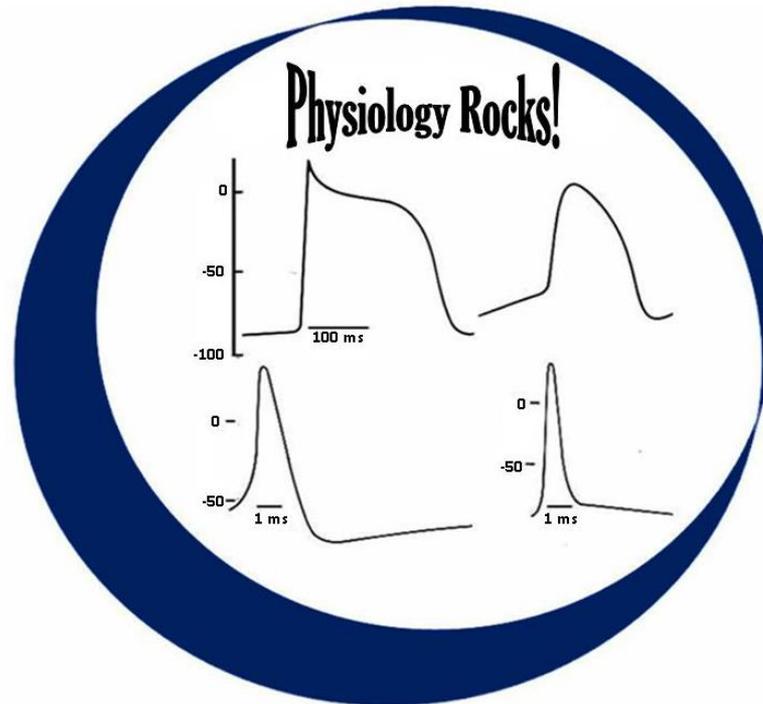


Lecture 16



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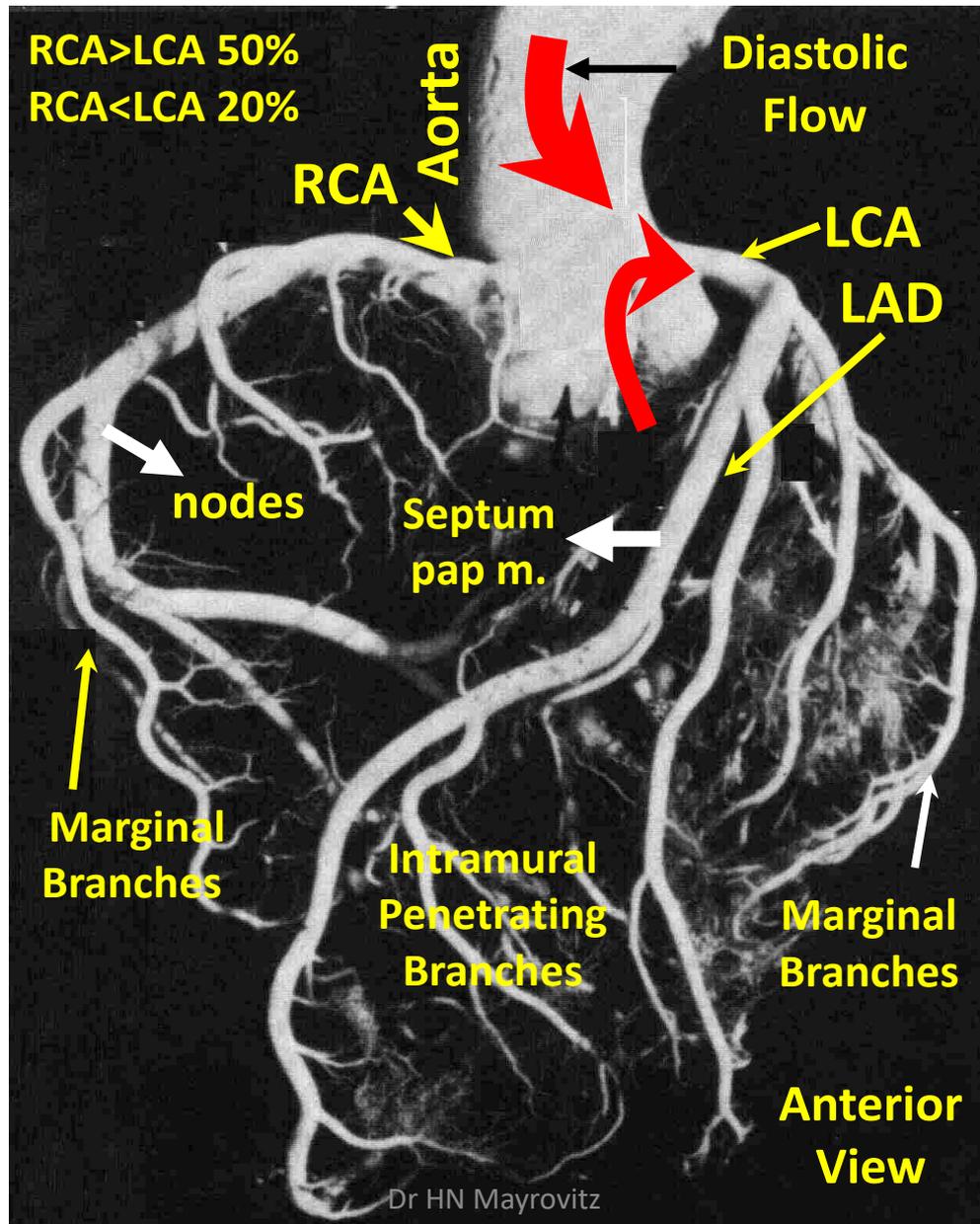
Topics

- Heart circulation features
- Microcirculation features
- Lymphatic system features
- Venous system features

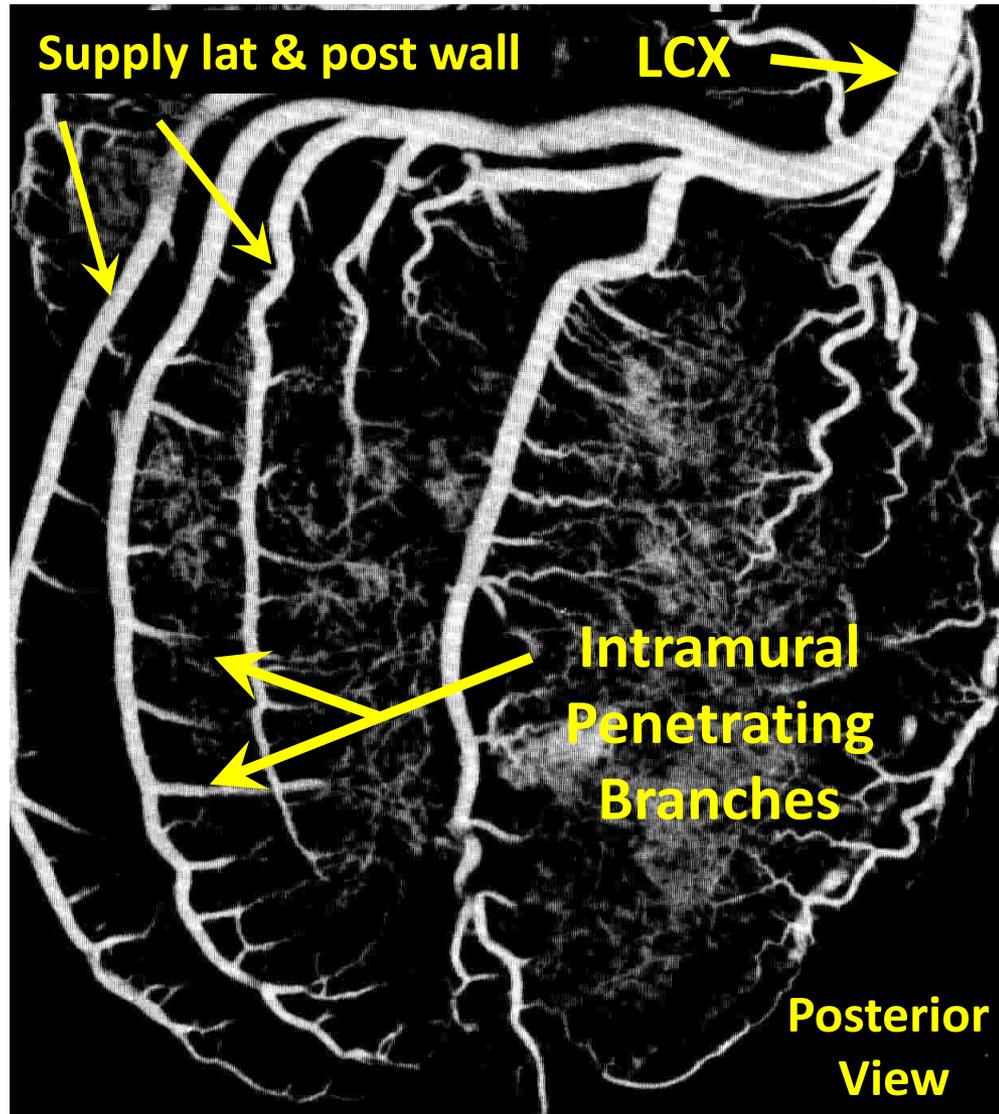
Features of Coronary Circulation

- **Vasculature**
- **Phasic Blood Flow Features**
- **Myocardial Oxygen Extraction**
- **Coronary Autoregulation**
- **Regional blood flow**

