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Presentation

PRINCIPLES OF
HUMAN
PHYSIOLOGY

SIXTH EDITION

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CHAPTER **18**

The Urinary
System:
Renal Function

Chapter Outline

- 18.1 Functions of the Urinary System
- 18.2 Anatomy of the Urinary System
- 18.3 Basic Renal Exchange Processes
- 18.4 Regional Specialization of the Renal Tubules
- 18.5 Excretion

18.1 Functions of the Urinary System

- Regulate plasma ionic composition
- Regulate plasma volume
- Regulate plasma osmolarity
- Regulate plasma pH
- Remove metabolic waste products and foreign substances from plasma
- Other functions
 - Secrete erythropoietin and renin
 - Activate vitamin D₃ to calcitriol
 - Gluconeogenesis

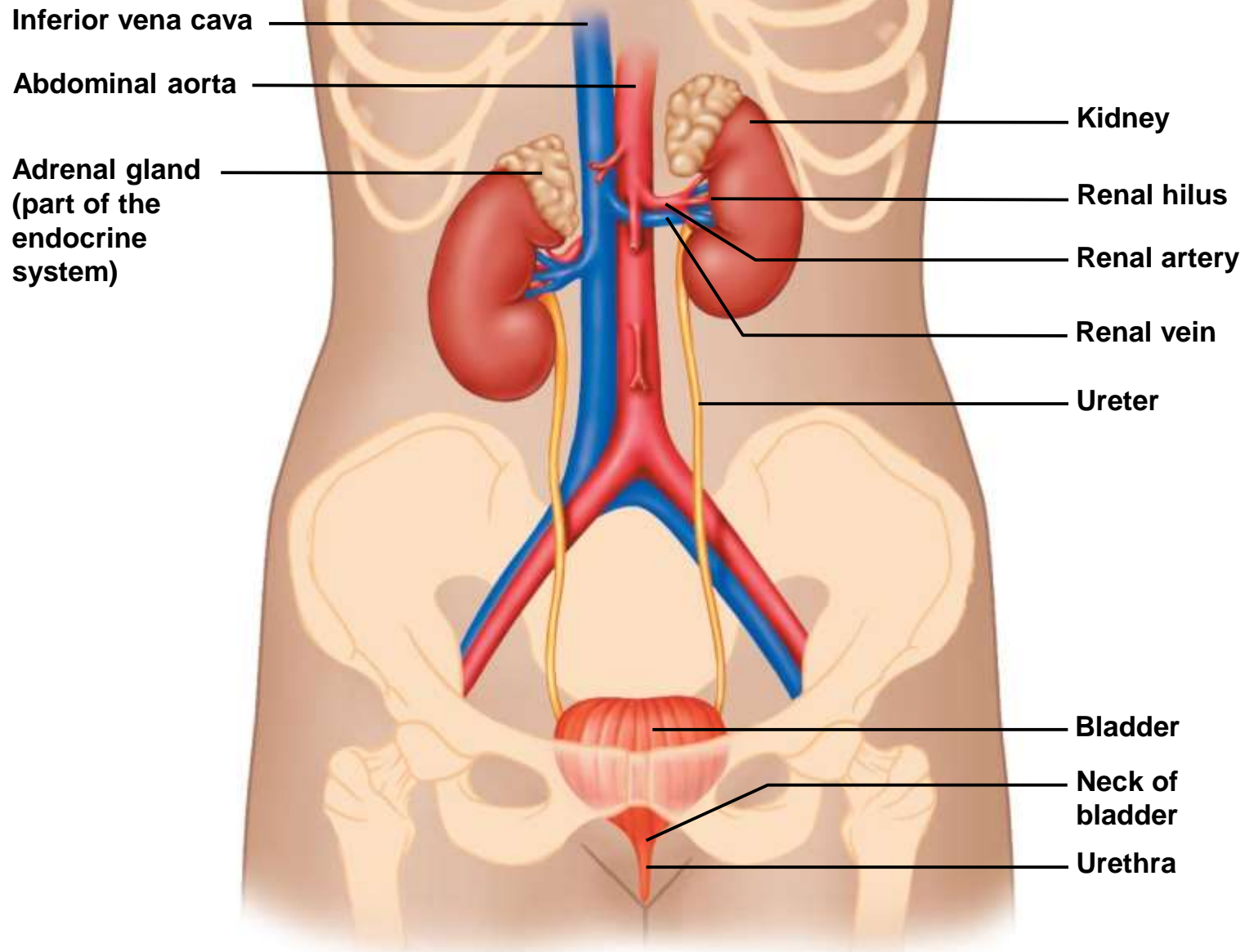
18.2 Anatomy of the Urinary System

- Structures of the urinary system
- Macroscopic anatomy of the kidney
- Microscopic anatomy of the kidney
- Blood supply to the kidney

Structures of the Urinary System

- Kidneys: form urine
- Ureters: transport urine from kidneys to bladder
- Bladder: store urine
- Urethra: excrete urine from bladder to outside of body

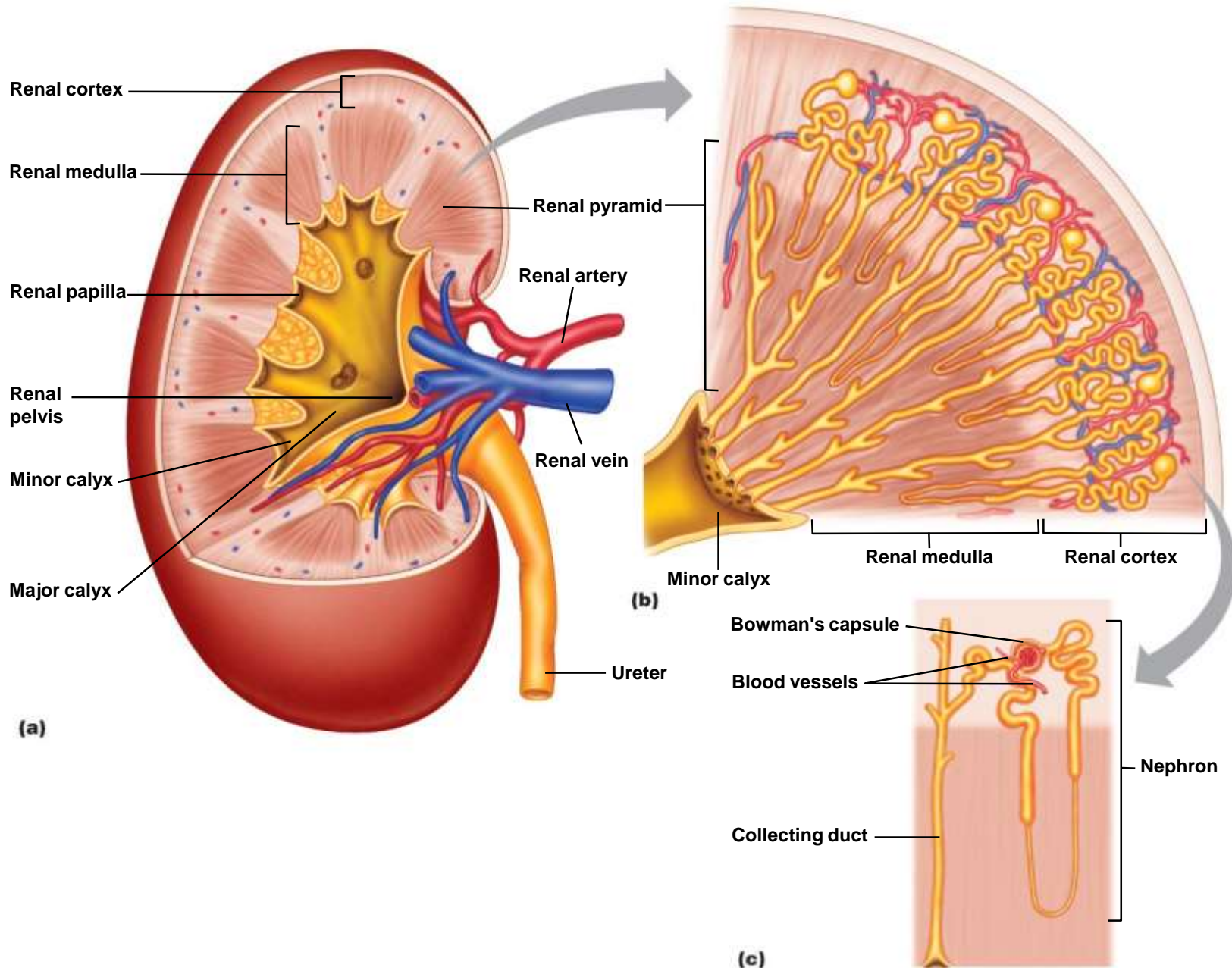
Figure 18.1 Structures of the urinary system.



Macroscopic Anatomy of the Kidneys

- Paired, bean shaped
- Approximate size of fist; 115–170 grams
- Retroperitoneal

Figure 18.2 Anatomy of a kidney.



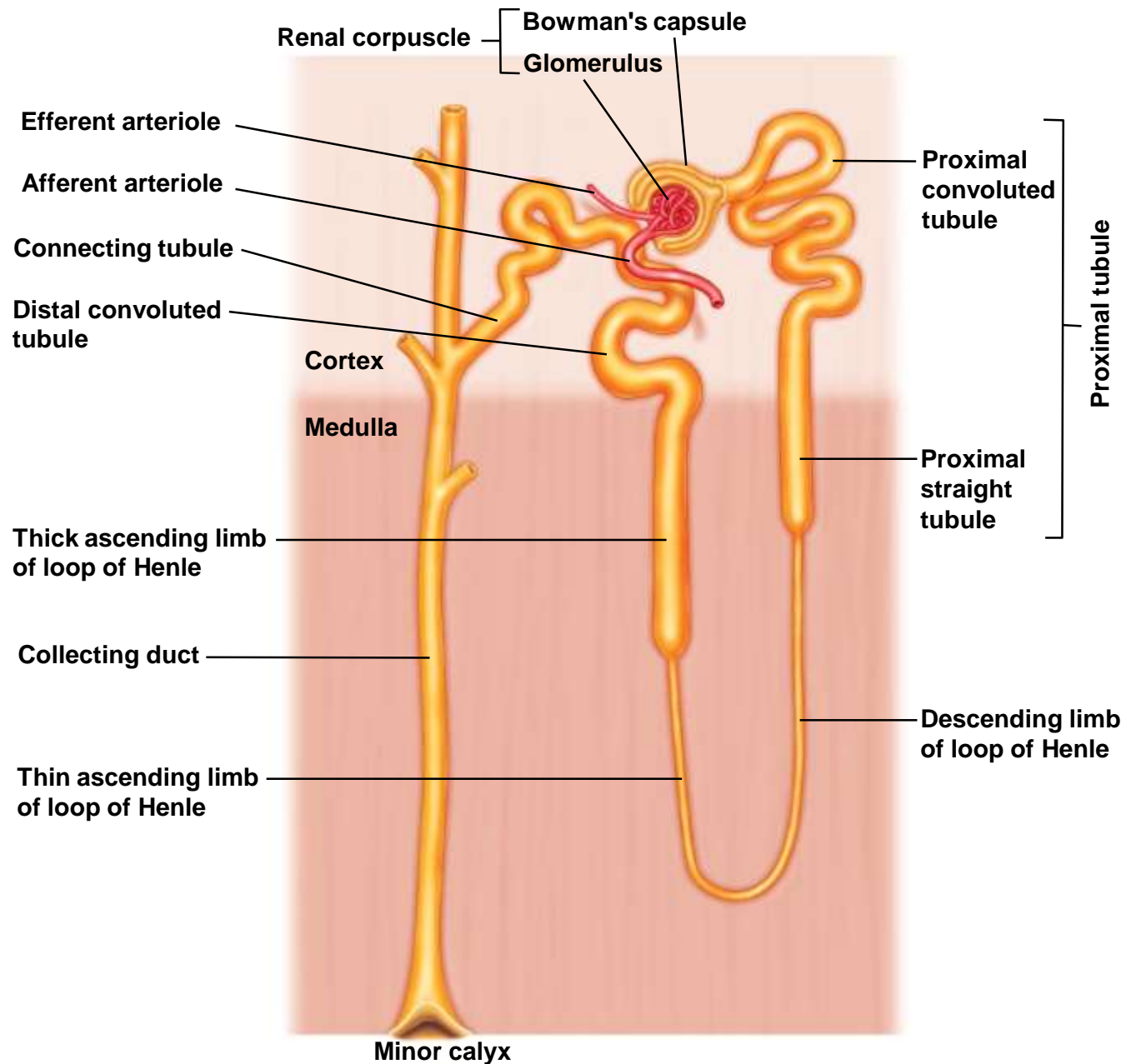
Microscopic Anatomy of the Kidney

- Nephron = functional unit
- Renal corpuscle
 - Glomerulus = capillary network for filtration
 - Bowman's capsule
 - Receives the filtrate
 - Inflow to renal tubules

Microscopic Anatomy of the Kidney

- Renal tubules
 - Proximal tubule
 - Proximal convoluted tubule
 - Proximal straight tubule
 - Loop of Henle
 - Descending limb
 - Thin ascending limb
 - Thick ascending limb
 - Distal convoluted tubule
 - Connecting tubule
 - Collecting duct

Figure 18.3 Anatomy of a nephron.



Microscopic Anatomy of the Kidney

- Cortical versus juxtamedullary nephrons
 - Cortical
 - Short loop of Henle
 - Most numerous, 80–85%
 - Juxtamedullary nephron
 - Long loop of Henle extends into medulla
 - Responsible for the medullary osmotic gradient
 - Both types produce urine

Figure 18.4 Locations of cortical and juxtamedullary nephrons.

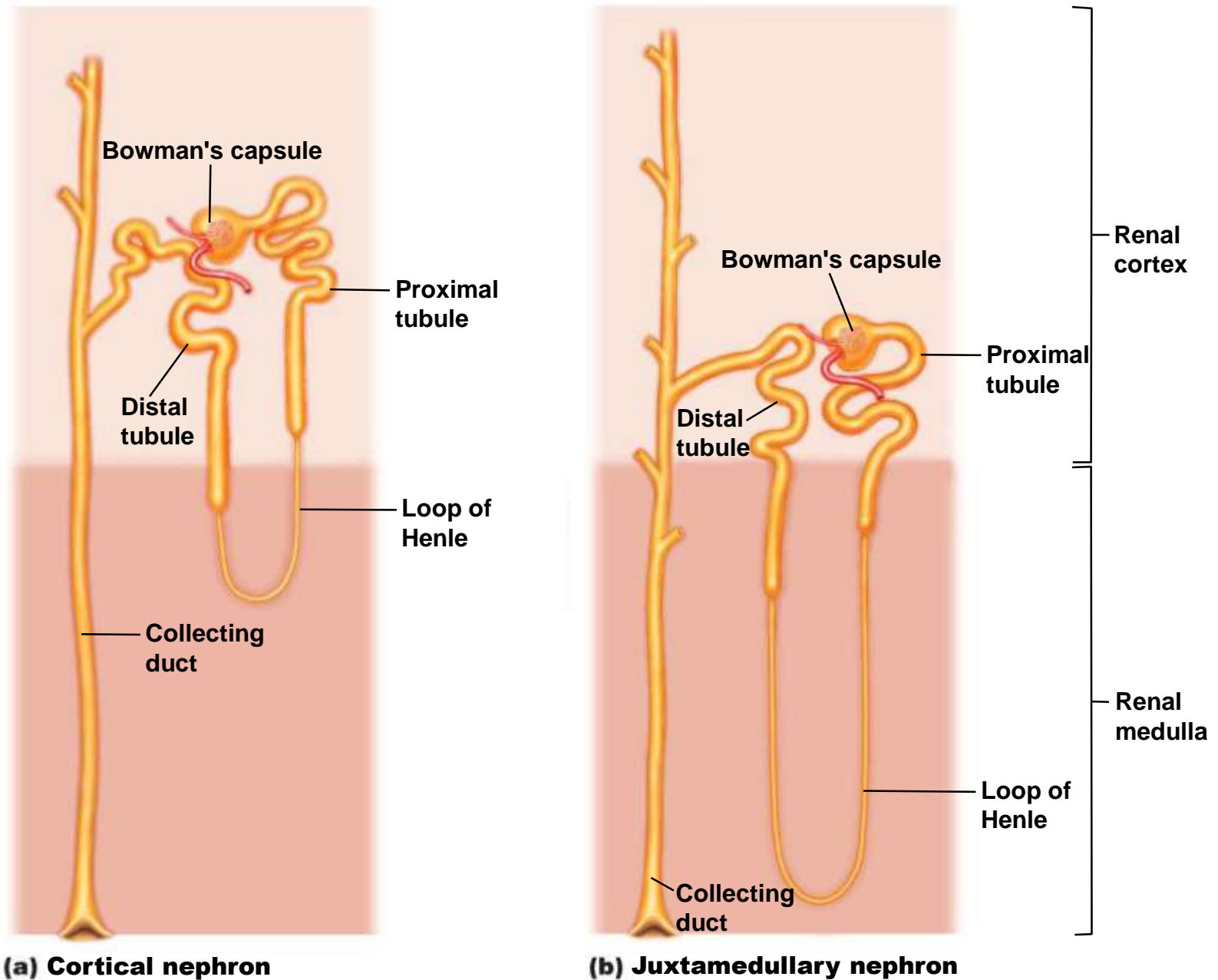
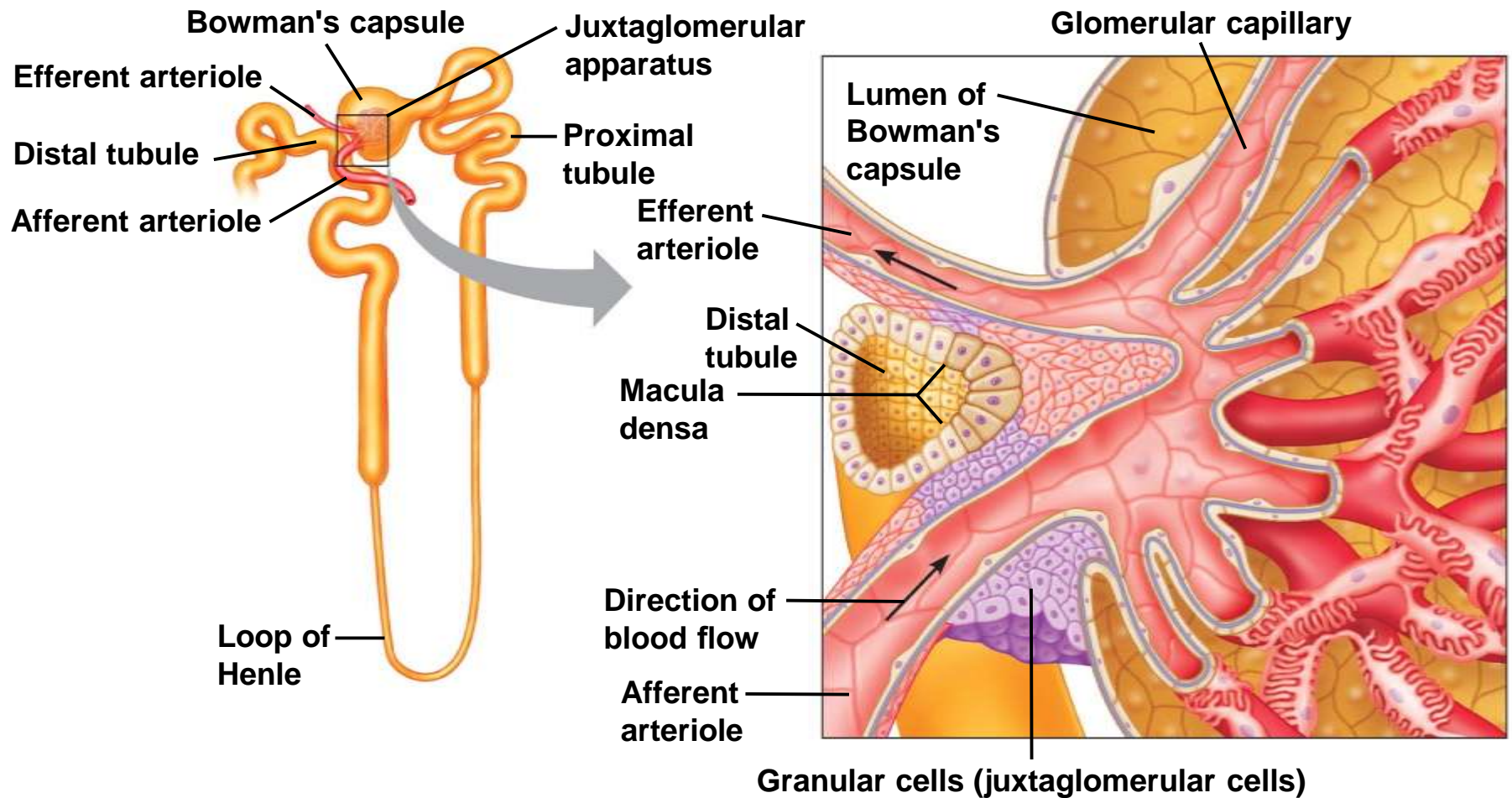


Figure 18.5 The juxtaglomerular apparatus.



