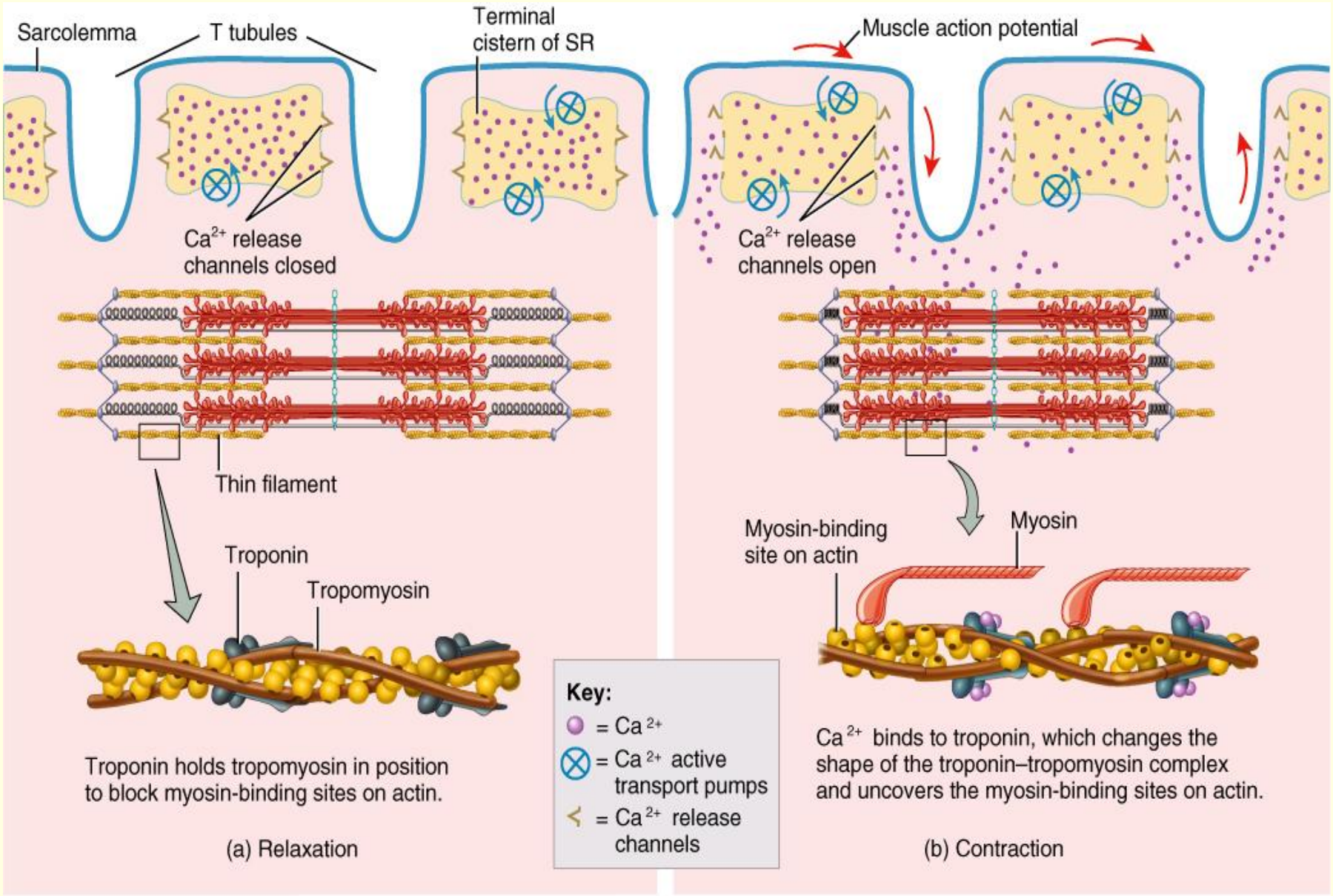
(a) Relaxed muscle



(b) Partially contracted muscle



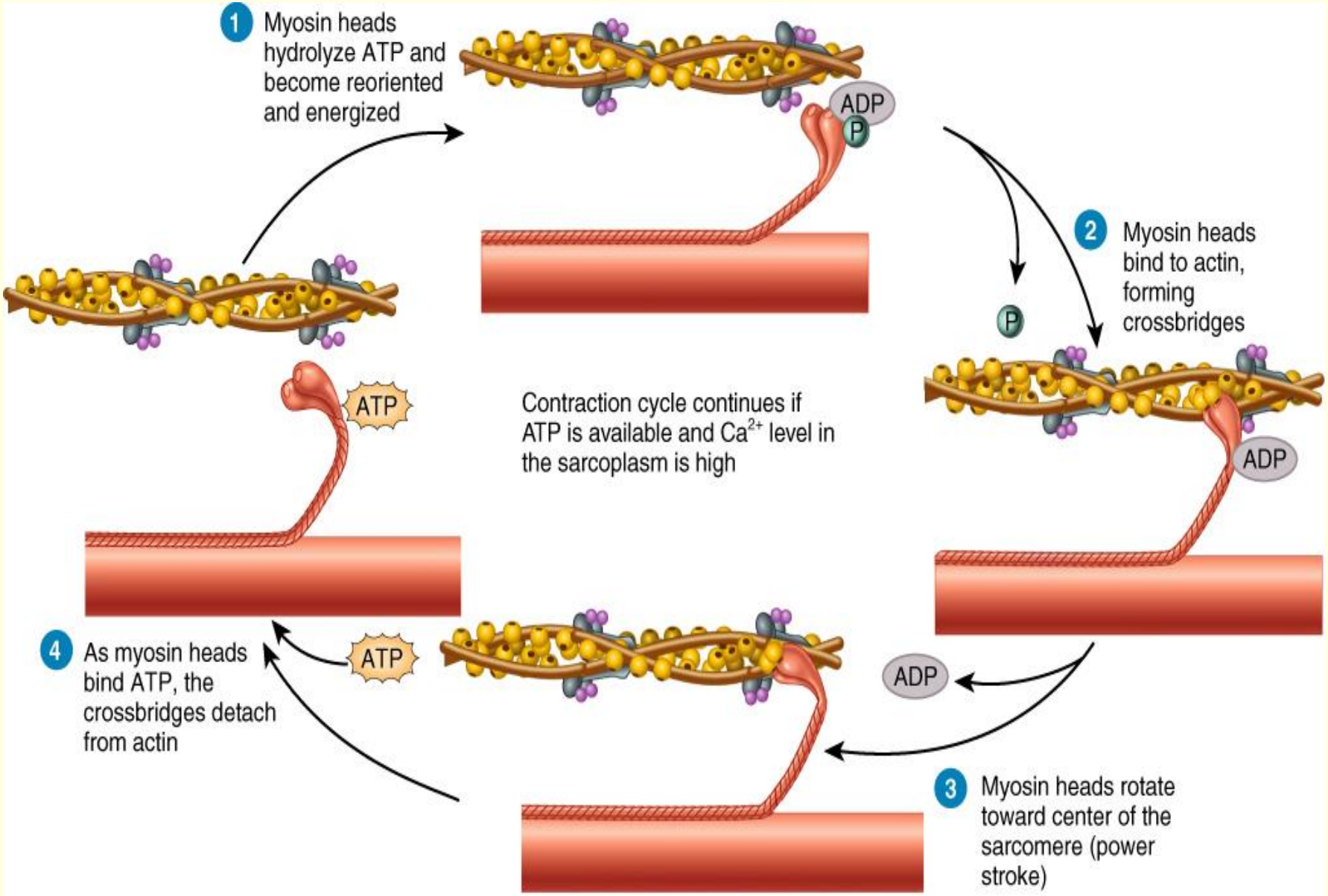
(c) Maximally contracted muscle


Sarcolemma
T tubules
Terminal cistern of SR
Muscle action potential
Ca2+ release channels closed
Ca2+ release channels open
Thin filament
Troponin
Tropomyosin
Myosin-binding site on actin
Myosin
Troponin holds tropomyosin in position to block myosin-binding sites on actin.
(a) Relaxation
Key:
= Ca2+
= Ca2+ active transport pumps
= Ca2+ release channels
Ca2+ binds to troponin, which changes the shape of the troponin–tropomyosin complex and uncovers the myosin-binding sites on actin.
(b) Contraction

