Water Balance and Osmoregulation

Principles of osmoregulation

Osmoregulatory organs

Why is water balance important?

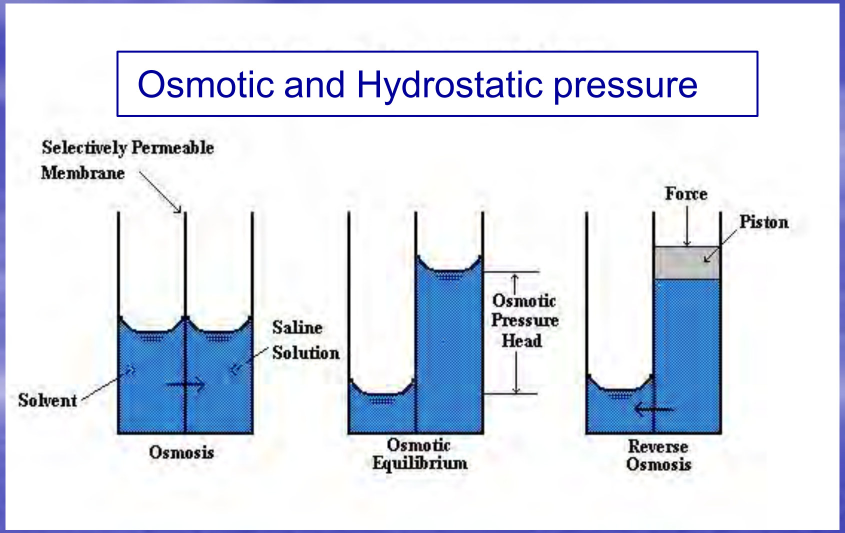
Cell survival depends on chemical reactions (metabolism).

Chemical reactions depend on collisions.

Collision frequency is dependent on concentration and mobility of reactants.

Bottom Line: changes in intracellular water influence metabolic rates.

What is *Osmolarity?*



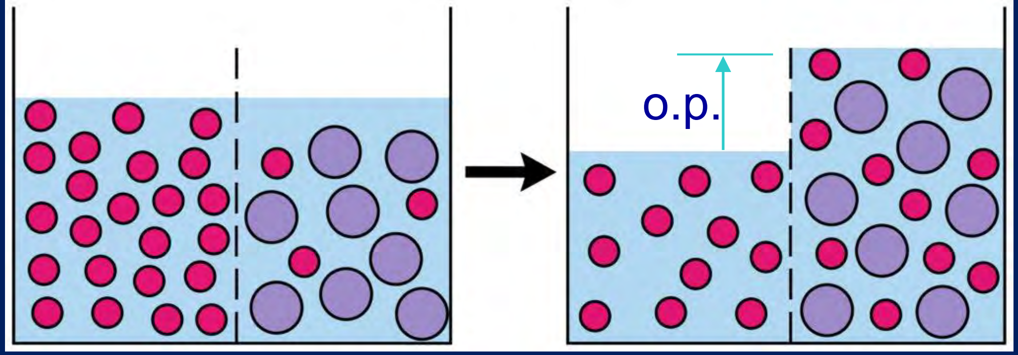
- Osmolarity refers to the concentration of *osmotically active* particles in a solution.
  - A mole of sugar in water yields a mole of osmotically active particles, but a mole of salt (NaCl) yields *two* moles of particles (Na^+ and Cl^-)
- Osmotically active particles are any components which contribute to differences in osmotic pressure
- Osmotic pressure refers to the tendency of solutions of dissimilar osmolarity to come to equilibrium via water movement ("osmosis").

A "mole" of a substance contains 6.022×10^{23} molecules or particles

Definitions

- Given a pair of solutions (e.g., blood, water) with different concentrations of osmotically active particles
- the one with the greater concentration is *hyperosmotic* (or *hypertonic**) to the other;
- the one with the lower concentration is *hypoosmotic* (or *hypotonic*) to the other.
- Water will flow from the hypoosmotic solution to the hyperosmotic one.

* to be exact, *tonicity* refers to salt concentration, whereas *osmolarity* is a more general term; however, they are often used interchangeably.



Body Fluids and Environments of Animals in Various Habitats

Environments	Animals	Osmolarity
Fresh Water: 5mOsm ('milliosmolar')	Mussel	43mOsm
	Pelomyxa	75
	Teleosts	268-296
	Frog	241
	Crayfish	440
Brackish Water: 107-268	Euryhaline invertebrates	268-297
Sea Water: 1000	Marine Teleosts	349-376
	Marine invertebrates	967-1032
	Marine elasmobranches	1000-1032
Salt Lakes: 7258-8064	*Artemia*	645-860
Humid Niches (80-95% RH) (85% RH ≈ 7600 mOsm)	Earthworms	161-215
	Insect larvae	268-537
	Mammals	268-311
	Adult insects	430-645
Dry air (<10% RH)	Reptiles	322-376
	Insects	430-645

Metabolic Water

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

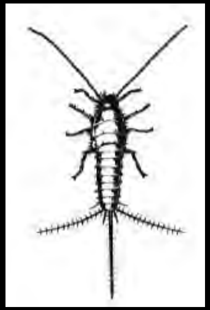
Food	$C_n(H_2O)_n$	Fats	Proteins
gm H_2O gained per gm food metabolized	0.56	1.07	0.40

Example: seals do not drink seawater, but must have fresh water to eliminate the salt that comes in with their food. If they eat invertebrates (salty), they become thinner as they burn their fat to produce the needed water. If they eat fish they become fatter, since fish have much less salt.

Water Balance

- INTAKES:
  - Drinking
    - Food (moisture; metabolic water)
    - $[C_n(H20)_n + nO_2 \rightarrow nCO_2 + nH_20 + \text{energy}]$
  - Osmosis
    - **Passive (hyperosmotic to environment)**
    - **Active (transport across epithelia)**
- LOSSES:
  - Feces
  - Urine
  - Osmosis (hypoosmotic to environment)
  - Evaporation

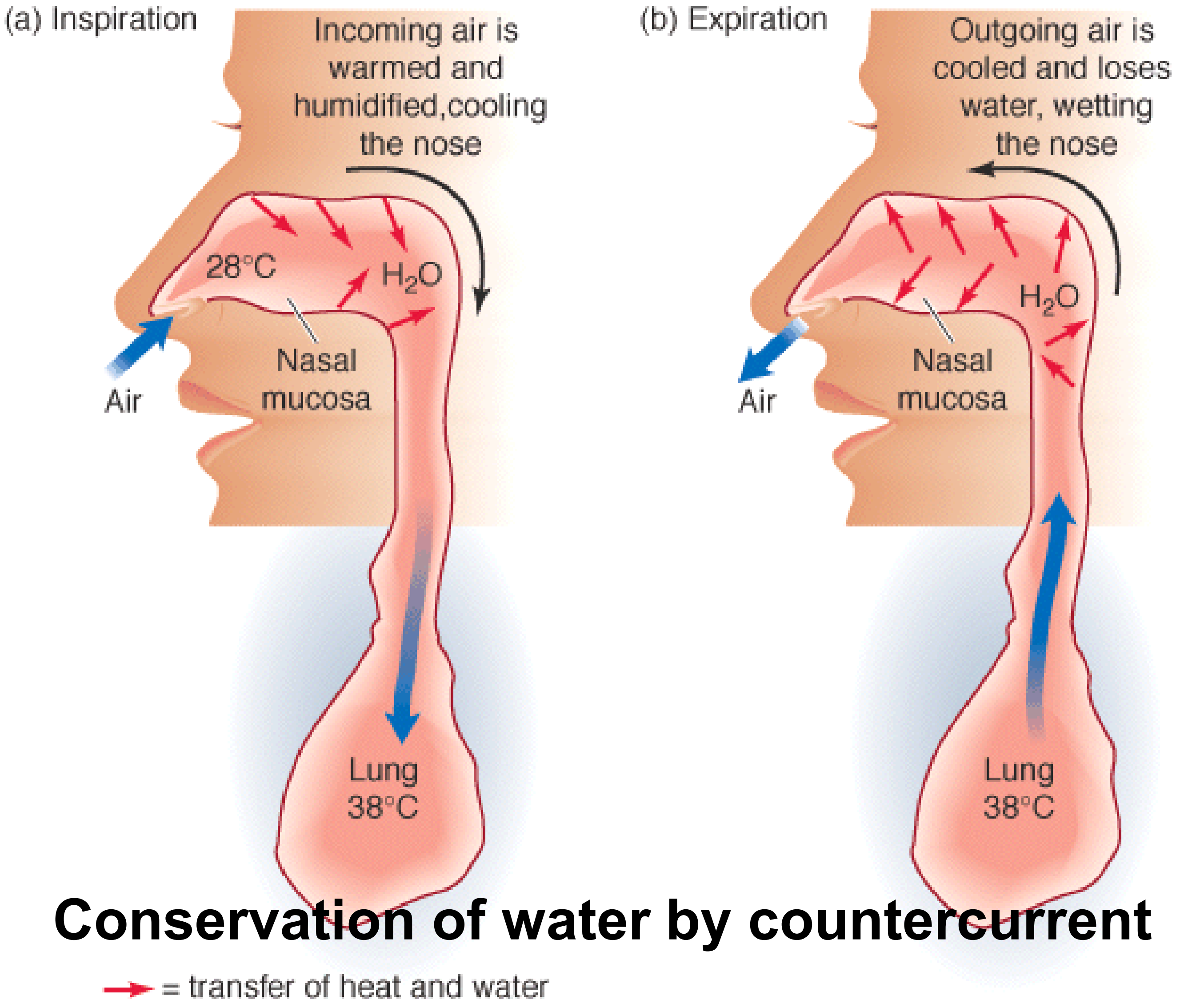
Example: terrestrial animal

- Losses:
  - Main loss: evaporation (respiratory)
  - Other losses: feces, urine, perspiration
- Gains:
  - Drinking
  - Food moisture
  - Metabolic water
  - Hygroscopy (in some insects)
    - E.g. firebrat  absorbs moisture at any RH>50%