Coronary Circulation

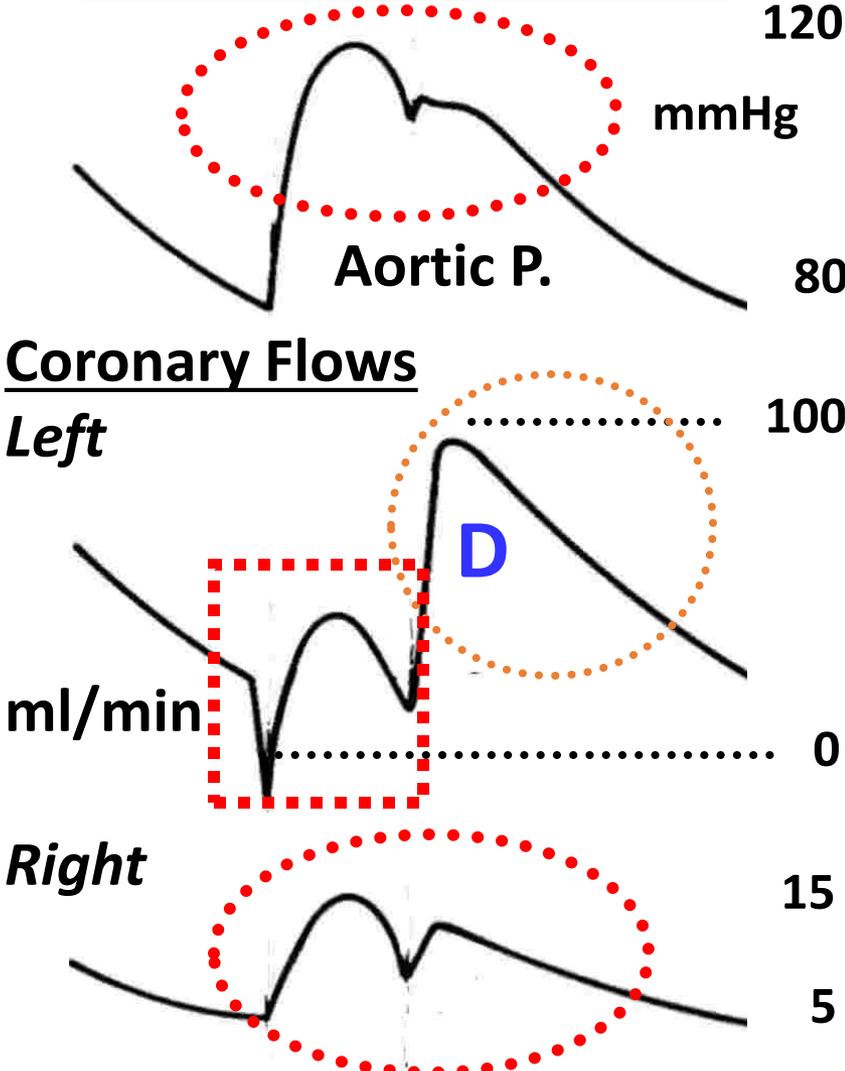


Coronary Circulation

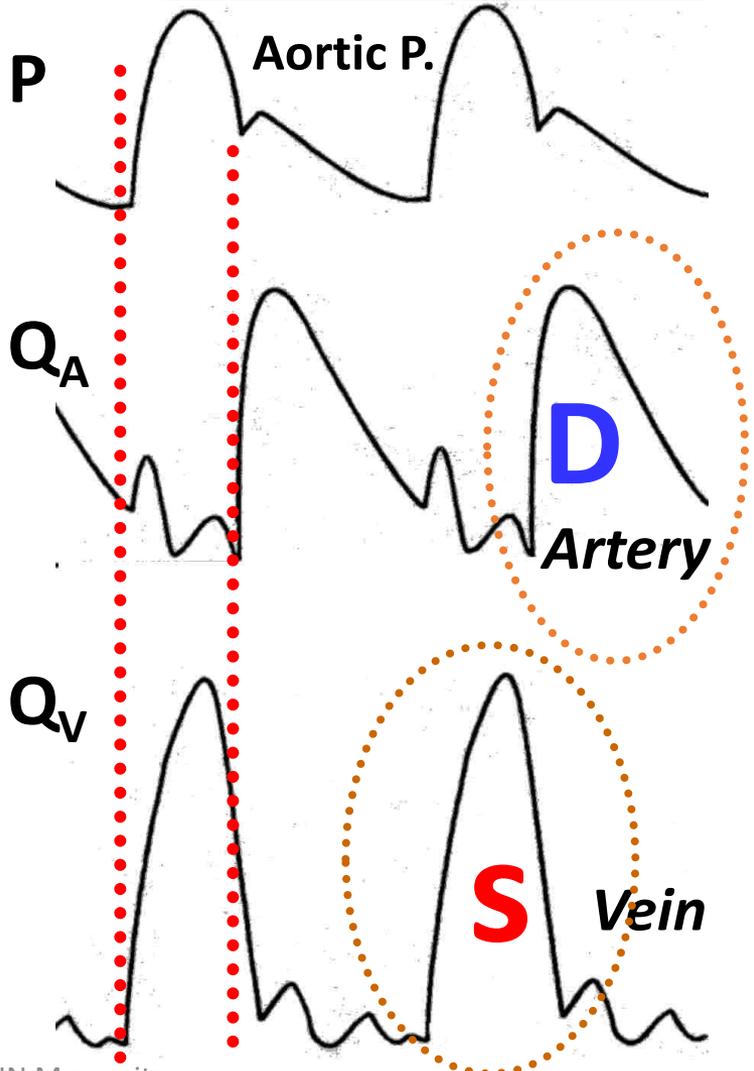


Phasic Coronary Blood Flow

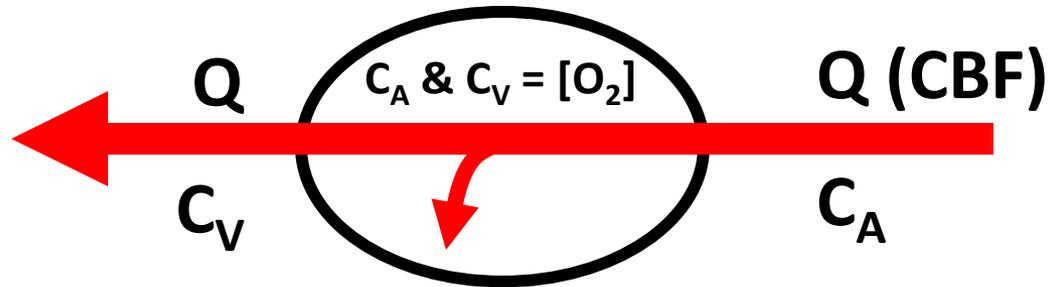
Left vs. Right Ventricle



Inflow vs. Outflow



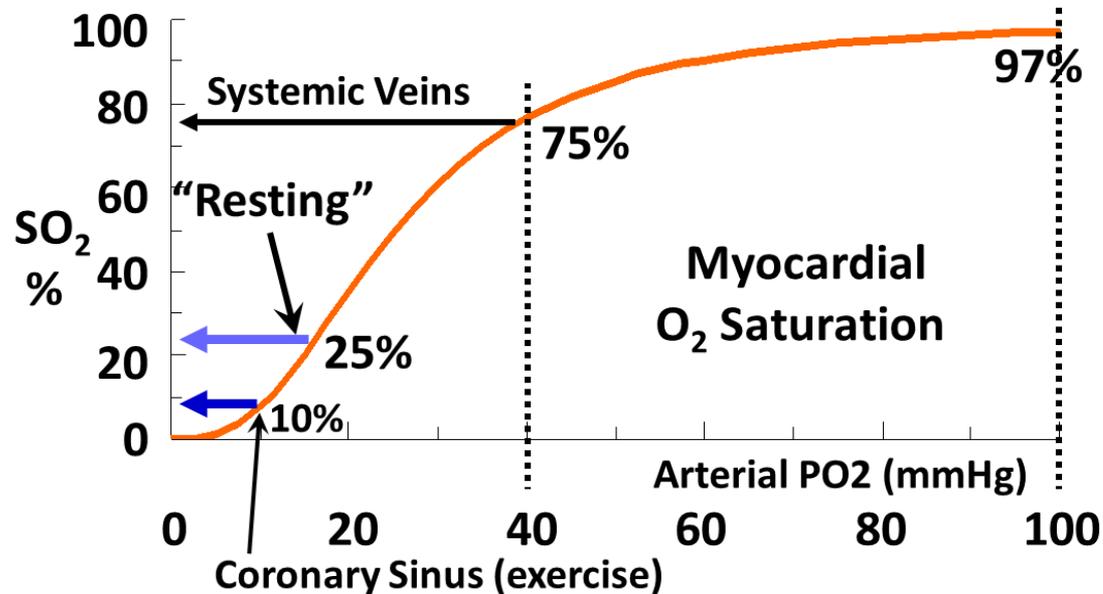
Myocardial O₂ Extraction



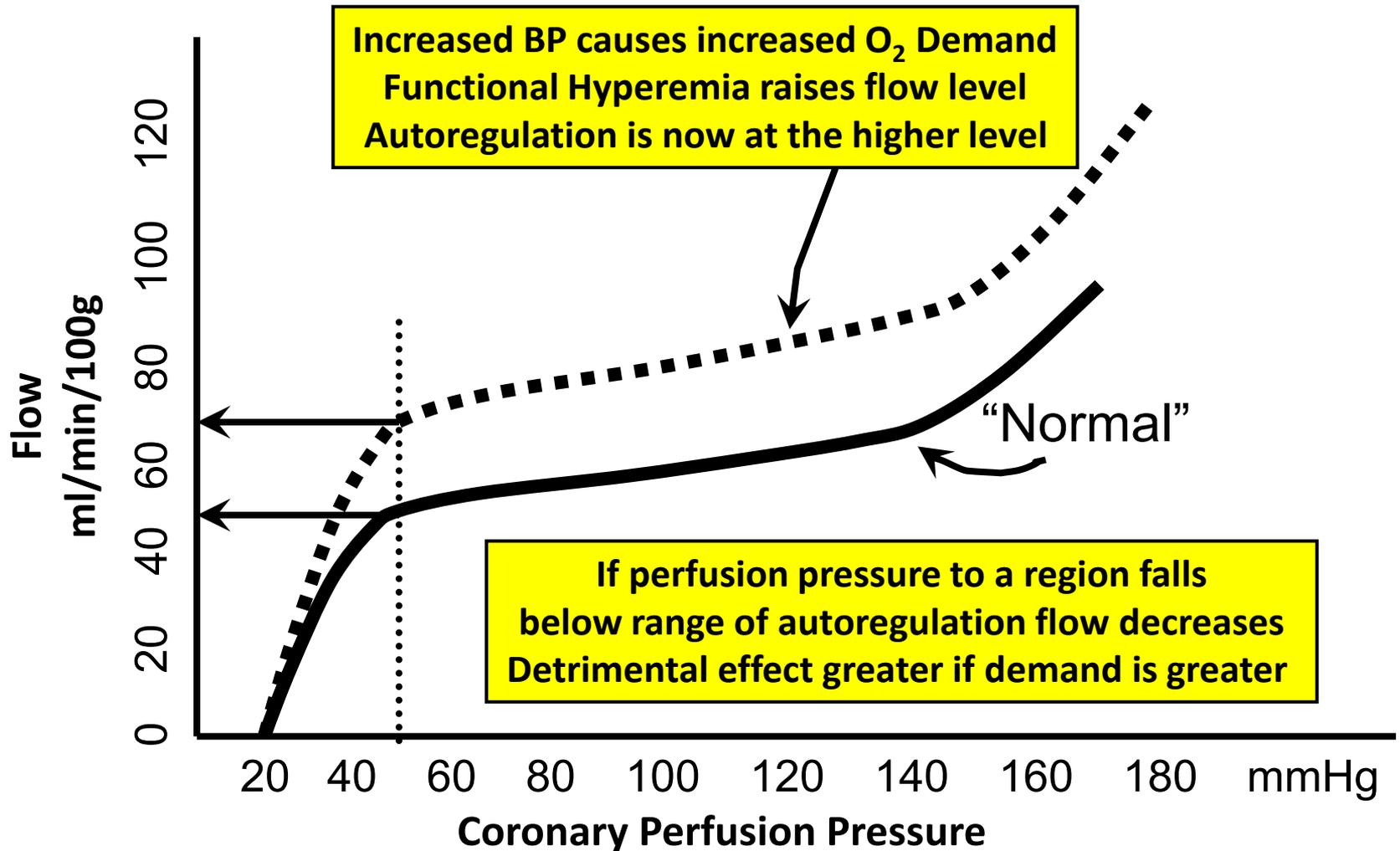
$$O_2 \text{ consumption} = Q (C_A - C_V) \text{ [ml/O}_2\text{/min]}$$

Extraction [mlO₂/100ml]

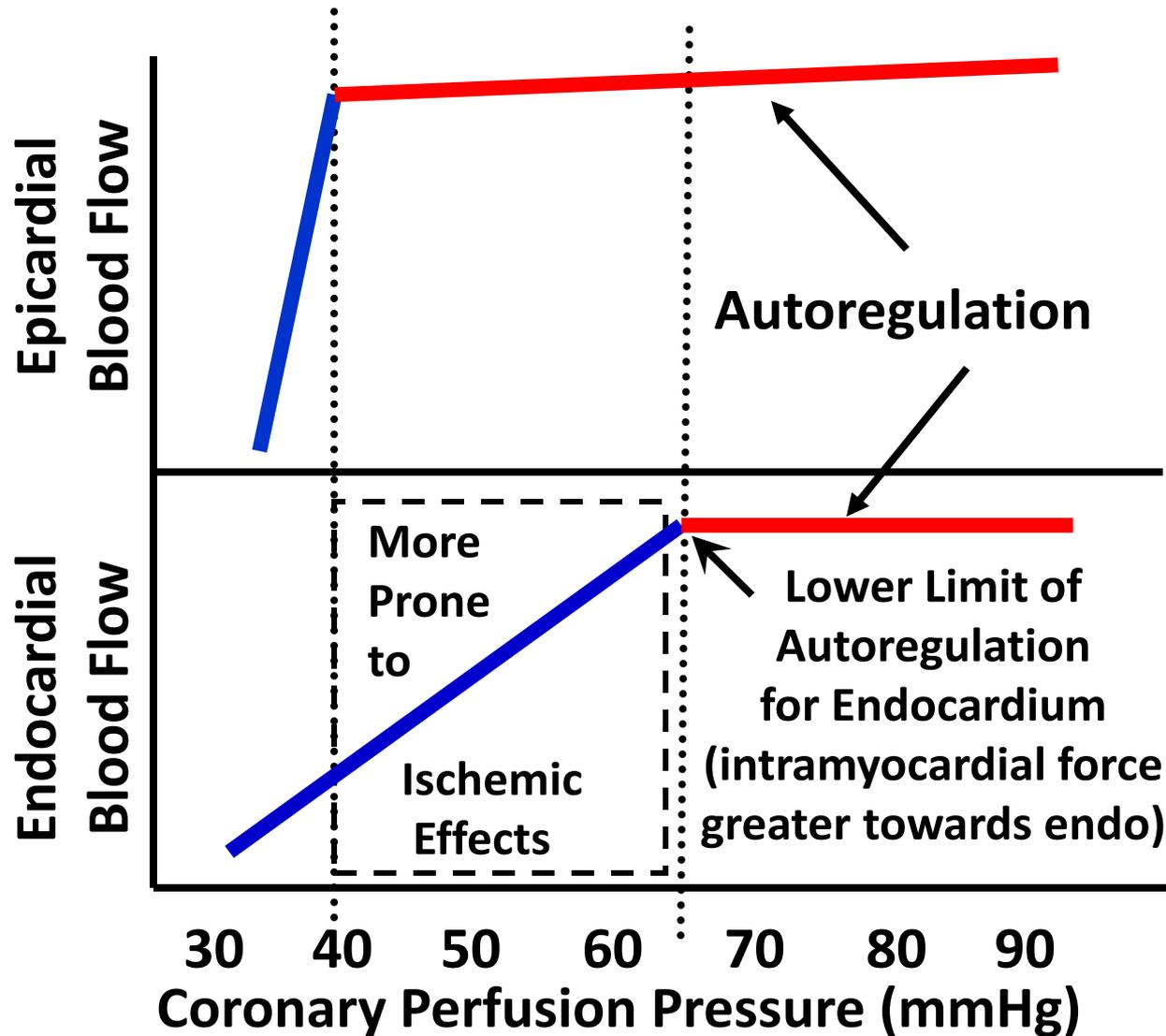
75-90% → Flow-Dependent



Coronary Autoregulation



Regional Autoregulatory Differences



Features of the Microvascular System

- Capillary wall and function Variability
- Classic view of transcapillary exchange
- Revised version - Role of the Glycocalyx

Online Videos

Normal Microcirculation.wmv (37.7MB)

<http://www.youtube.com/watch?v=gP9qFIFAyXk>

Vasoconstriction_NE.wmv (54.9MB)

http://www.youtube.com/watch?v=k8J_1uH-woE

Vasodilation_Adenosine.wmv (33.4MB)

<http://www.youtube.com/watch?v=PQ-Oq6mnITQ>

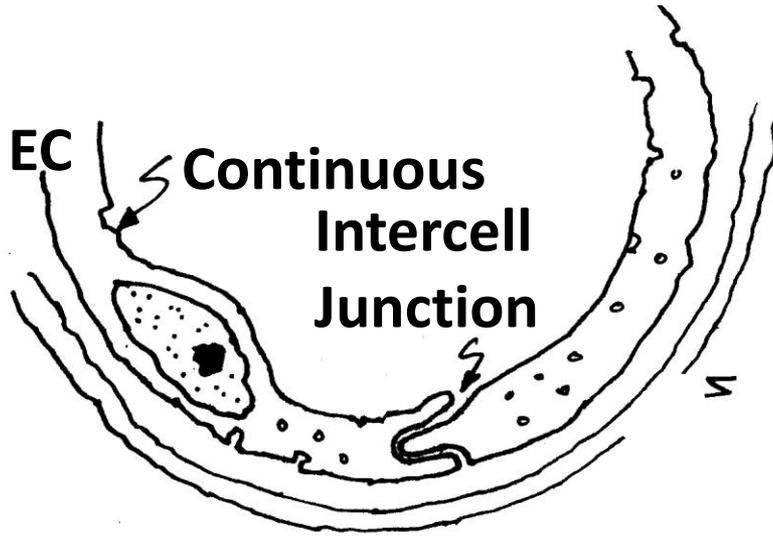
Vasomotion.wmv (48.3MB)

http://www.youtube.com/watch?v=6E_OLwVsf9w

CapillaryBloodFlow.wmv (66.5MB)

<http://www.youtube.com/watch?v=QuWhKN1bHLA>

Capillary Variability Among Tissues



- Heart
 - Skeletal M.
 - Skin
 - Lung
 - Brain-Spinal cord-Retina
- Tight Junctions: $r \leq 0.5 \text{ nm}$
- "Small pore size"
 $r \sim 2.5 \text{ nm}$