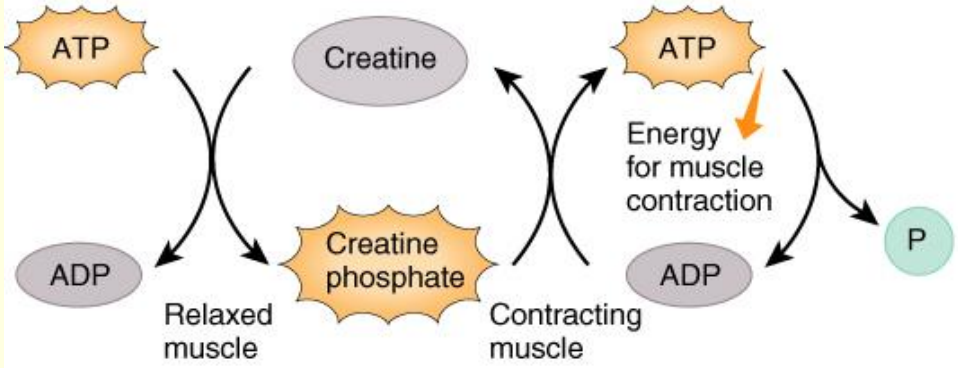
10.09

Cardiac Muscle contraction Vs. Skeletal Muscle

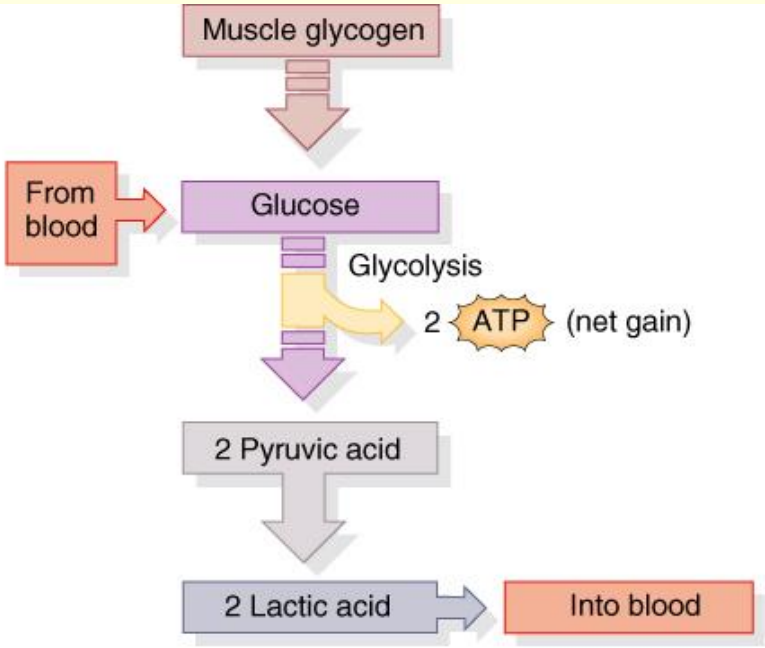
- Sliding filament hypothesis
- No tetany (Long refractory period because of plateau)
- Fatty acids main source of energy unlike skeletal muscle (Anaerobic and Aerobic)
- Attachment and detachment cycle and ATP dependence is the same


1 Myosin heads hydrolyze ATP and become reoriented and energized
ADP
P
2 Myosin heads bind to actin, forming crossbridges
P
ADP
ATP
Contraction cycle continues if ATP is available and Ca^{2+} level in the sarcoplasm is high
4 As myosin heads bind ATP, the crossbridges detach from actin
ATP
ADP
3 Myosin heads rotate toward center of the sarcomere (power stroke)