Blood Supply

- Renal arteries enter kidney at hilus
- Receive 20% of cardiac output at rest
 - Account for less than 1% of body weight
 - Account for 16% of ATP usage by body
 - Function is to filter blood
- Renal veins exit at hilus

Figure 18.6a Blood supply to the kidneys.

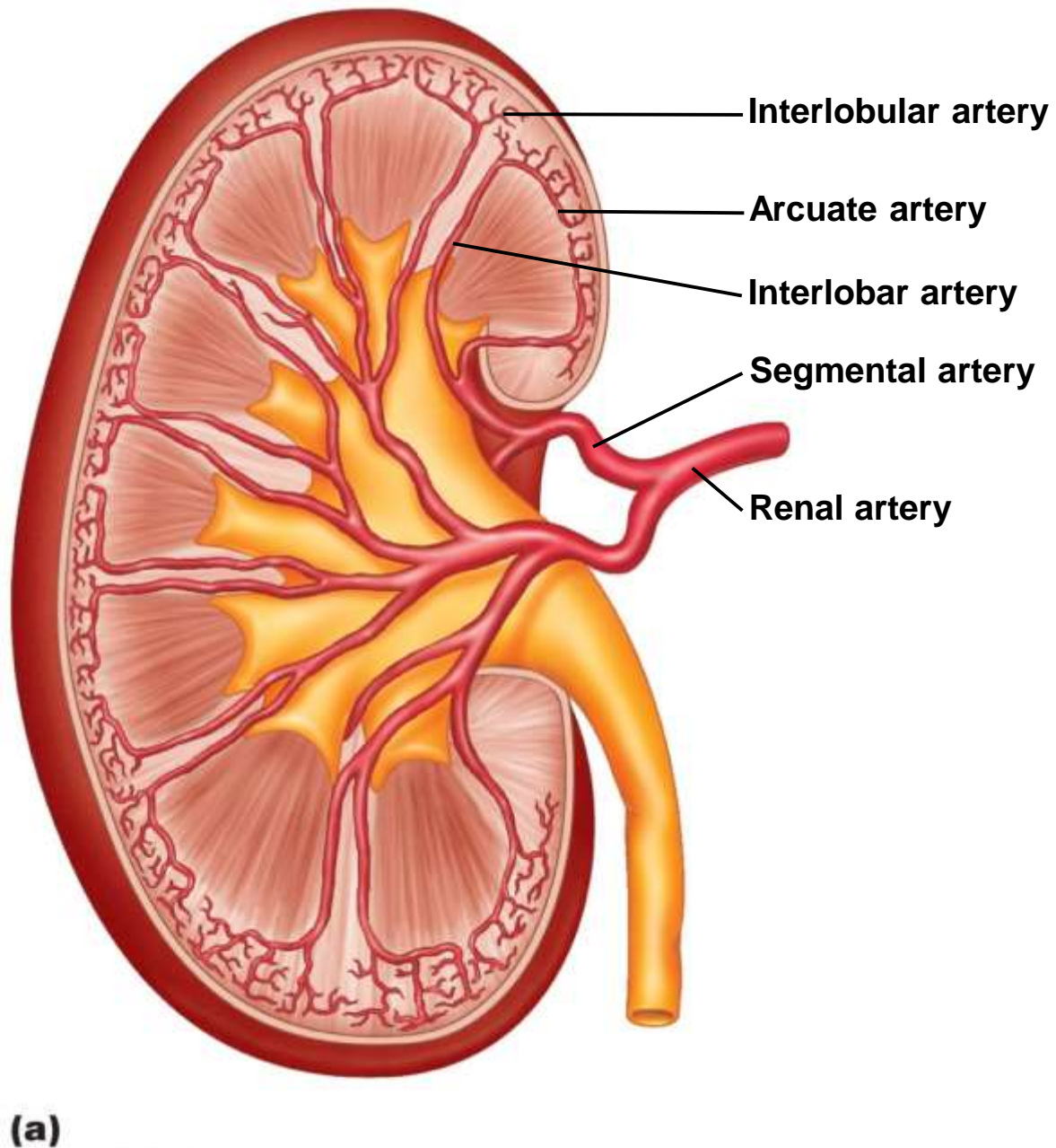
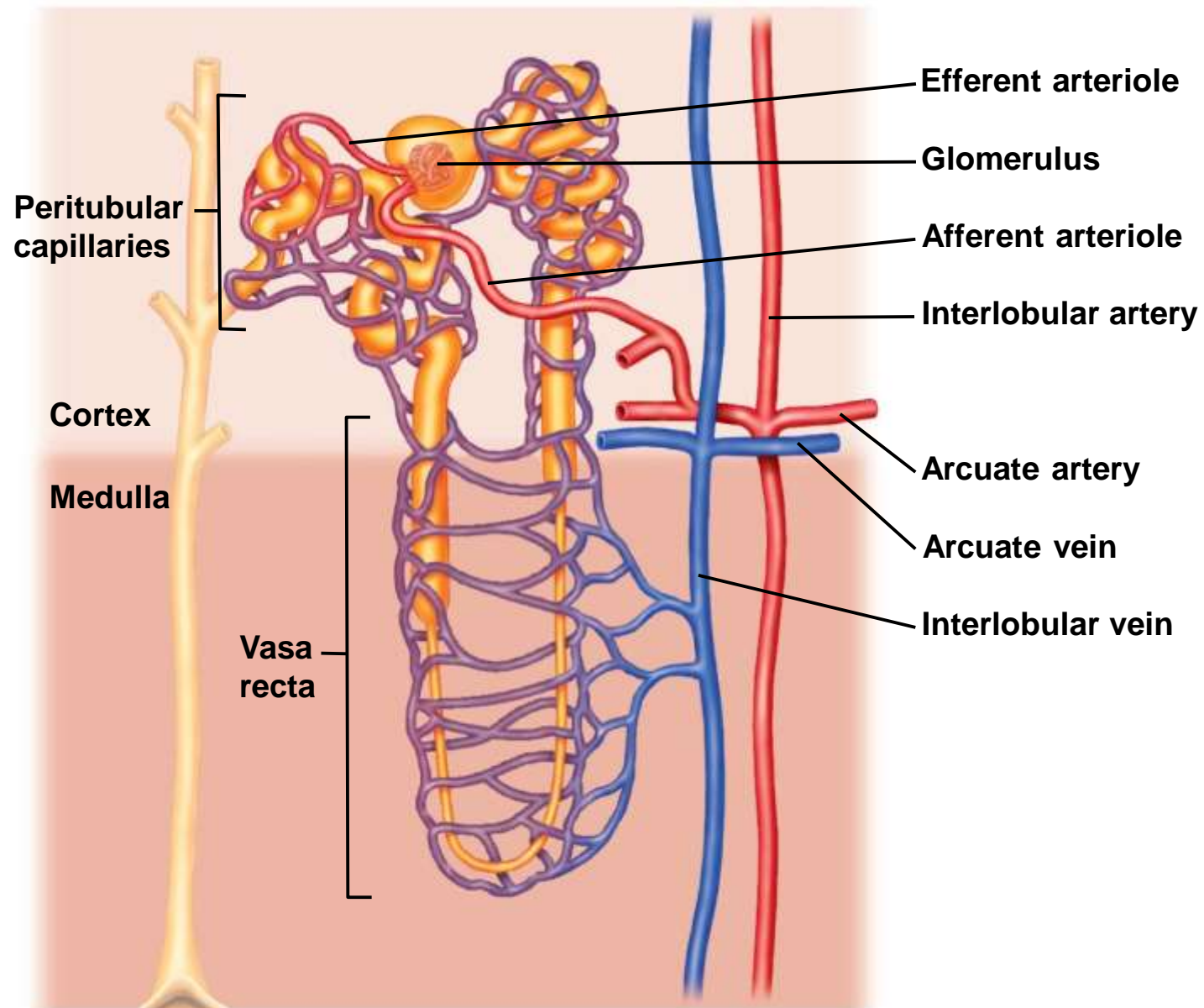


Figure 18.6b Blood supply to the kidneys.

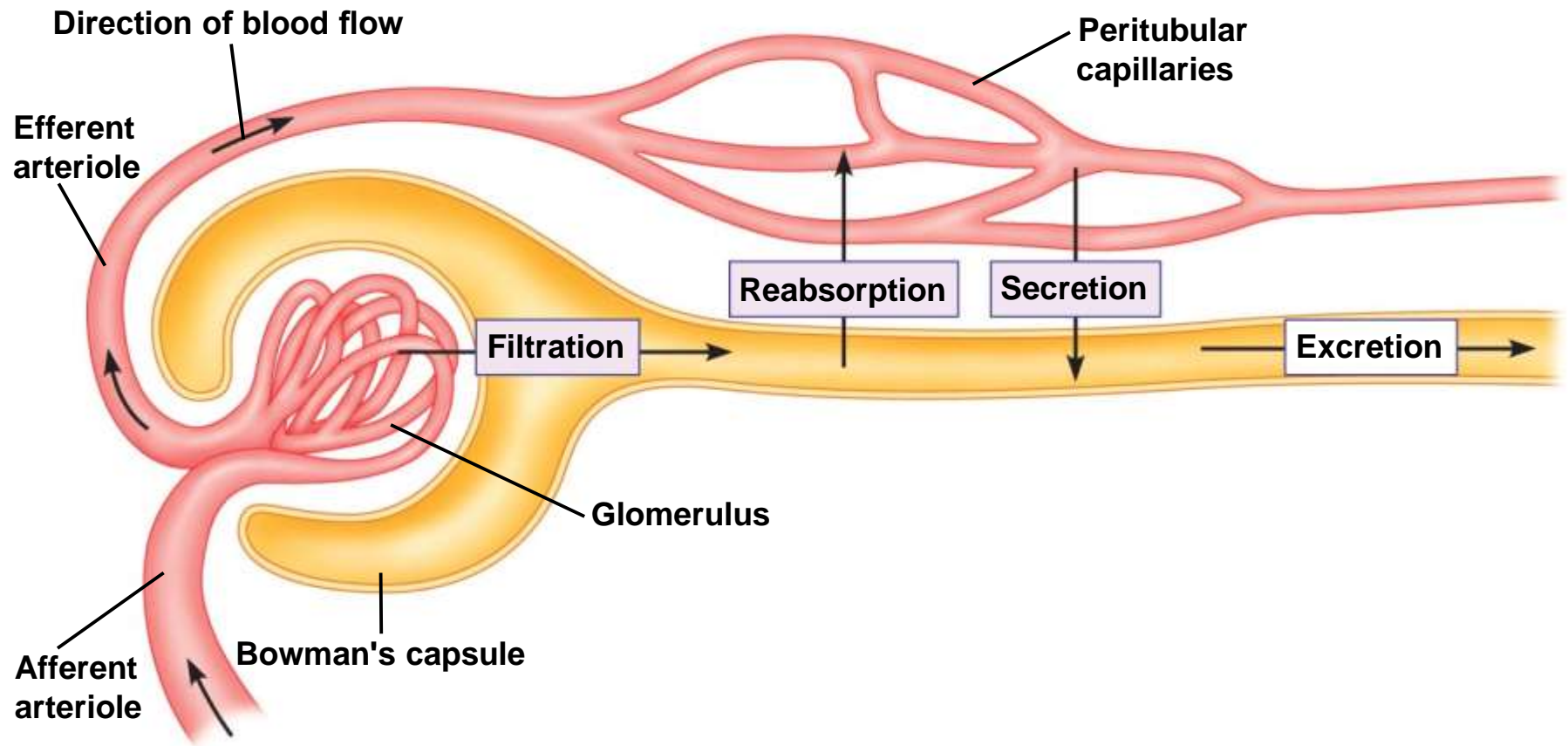


(b)

18.3 Basic Renal Exchange Processes

- Glomerular filtration: from glomerulus to Bowman's capsule
- Reabsorption: from tubules to peritubular capillaries
- Secretion: from peritubular capillaries to tubules
- Excretion: from tubules out of body

Figure 18.7 The three exchange processes in the renal tubules.



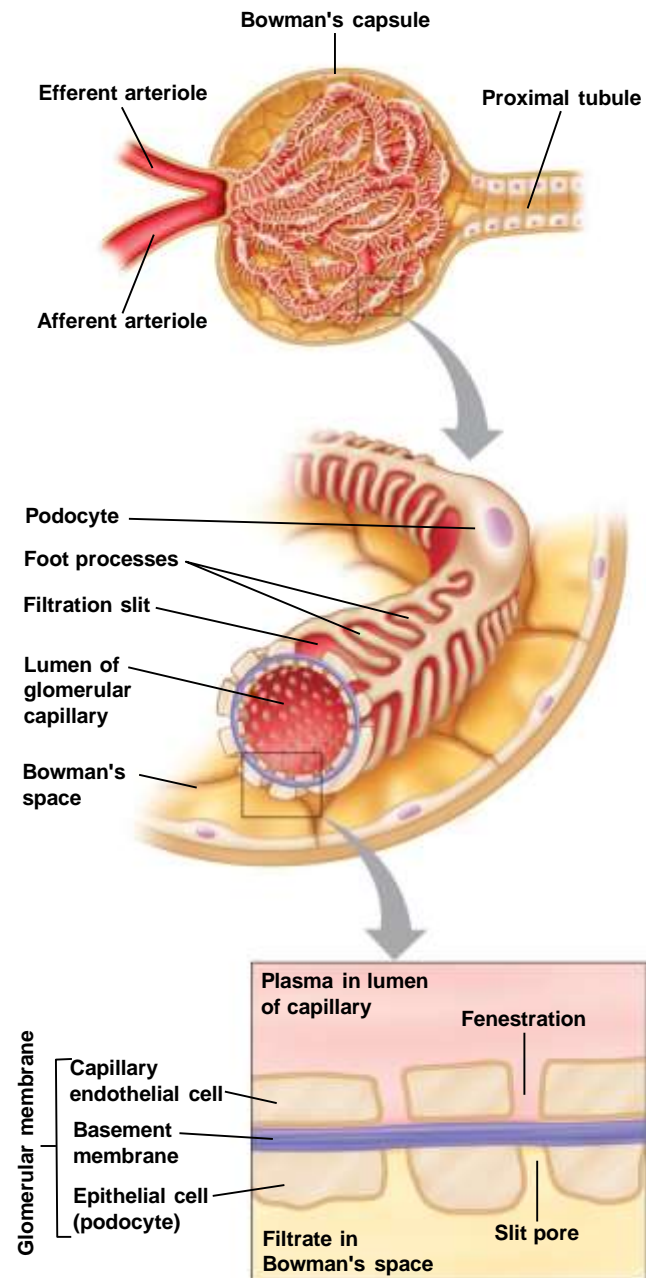
Glomerular Filtration

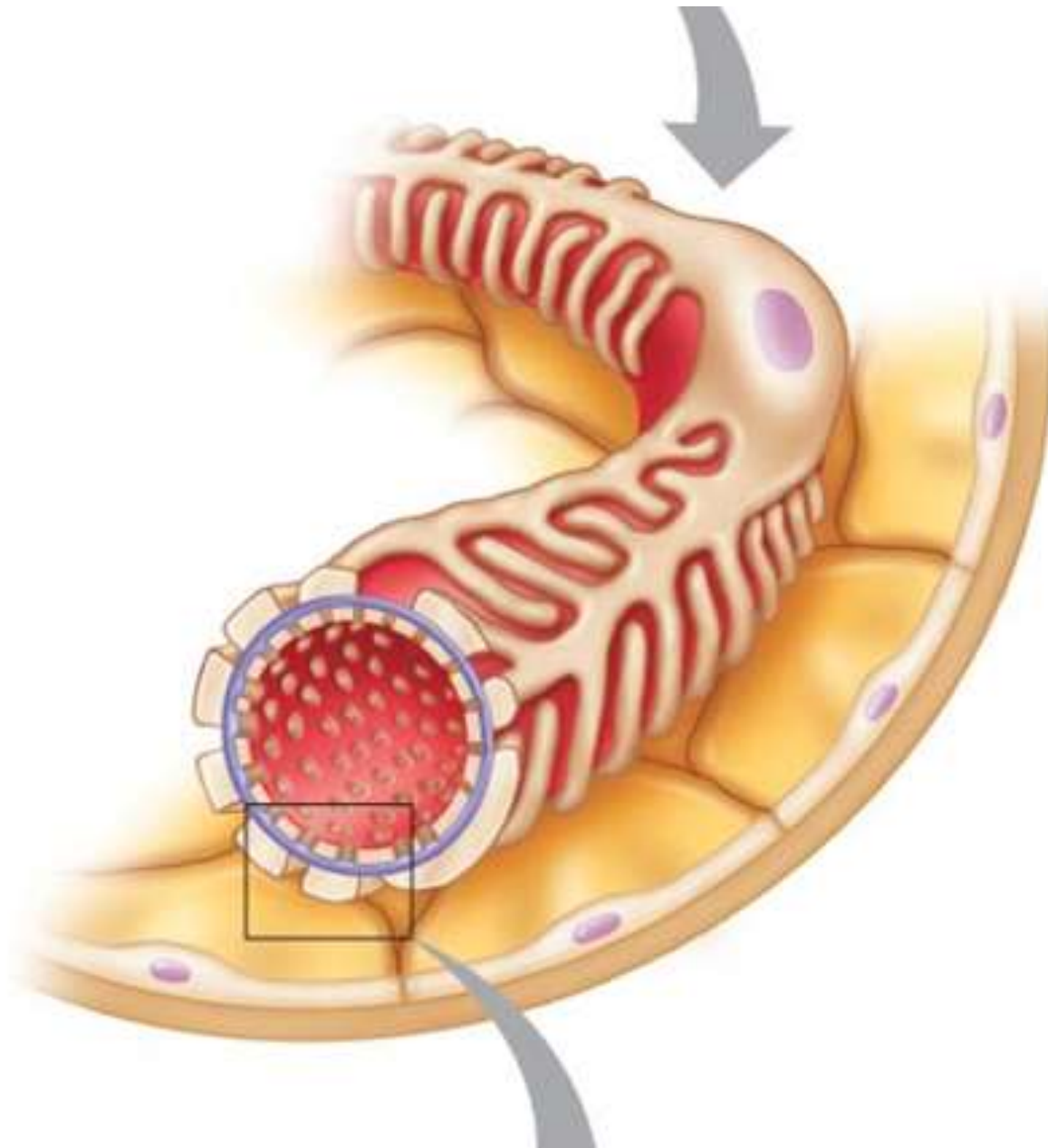
- Movement of protein-free plasma from glomerulus to Bowman's capsule

$\text{GFR} = 125 \text{ mL/min or } 180 \text{ L/day}$

- Glomerular filtrate must cross three barriers to enter Bowman's capsule
 - Capillary endothelial layer
 - Surrounding epithelial layer
 - Basement membrane sandwiched between these two layers

Figure 18.8 Anatomy of the renal corpuscle.