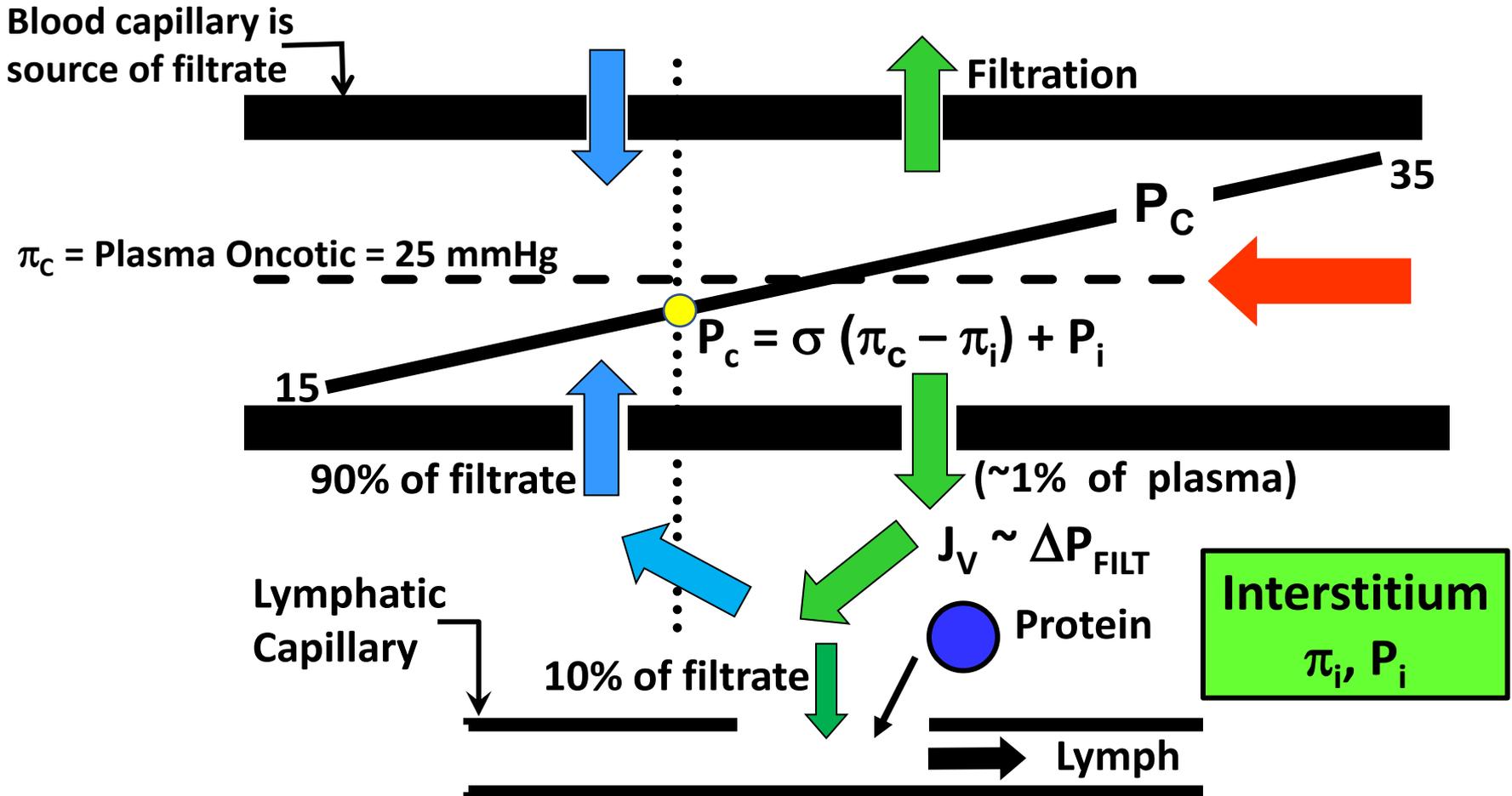
- Kidney glomeruli
 - Intestinal mucosa
 - Endocrine Glands
- 3-8 nm



- Bone Marrow
- Spleen
- Liver

	Radius (nm)
Solutes	
NaCl	0.14
Glucose	0.16
Proteins	
Albumin	3.5
Myoglobin	1.9

Classic View of Fluid Exchange

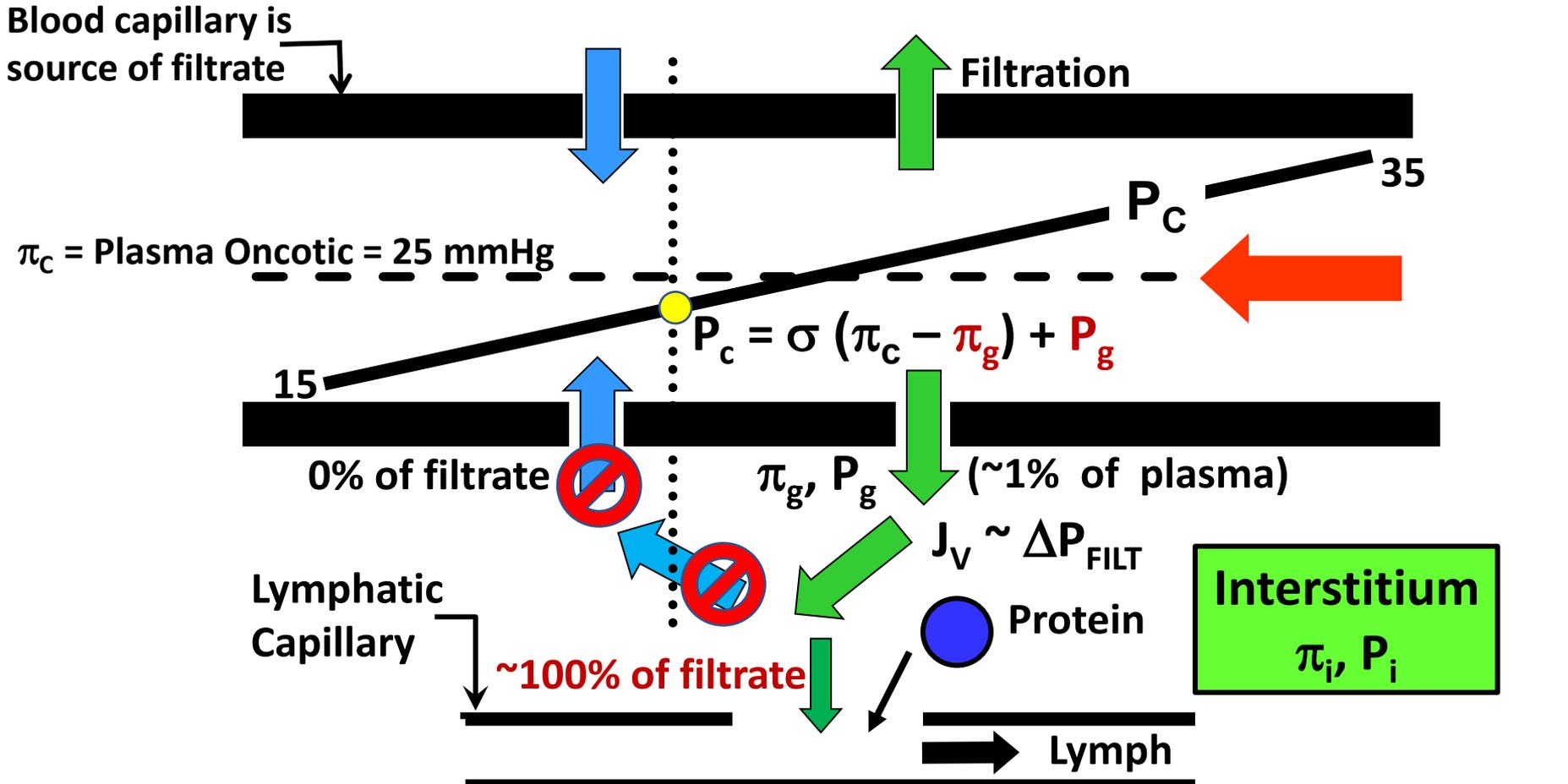


$$\Delta P_{\text{FILT}} = (P_c - P_i) - \sigma (\pi_c - \pi_i) = 0 ?$$

$$P_c = \sigma (\pi_c - \pi_i) + P_i$$

π_i = Interstitial Oncotic pressure
 P_i = Interstitial hydrostatic pressure
 σ = reflection coefficient

Proposed Revision to Classic View of Fluid Exchange



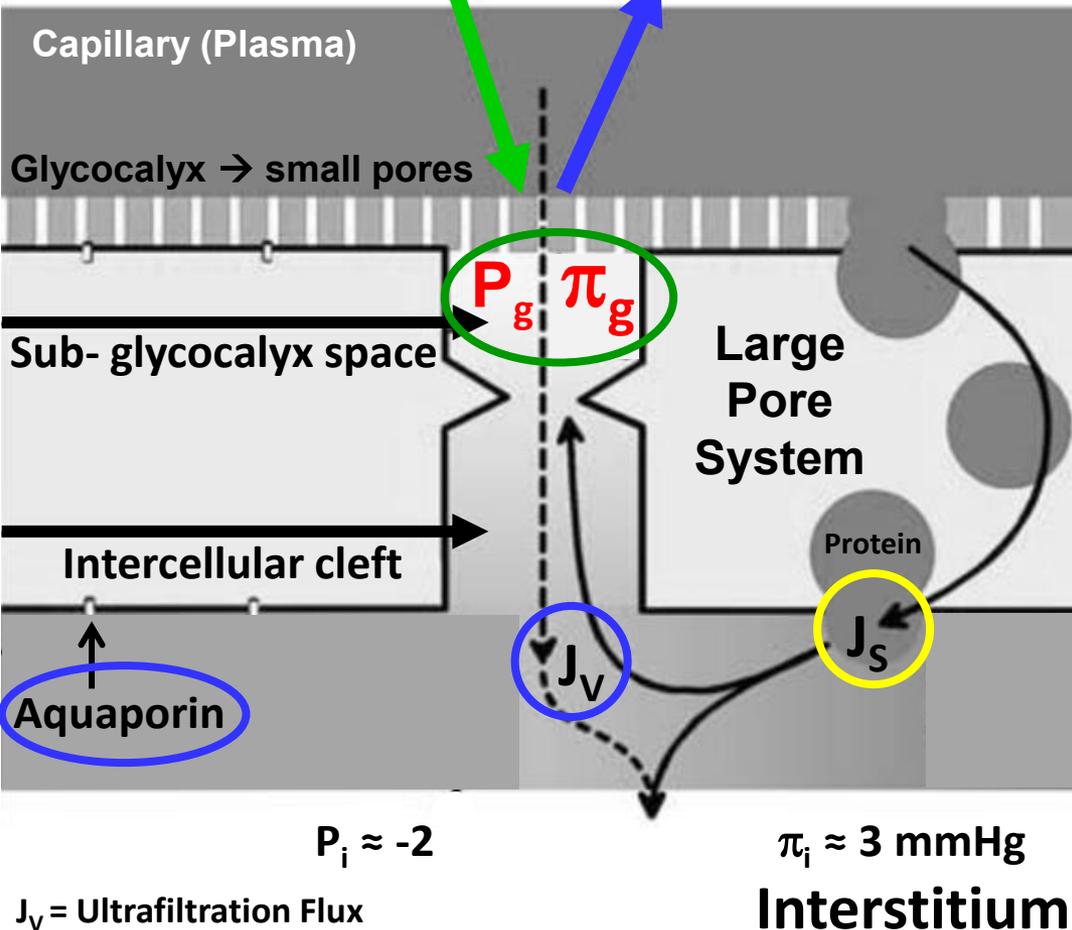
$\Delta P_{\text{FILT}} = (P_c - P_g) - \sigma (\pi_c - \pi_g)$ Most but not all tissues

π_g = Sub-glycocalyx Oncotic pressure
 P_g = Sub-glycocalyx hydrostatic pressure

Supporting Evidence: J Physiology 2004;557:704,
 Cardiovascular Res 2010;87:198-210,
 Clin Invest 2014; 124 (3):915-921

Proposed Process: Filtration

Arterial $P_c = 35$ $\pi_c = 25$ mmHg



- Plasma flows through small pores in the glycocalyx lining endothelial cell surface. Pores have high conductance for plasma flux J_v
- Proteins move slowly through a separate large pore system (J_s) via transcytosis
- Some *protein back-diffuses* to sub-glycocalyx affecting π_g but J_v “wash-out” dilutes;
 - $\pi_g < \pi_i$
 - $P_g > P_i$ → (due to J_v)

$$\Delta P_{\text{FILT}} = (P_c - P_g) - \sigma (\pi_c - \pi_g)$$

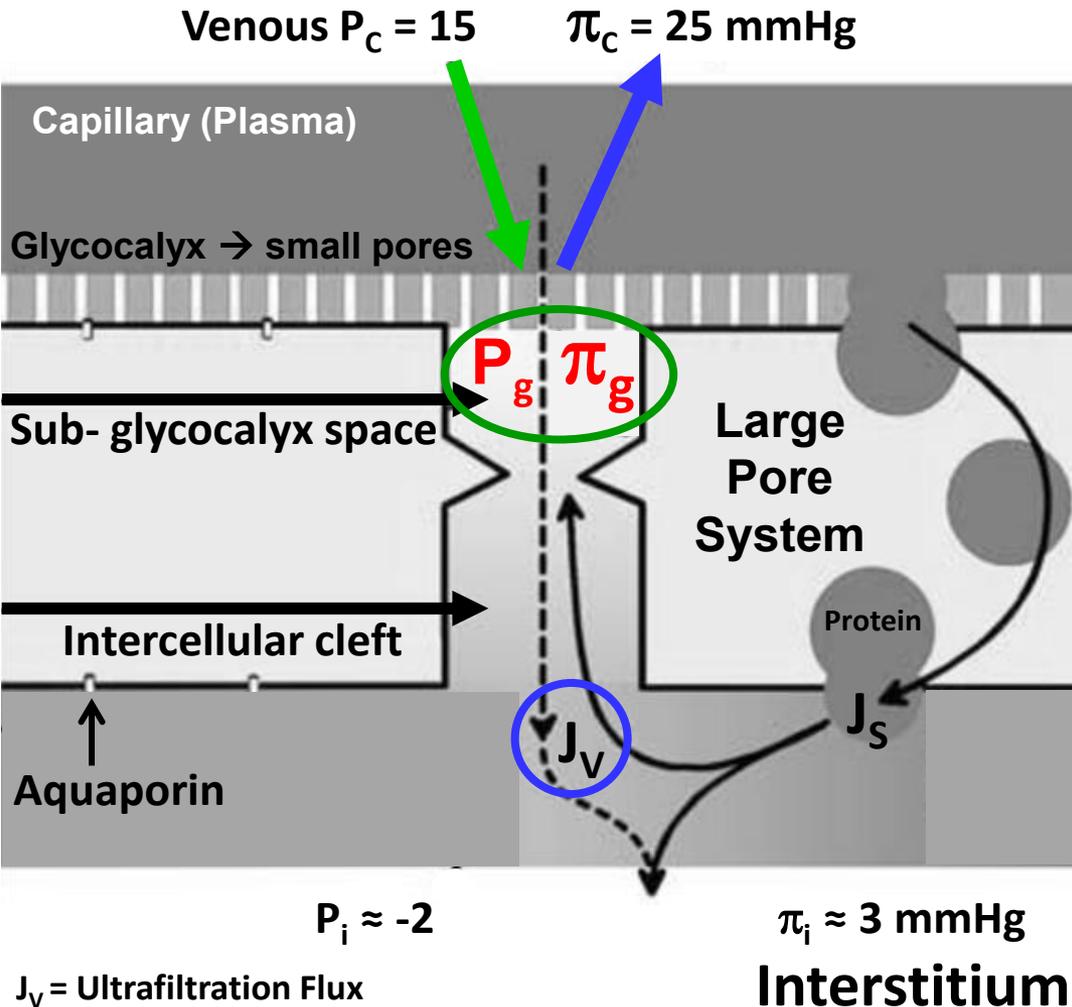
Filtration flux (J_v) is less than predicted by the classical (Starling) model