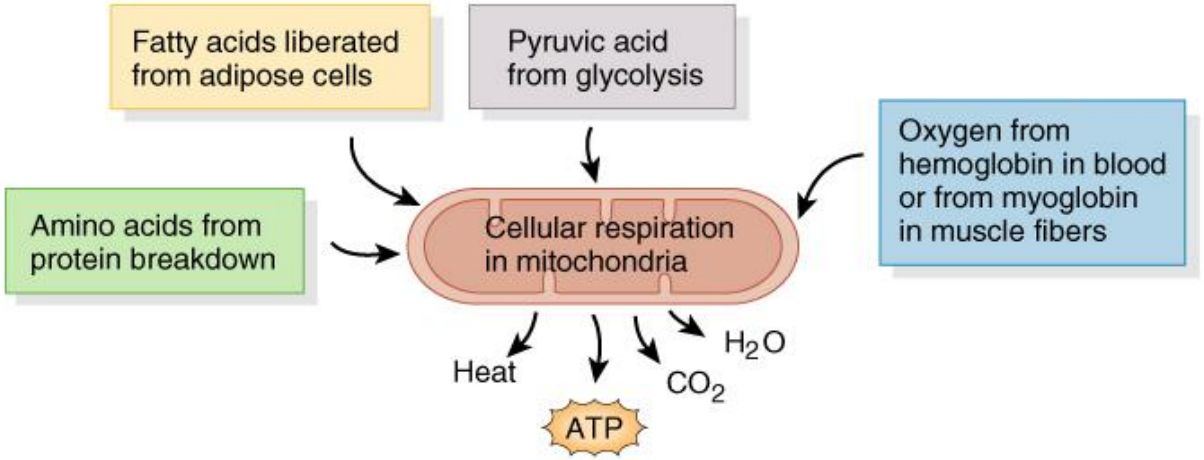
10.08



(a) ATP from creatine phosphate



(b) ATP from anaerobic respiration