Some representative water loss rates

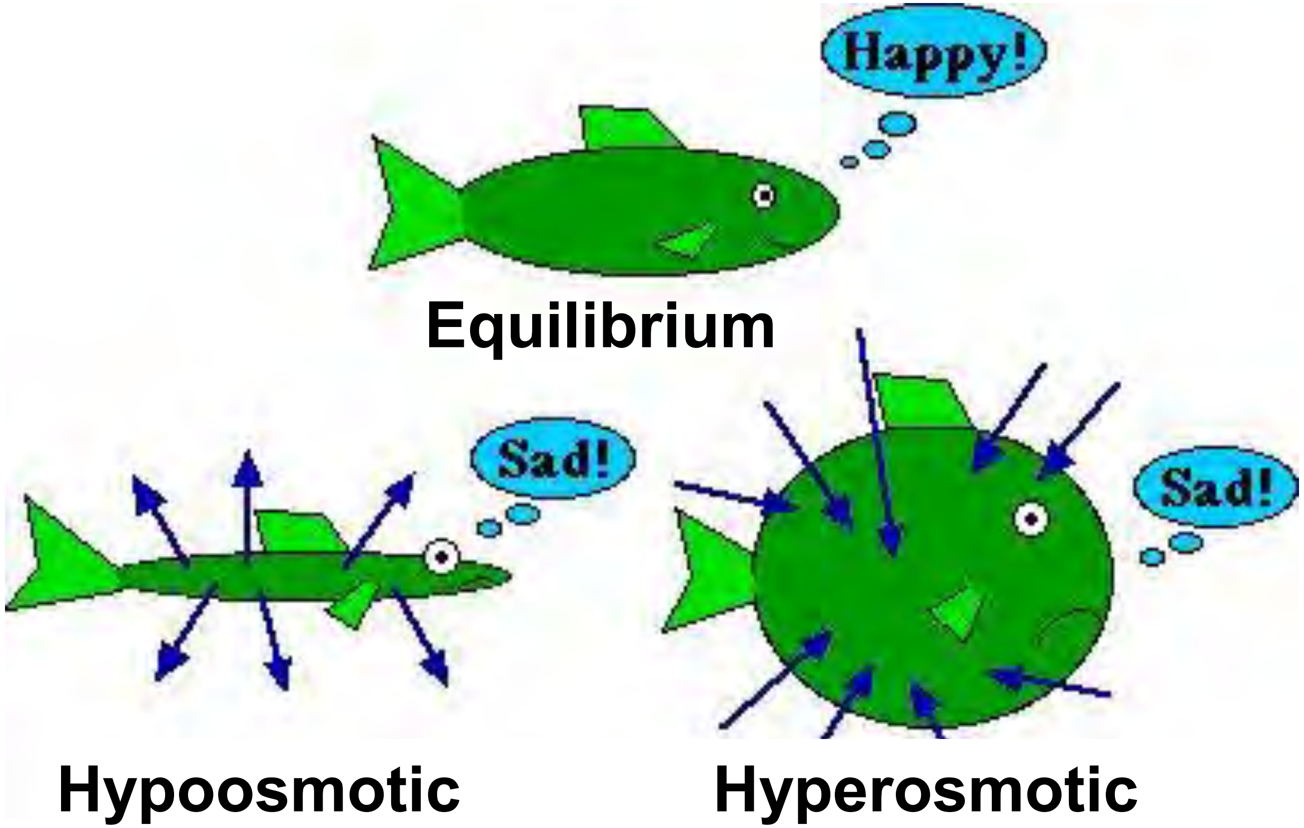
Animal	Conditions	Water Loss ($mg \cdot cm^{-2} \cdot h^{-1}$)
Scorpion	30°C,0%RH	0.02
Locust	30°C,0%RH	0.7
Frog	25°C,100%RH	4.9
Gecko	30°C,0%RH	0.22
Sparrow	30°C	1.48
Poorwill	30°C	0.86
Cactus mouse	30°C	0.66
Oryx	22°C	3.24
Human	35°C, nude, in sun	22.32

Respiratory water loss



Conservation of water by countercurrent

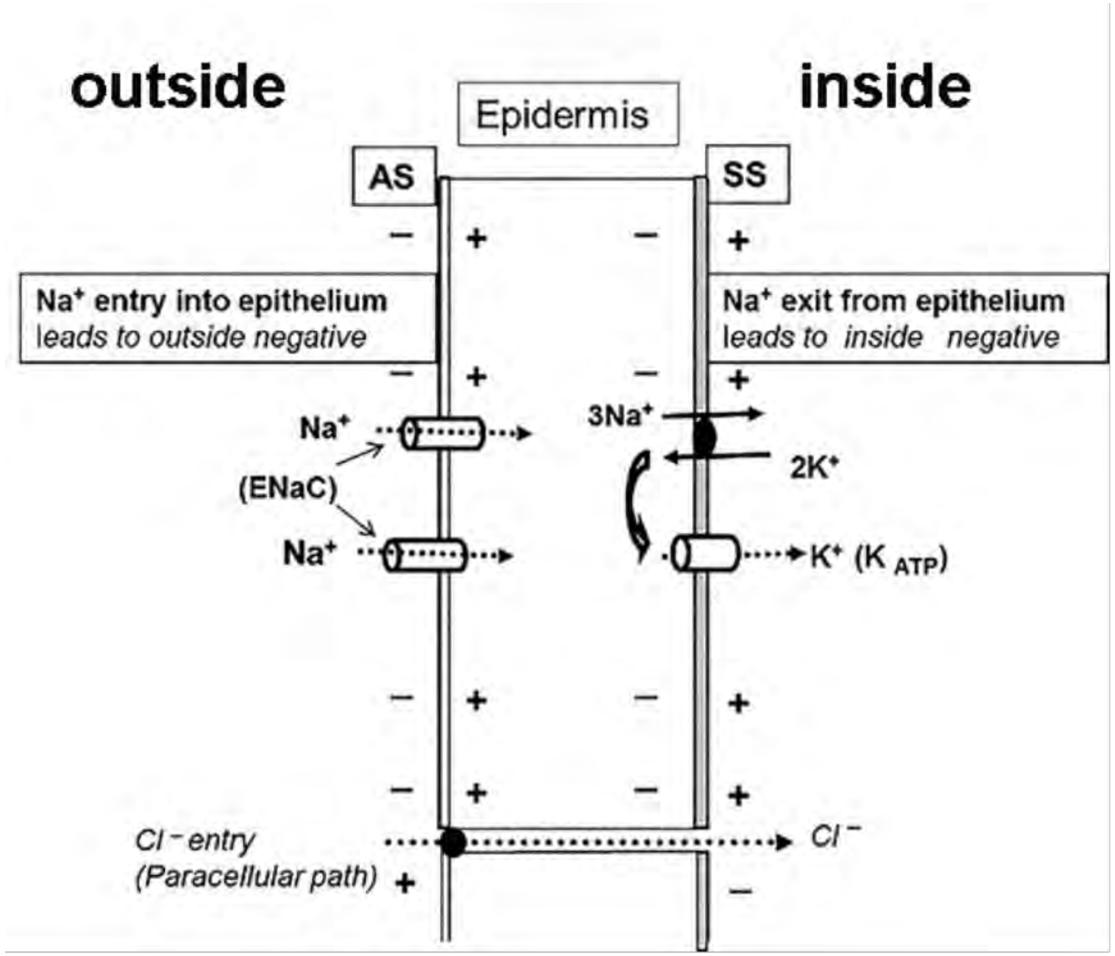
Aquatic animals



Freshwater animals are hyperosmotic to their environment

- Problem:
  - water taken on through gills (fish, arthropods, amphibians, etc.) or skin (amphibians)
- Solution:
  - Secrete copious, dilute urine
  - Absorb salts via active pumping at gills (ionocytes) or skin to make up for urinary losses
    - Often cotransported with waste ions: e.g., Na^+ for H^+ or NH^+, Cl^- for HCO_3^-, etc.

Active transport of Na+ across frog skin

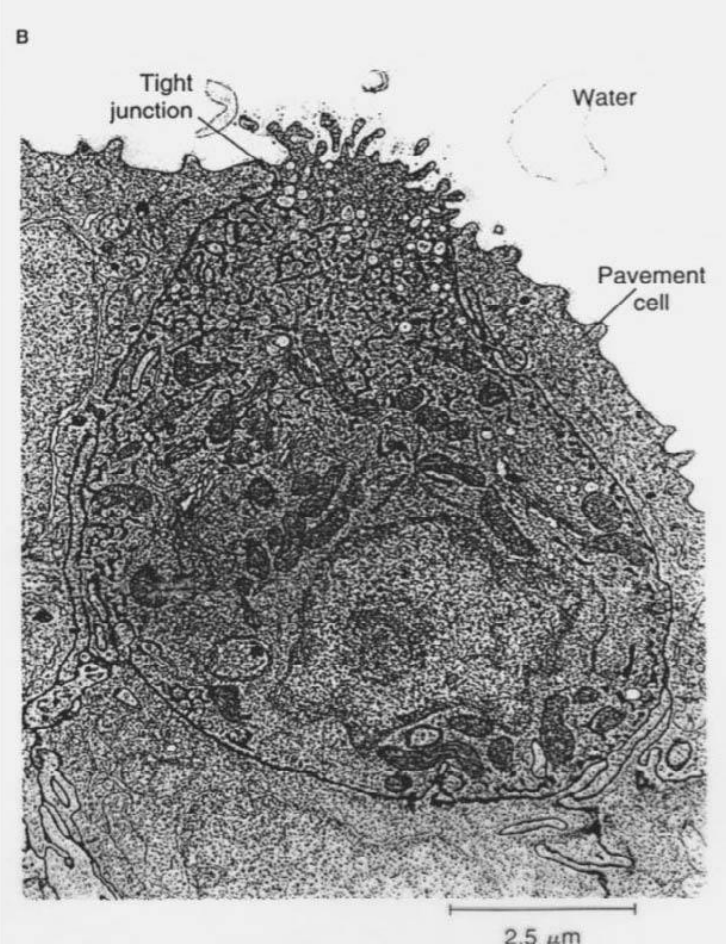


Saltwater fish

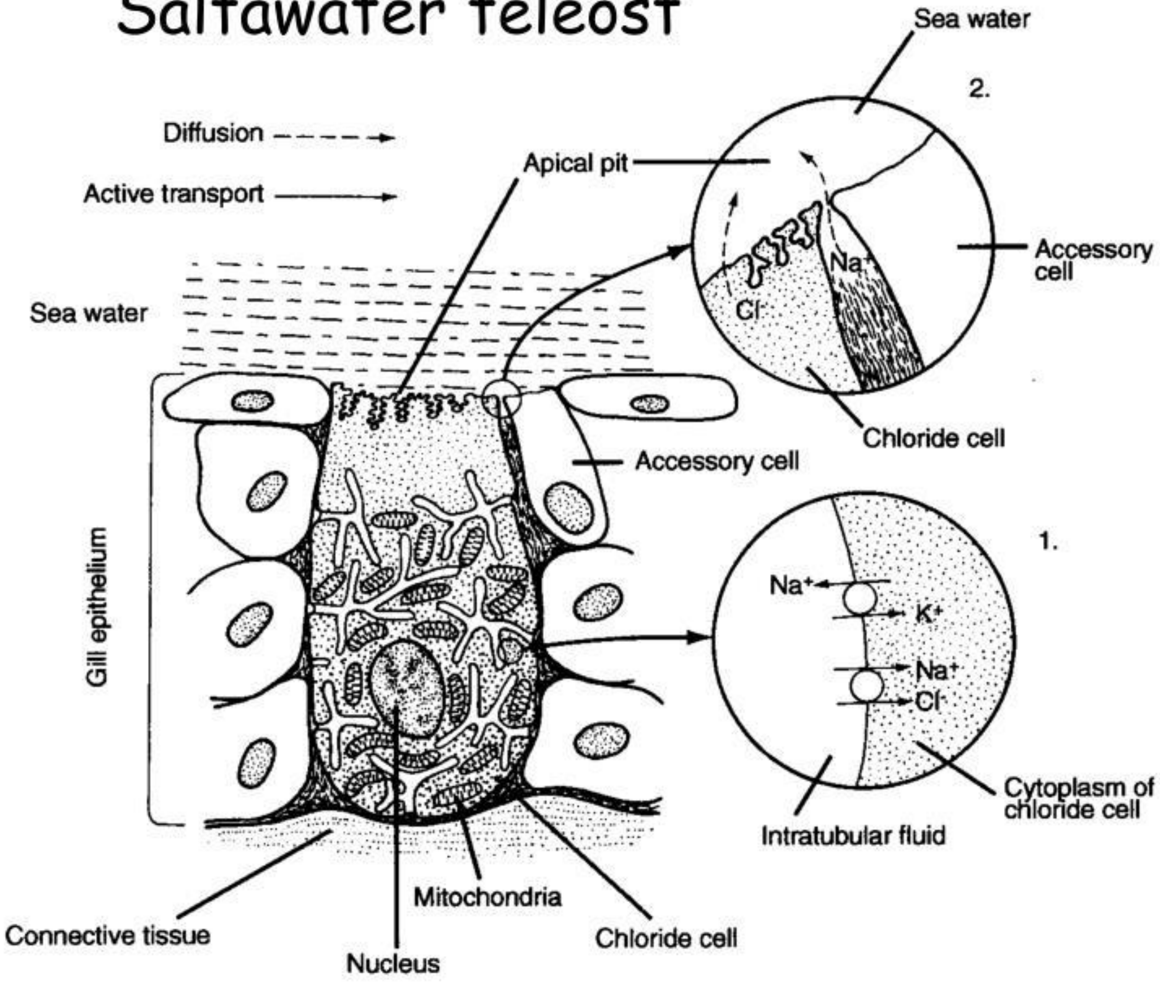
- Problem: Hypoosmotic to seawater
  - Water loss through gills
- Solution:
  - Elasmobranchs:
    - **Remain slightly hyperosmotic by retaining urea (and TMAO).**
  - Teleosts:
    - **Drink salt water; active transport of selected ions cotransports water from gut to blood.**
    - **Extrude Cl^-, Na^+ from gills (ionocytes), Mg^{++}, SO_4^{--}, Ca^{++} via kidneys.**
    - **Excrete minimal urine. (Urine is isotonic to blood (FW origin of teleosts?))**