Glomerular Filtration

- Starling forces
 - Glomerular capillary hydrostatic pressure
 - Bowman's capsule oncotic pressure
 - Bowman's capsule hydrostatic pressure
 - Glomerular oncotic pressure

Glomerular Filtration

- Starling forces favoring filtration
 - Glomerular capillary hydrostatic pressure
 - 60 mm Hg
 - High due to resistance of efferent arteriole
 - Bowman's capsule oncotic pressure
 - 0 mm Hg
 - Low due to lack of protein in filtrate

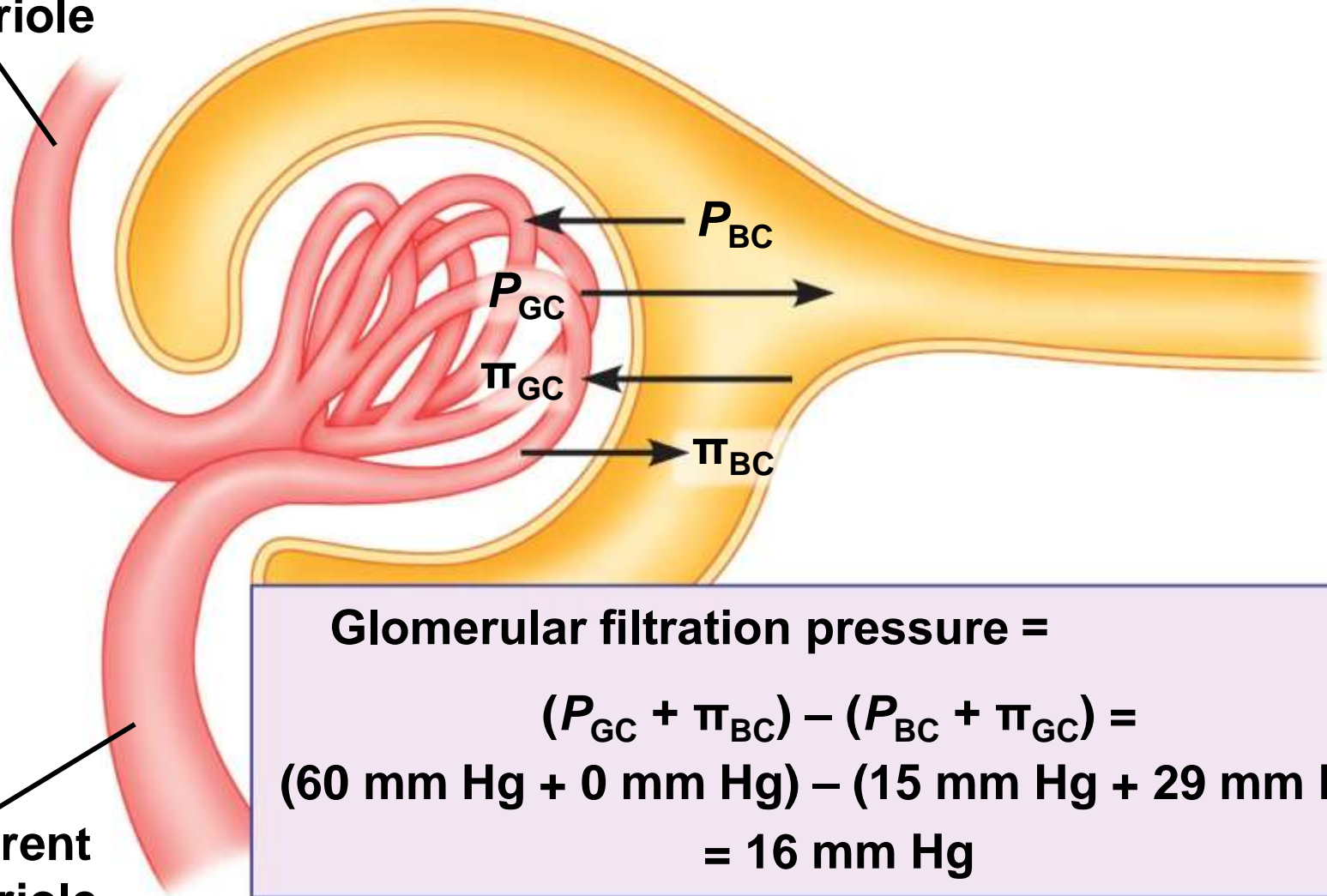
Glomerular Filtration

- Starling forces opposing filtration
 - Bowman's capsule hydrostatic pressure
 - 15 mm Hg
 - Relatively high (compared to systemic capillaries) due to large volume of filtrate in closed space
 - Glomerular oncotic pressure
 - 29 mm Hg
 - Higher than in systemic capillaries due to plasma proteins in smaller volume of plasma

Figure 18.9a Glomerular filtration.

Efferent
arteriole

Afferent
arteriole



Glomerular filtration pressure =

$$\begin{aligned} & (P_{GC} + \pi_{BC}) - (P_{BC} + \pi_{GC}) = \\ & (60 \text{ mm Hg} + 0 \text{ mm Hg}) - (15 \text{ mm Hg} + 29 \text{ mm Hg}) \\ & = 16 \text{ mm Hg} \end{aligned}$$

(a) Glomerular filtration pressure

Glomerular Filtration

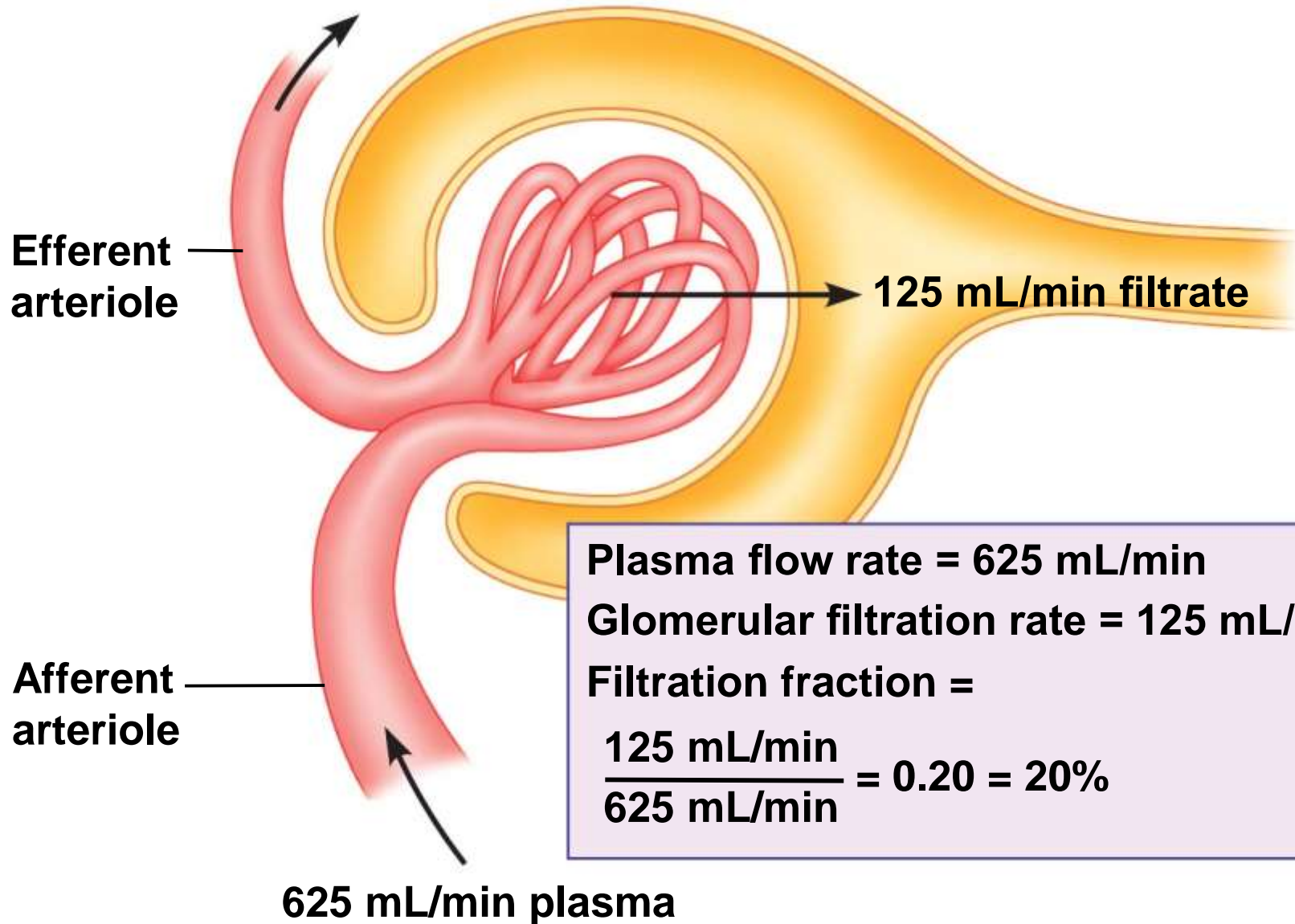
- Glomerular filtration rate (GFR)
 - Filtration pressure = $(P_{GC} + \pi_{BC}) - (P_{BC} + \pi_{GC})$
 $= (60 + 0) - (15 + 29) = 16 \text{ mm Hg}$
 - Renal plasma flow = 625 mL/min
 - GFR = 125 mL/min = 180 L/day
 - Compared to systemic capillaries
 - Filtration pressure = 2 mm Hg
 - Filtration rate = 3 L/day

Glomerular Filtration

- Filtration fraction
 - Filtration fraction = $\text{GFR} / \text{renal plasma flow}$
 - 625 mL plasma enters kidneys per minute
 - 125 mL filtered into Bowman's capsule
 - $125/625 = \text{filtration fraction} = 20\%$

Figure 18.9b Glomerular filtration.

500 mL/min plasma



(b) Glomerular filtration rate and filtration fraction

Glomerular Filtration

- Filtered load = $GFR \times P_x$
- Small molecules that are filtered without impedance are freely filterable
- Quantity filtered = filtered load
 - Depends on plasma concentration of solute and GFR
- Filtered load of glucose
 - $GFR = 125 \text{ mL/min}$
 - Plasma [glucose] = $100 \text{ mg/dL} = 1 \text{ mg/mL}$

$$\begin{aligned} \text{Filtered load of glucose} = \\ (125 \text{ mL/min}) \times (1 \text{ mg/mL}) = 125 \text{ mg/min} \end{aligned}$$

Regulation of GFR

- 180 liters fluid filtered/day
 - Only 1.5 liters urine is excreted/day (<1%)
 - >99% of filtered fluid is reabsorbed
- Small increase in GFR → large increase in volume of fluid filtered and excreted
- GFR is highly regulated

Glomerular Filtration

- Intrinsic regulation of GFR
 - Myogenic regulation
 - Smooth muscle in wall of afferent arteriole
 - Contracts in response to stretch
 - Tubuloglomerular feedback
 - Macula densa cells secrete paracrine factors in response to an increase in flow of fluid past them
 - Smooth muscles of arterioles contract in response to these paracrines

Figure 18.10 Effect of mean arterial pressure on glomerular filtration rate.

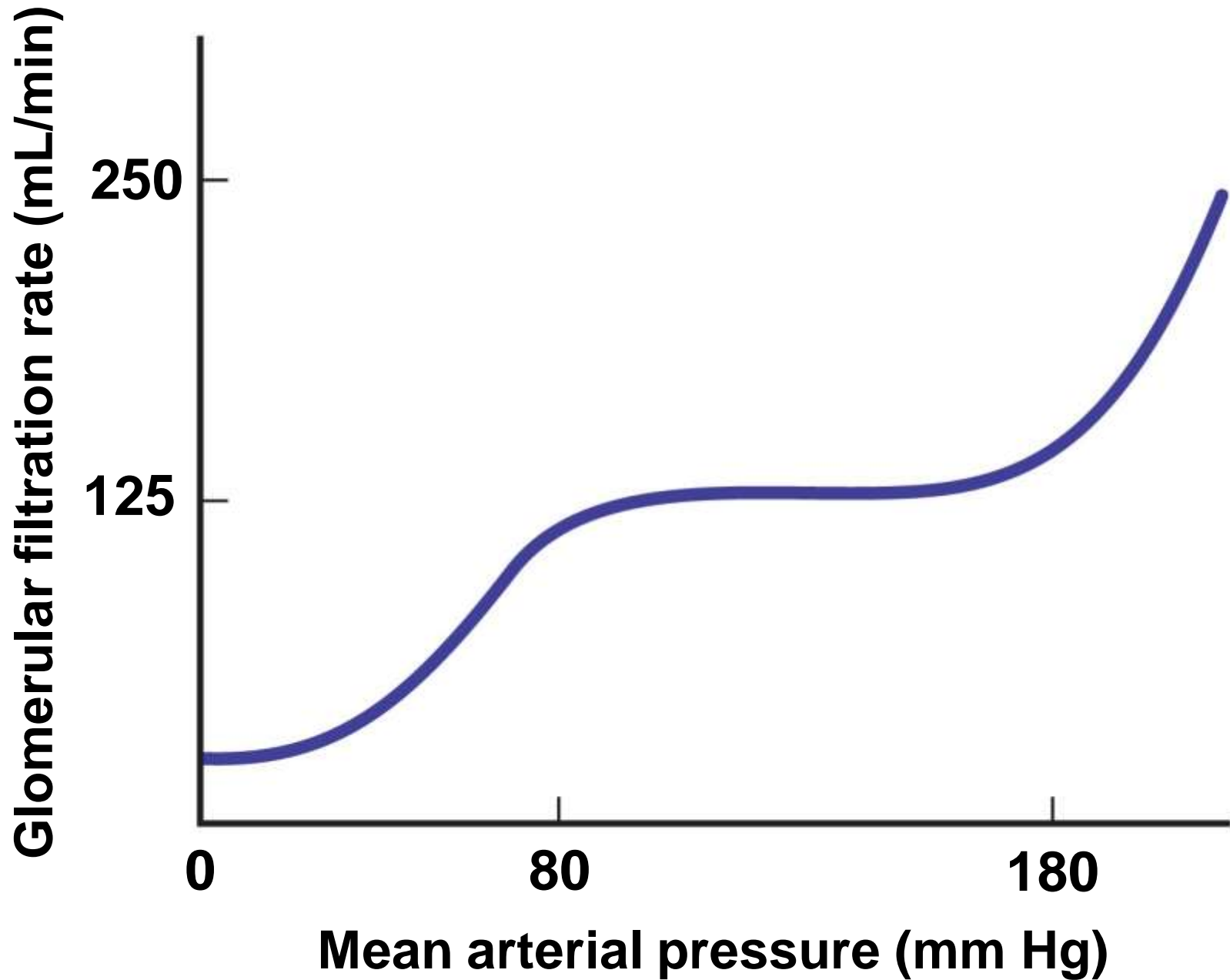
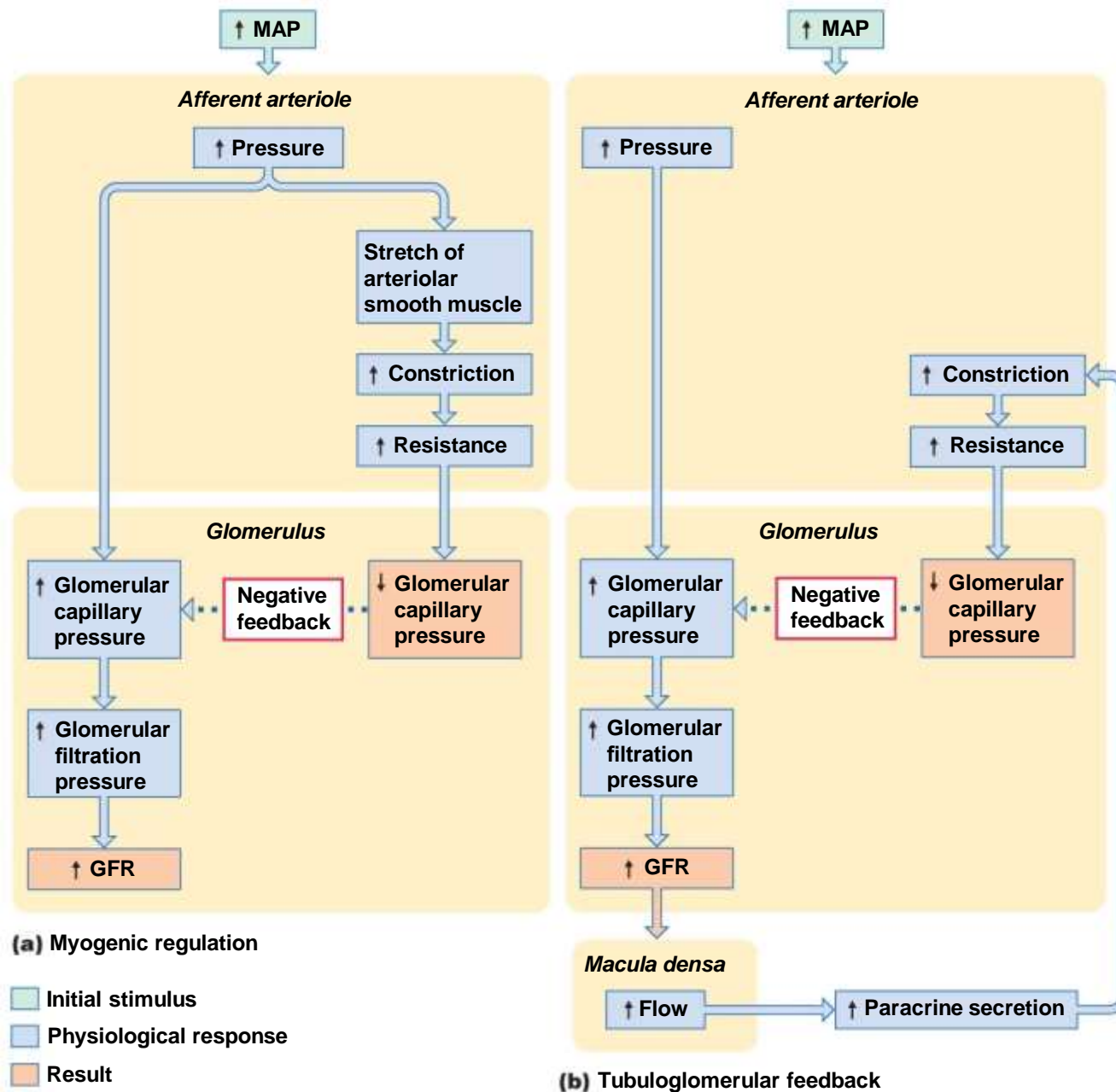


Figure 18.11 Intrinsic controls of glomerular filtration rate.