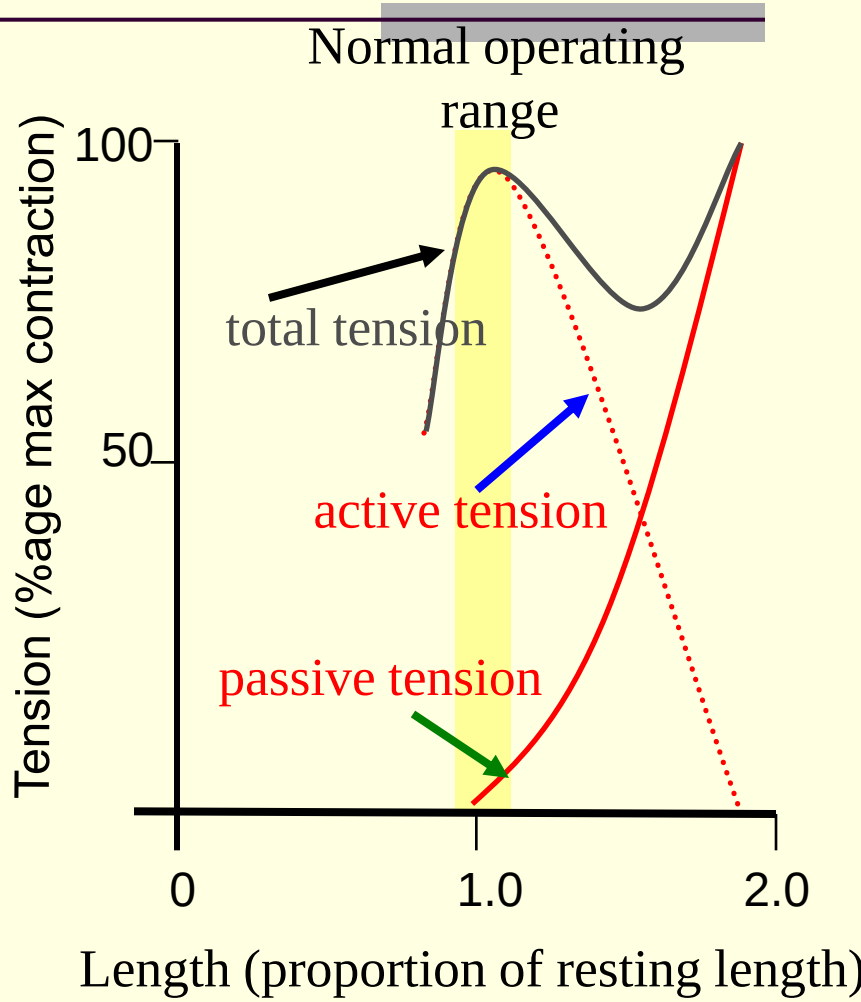


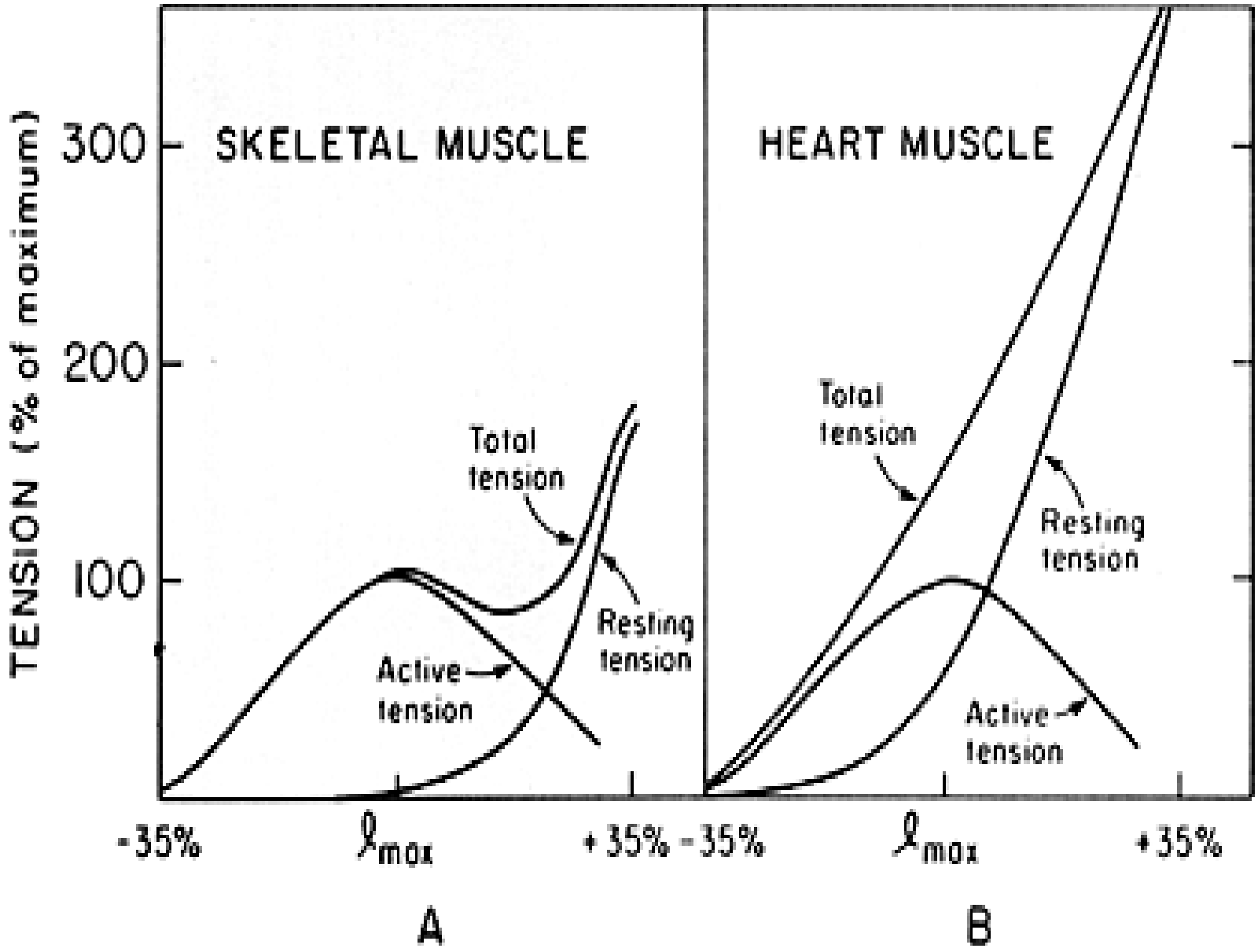
(c) ATP from aerobic cellular respiration