Chloride Cell

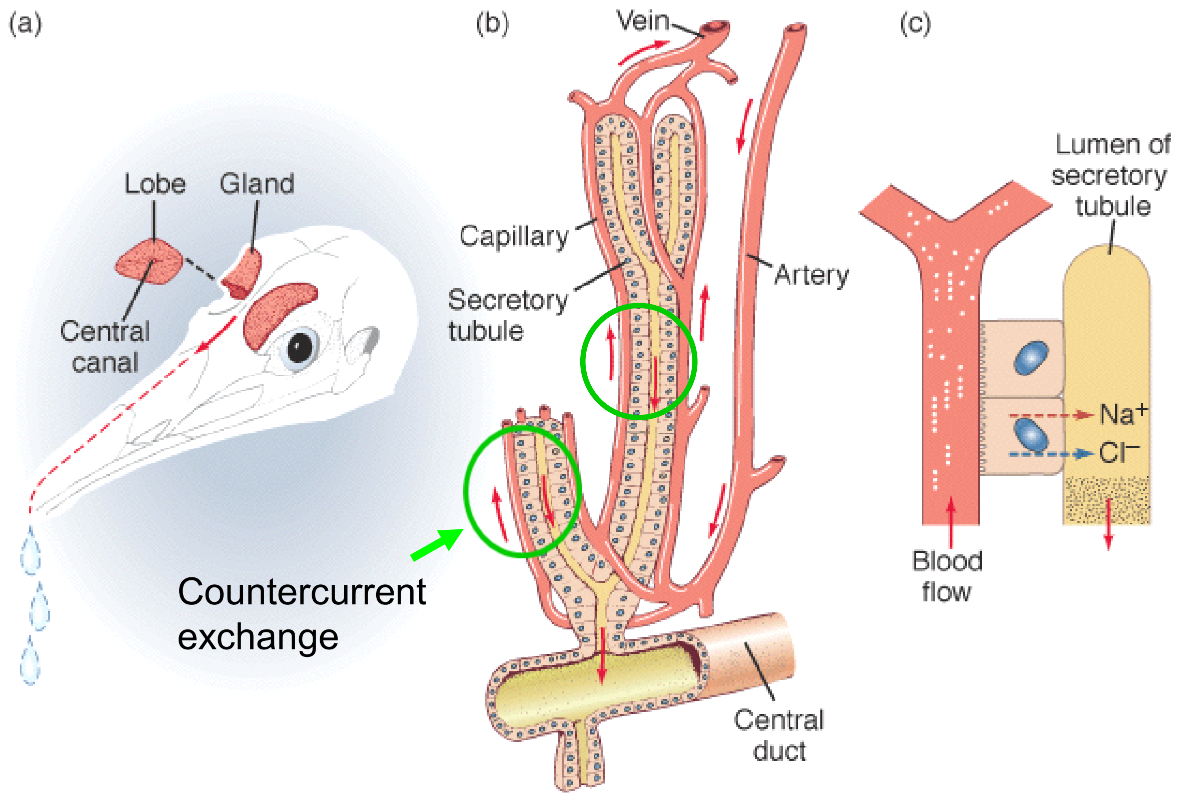
Saltawater teleost



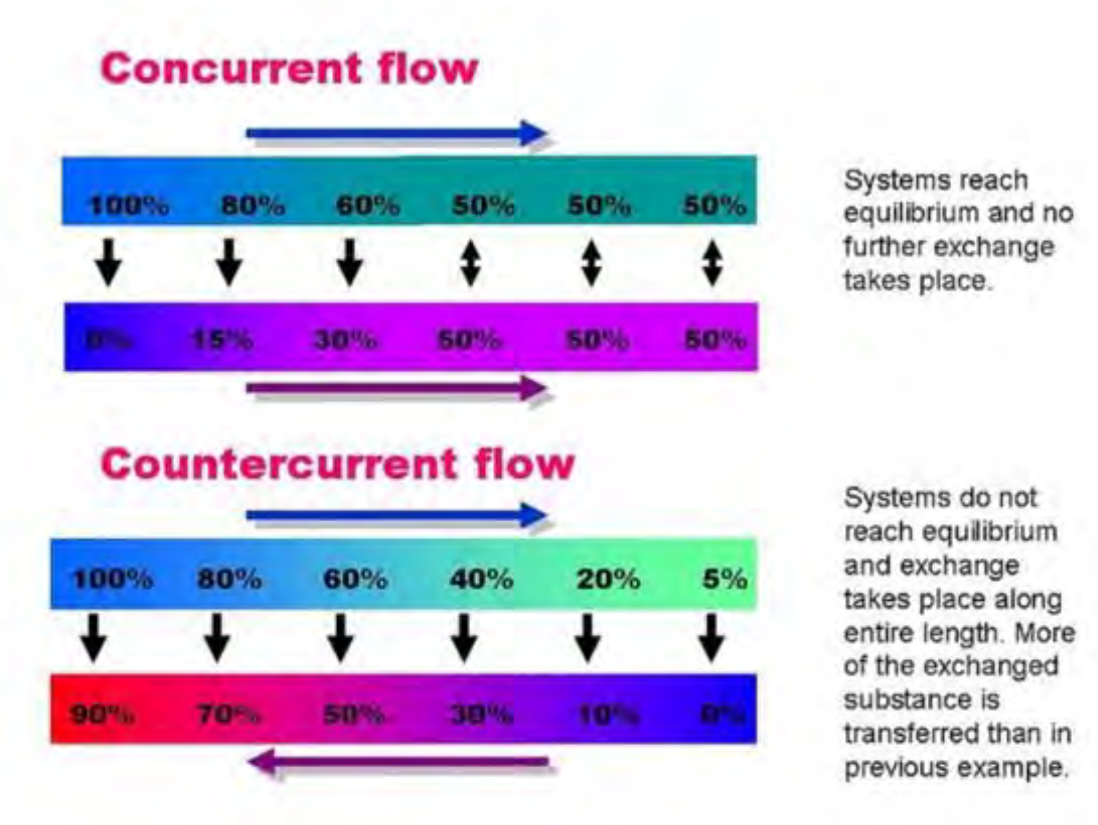
Location:
Gill & Operculum epithelia

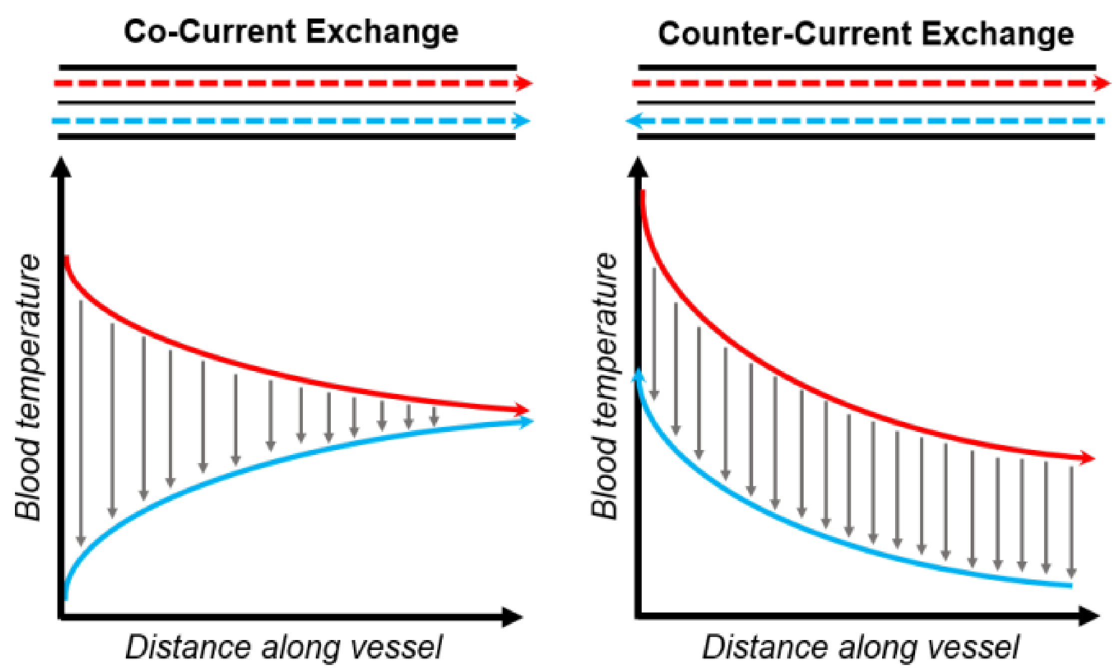


Marine birds and reptiles cannot produce hyperosmotic urine, but instead use salt glands