Glomerular Filtration

- Extrinsic control of GFR
 - Decreases in BP can decrease GFR
 - Directly (decrease in filtration pressure)
 - Indirectly through extrinsic controls

Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.

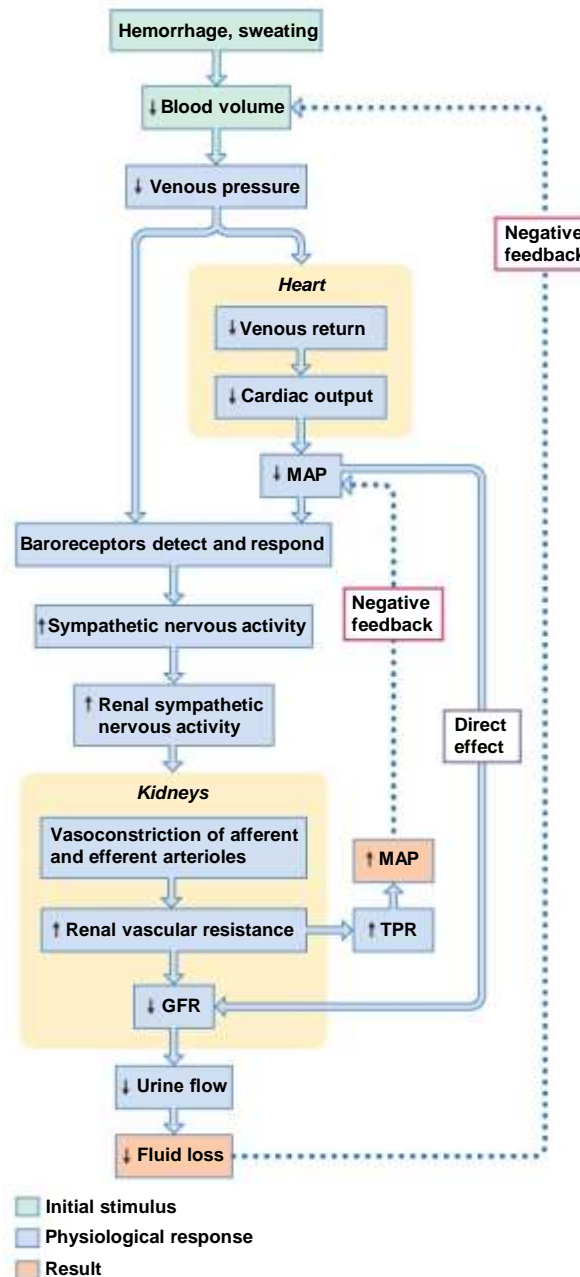
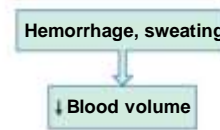


Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.






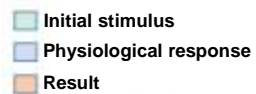
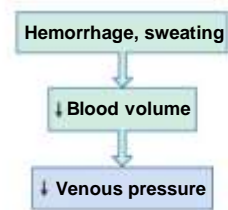
-  Initial stimulus
-  Physiological response
-  Result

Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.



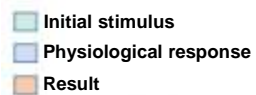


Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.

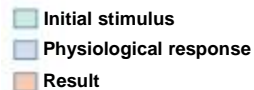
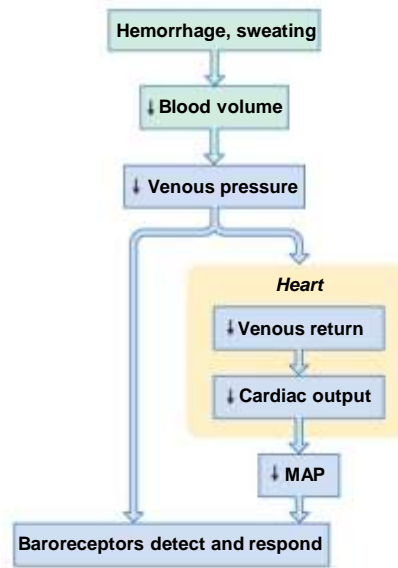


Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.

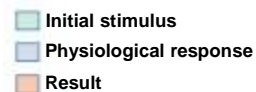
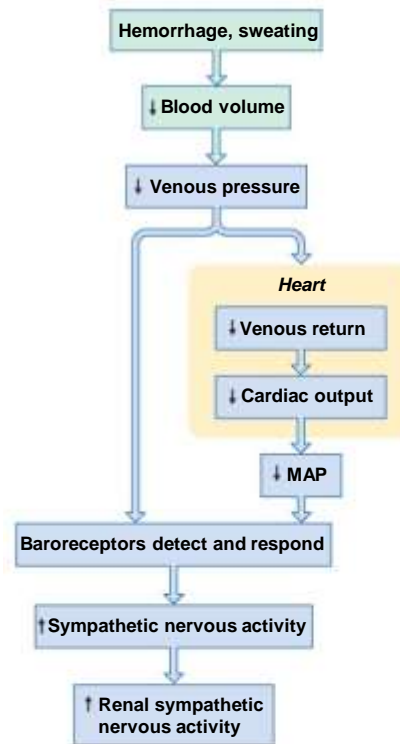
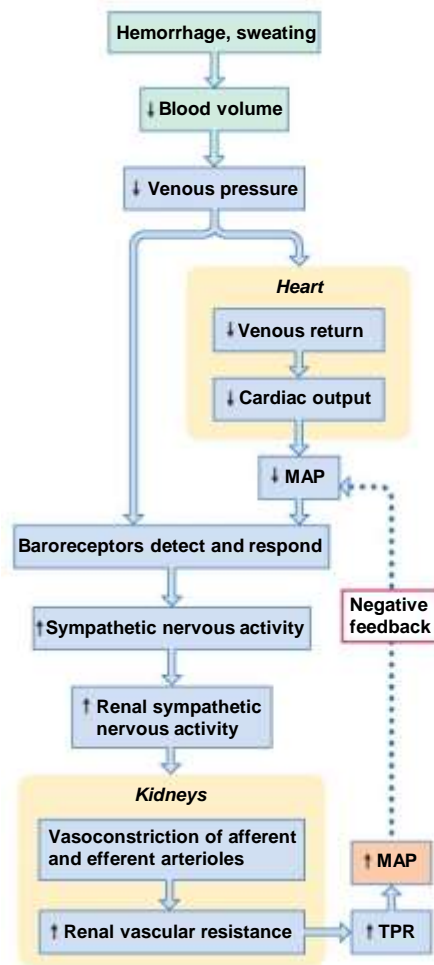


Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.



- Initial stimulus
- Physiological response
- Result

Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.

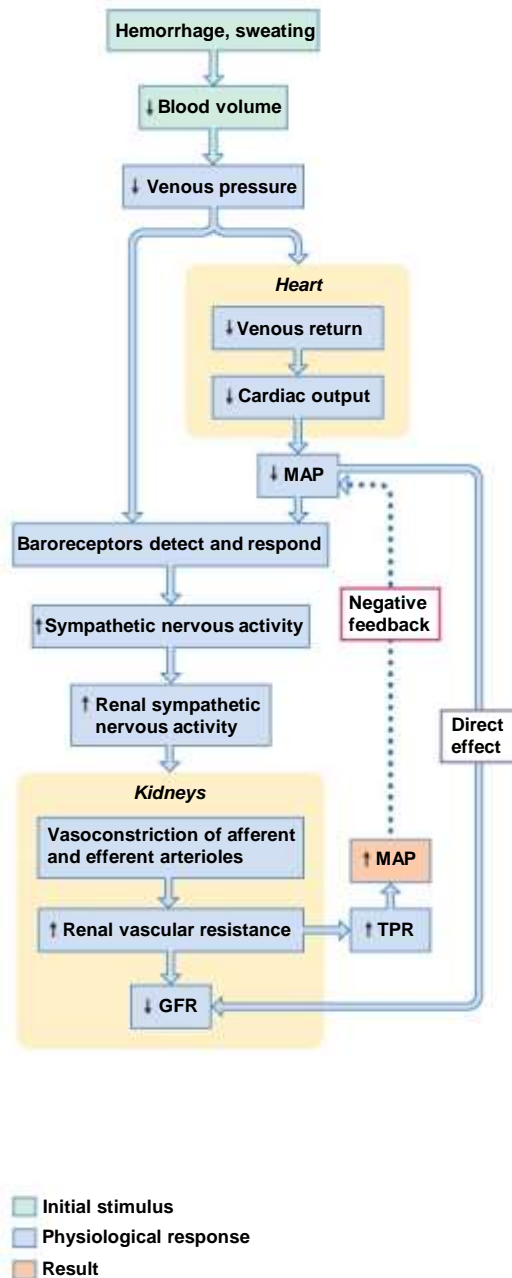
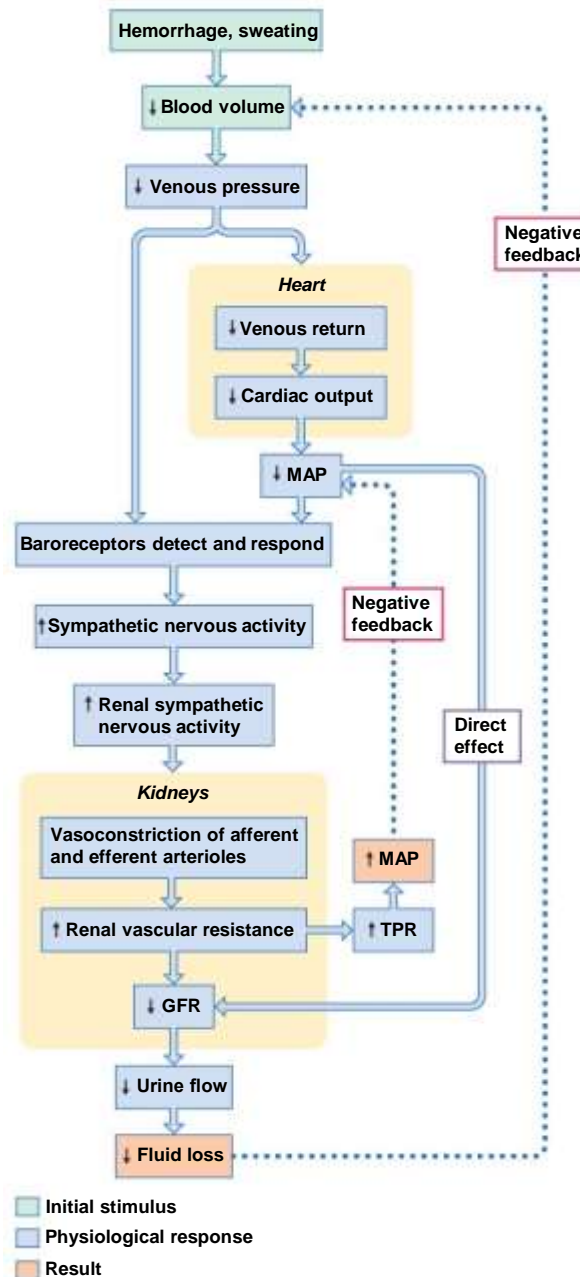


Figure 18.12 Extrinsic control of GFR and renal vascular resistance during fluid loss due to hemorrhage or sweating.



Reabsorption

- Movement from tubules into peritubular capillaries (returned to blood)
 - Most occurs in proximal tubules
 - Most is not regulated

TABLE 18.1 Normal Rates of Filtration and Reabsorption for Water and Selected Solutes

Substance	Filtration rate	Reabsorption rate	Percentage of filtered load reabsorbed
Water	180 liters/day	178.5 liters/day	99.2%
Glucose	800 millimoles/day	800 millimoles/day	100%
Urea	933 millimoles/day	467 millimoles/day	50%
Na ⁺	25.20 moles/day	25.05 moles/day	99.4%
K ⁺	720 millimoles/day	620 millimoles/day	86.1%
Ca ²⁺	540 millimoles/day	530 millimoles/day	98.1%
Cl ⁻	18.00 moles/day	17.85 moles/day	99.2%
HCO ₃ ⁻	4.320 moles/day	4.318 moles/day	>99.2%

Reabsorption

- Solute reabsorption
 - Most occurs in proximal convoluted tubules
 - Some occurs in distal convoluted tubules
 - Barrier for reabsorption
 - Epithelial cells of renal tubules
 - Endothelial cells of capillaries (minimal)

Figure 18.13 The barriers to reabsorption.

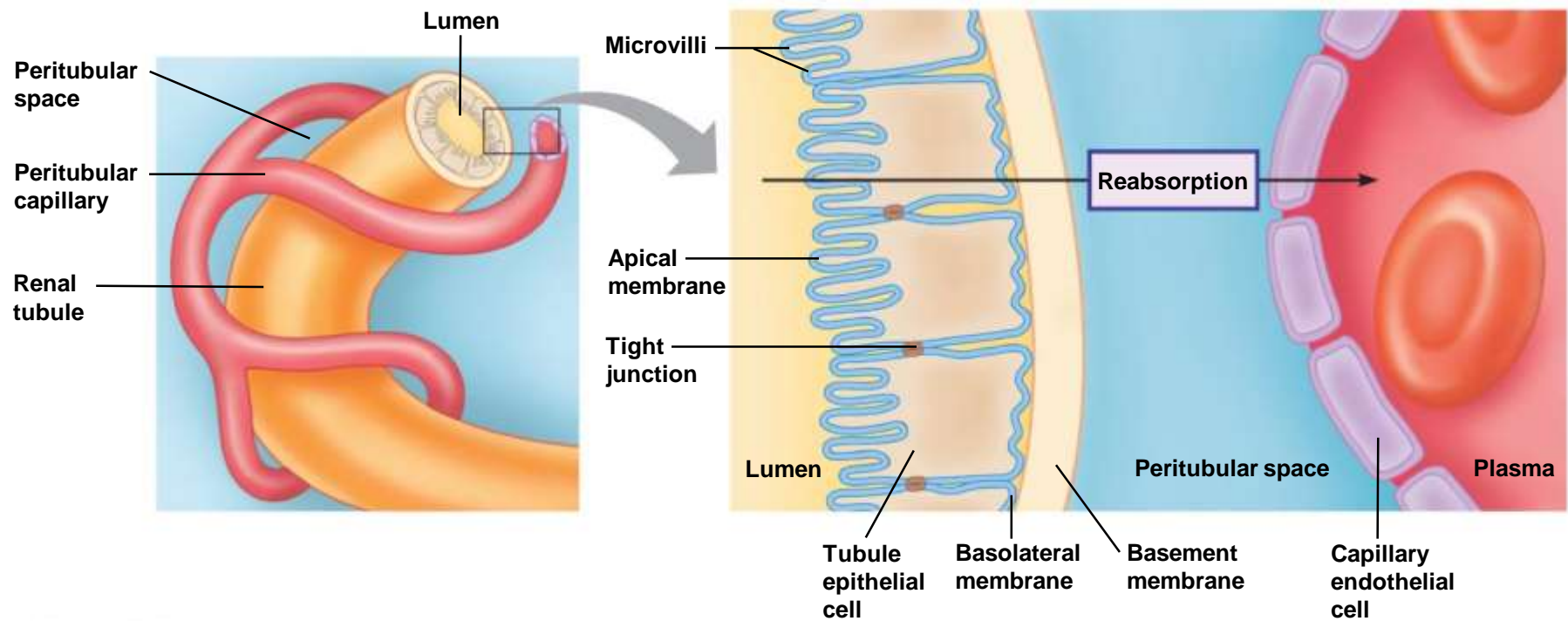
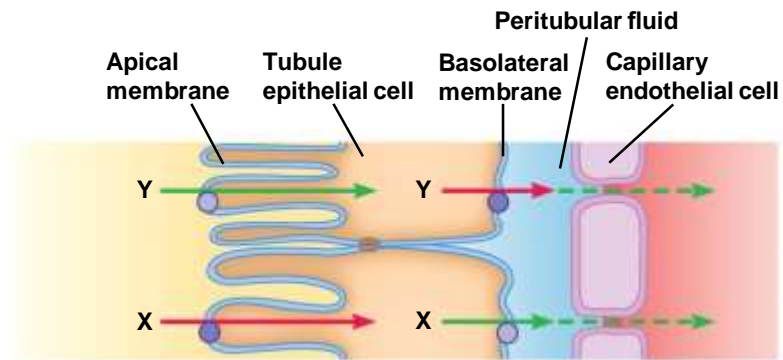
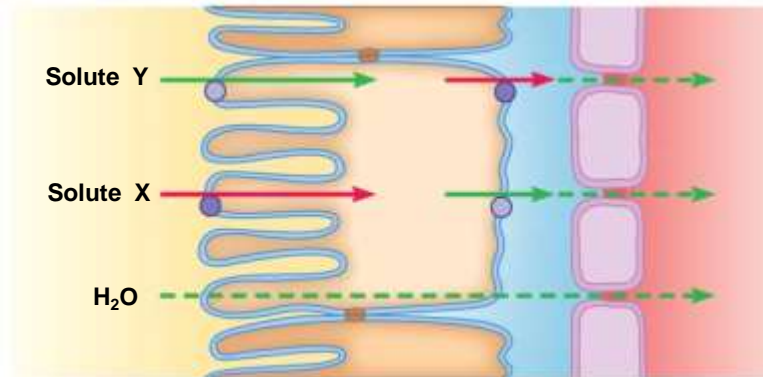


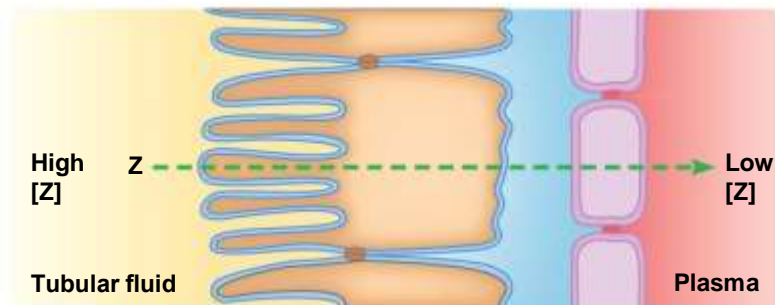
Figure 18.14 Mechanisms of solute and water reabsorption.