- Aquaporins provide $\approx 10\%$ of H_2O conductance

J_v = Ultrafiltration Flux
 J_s = Protein Flux
 π_g = Oncotic pressure (glycocalyx)
 π_i = Oncotic pressure (interstitium)

After Levick and Michelle Cardiovascular Research 2010;87:198-210

Proposed Process: Absorption



- At lower filtration rates (toward venous side) protein back-diffusion increase so π_g **increases as J_V decreases**
- At lower filtration rates the “wash-out” dilution process is reduced
→ Further increasing π_g

Diminished Absorption Likelihood

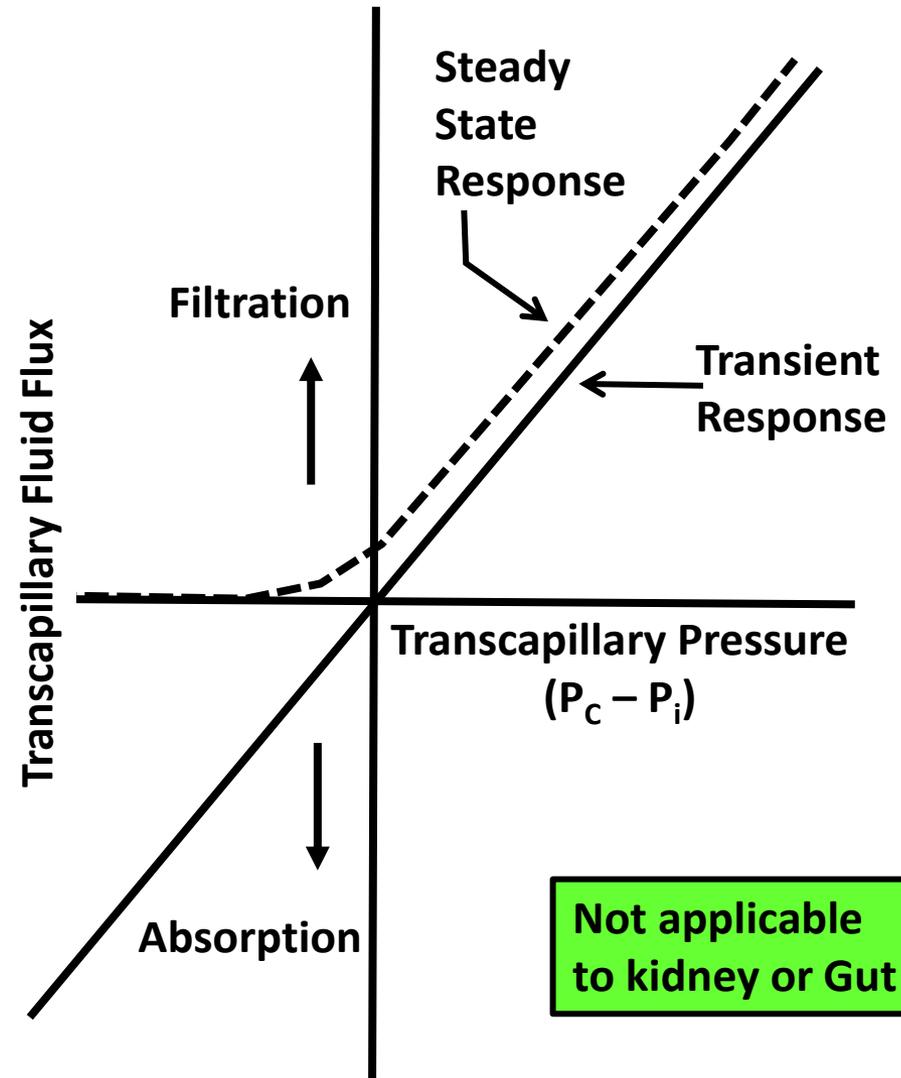
- Microvessels in most tissues do not show sustained absorption in capillary and postcapillary regions with the following exceptions
 - transiently with low pressures as in shock
 - due to arteriolar vasomotion causing low capillary pressure

J_V = Ultrafiltration Flux
 J_S = Protein Flux
 π_g = Oncotic pressure (glycocalyx)
 π_i = Oncotic pressure (interstitium)

After Levick and Michelle Cardiovascular Research 2010;87:198-210

Transcapillary Exchange Processes: **Summary**

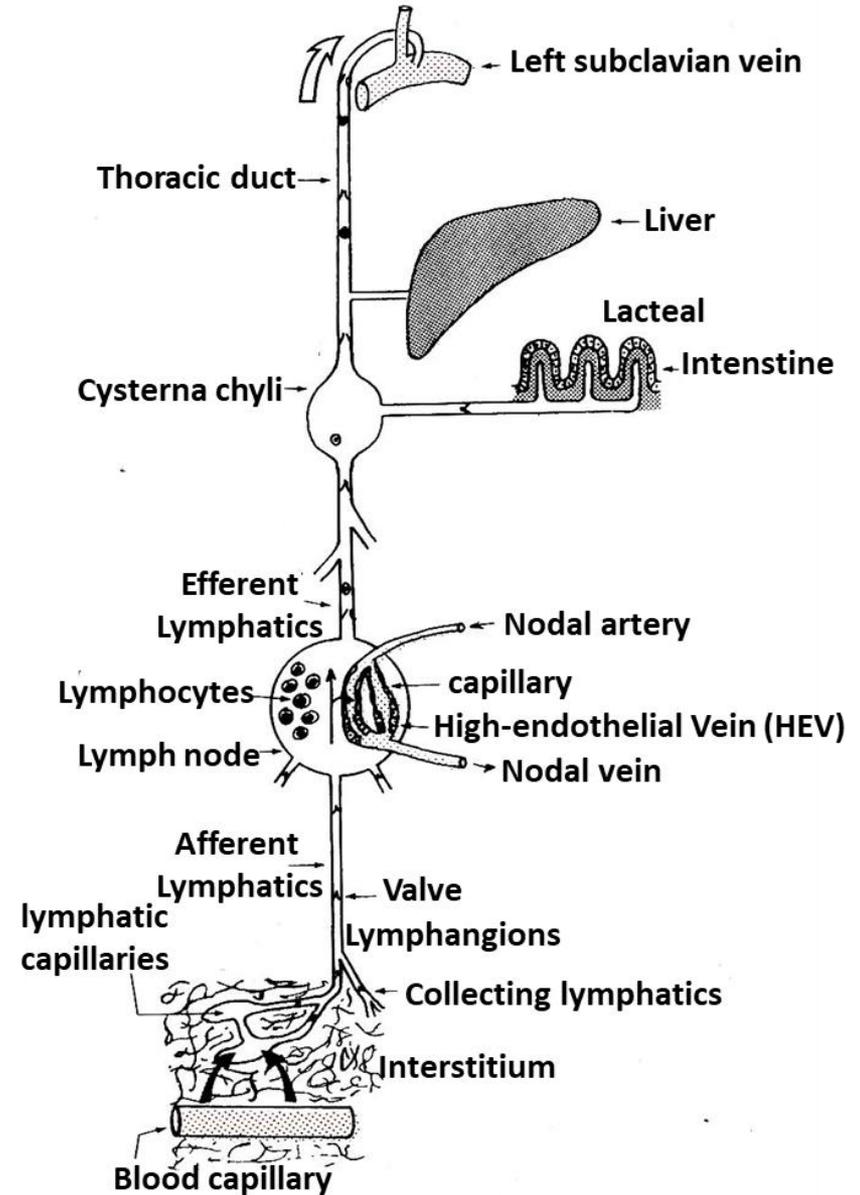
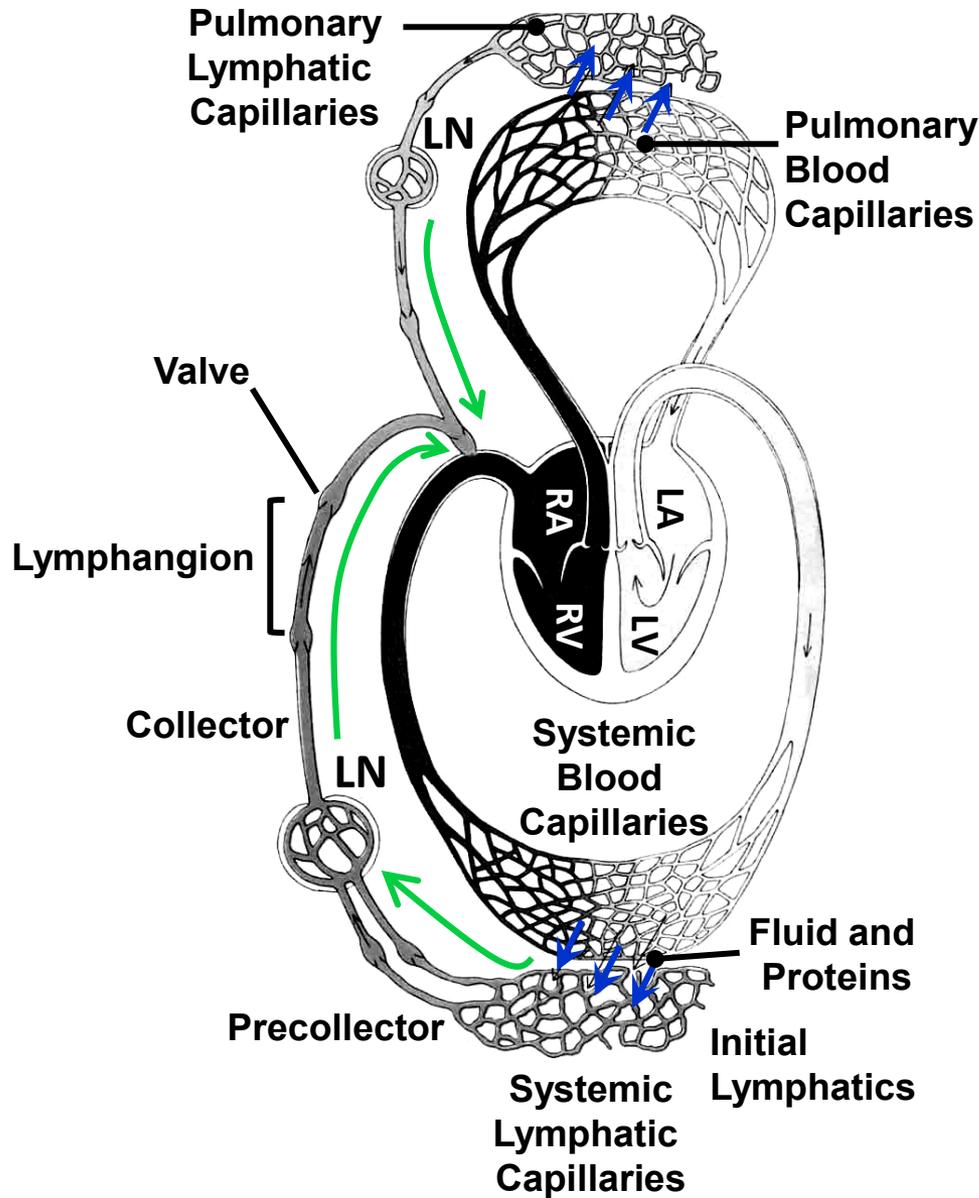
- Filtration is maintained in the steady state
- Interstitial protein concentration (oncotic pressure, π_i) has little effect on controlling filtration
- Main influence is π_g
- Post capillary absorption of fluid only occurs transiently
- This concept has led to the view that “All edema is lymphedema”