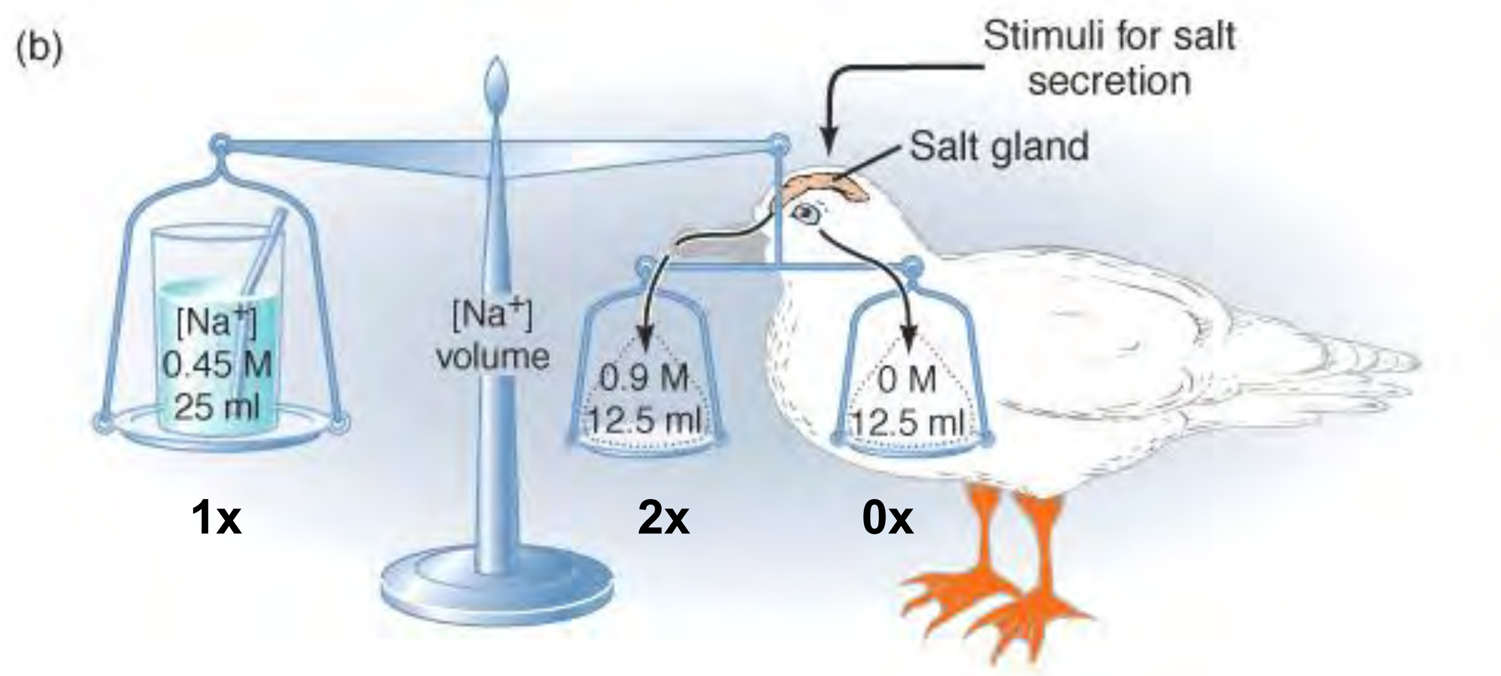


Countercurrent Exchange

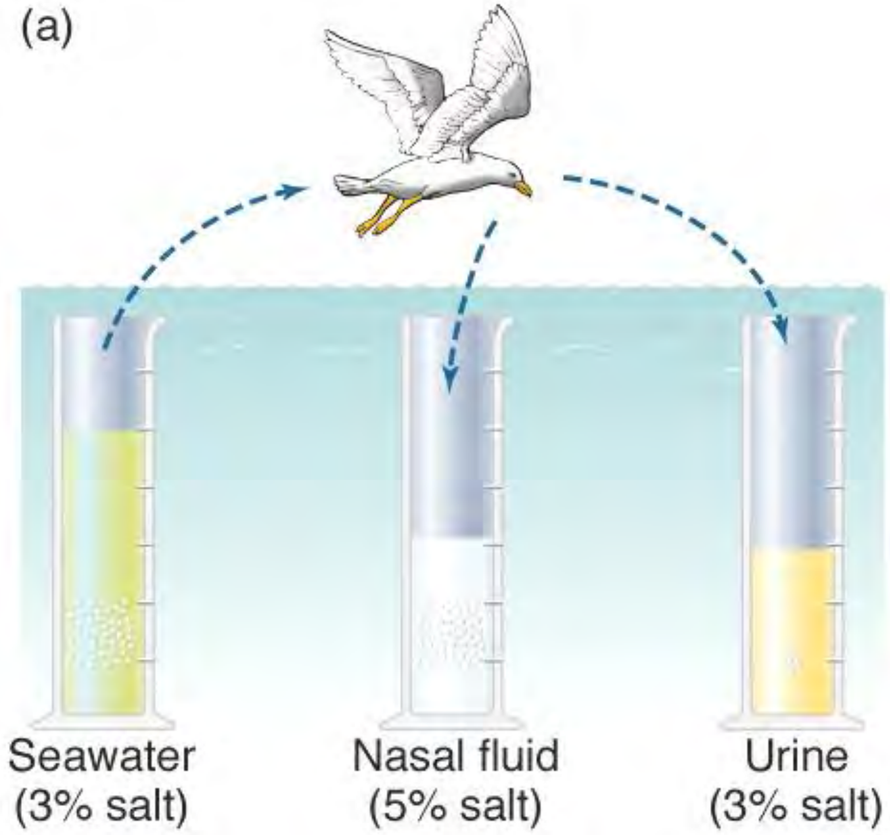




Seagull: salt gland secretes all the ingested salt in half the water ingested, producing a net gain of salt-free water.

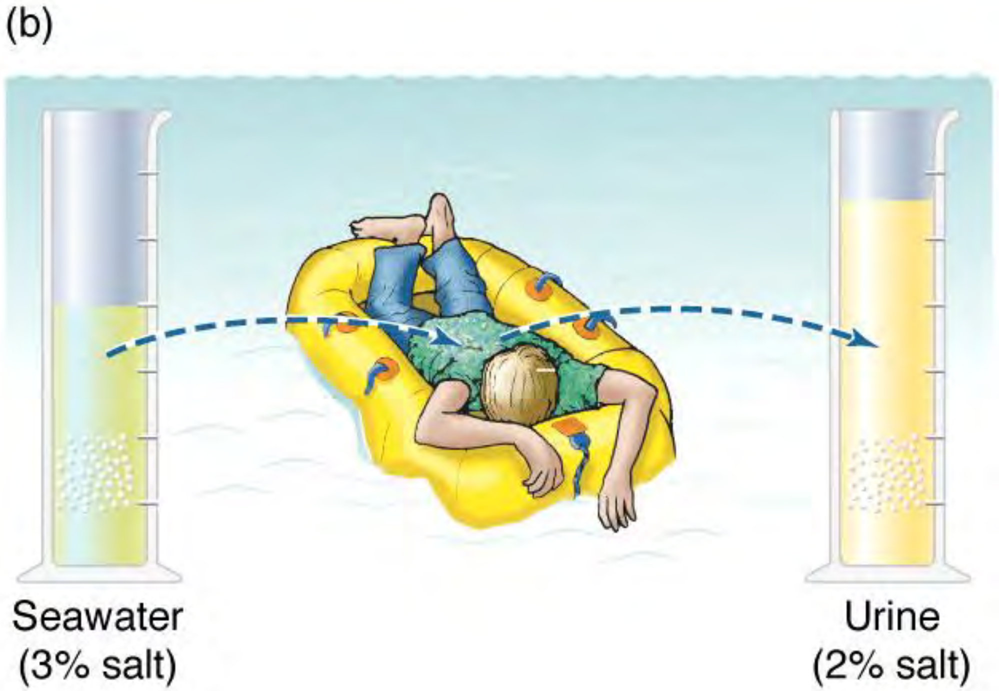


Seabirds do it, but don't you try it!



Human: 6gm Na^+ per liter urine.

Seawater: 12gm Na^+ per liter.



Concentrating power of marine bird salt glands

Species	Sodium Concentration (mmol liter^{-1})	Approximate Osmolarity mOsm
Seawater	400	1000
Cormorant	500-600	1132
Blackback Gull	700-900	1646
Penguin	725-800	1569
Albatross	800-900	1749
Leach's Petrel	900-1100	2058

Marine Mammals

- Mammals are capable of producing urine more concentrated than their plasma.
- This allows them to excrete ions and waste with minimal water loss
- Marine mammals do not drink seawater, although they may ingest some with food. Most of their water intake comes in with their food.

Maximum urine concentrating powers of various mammals

Animal	Urine (mOsm)	u/p osm. ratio
Human	1400-1480	~4.0
Porpoise	1833	
Seal	2150-2420	
Dog	2006-2660	
Lab rat	2560-3000	~8.9
Camel	2500-3170	~8
Squirrel	3900	9.5
Desert rat	5500-6000	10.3-14
Australian Hopping Mouse	10,000	

Summary of marine vertebrates

animals	blood conc. relative to medium	Urine conc. relative to blood	osmoregulation in Marine Vertebrates
elasmo-branchs (sharks, skates, rays)	isosmotic	isosmotic	 x — does not drink sea water; isosmotic urine; hyper-osmotic NaCl from rectal gland
Teleost (bony) fish	hypo-osmotic	isosmotic	 — drinks sea water; isosmotic urine; secretes salt from gills
Reptiles	hypo-osmotic	isosmotic	 — drinks sea water; isosmotic urine; hyper-osmotic tears
Mammals	hypo-osmotic	hyper-osmotic	 x — does NOT drink sea water
Birds	hypo-osmotic	weakly hyper-osmotic	 — drinks sea water; hyper-osmotic nasal secretion; weakly hyper-osmotic urine

Terrestrial mammals

- Camels:
  - Camels conserve water by loosening the regulation of body temperature. They store heat during the day and release it at night. A hydrated camel's body temperature varies between 36-38^{o}C; a dehydrated one's temperature varies between 34 and 41^{o}C. Higher body temperature means less heat gain from the environment, and cuts evaporative water loss to 0.28 liter per hour (compared to about 1 liter per hour for a human.

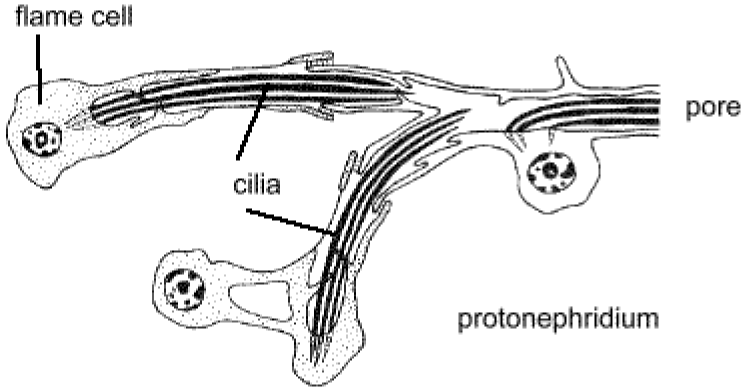
- Desert (kangaroo) rats:
  - Desert rats never drink water. All their water comes from metabolism of the food they eat and the water contained in that food. They can conserve the water because they produce a highly concentrated urine.