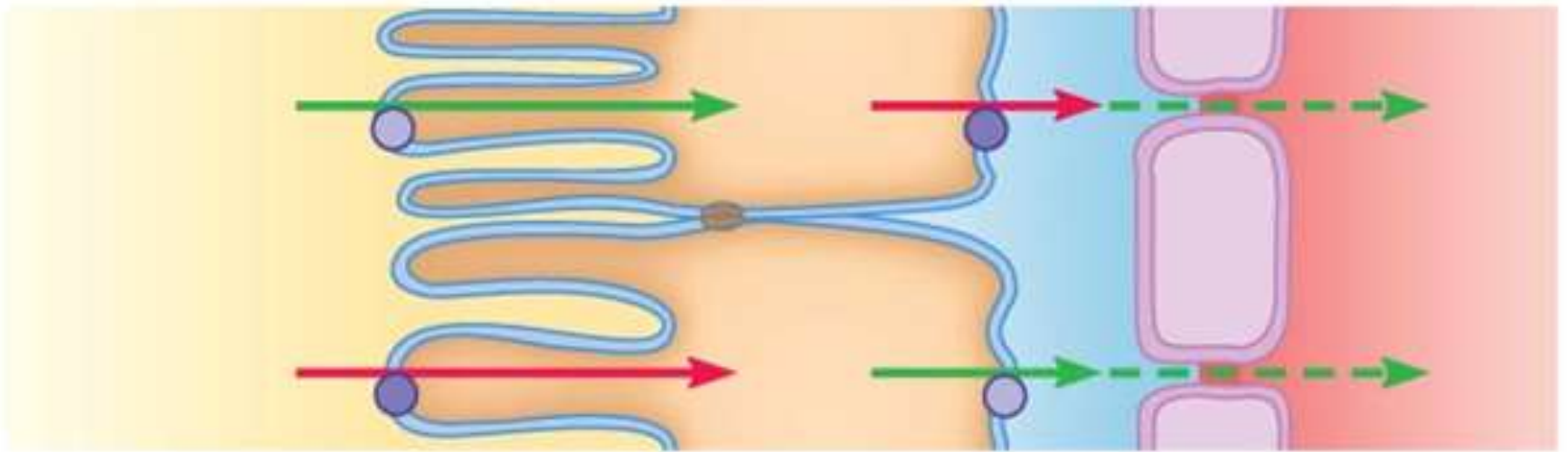
(a) Active solute reabsorption



(b) Water reabsorption (passive)

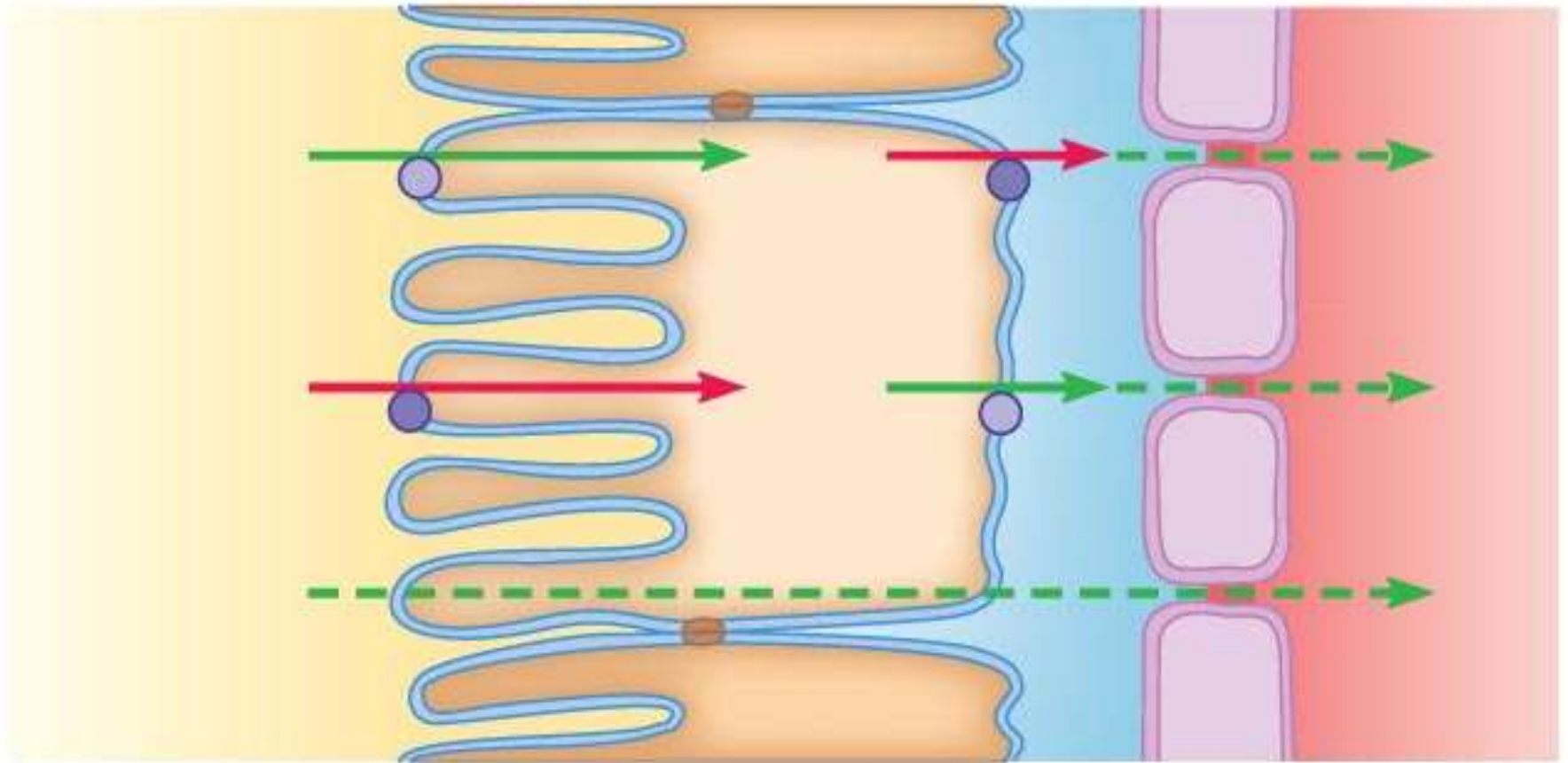


(c) Passive solute reabsorption via diffusion

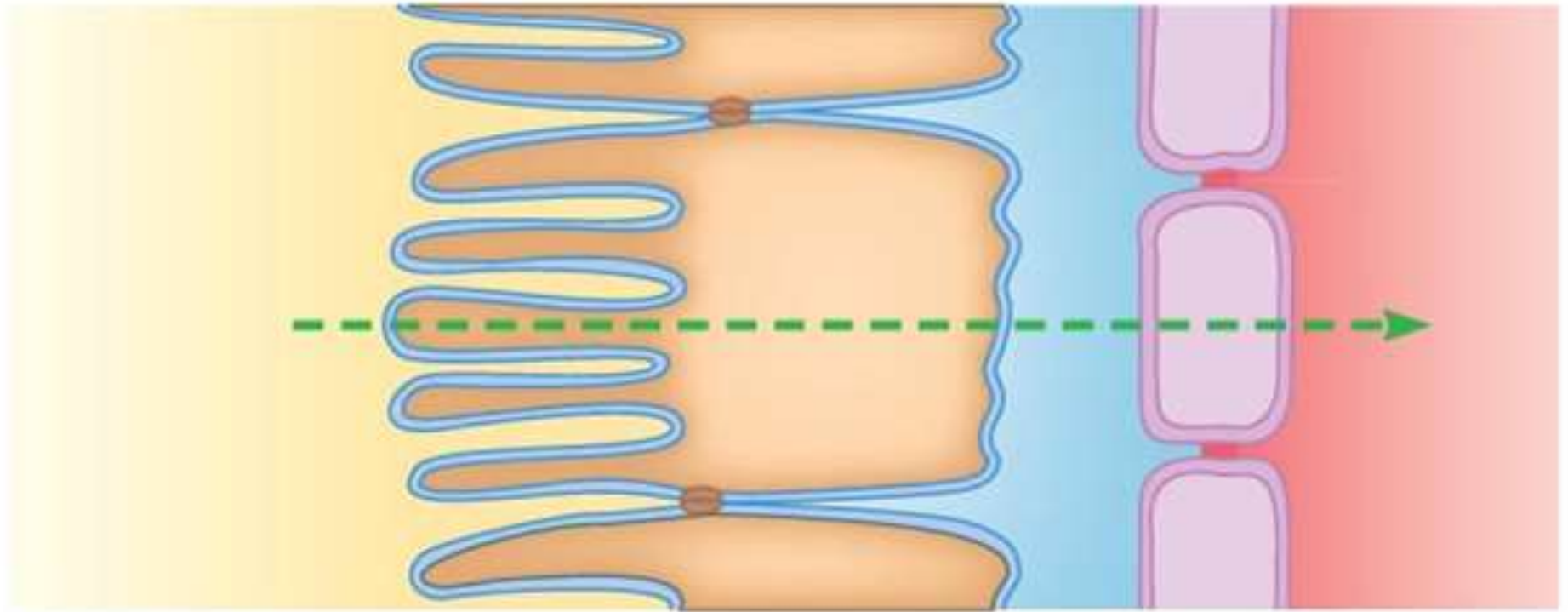


(a)

(a)



(b)



(c)

Transport Maximum

- Rate of transport when carriers are saturated
- When solute is transported across epithelium by carrier proteins, saturation of carriers can occur
- Renal threshold: for a solute that is normally 100% reabsorbed
 - If solute in filtrate saturates carriers, then some solute is excreted in urine
 - Solute in plasma that causes solute in filtrate to saturate carriers and spill over into urine = renal threshold

Transport Maximum

- Example: glucose reabsorption
 - Freely filtered at glomerulus
 - Normally 100% actively reabsorbed in proximal tubules
 - Normally no glucose appears in urine
- Carrier proteins for glucose reabsorption
 - Apical membrane: secondary active transport
 - Basolateral membrane: facilitated diffusion

Transport Maximum

- Renal handling of glucose
 - Plasma [glucose] = 100 mg/dL
 - Filtered load glucose = 125 mg/min
 - Transport maximum for glucose reabsorption = 375 mg/min
 - Theoretical renal threshold = 300 mg/dL
 - $\text{GFR} \times \text{renal threshold} = \text{transport maximum}$
 - Actual renal threshold = 160–180 mg/dL
 - Filtered load = 225 mg/min

Figure 18.15 Mechanism of glucose reabsorption.

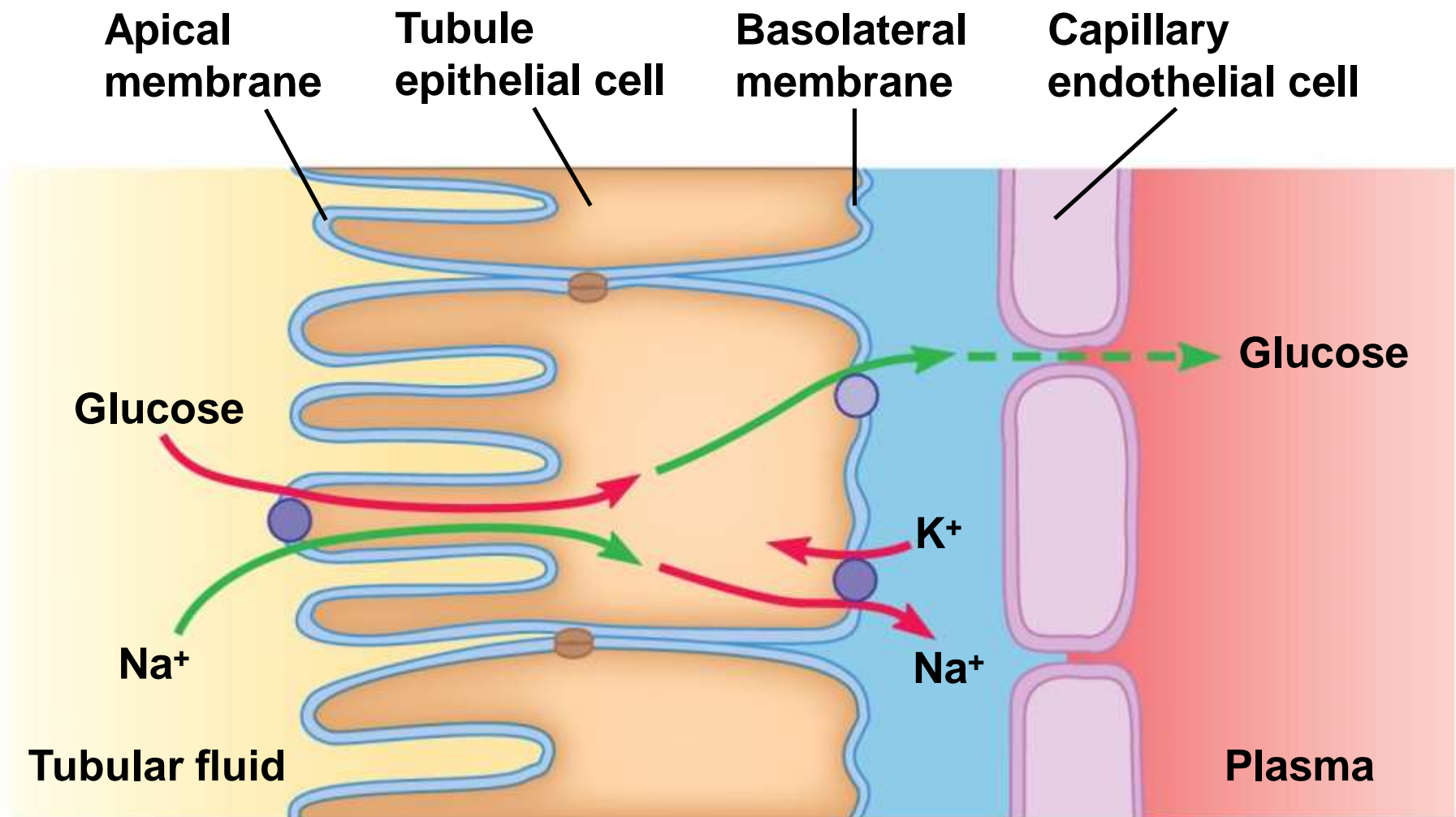
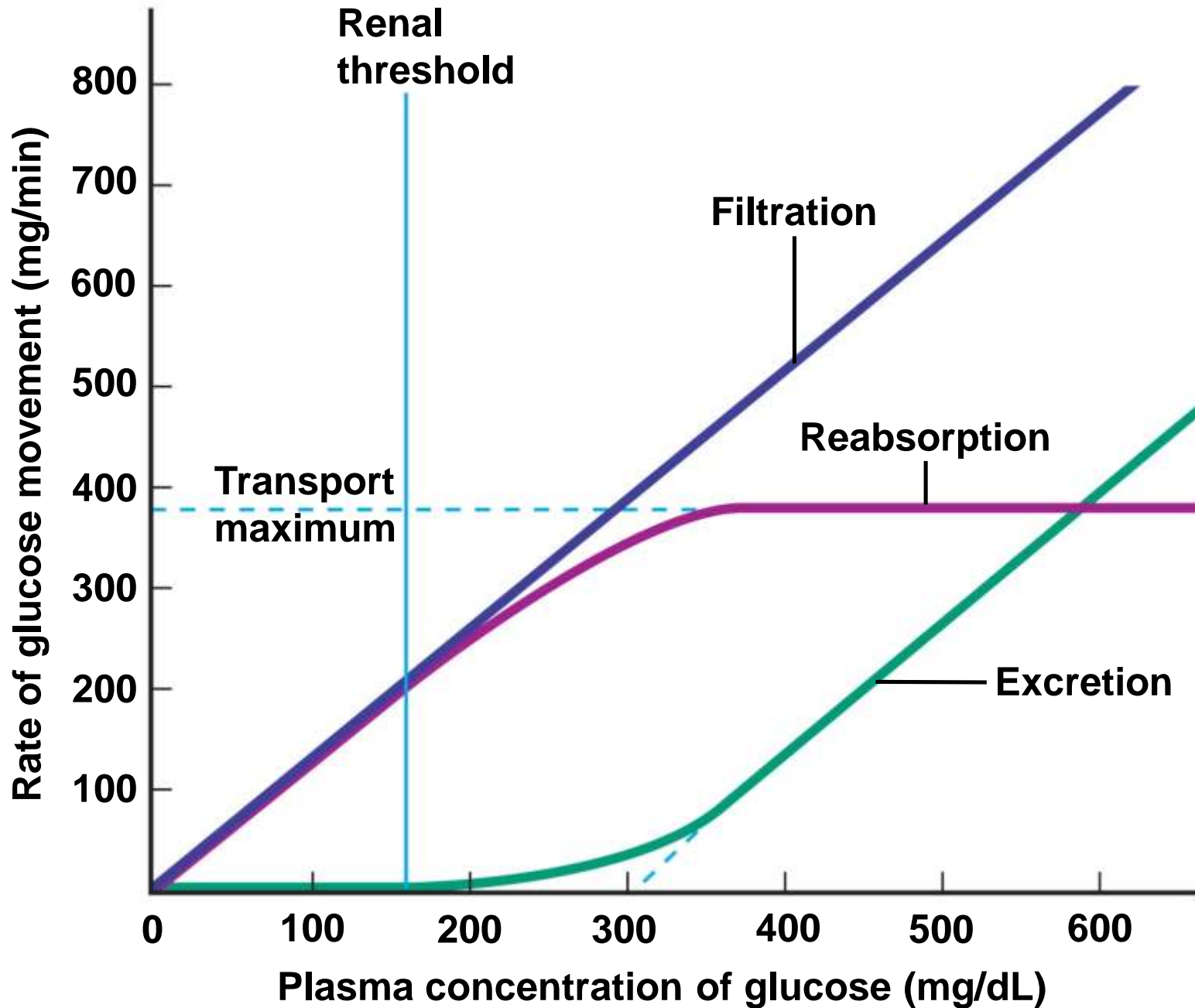


Figure 18.16 Glucose filtration, reabsorption, and excretion as a function of plasma glucose concentration.