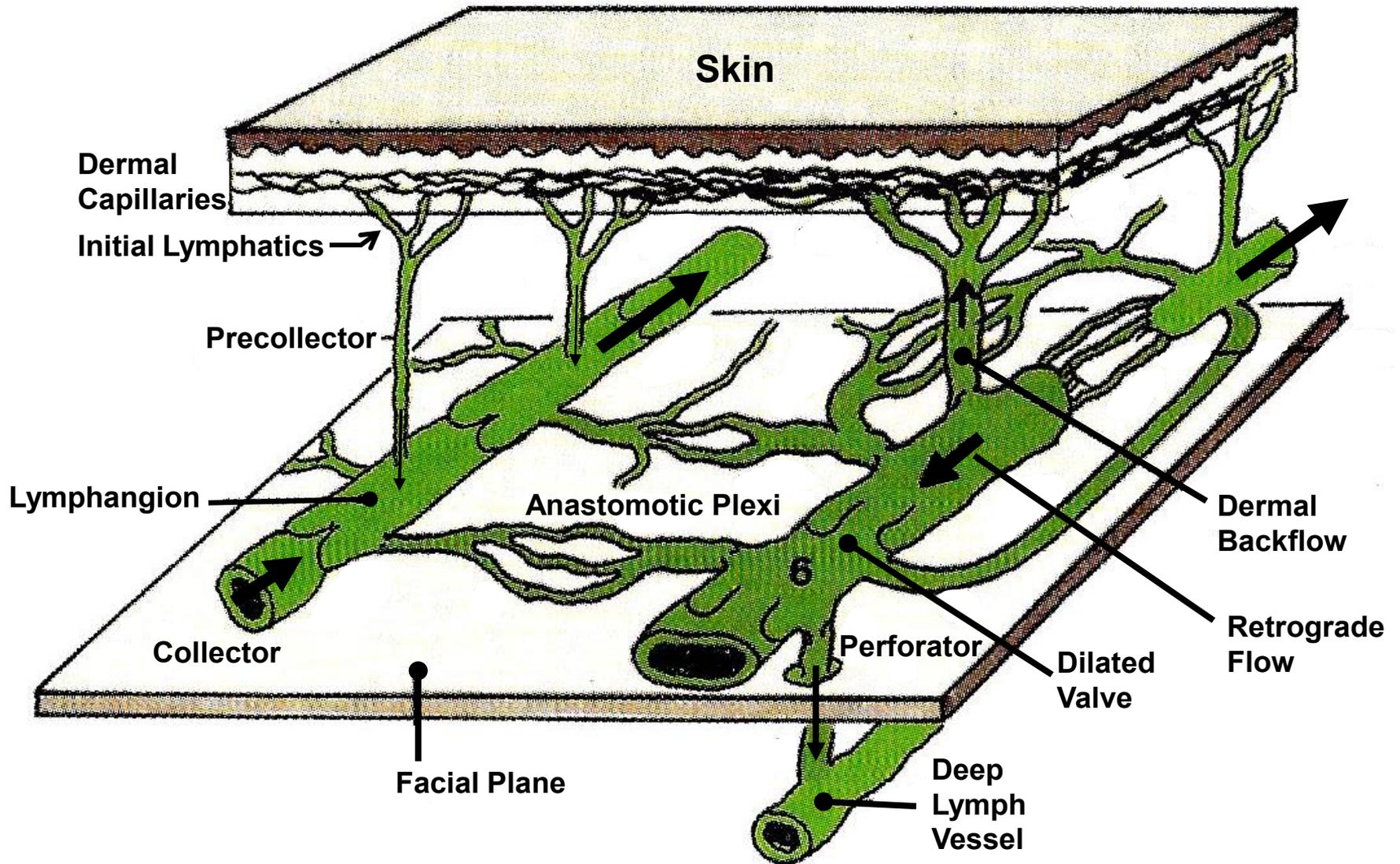
Features of the Lymphatic System

- **Functional arrangements**
- **Designations and features**
- **Initial lymphatics and lymphangions**
- **Edema and lymphedema**

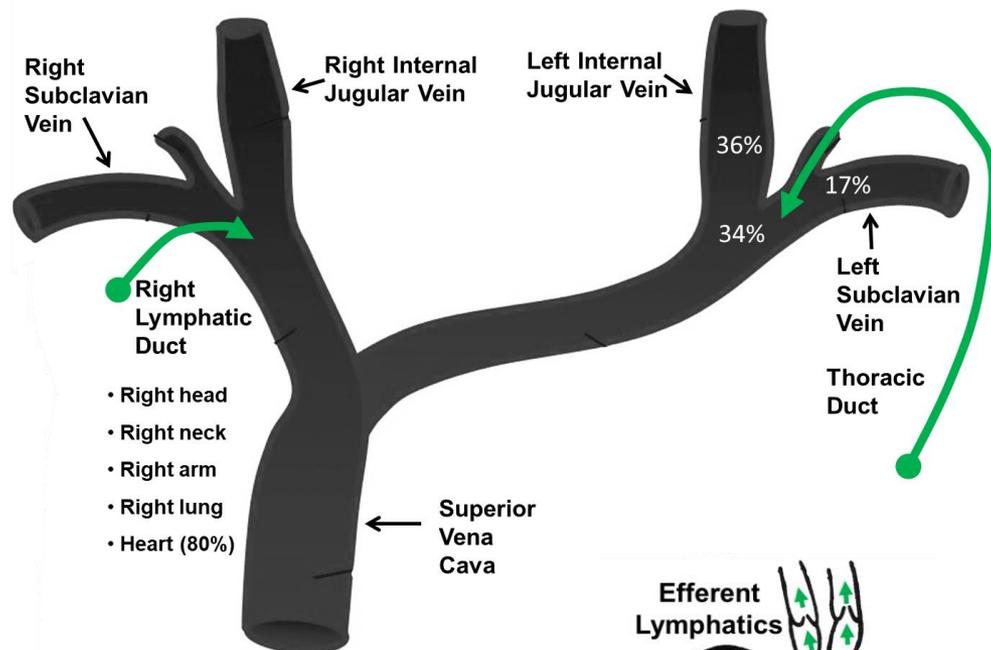
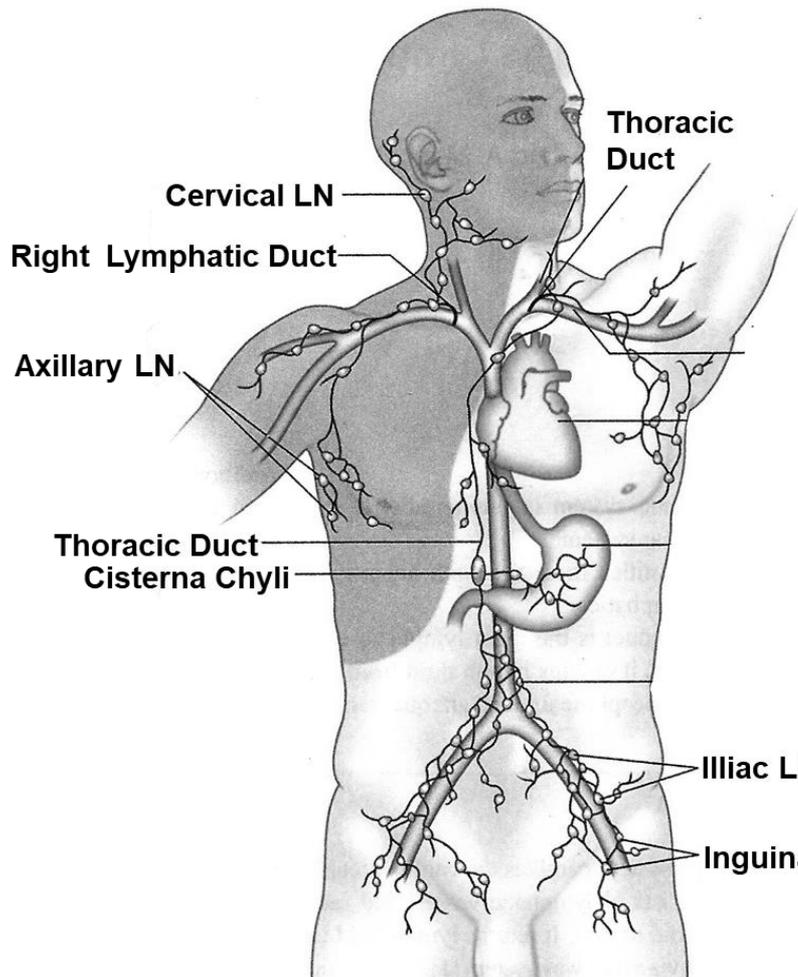
Lymphatic Functional Arrangements



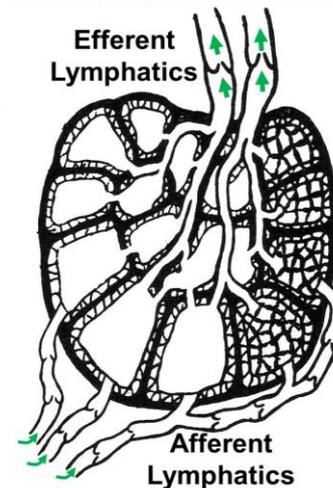
Lymphatic Vessel Designations and Features



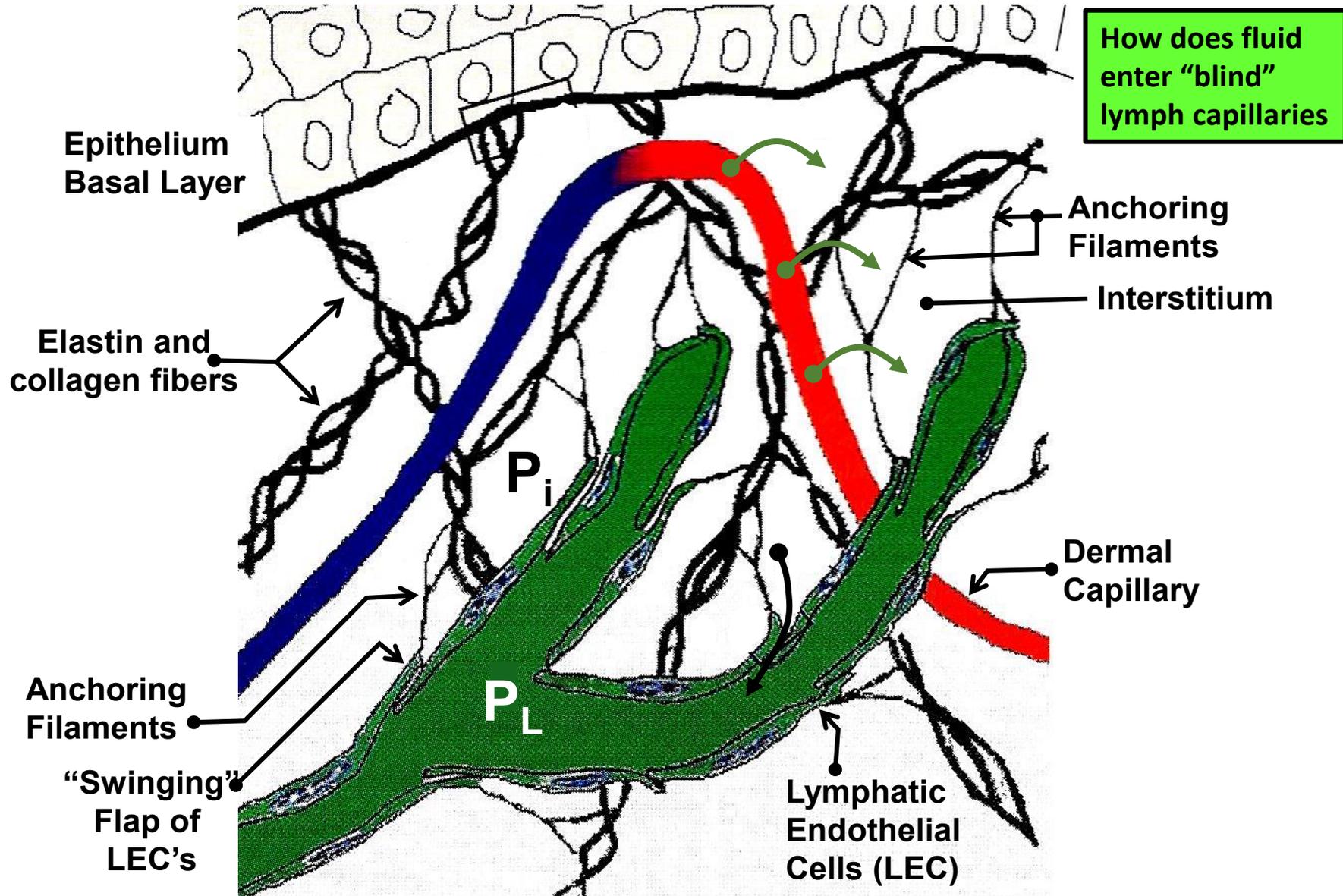
Lymphatic Drainage-Ducts-Nodes



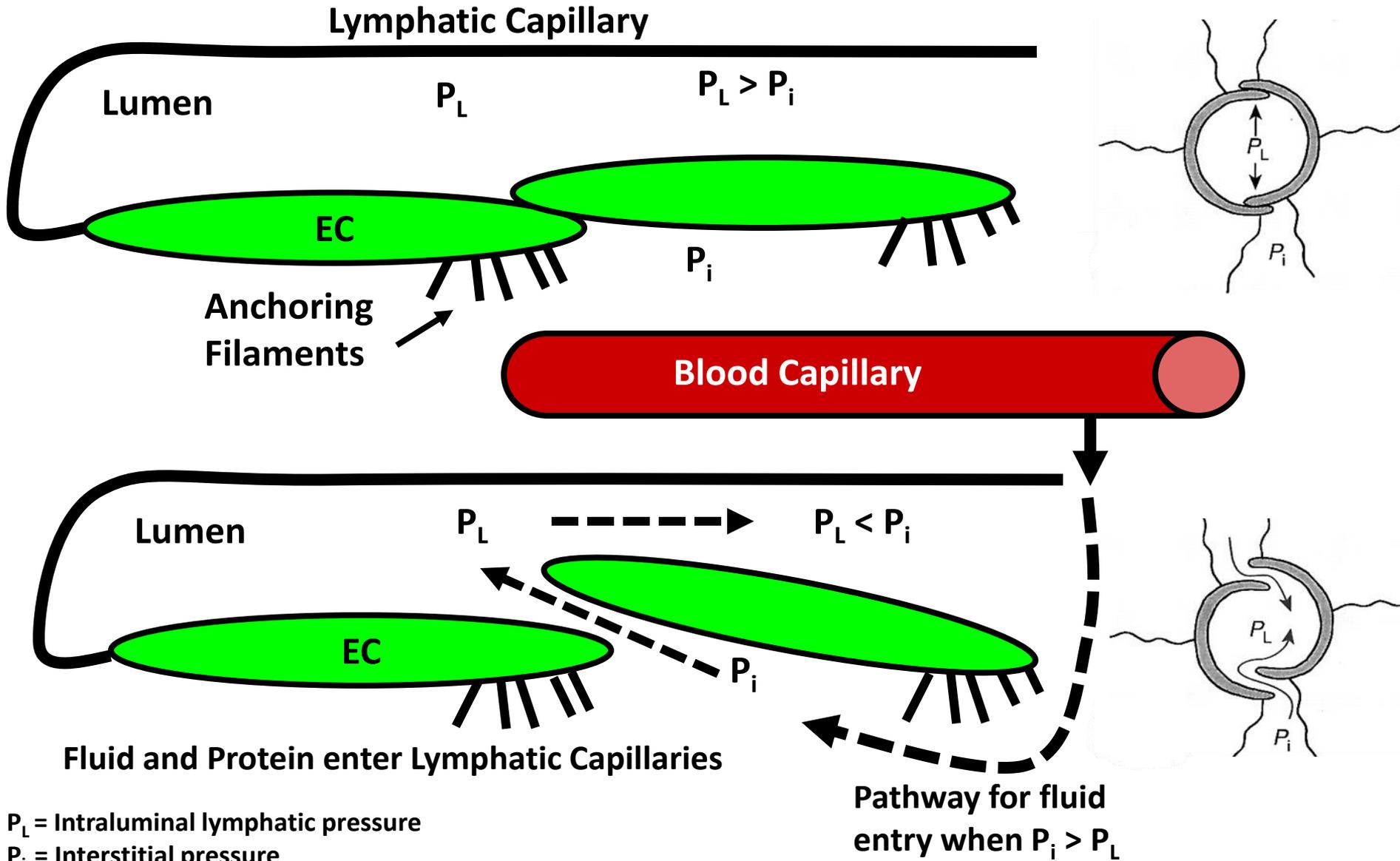
- Right head
- Right neck
- Right arm
- Right lung
- Heart (80%)