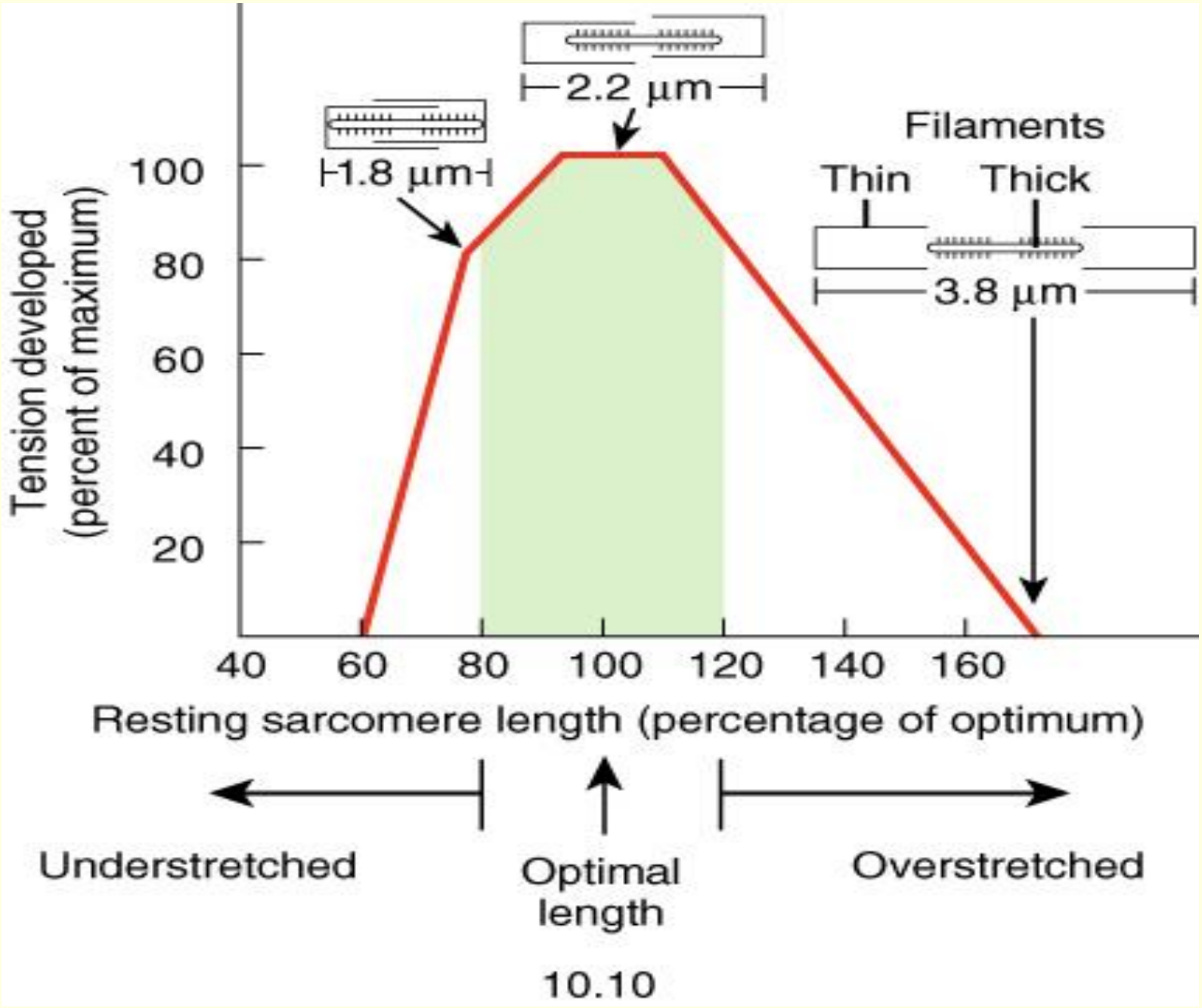
10.13

Length-Tension Relation for Skeletal Muscle

- Active tension cannot be measured directly
- What can be measured?
  - (1) passive tension - *tension required to extend a resting muscle*
  - (2) total tension - *active tension and passive combined*
- Active is calculated from 1 & 2
- (AT = TT – PT)
- Note that active tension falls away linearly with increasing length