Secretion

- Solute moves from peritubular capillaries into tubules
- Barriers are the same as for reabsorption
- Transport mechanisms are the same, but in the opposite direction
- Secreted substances
 - Potassium
 - Hydrogen ions
 - Choline
 - Creatinine
 - Penicillin

18.4 Regional Specialization of the Renal Tubules

- Nonregulated reabsorption in the proximal tubules
- Regulated reabsorption and secretion in the distal tubules and collecting ducts
- Water conservation in the loop of Henle

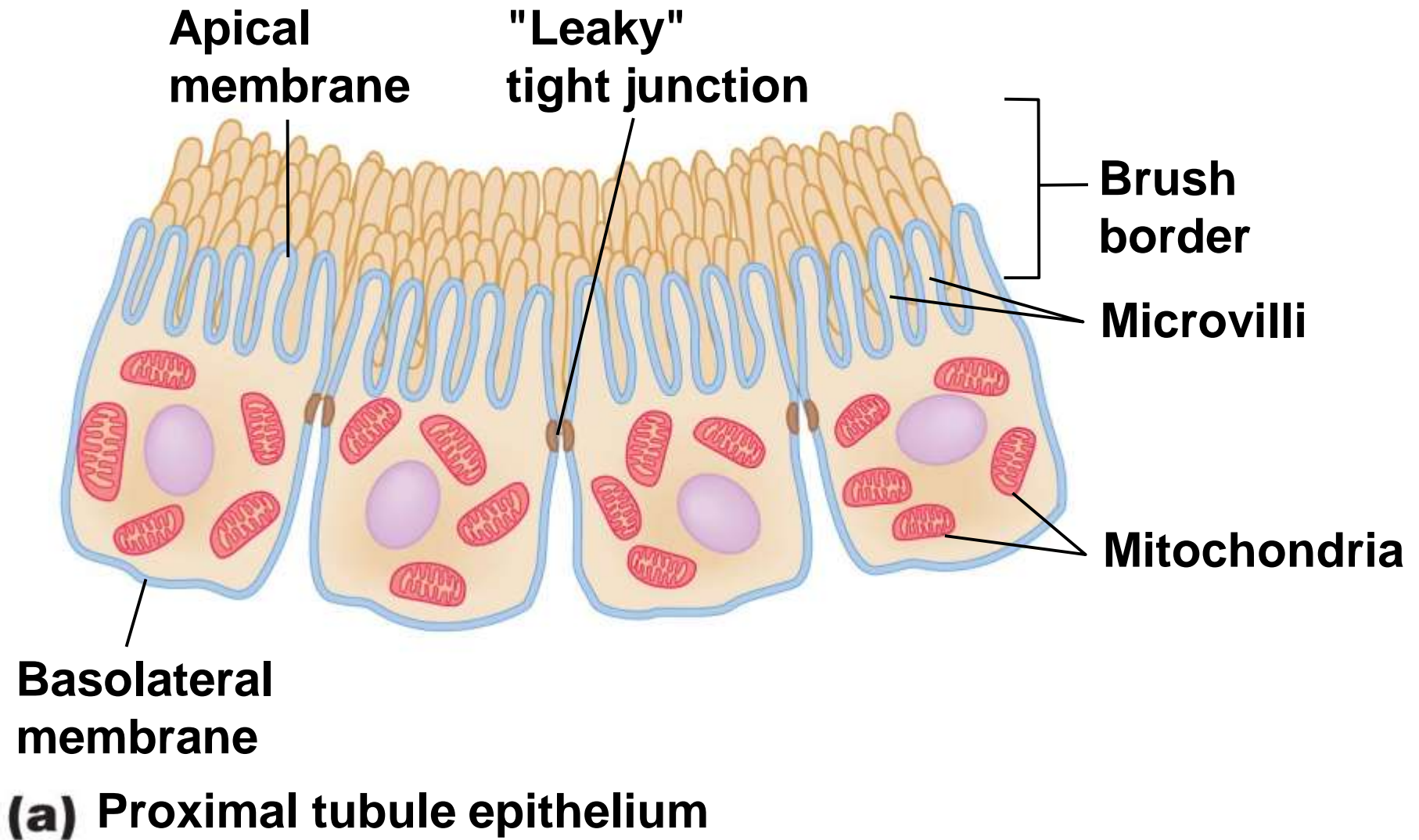
TABLE 18.2 Sites at Which Substances Are Reabsorbed and Secreted Across Renal Tubules

Tubule segment	Substances reabsorbed		Substances secreted
Proximal tubule	Na^+ Cl^- K^+ Ca^{2+} HCO_3^- Water	Glucose Amino acids Vitamins Urea Choline	H^+
Loop of Henle (descending limb)	Water		
Loop of Henle (ascending limb)	Na^+ Cl^- K^+	Mg^{2+} Ca^{2+}	
Distal tubule	Na^+ Ca^{2+} Cl^- Water		K^+ H^+
Collecting duct	Na^+ K^+ Cl^- Ca^{2+}	HCO_3^- H^+ Urea Water	K^+ H^+

Nonregulated Reabsorption in the Proximal Tubules

- Proximal tubule is the mass reabsorber
 - 70% sodium and water
 - 100% glucose
- Brush border provides for large surface area
- Leaky tight junctions allow paracellular transport

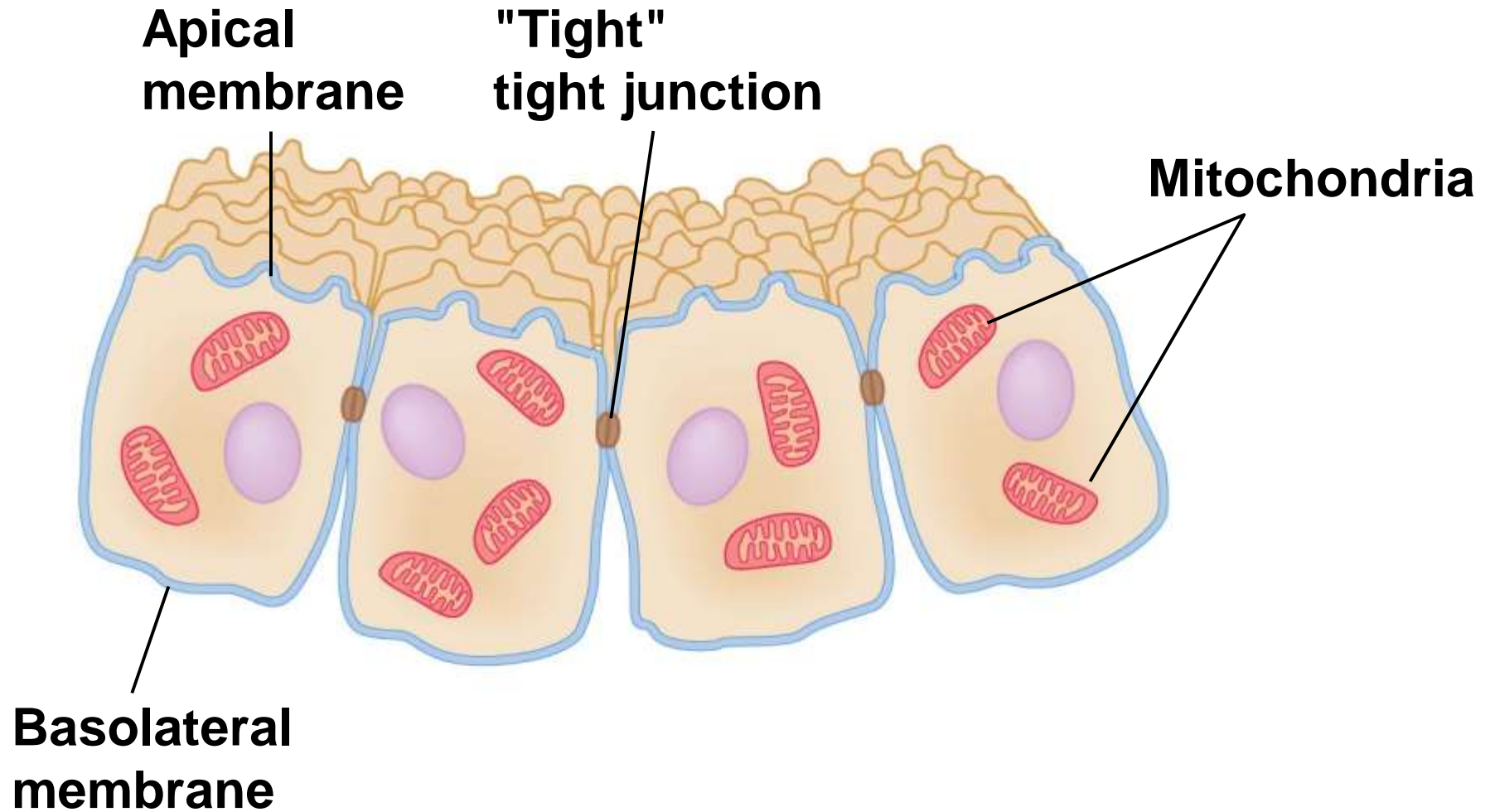
Figure 18.17a Epithelial cells in selected portions of a renal tubule.



Regulated Reabsorption and Secretion in the Distal Tubules and Collecting Ducts

- Transport is regulated across epithelium
- Tight junctions limit paracellular transport

Figure 18.17b Epithelial cells in selected portions of a renal tubule.



(b) Distal tubule and collecting duct epithelium

Water Conservation in the Loop of Henle

- Loop of Henle establishes conditions necessary to concentrate urine
- Minimizes water loss

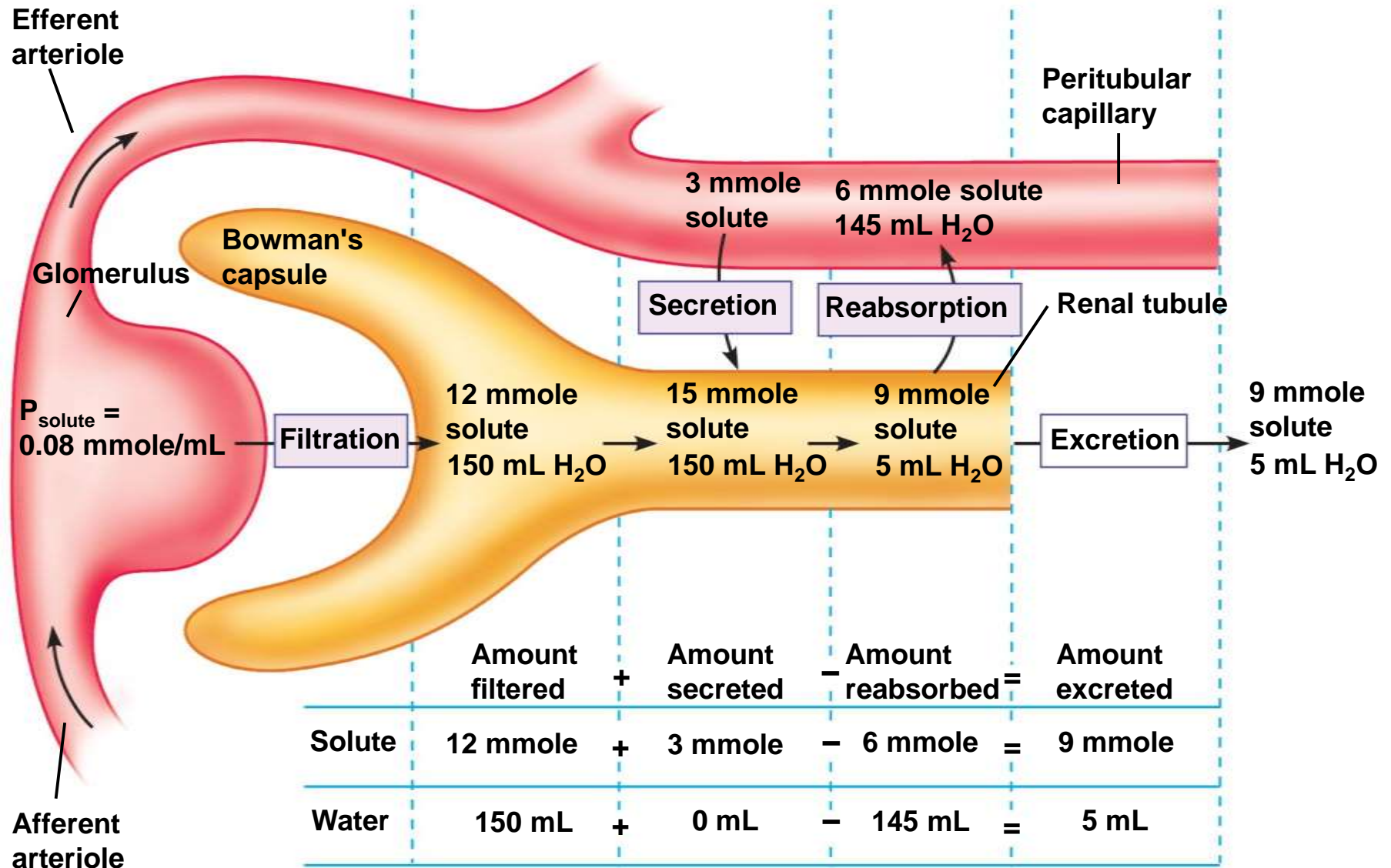
18.5 Excretion

- Excretion rate
- Clearance
- Micturition

Excretion Rate

- Amount of substance excreted = amount filtered + amount secreted – amount reabsorbed
- Amount excreted depends on three factors:
 - Filtered load
 - Secretion rate
 - Reabsorption rate
- If amount of solute excreted per minute is less than filtered load → solute was reabsorbed
- If amount of solute excreted per minute is greater than filtered load → solute was secreted

Figure 18.18 Schematic representation of the four basic renal processes.



Clearance

- Volume of plasma from which a substance has been removed by kidneys per unit time (volume of plasma that contains the amount of a substance that has been excreted per unit time)

$$\text{Clearance} = \frac{\text{excretion rate}}{\text{plasma concentration}} = \frac{U_x \times V}{P_x}$$

Clearance

- Clearance of inulin

- Clearance of substance freely filtered and neither reabsorbed nor secreted = GFR
- Amount of inulin excreted in urine = amount that was filtered = filtered load
- Excretion rate = filtered load = $\text{GFR} \times P_i$

$$\text{Clearance}_i = \frac{\text{excretion rate}}{\text{plasma concentration}} = \frac{\text{GFR} \times P_i}{P_i} = \text{GFR}$$

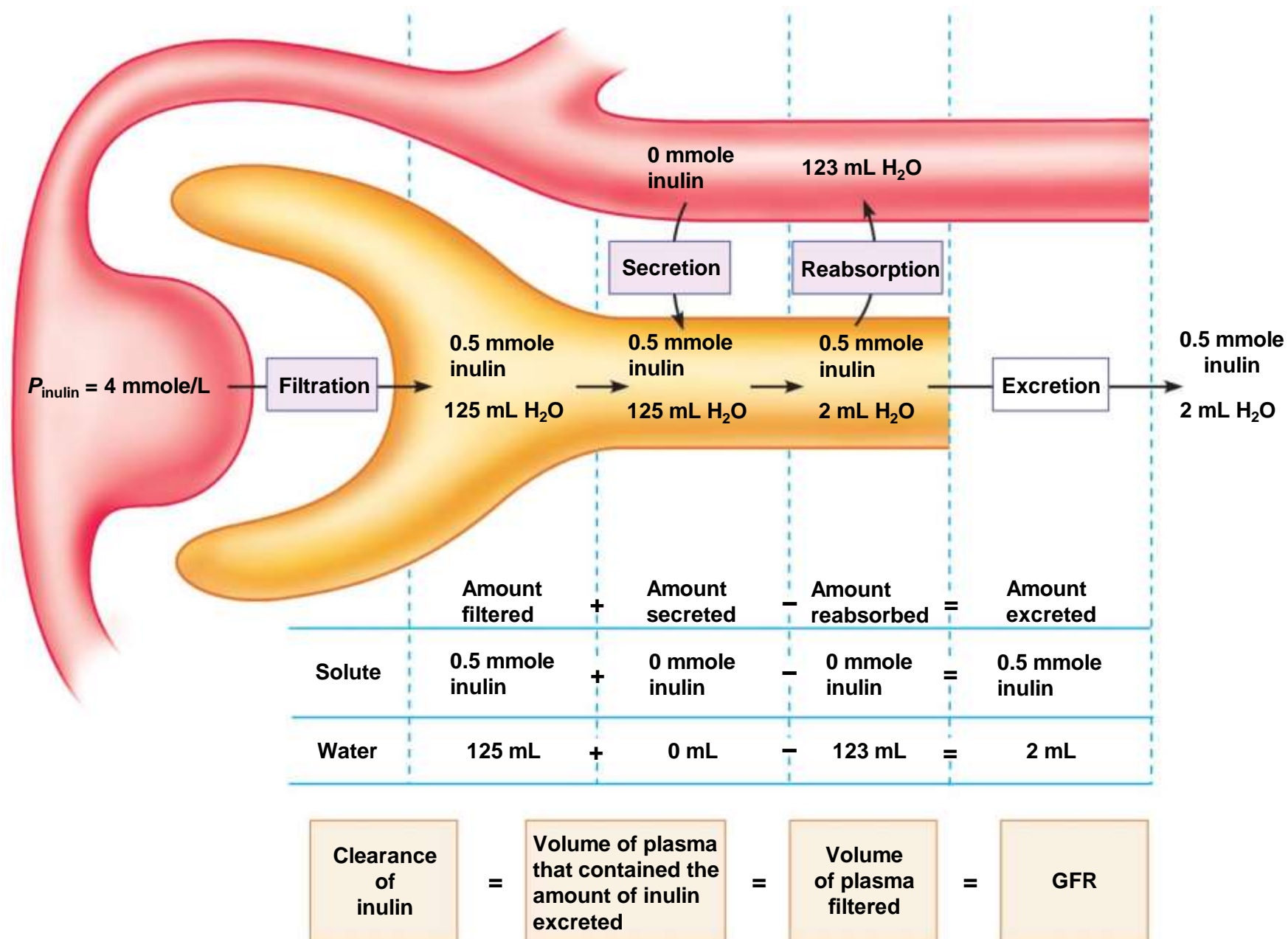
Clearance

- Inulin clearance

$$C_{\text{inulin}} = \frac{(U_{\text{inulin}})(V)}{P_{\text{inulin}}} =$$

$$C_{\text{inulin}} = \frac{(250 \text{ mmole/L}) (2.0 \text{ mL/min})}{(4 \text{ mmole/L})} = 125 \text{ mL/min}$$

Figure 18.19 Clearance of inulin.