Initial Lymphatics – Lymph Capillaries

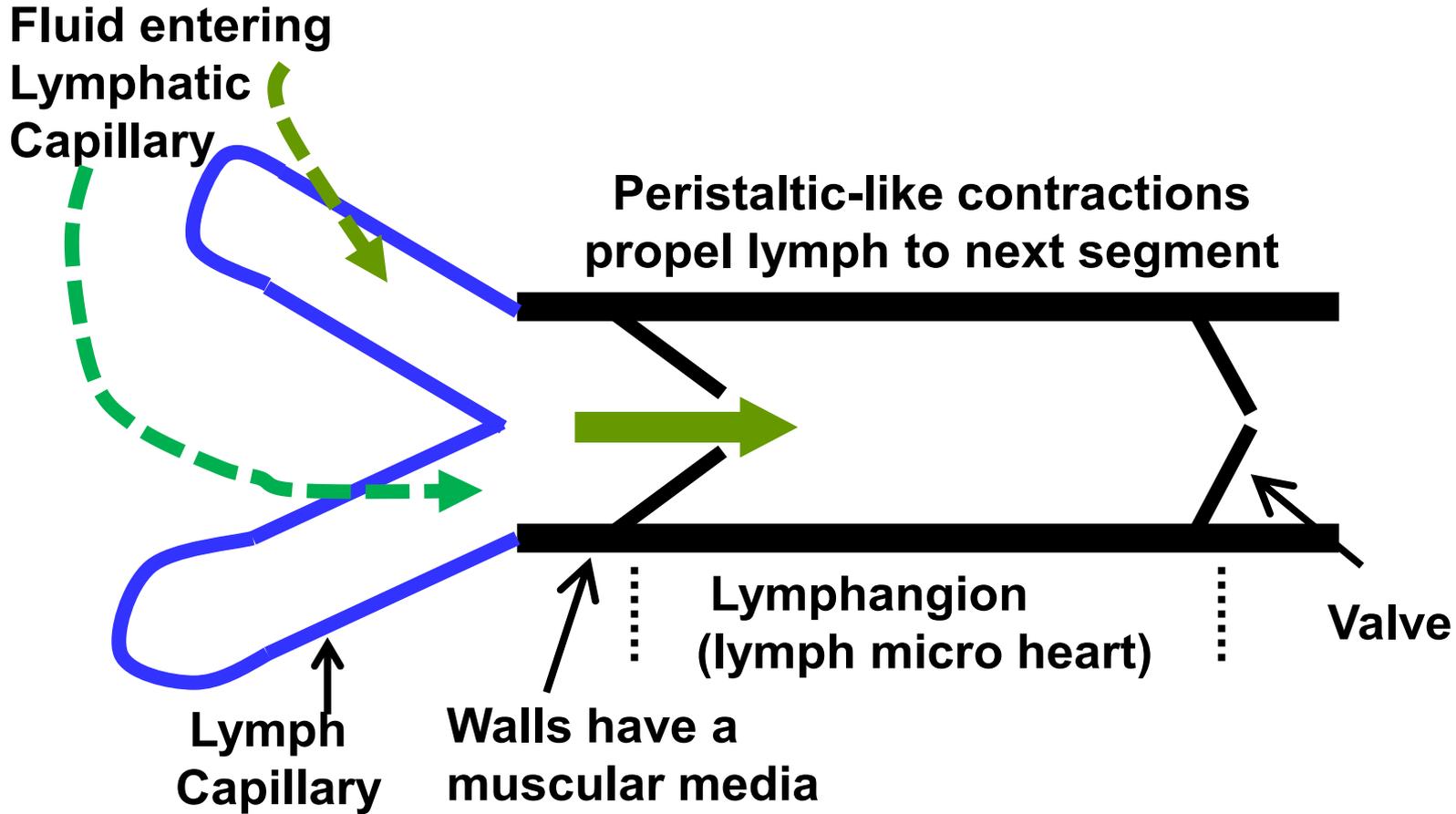


Entry into Lymphatic Capillaries



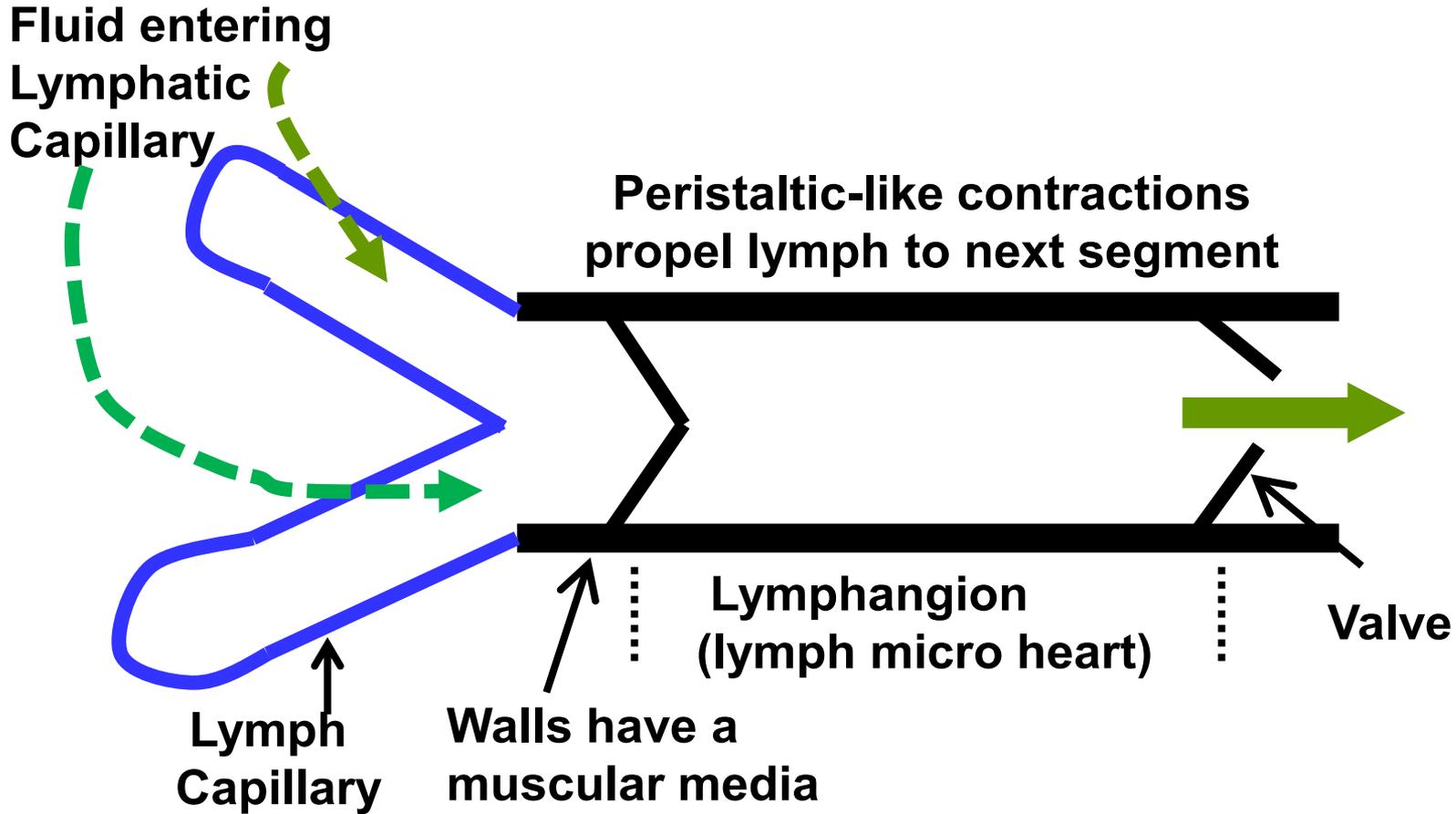
P_L = Intraluminal lymphatic pressure
 P_i = Interstitial pressure
 EC = Endothelial cell

Lymphangions: Lymphatic “Hearts”



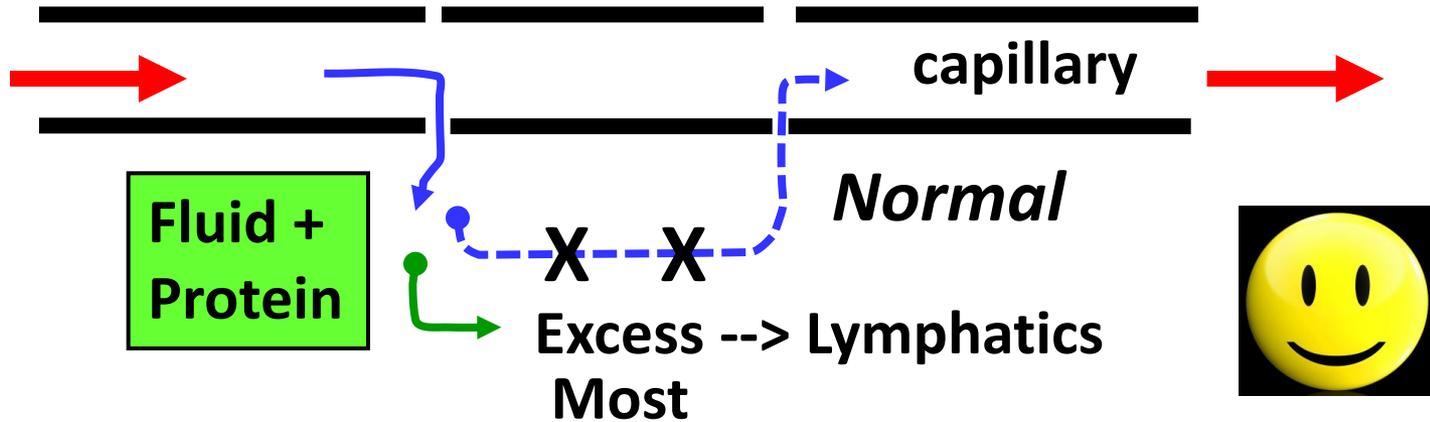
Contraction force and frequency is preload and afterload dependent - analogous to heart

Lymphangions: Lymphatic “Hearts”



Contraction force and frequency is preload and afterload dependent - analogous to heart

Edema and Lymphedema



*If Net Filtration Exceeds
Lymphatic Transport Capacity*

Overload = Edema



+ [Protein]

= Lymphedema



Clinical Lymphedema Images



**Unilateral Breast Cancer
Treatment-Related LE**



**Unilateral Lower
Extremity Lymphedema**

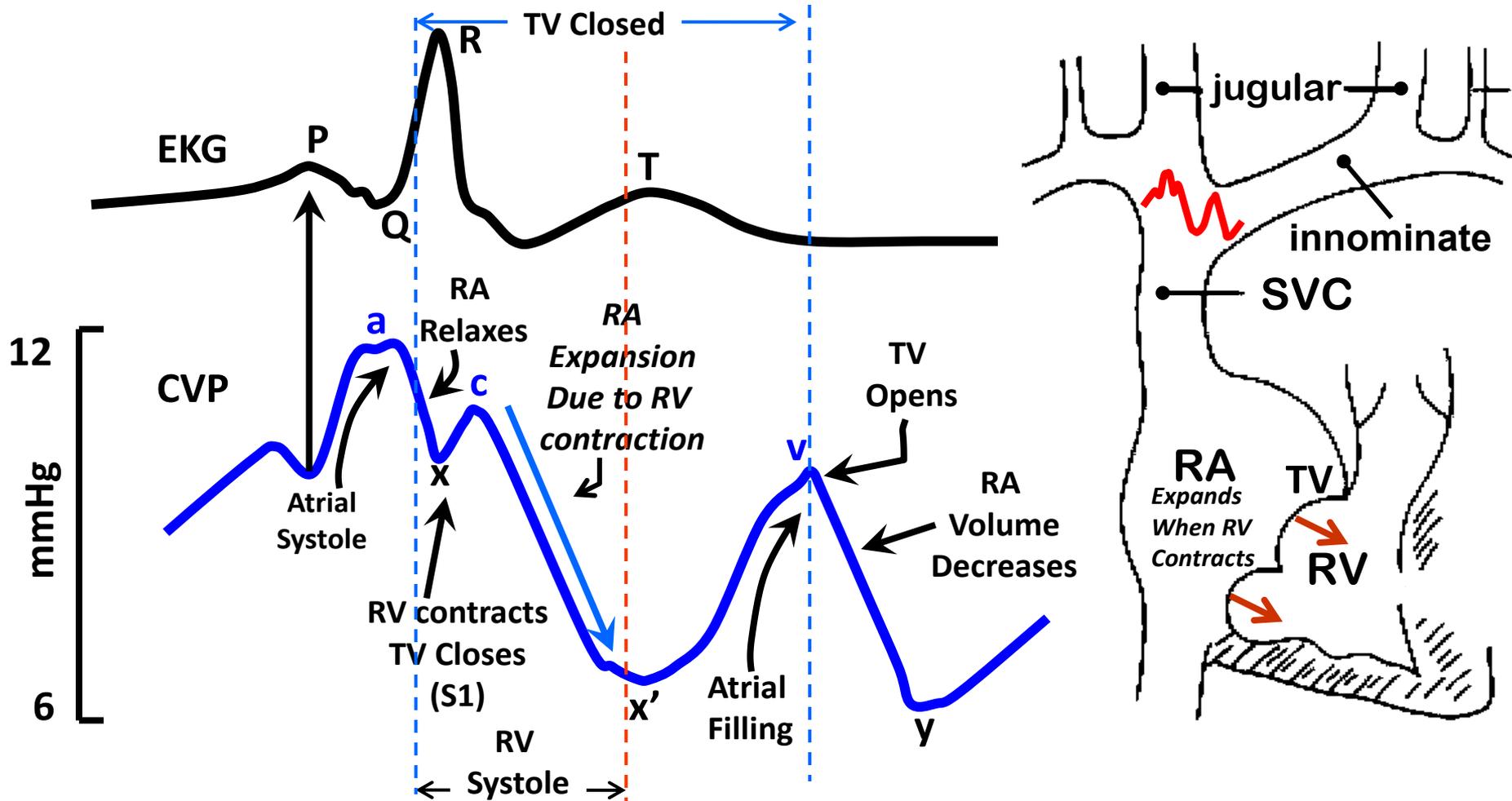


**Bilateral Lower
Extremity Lymphedema**

Features of the Venous System

- **Review of Central Venous Pressure Pulse**
- **Venous valves and calf muscle pump**
- **Ambulatory venous pressures**
- **Venous Valve Dysfunction**
- **Respiratory Pump**
- **Reservoir Function**