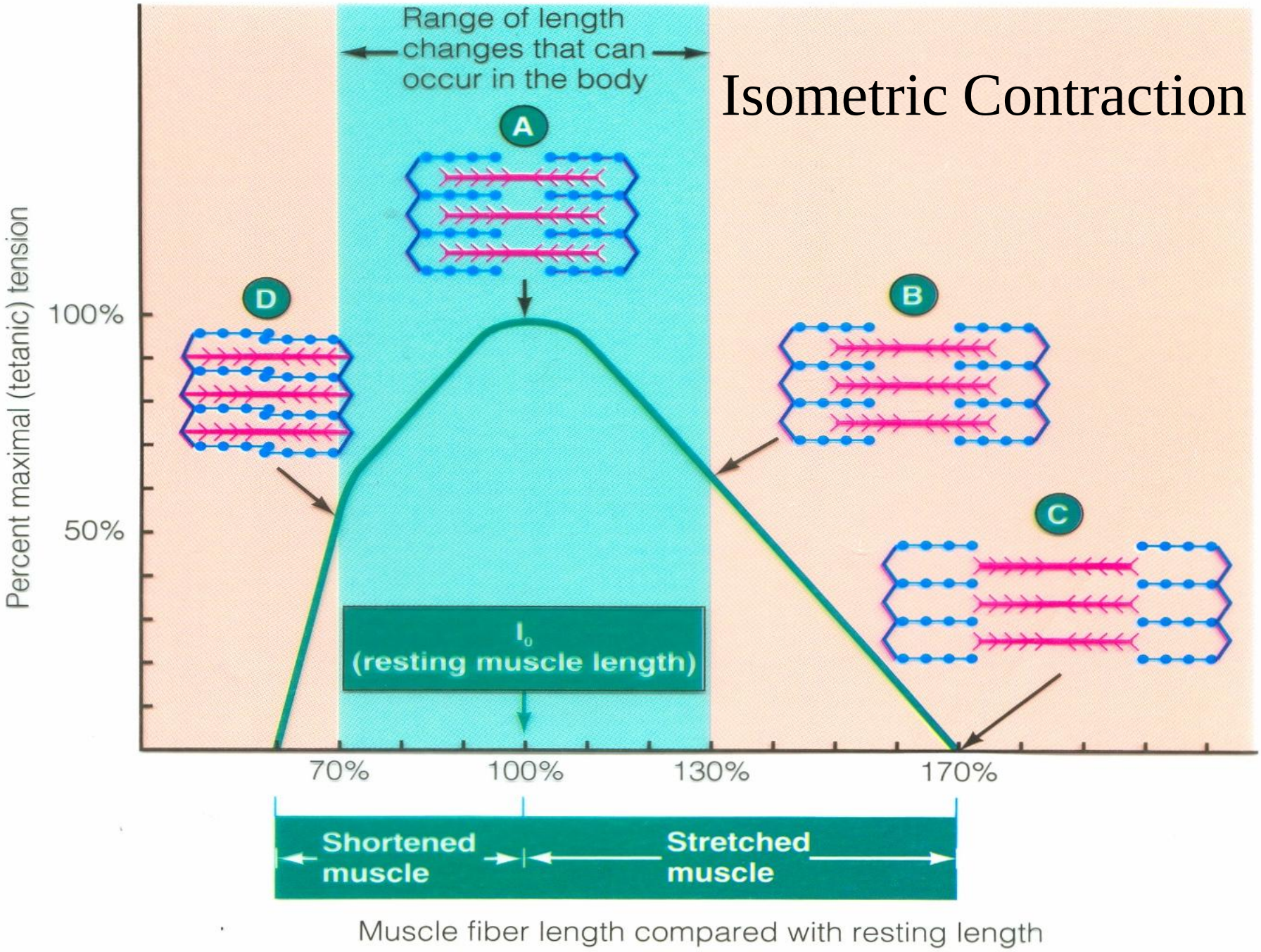



TENSION (% of maximum)
300
200
100
SKELETAL MUSCLE
HEART MUSCLE
Total tension
Resting tension
Active tension
Total tension
Resting tension
Active tension
-35%
l_{max}
+35%
-35%
l_{max}
+35%
A
B


2.2 µm
1.8 µm
Filaments
Thin
Thick
3.8 µm
Tension developed (percent of maximum)
100
80
60
40
20
40
60
80
100
120
140
160
Resting sarcomere length (percentage of optimum)
Understretched
Optimal length
Overstretched

10.10

Isometric Contraction



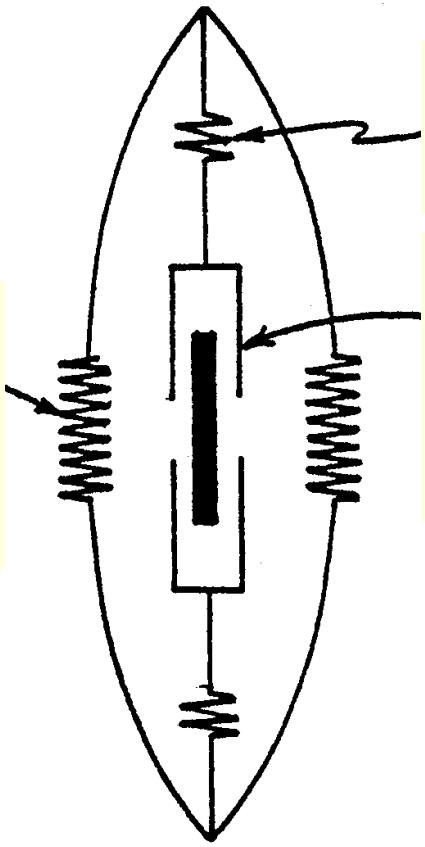
SERIES ELASTIC ELEMENTS

CONTRACTILE COMPONENT

(ACTIVE TENSION)