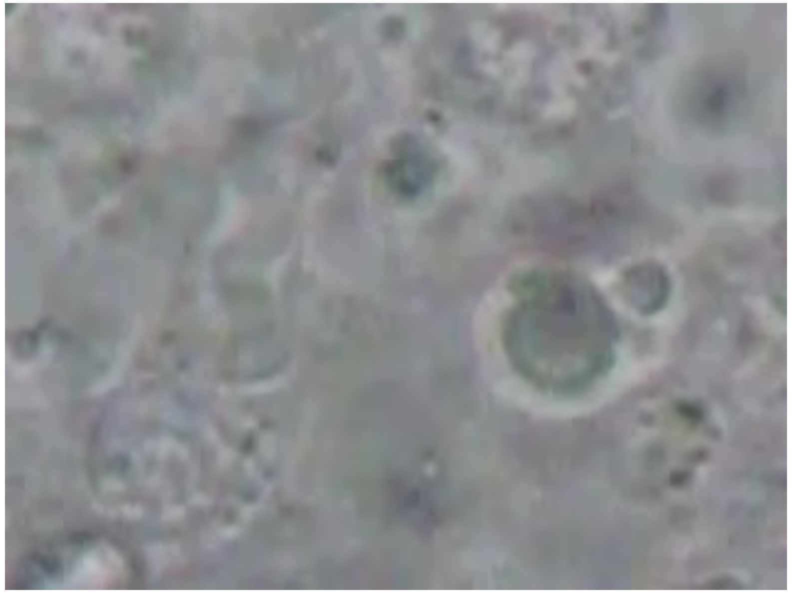
Gains	mL	Losses	mL
Metabolic	54.0	Urine	13.5
Water in food	6.0	Feces	2.6
		Evaporation	43.9
Total gain	60.0	Total loss	60.0

Water Balance and Osmoregulation II

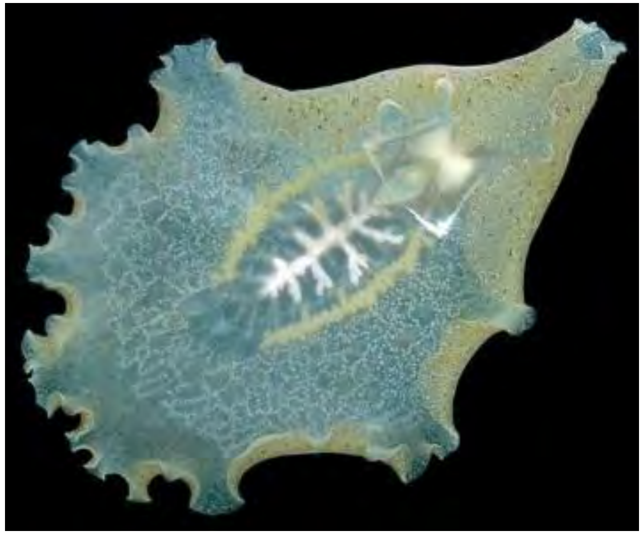
Kidneys and other excretory organs

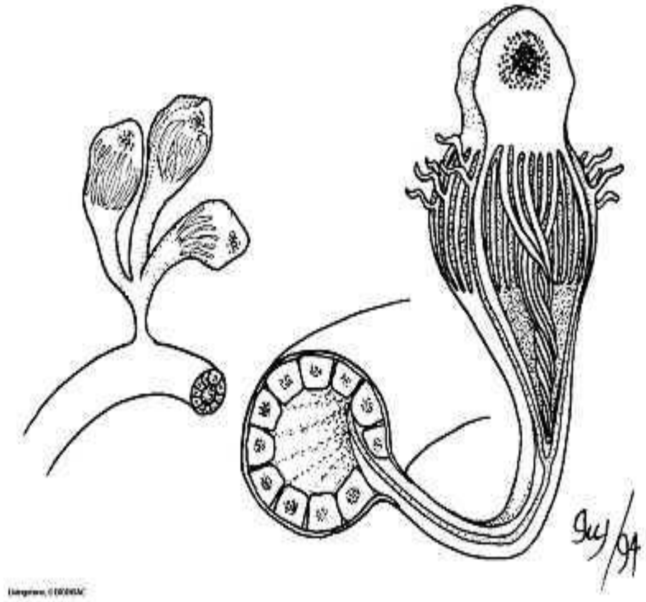
Flame Cells



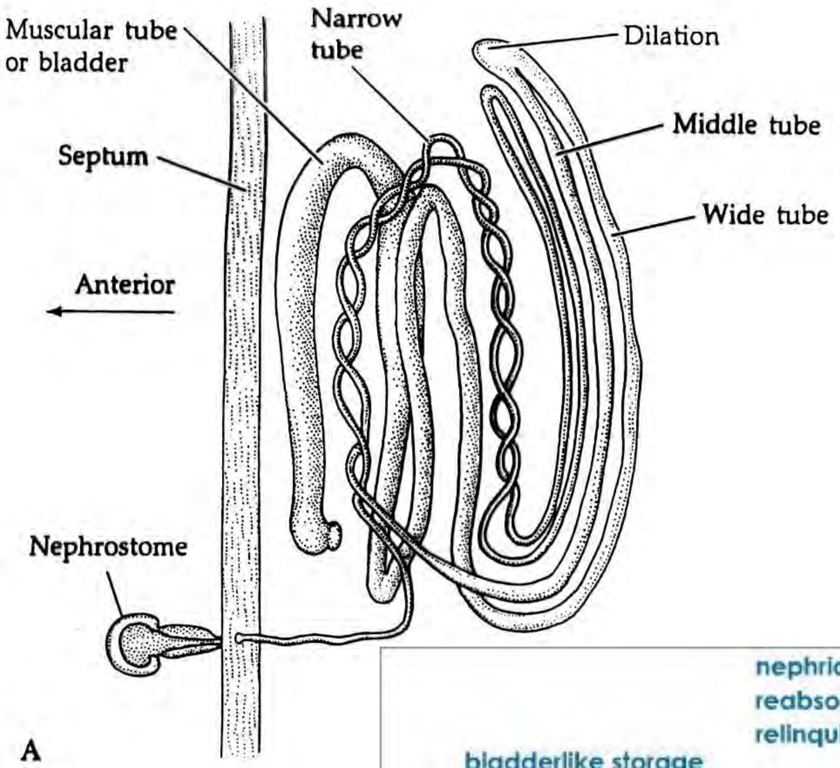


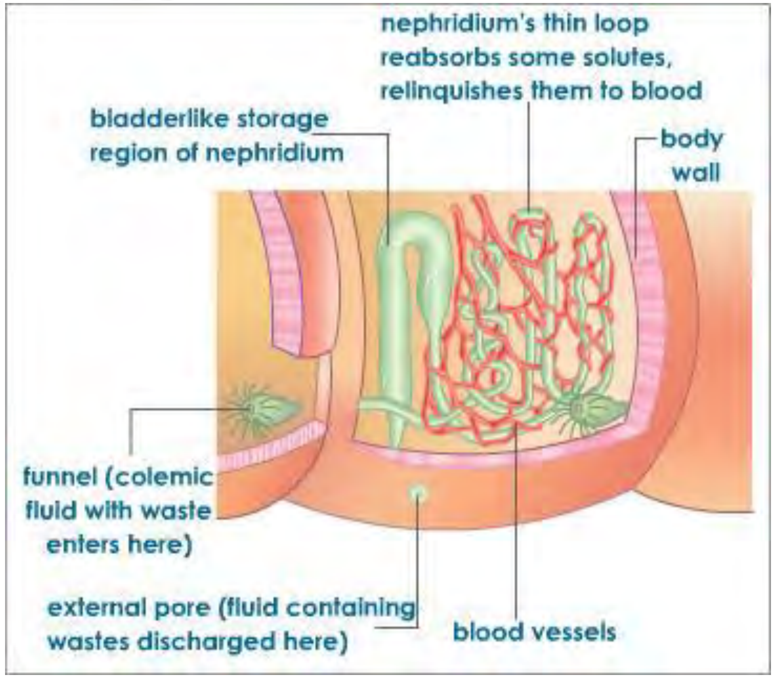
Flame cells (solenocytes) are found in a variety of marine invertebrate animals including acoelomate Platyhelminthes (flatworms) and cephalochordates (*Amphioxus*)