Central Venous Pulse in Relation to EKG



a-wave: Venous distension and backward pressure wave during right atrial (RA) systole

x-decent: RA relaxes

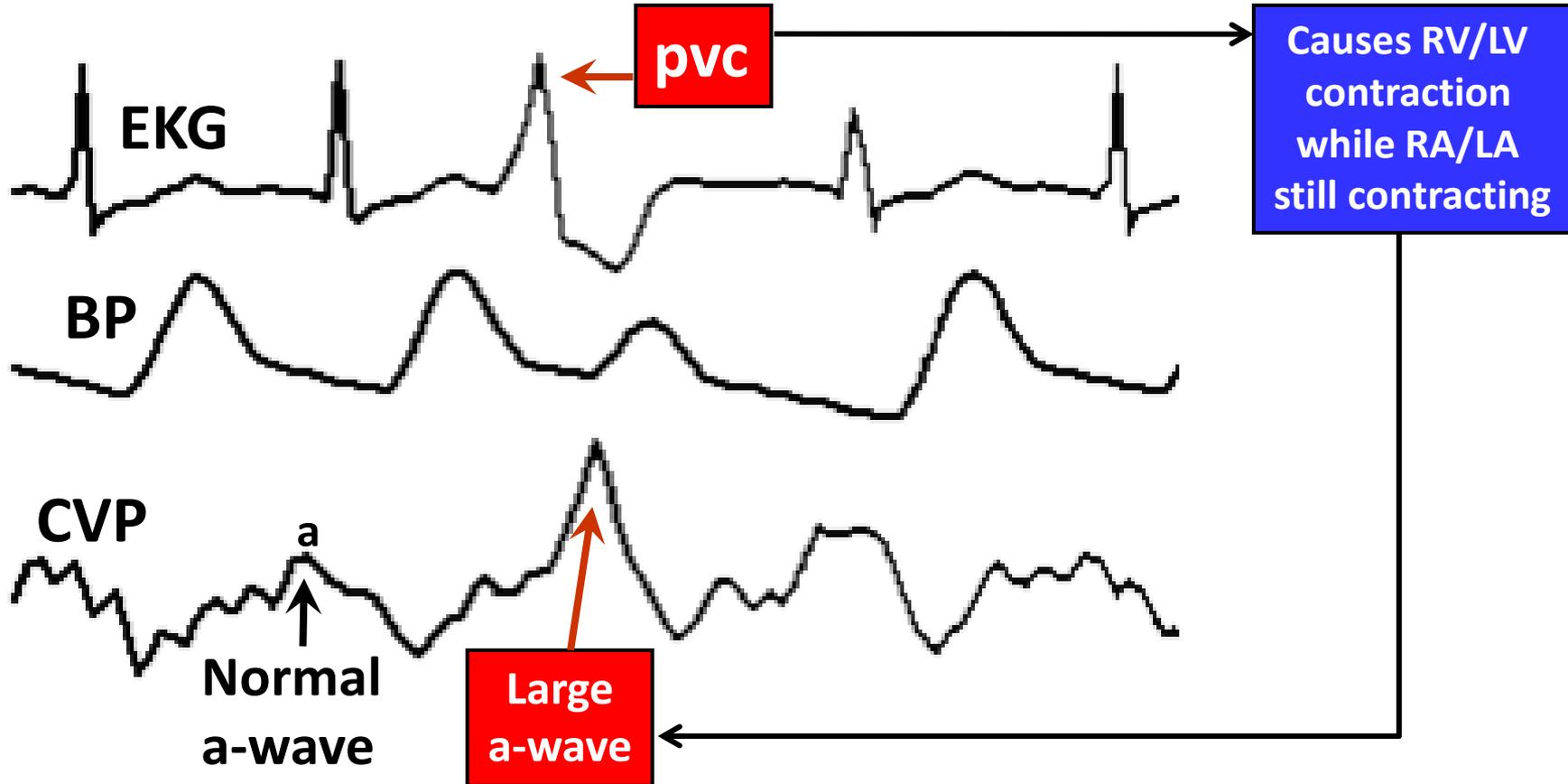
c-wave: RV contraction closes TV that bulges into RA (interrupts decent) → RAP transient increase

x': continuation of x-decent (RV contraction continues “expands” atrium – RAP falls)

v-wave: Rise in RAP with atria filling (Relaxing RV → RA expansion reversed)

y-decent: Decline in RAP when tricuspid valve reopens – RV filling

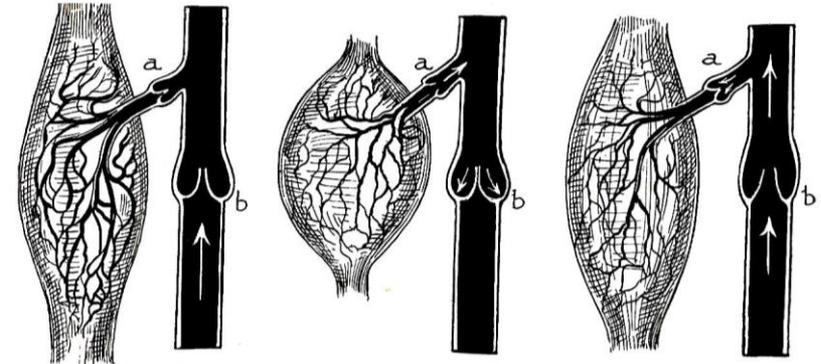
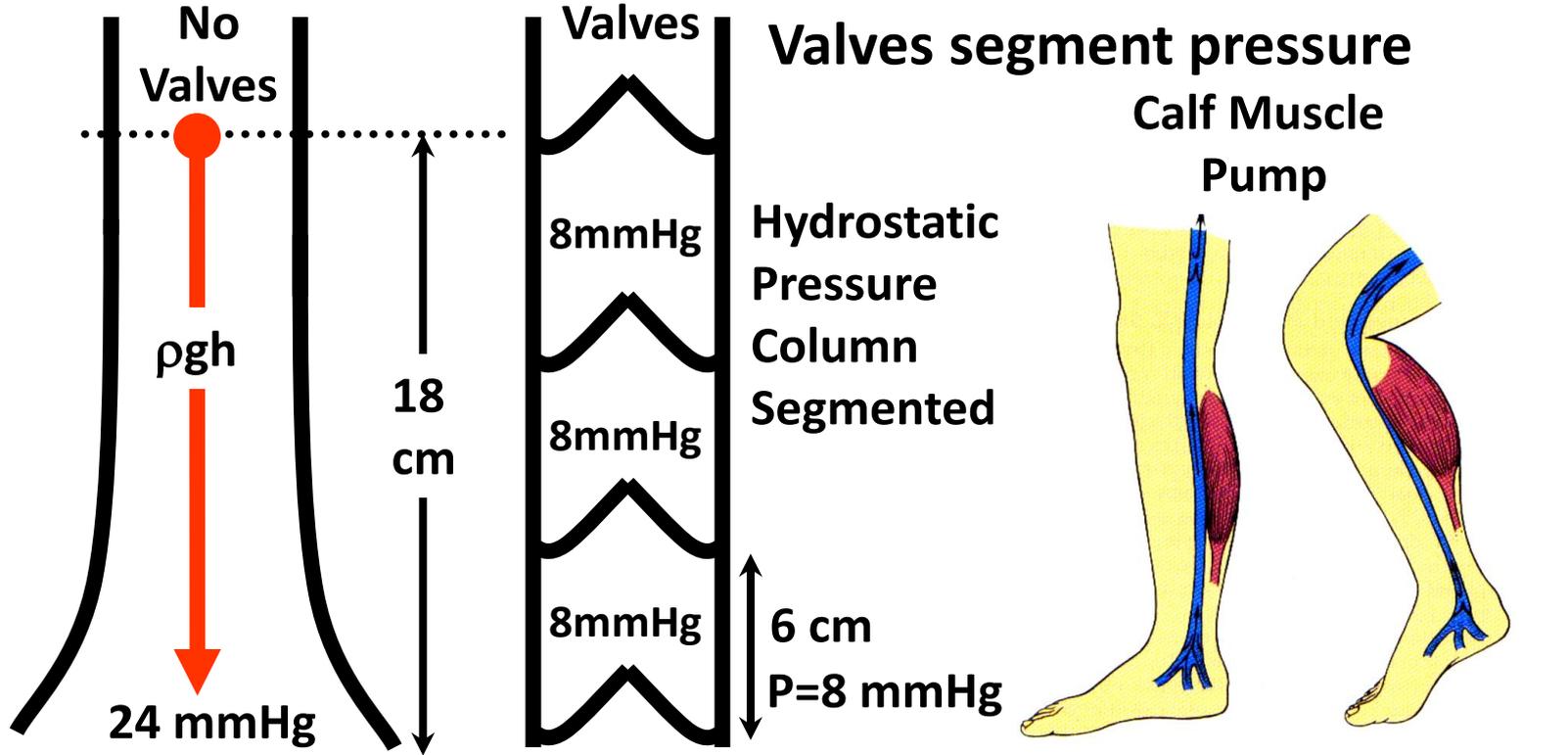
Large a-wave if atrium contracts while RV is not relaxed



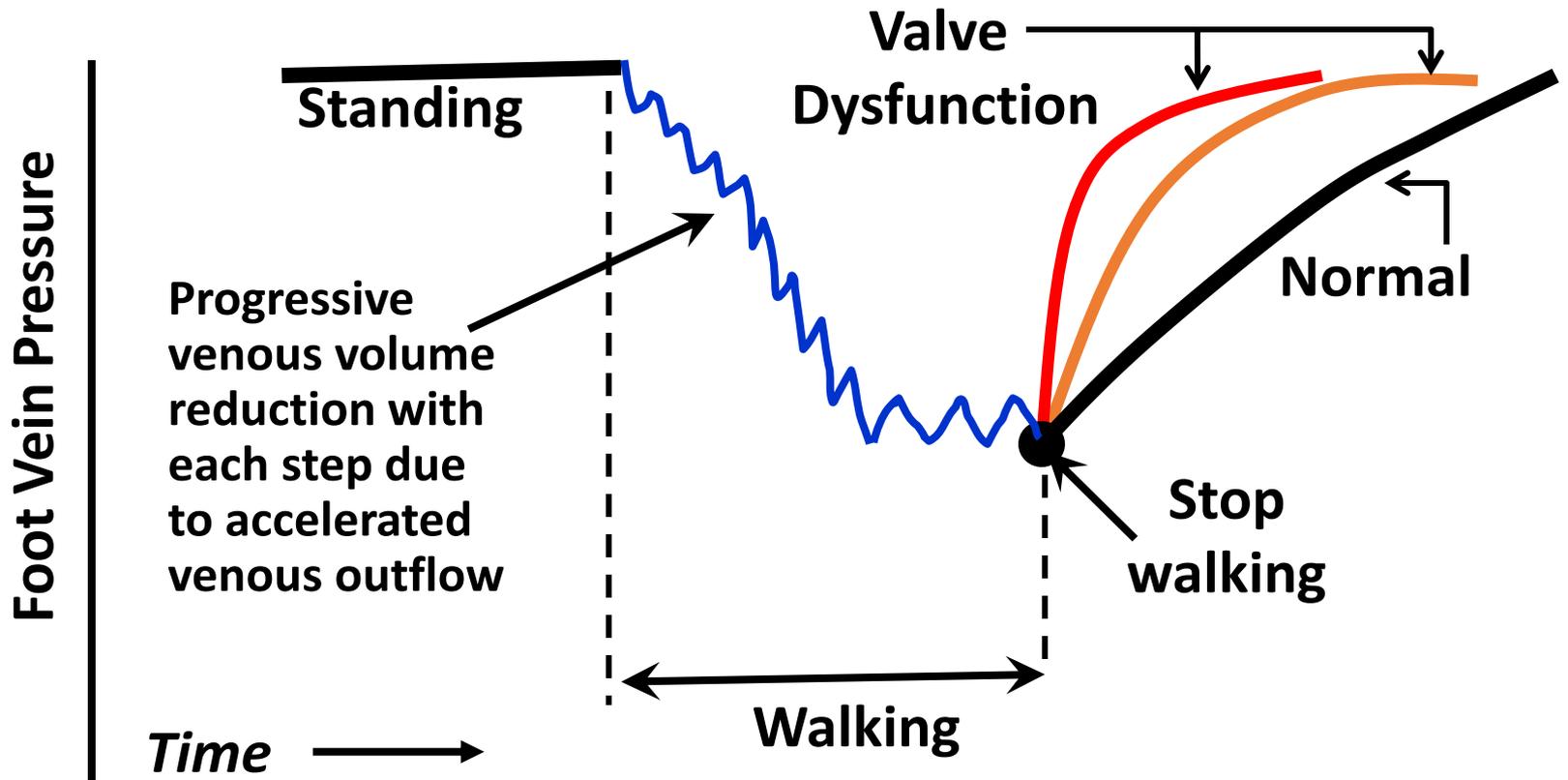
Tid Bits

- *a-waves increased if RA contracts while RV contracts*
- *a-waves increased if tricuspid valve stenosis*
- *a-waves increased if the atrium contracts with the TV closed*
- *a-waves disappear in atrial fibrillation*
- *a-waves increased if low RV compliance*