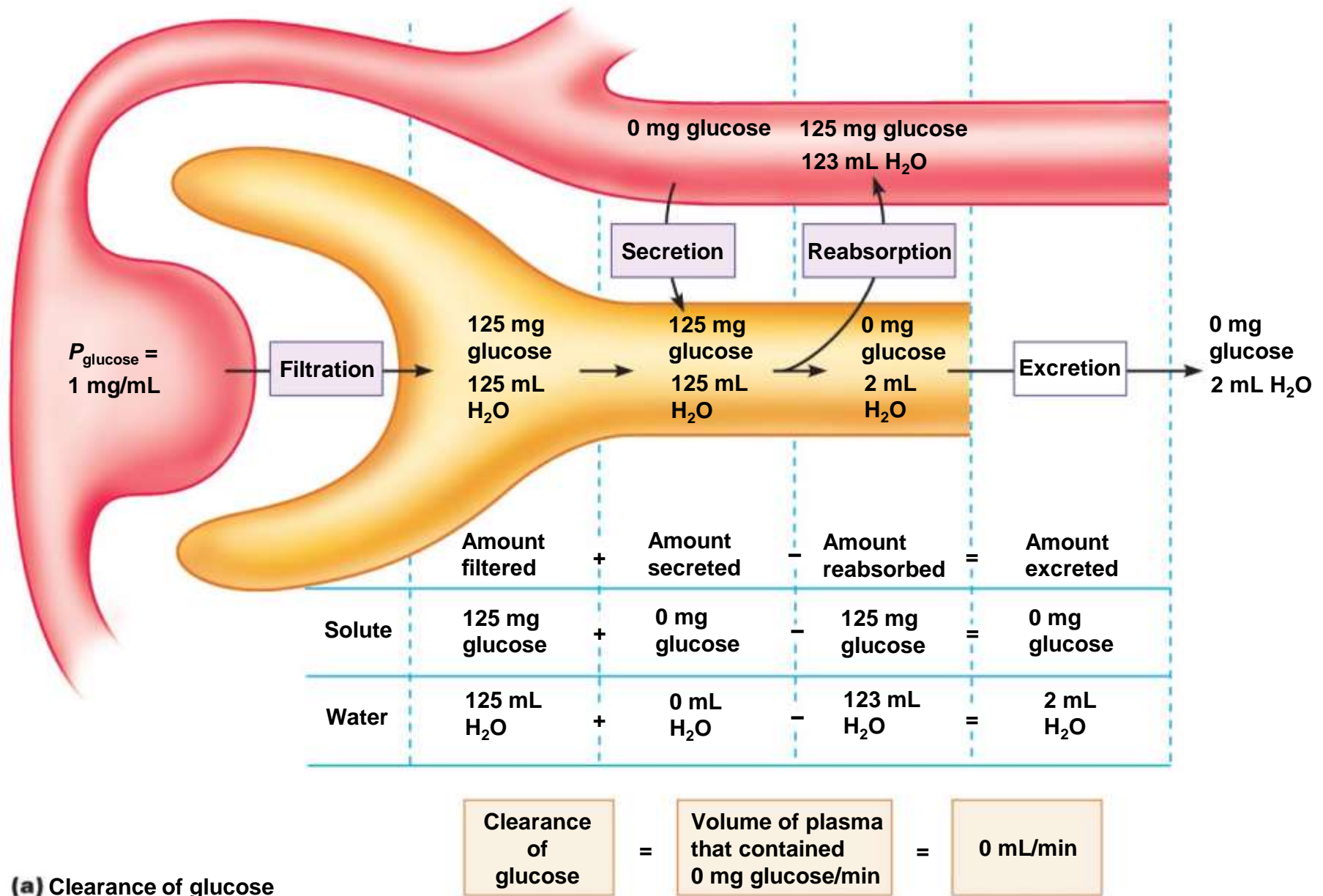
Clearance

- Use of creatinine to estimate GFR
 - Creatinine: by-product of muscle metabolism
 - Produced in body
 - Freely filtered
 - Not reabsorbed
 - Small amount secreted
 - Clearance: "estimate" of GFR
 - Clearance is a little greater than GFR: 140 mL/min

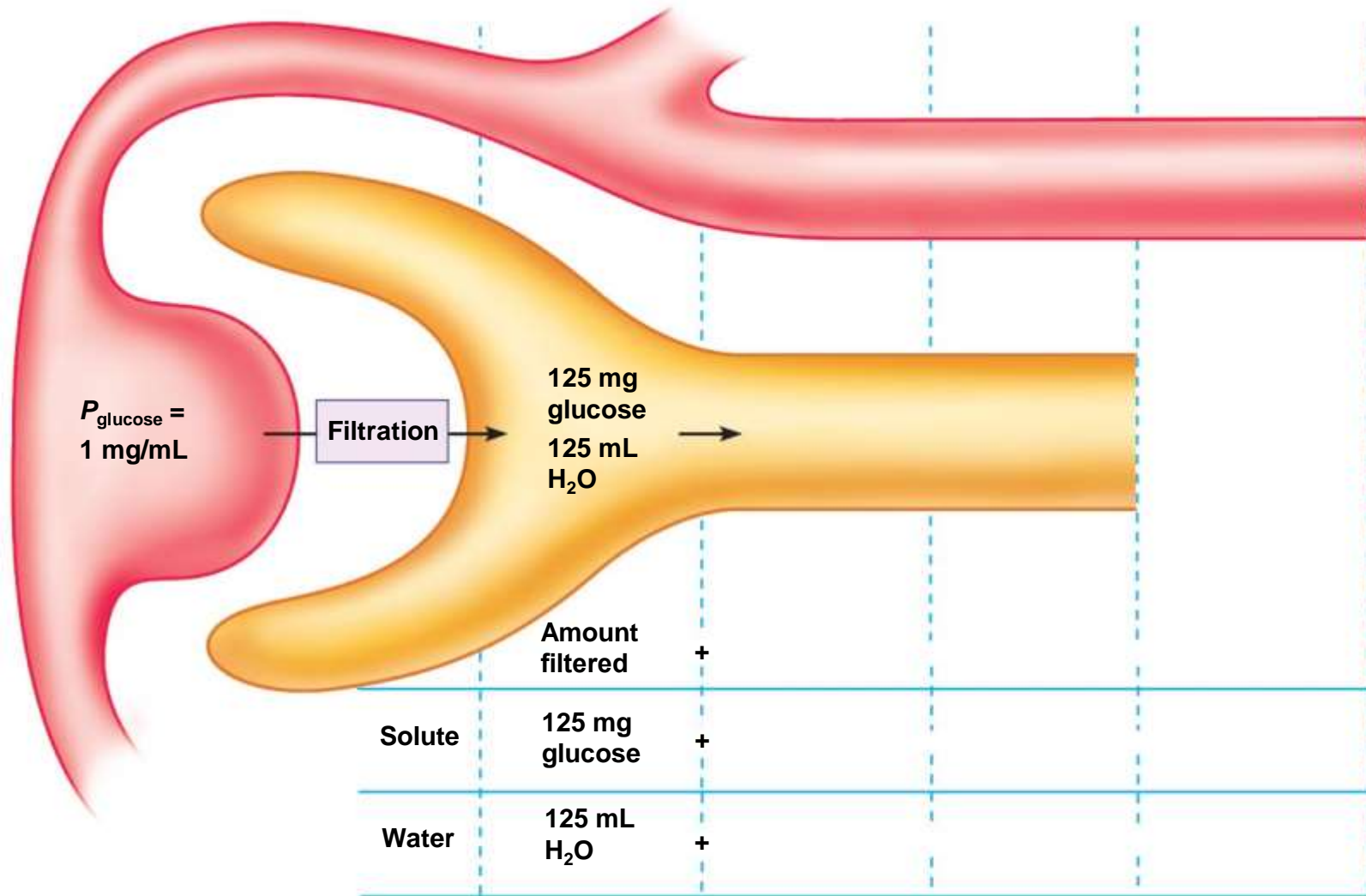
Clearance

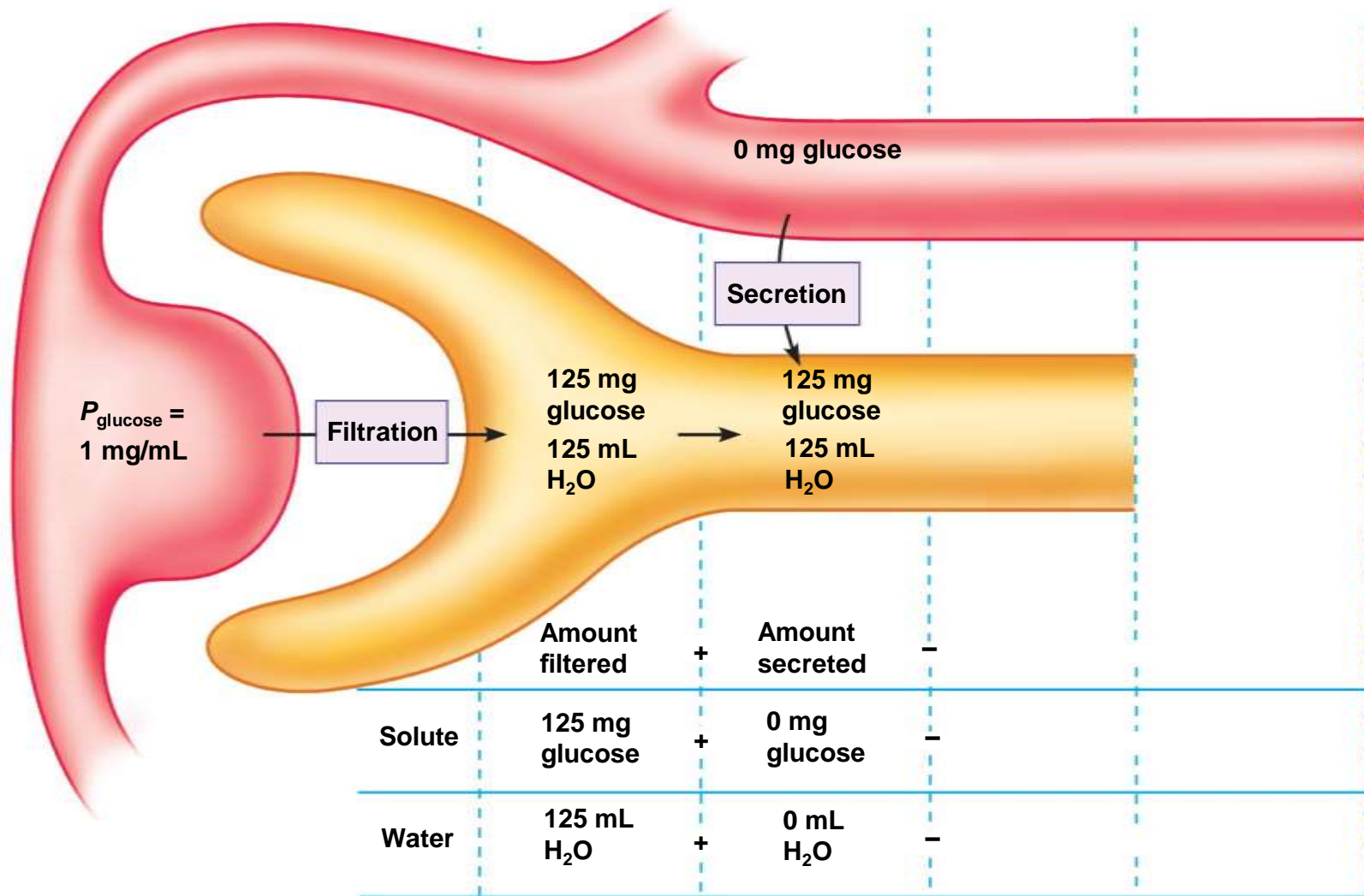
- Clearance of glucose
 - Clearance of substance completely reabsorbed = 0

$$\text{Clearance}_g = \frac{U_g \times V}{P_g} = \frac{(0 \text{ mmole/L}) \times V}{P_g} = 0 \text{ mL/min}$$