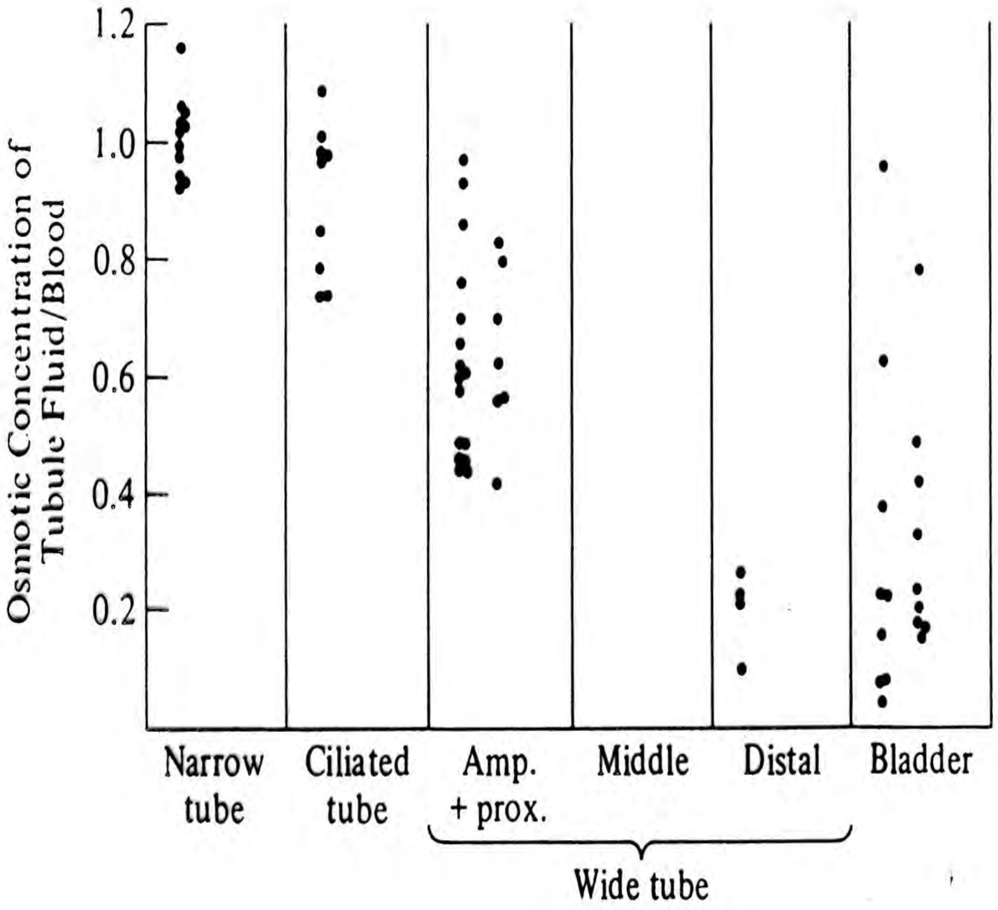




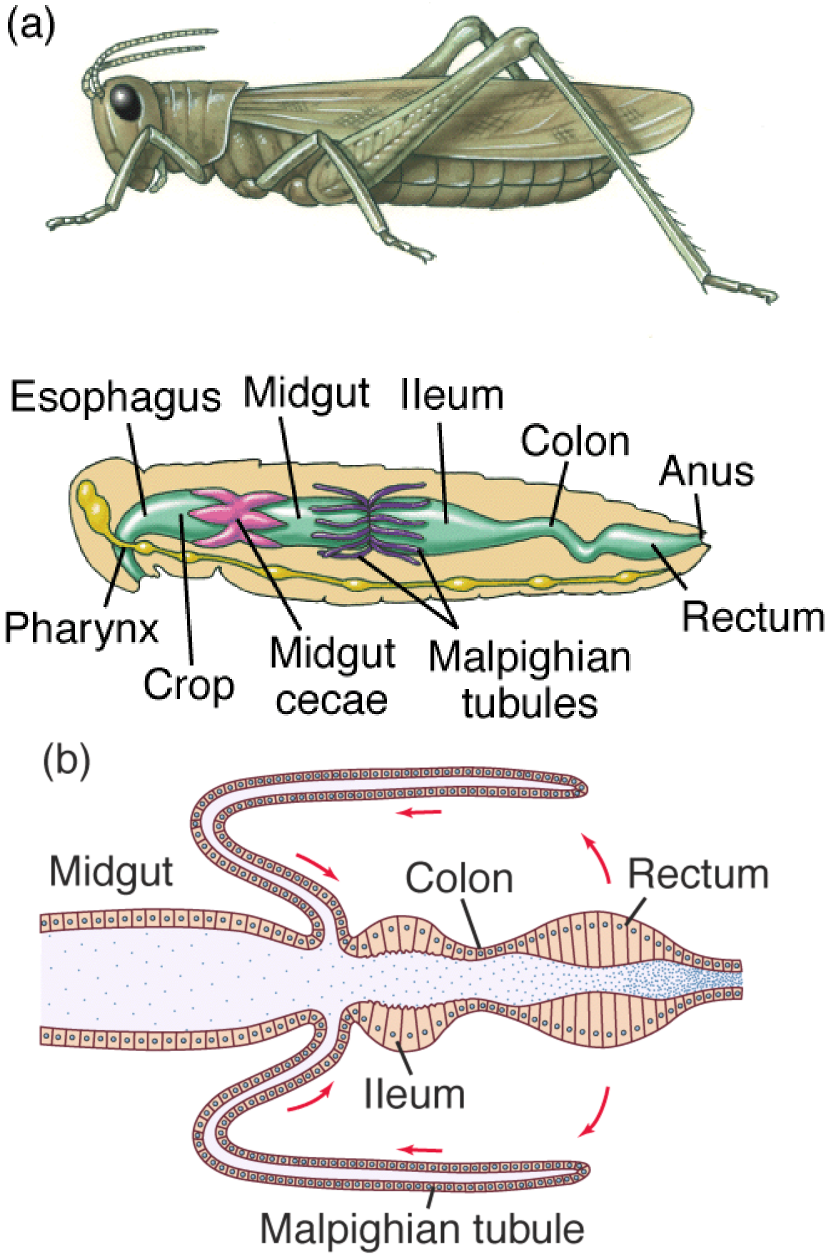
Annelid nephridia

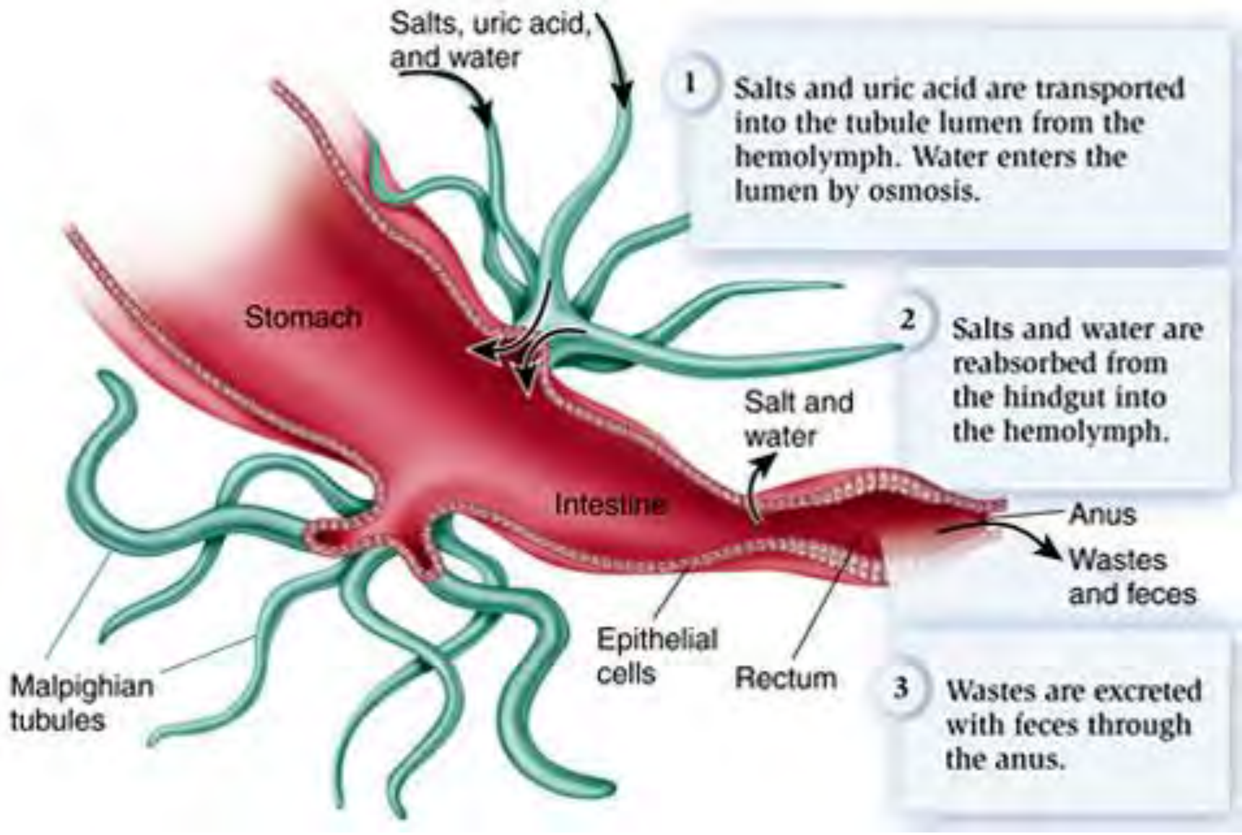




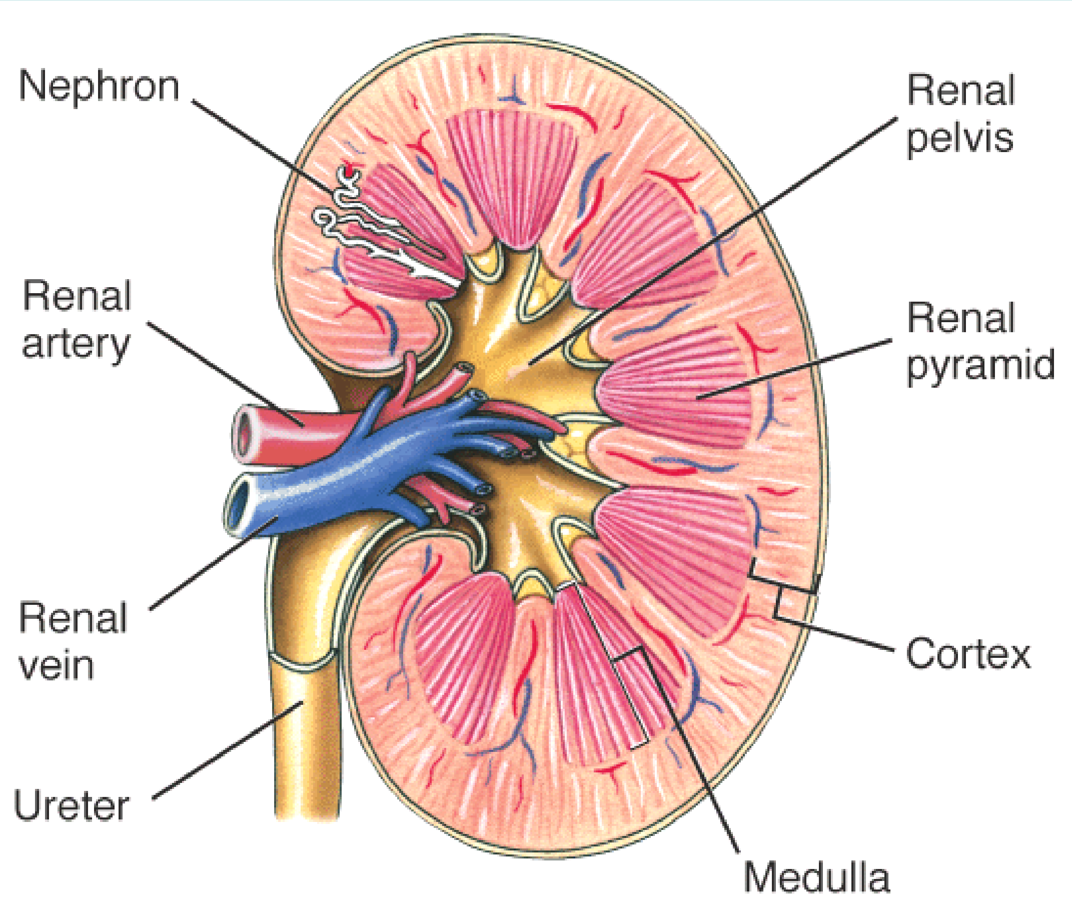


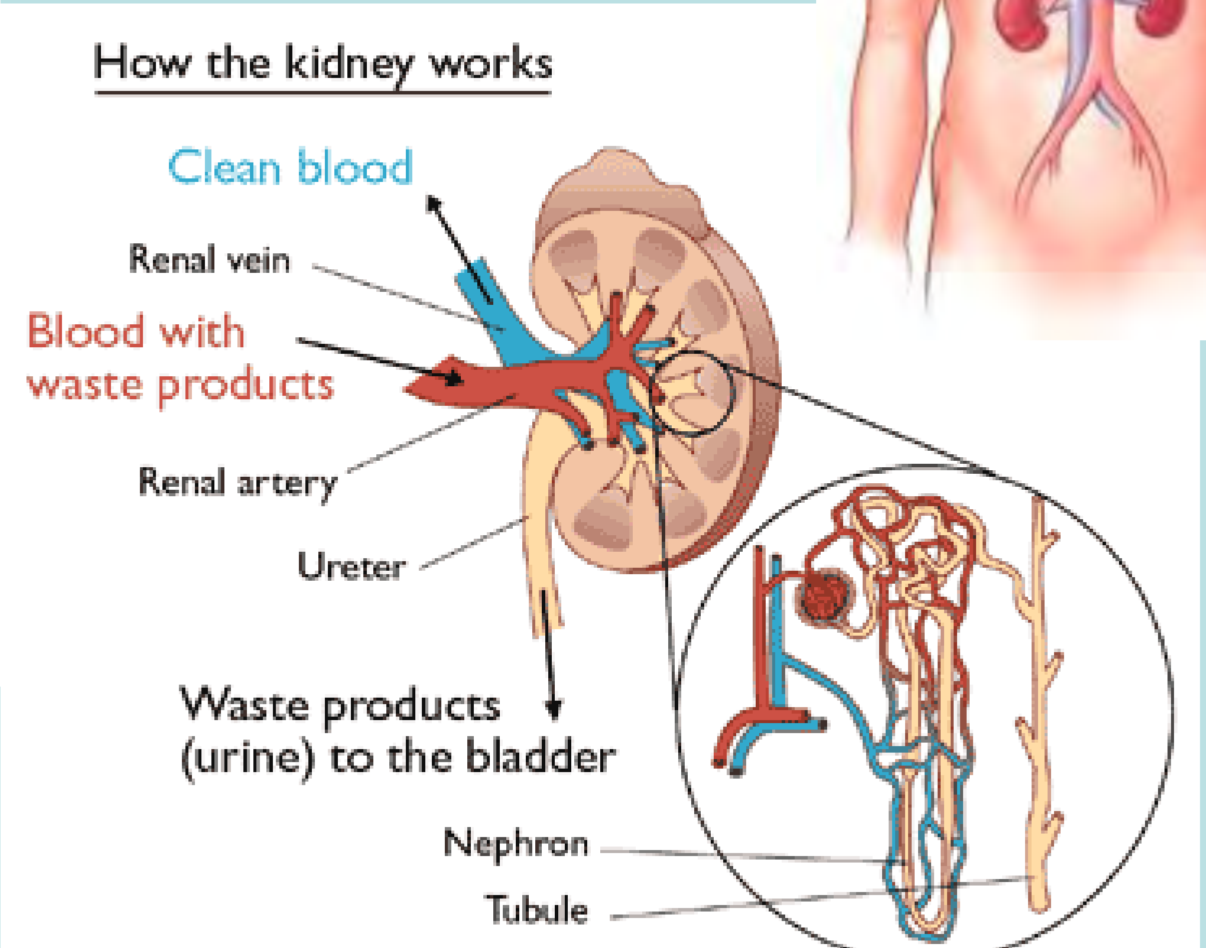
Insect Malpighian tubules