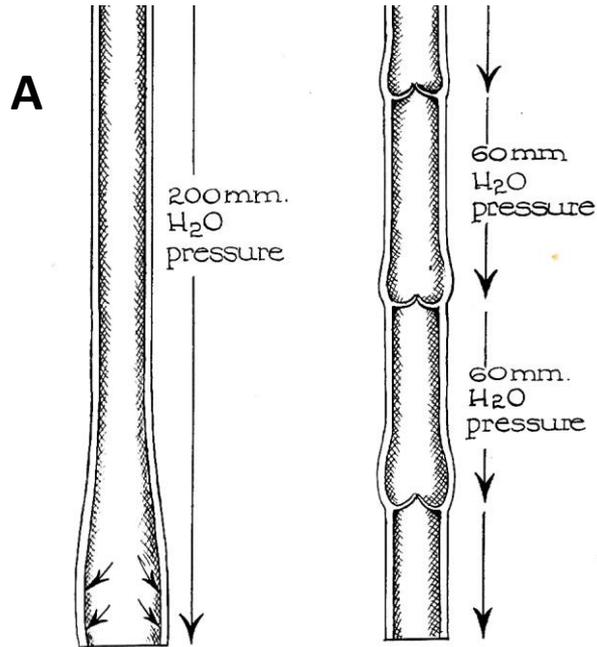
Valves and Calf Muscle Pump



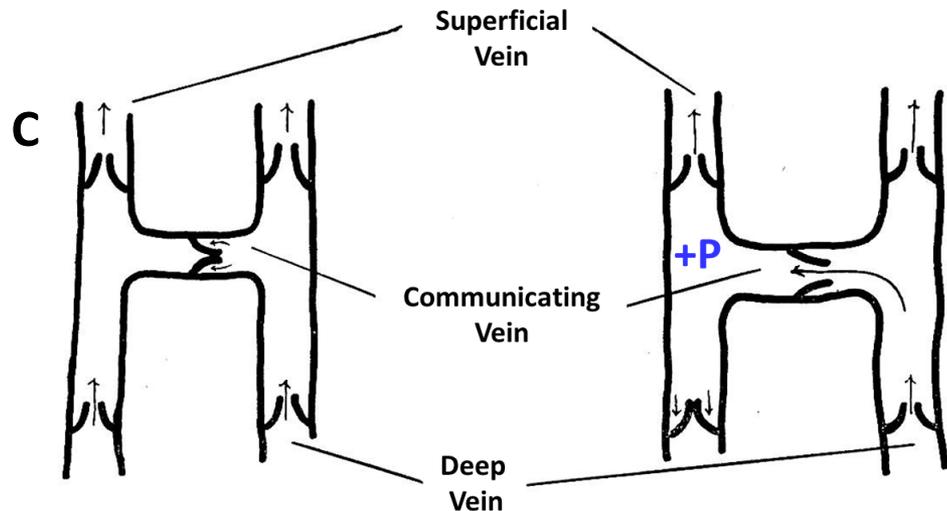
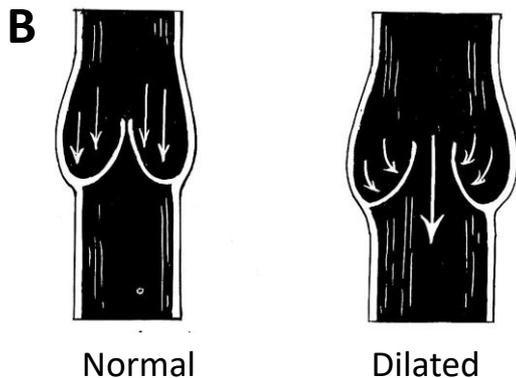
Ambulatory Venous Pressure



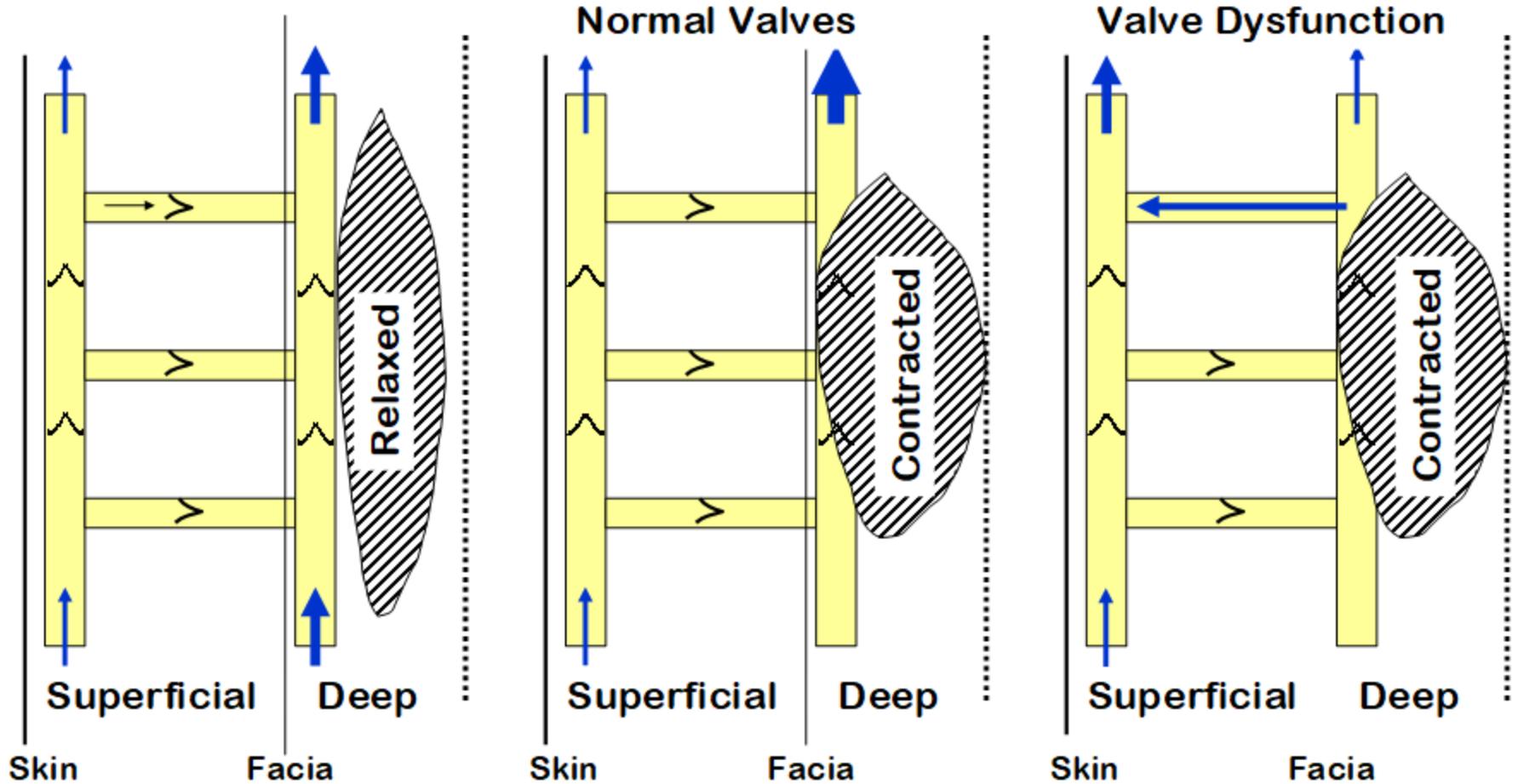
Venous Valve Segmentation and Incompetence



- (A) Segmentation reduces gravitational pressure component that contributes to passive dilation
- (B) Venular overdilation or valve structural change leads to venous valve incompetence
- (C) When incompetence of communication vein valves then increased pressure in superficial veins that may lead to vein wall changes and skin breakdown

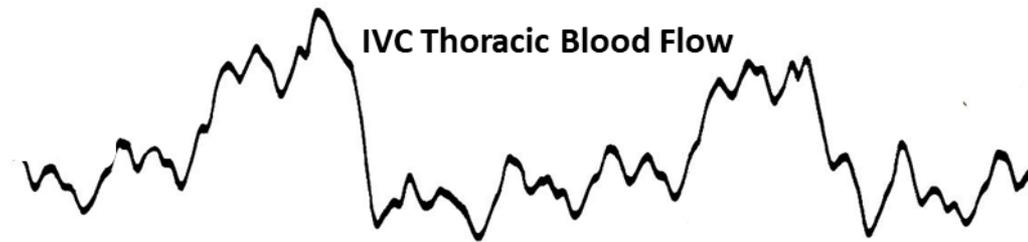
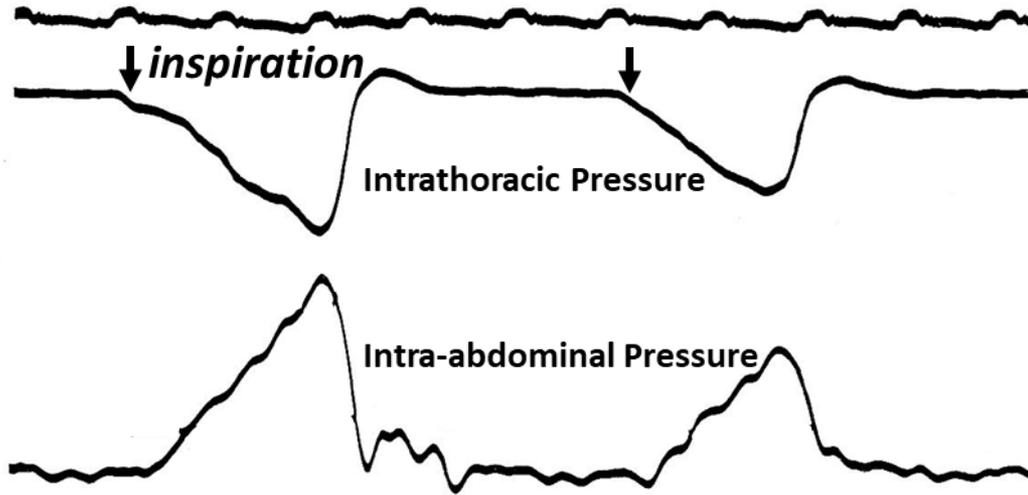


Venous Valve - Dysfunction



Respiratory Pump

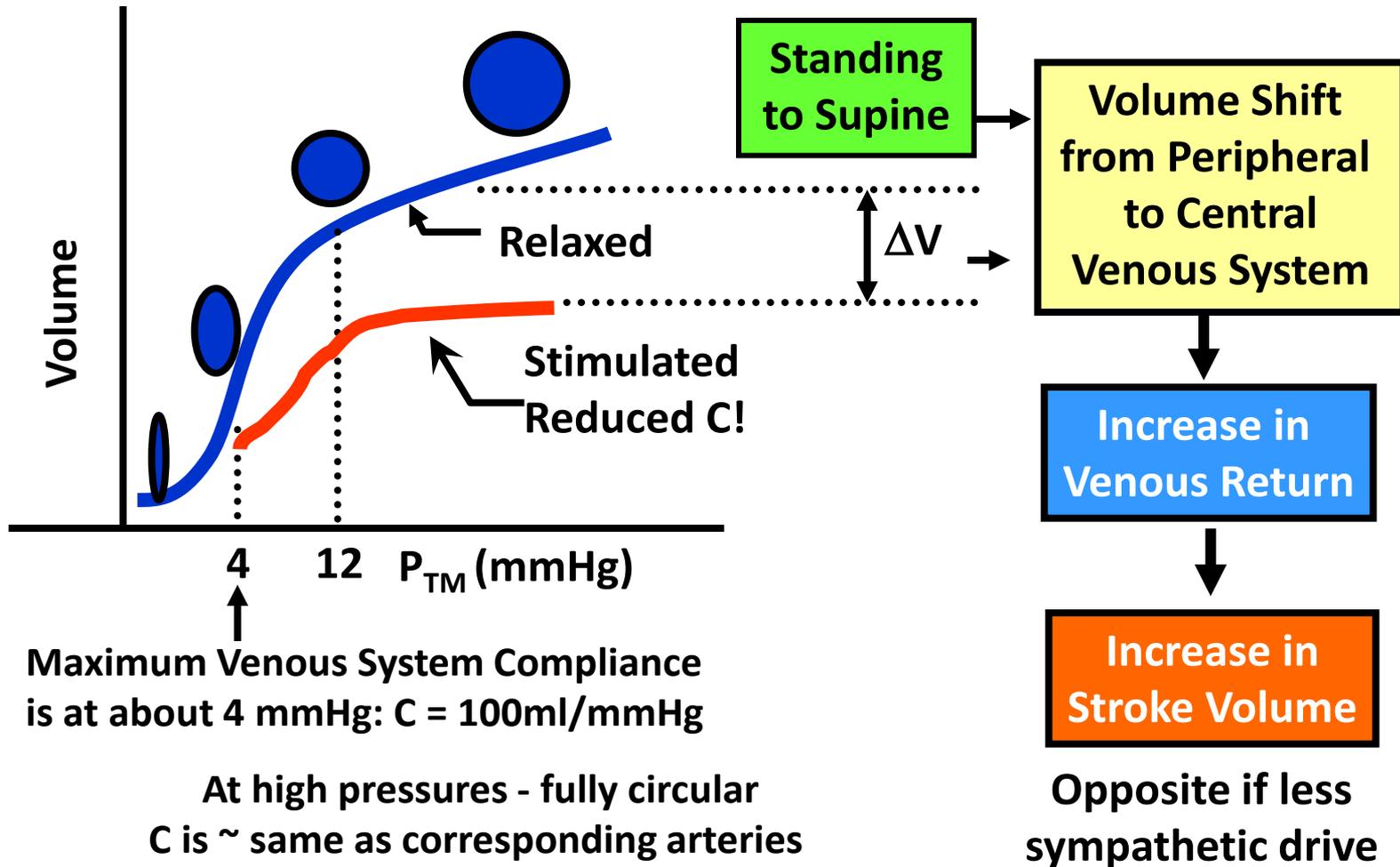
Aortic Pressure



- Inspiration causes
 - decreased thoracic pressure
 - increased abdominal pressure
- Reduced thoracic pressure increases transmural pressure in thoracic IVC
- Lowers resistance
- **increased blood flow**

- Thus, inspiration is normally associated with increased blood to the right heart
- This action is referred to as the **Respiratory Pump** → **aids venous return**

Venous Volume Reservoir Role



End of CV Physiology Lecture 16