PARALLEL ELASTIC ELEMENTS

(PASSIVE TENSION)

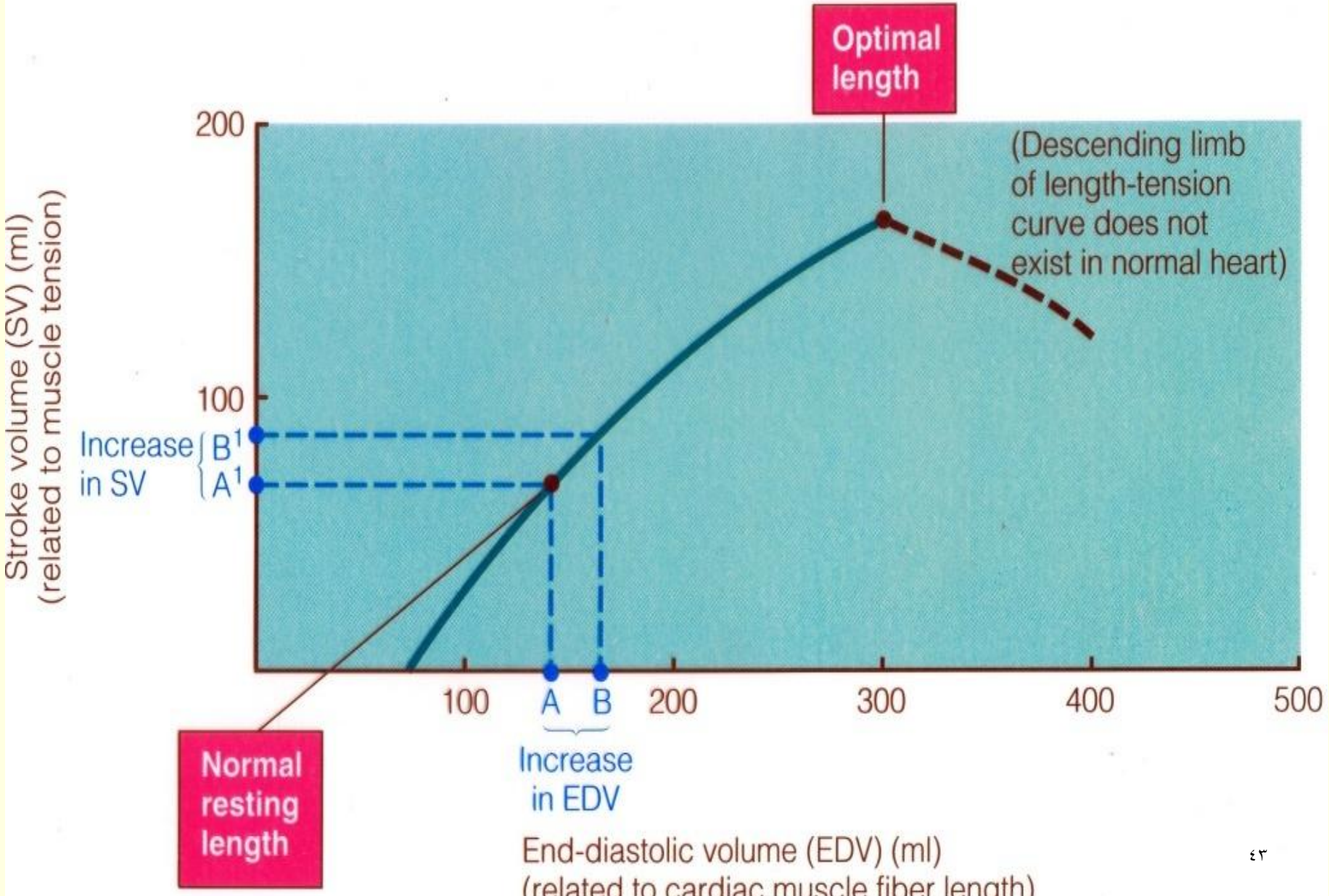


TOTAL TENSION

Cardiac Muscle length-tension relationship

- Cardiac muscle works at much less than its maximum length in contrast to skeletal
- Total, Active and Passive length-tension relationship differ
- Frank-Starling law of the heart

Intrinsic Control of Stroke Volume (Frank-Starling Curve)



Thank You