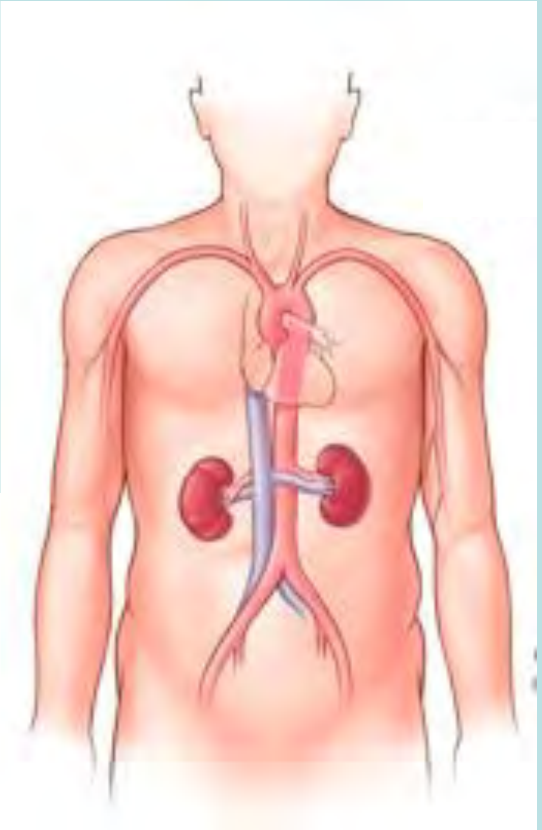




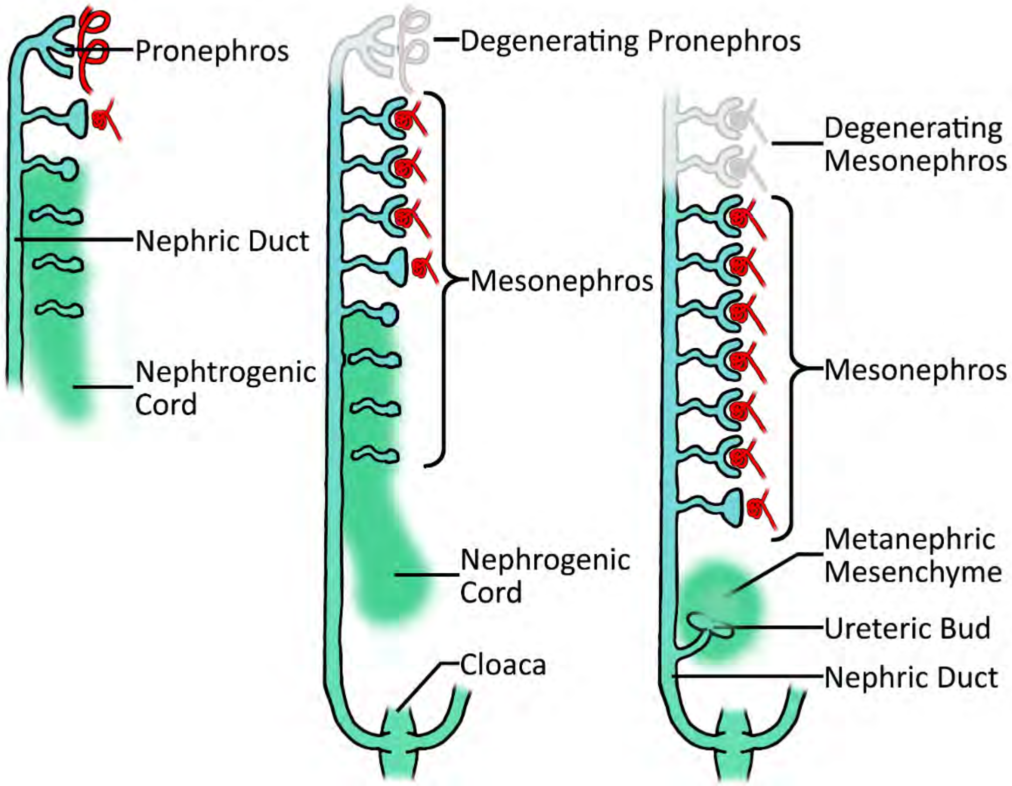
The Mammalian Kidney

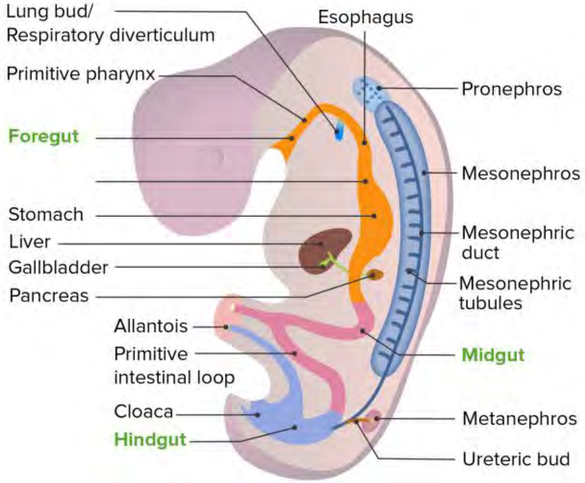


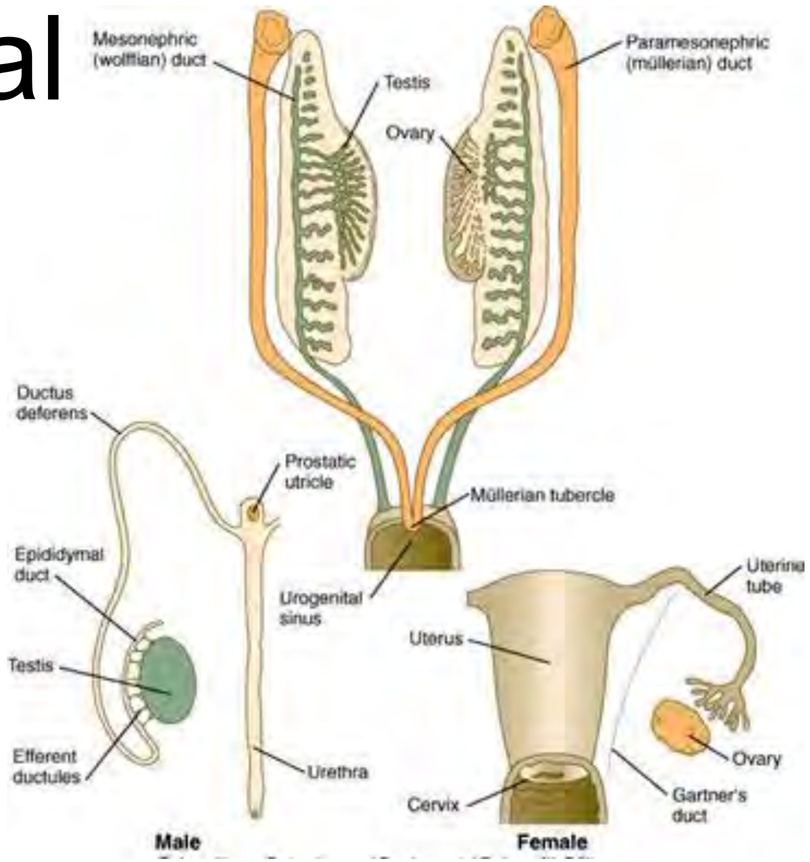


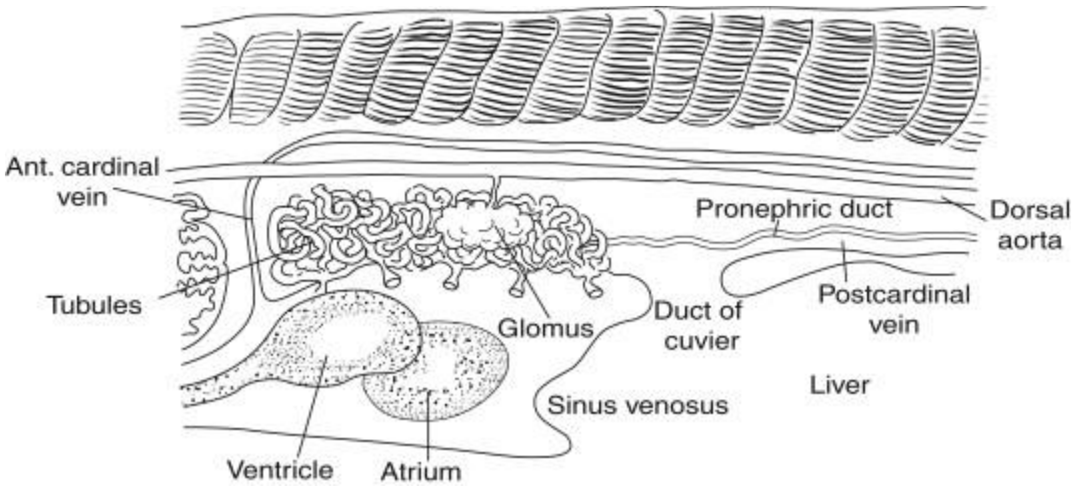