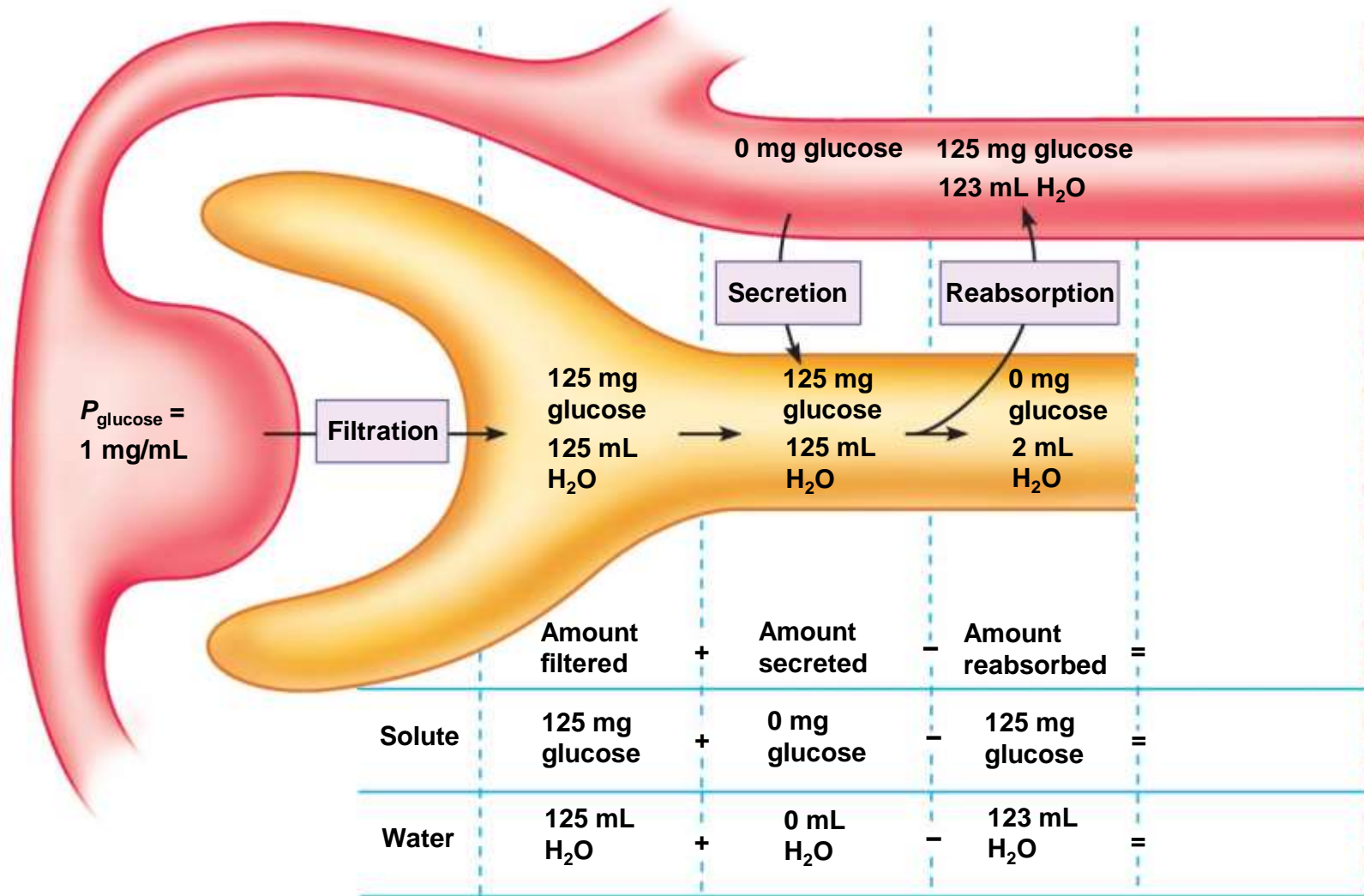


(a) Clearance of glucose

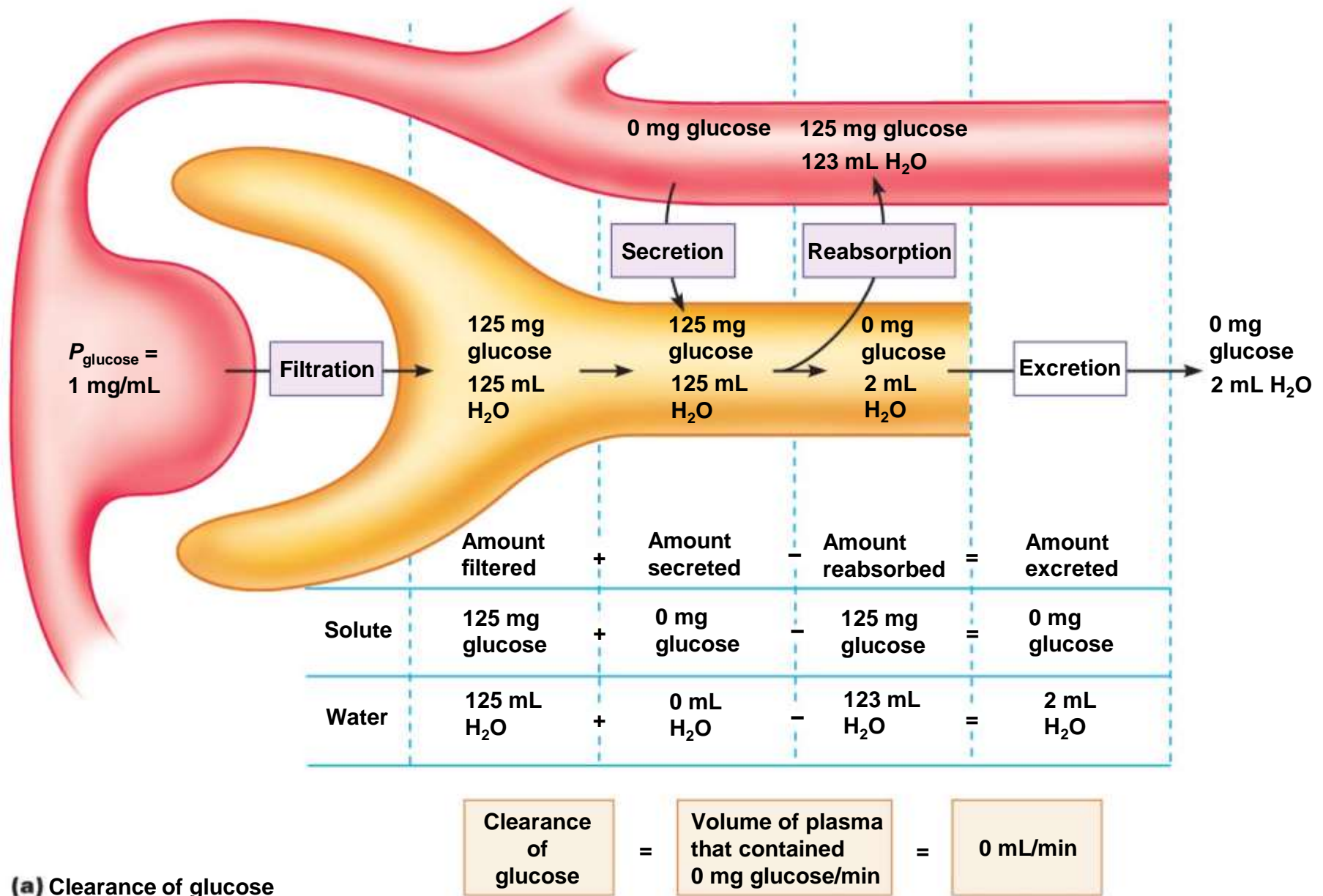
**(a) Clearance of glucose**



(a) Clearance of glucose



(a) Clearance of glucose



(a) Clearance of glucose

Clearance

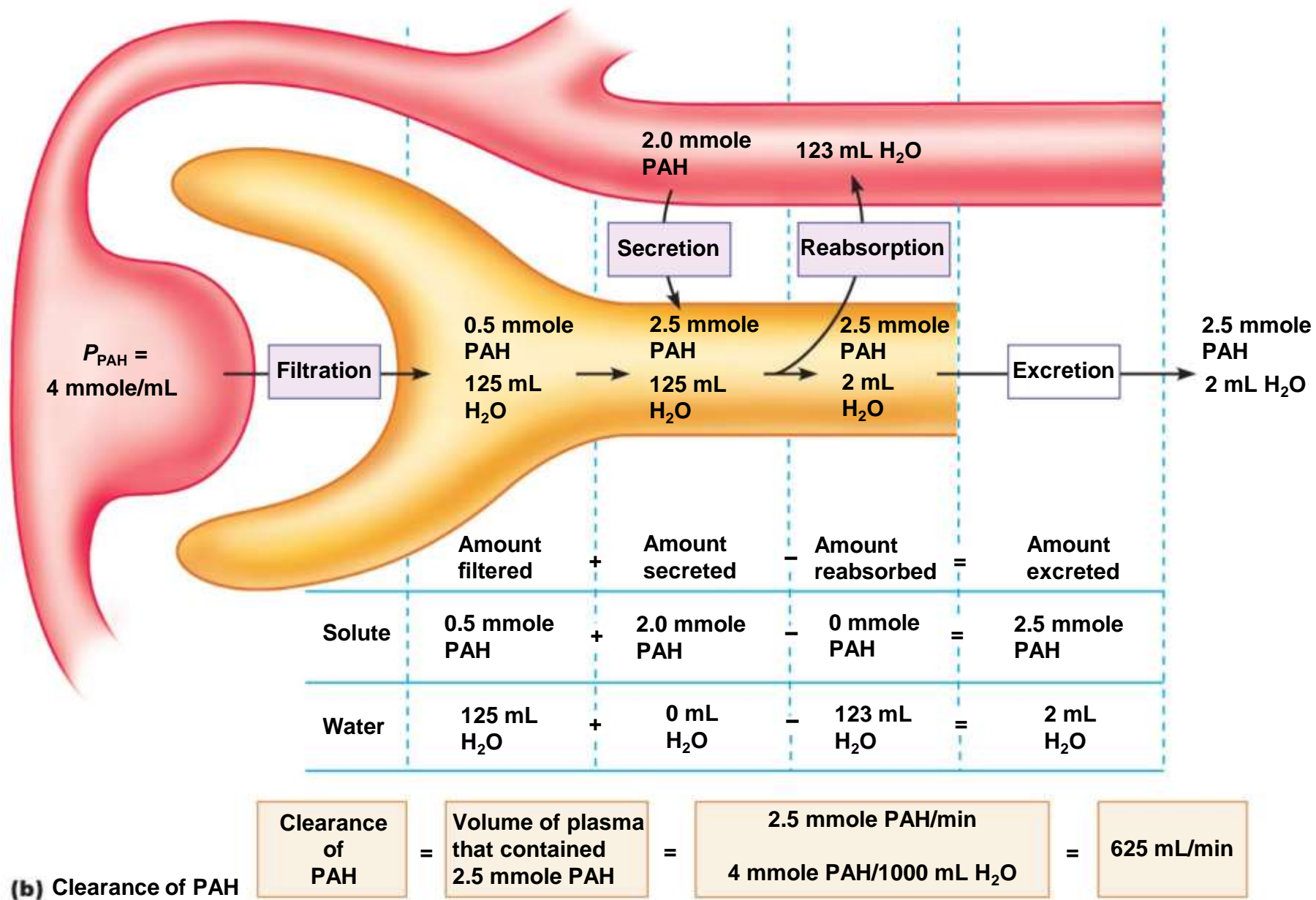
- Clearance of PAH
 - Clearance of substance freely filtered, fully secreted, and not reabsorbed = renal plasma flow rate
 - Amount excreted = amount contained in volume of plasma that entered the kidneys

Clearance

- Renal blood flow
 - PAH clearance = measure of renal plasma flow
 - Converts plasma flow to blood flow
 - Blood is 55% plasma

$$\text{Renal blood flow} = \frac{\text{clearance PAH}}{1 - \text{hematocrit}} = \frac{625 \text{ mL/min}}{0.55} = 1136 \text{ mL/min}$$

Figure 18.20b Examples of clearance.



Clearance

- Determining the fate of solutes in renal tubules
 - If $C_x > \text{GFR}$, then substance was secreted
 - If $C_x < \text{GFR}$, then substance was reabsorbed

TABLE 18.3 Clearance of Some Common Substances Processed by the Kidneys

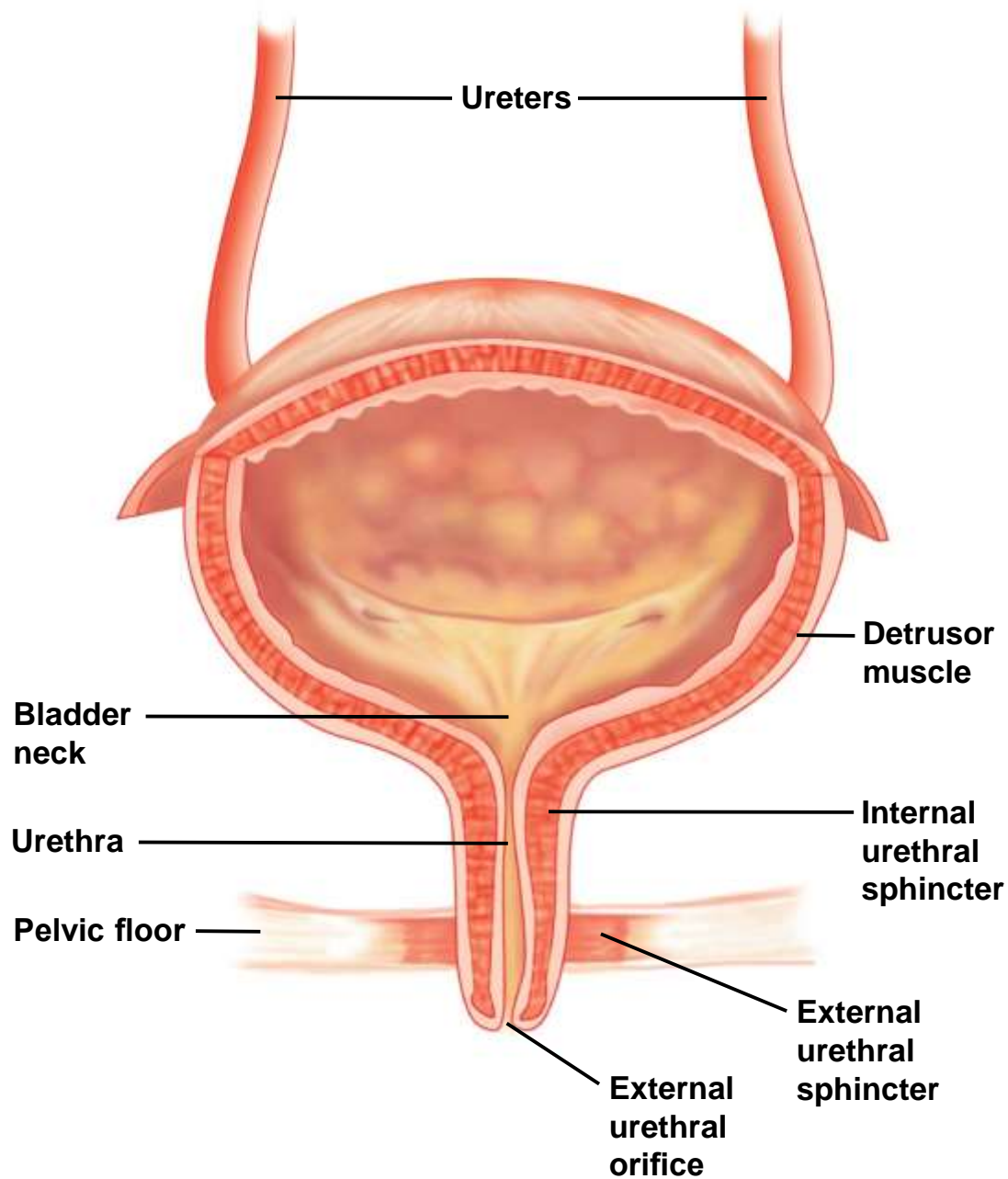
Substance	Clearance rate (mL/min)	Net renal processing (reabsorption or secretion)*
PAH	650	Secretion
Creatinine	140	Secretion
Inulin	125	None
Potassium	12.0	Reabsorption
Chloride	1.3	Reabsorption
Sodium	0.9	Reabsorption
Glucose	0	Reabsorption

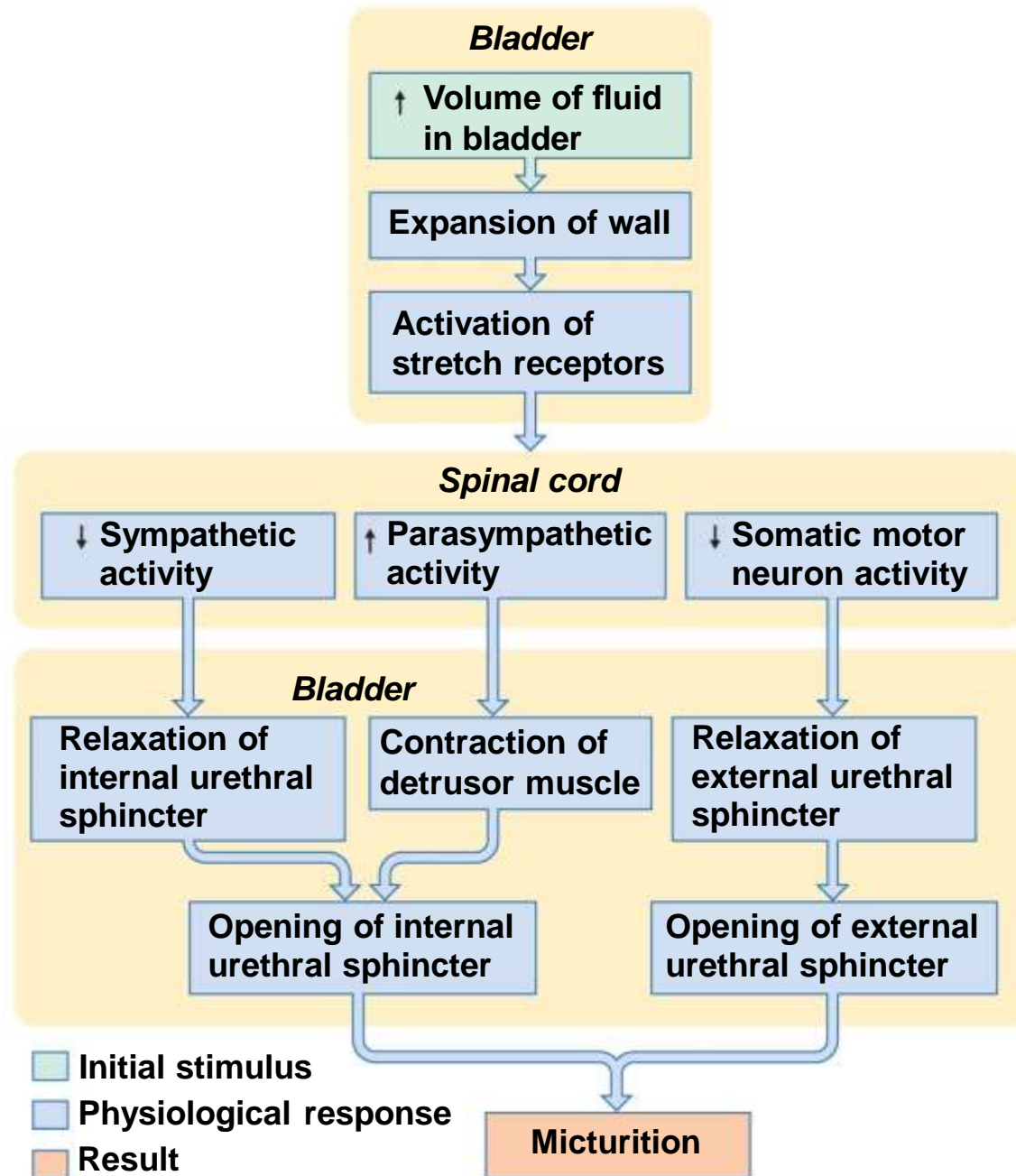
*GFR = 125 mL/min. If clearance is greater than GFR, net secretion has occurred; if clearance is less than GFR, net reabsorption has occurred.

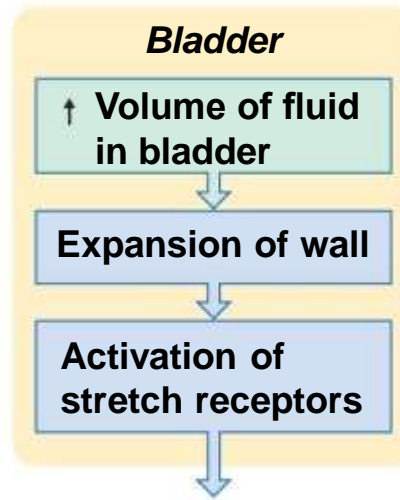
Micturition

- Micturition = urination
- Urine formed in renal tubules
- Fluid drains into renal pelvis and into ureter
- Ureters lead to bladder
- Bladder stores urine until it is excreted

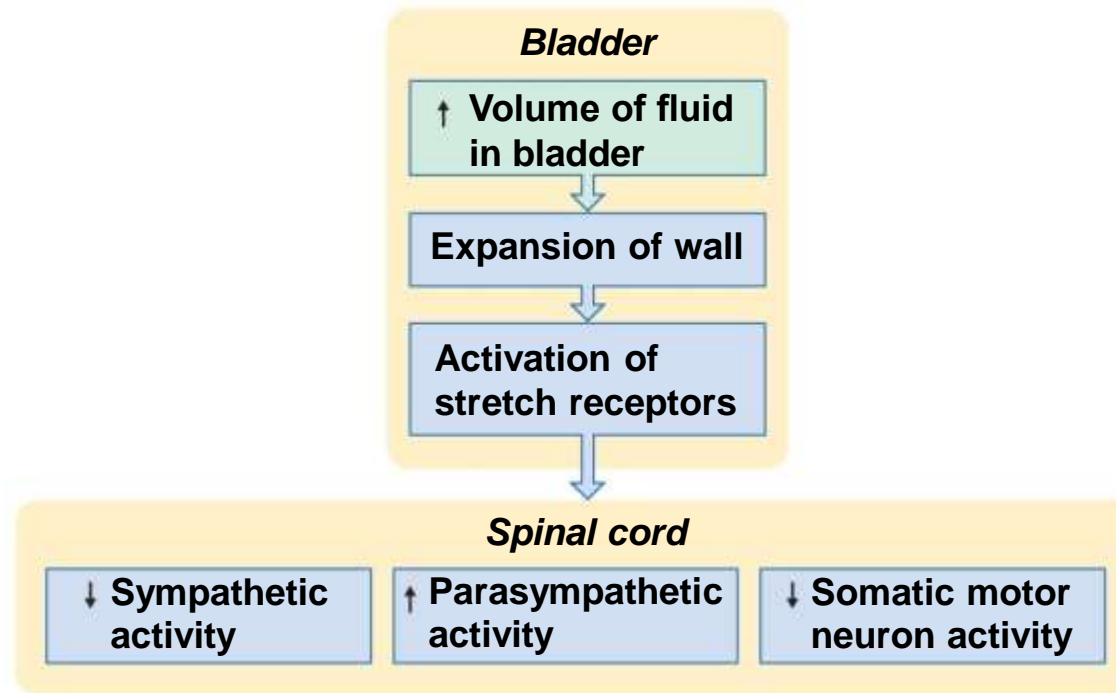
Figure 18.21 Anatomy of the urinary bladder and urethra.



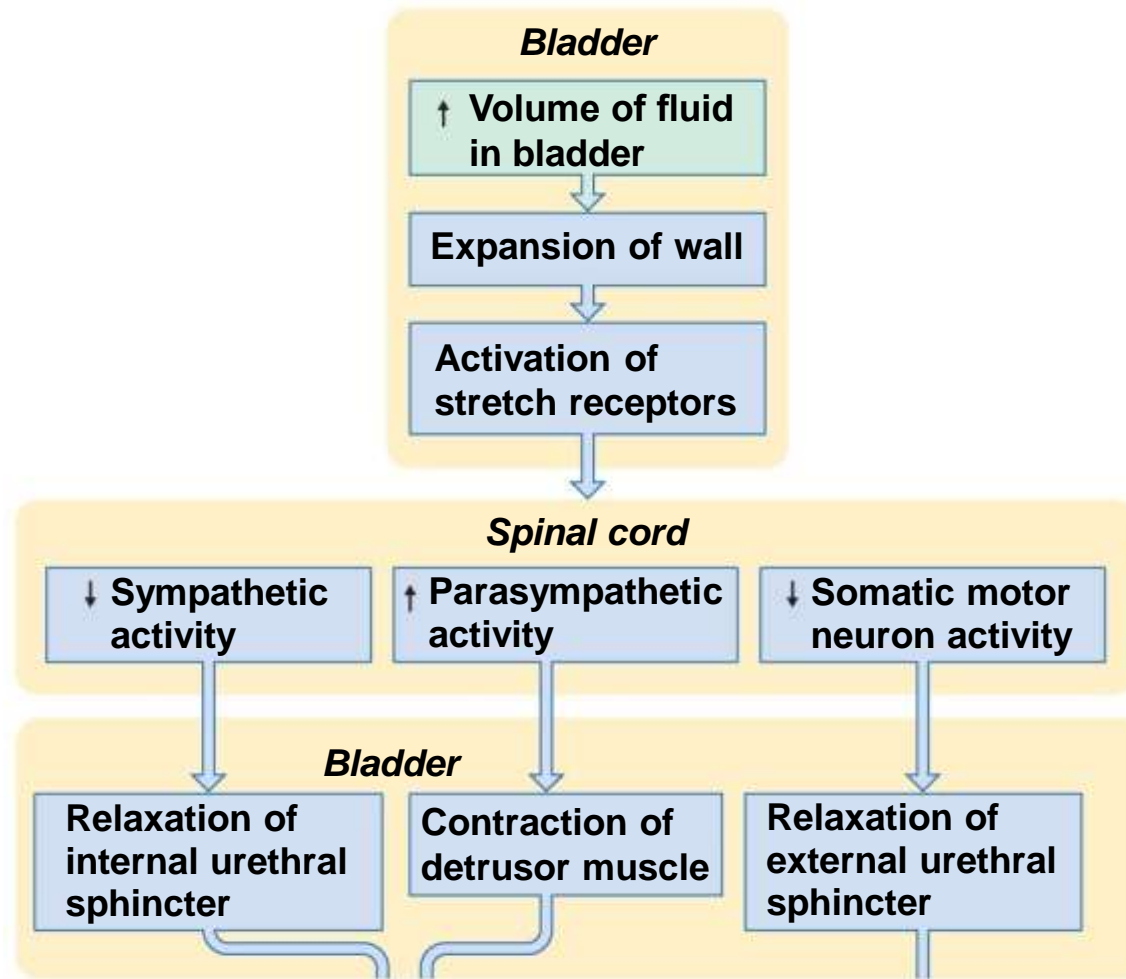




- Initial stimulus
- Physiological response
- Result



- Initial stimulus
- Physiological response
- Result



- Initial stimulus
- Physiological response
- Result