Origin of kidneys and Urogenital Tract

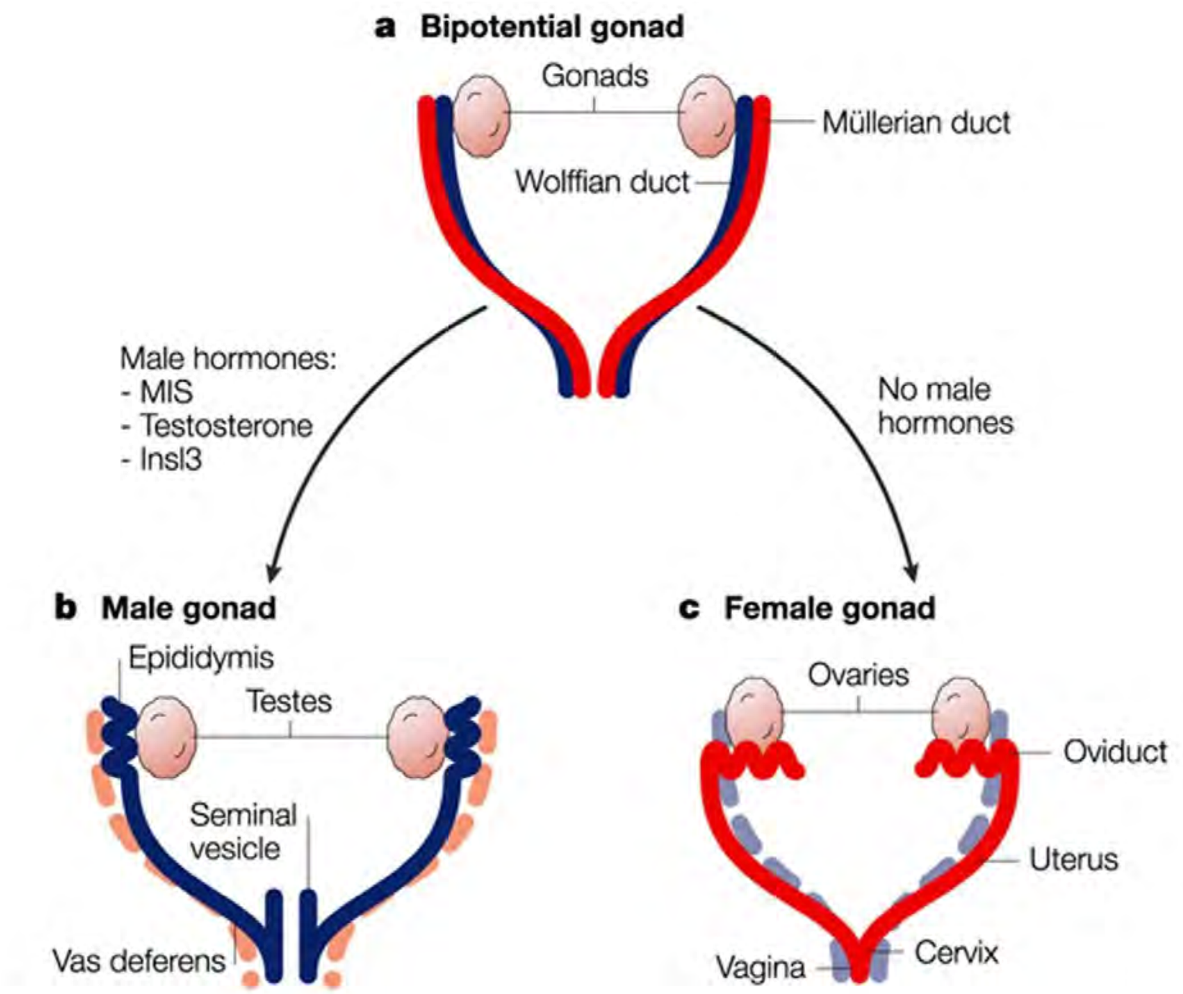




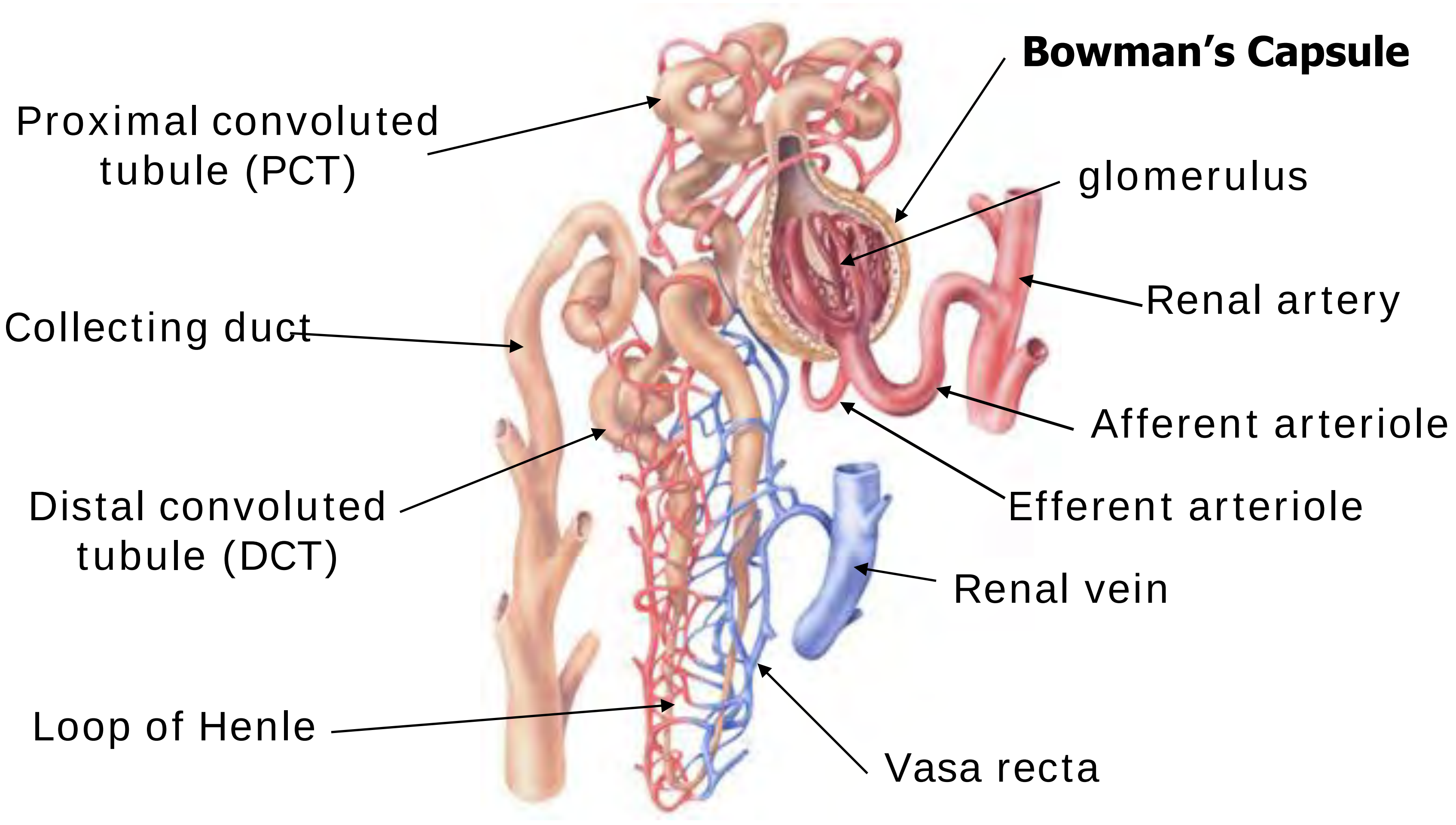




Development of Male and Female Reproductive Tracts

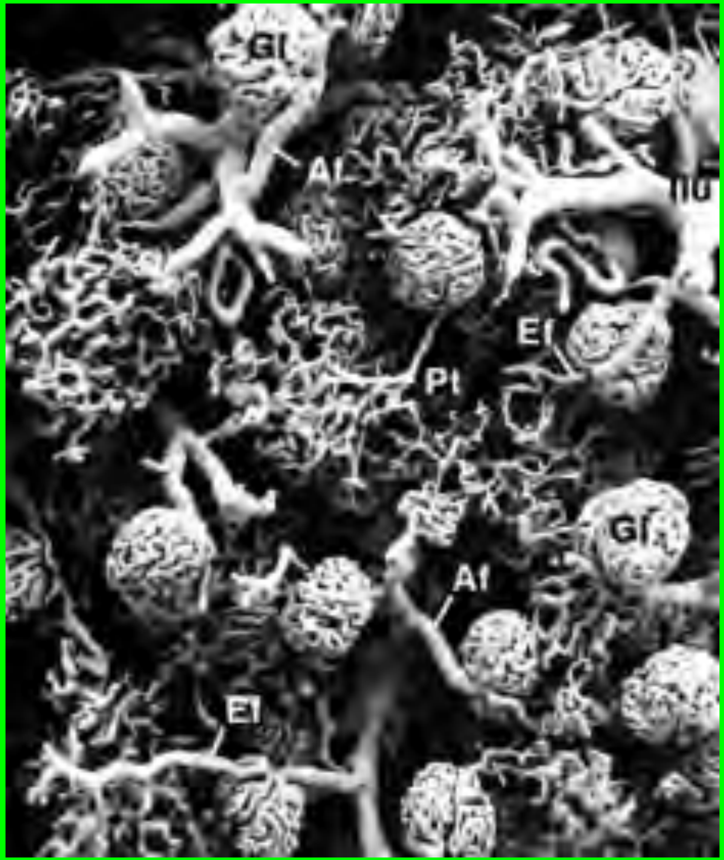


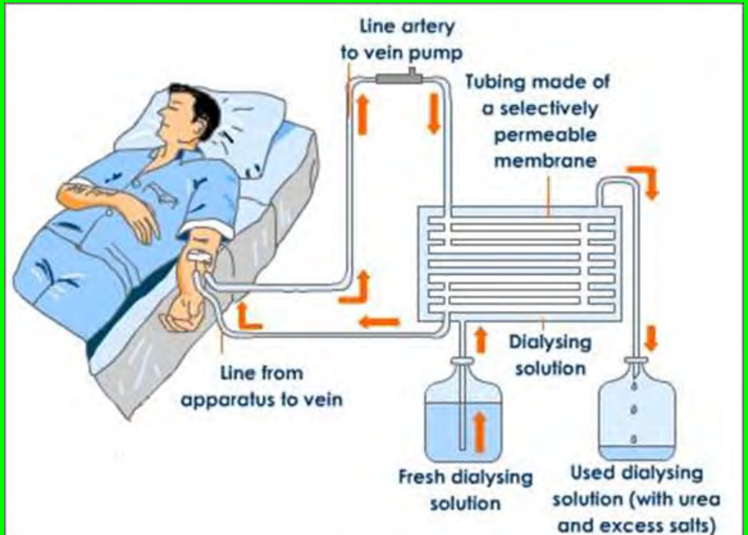
The nephron

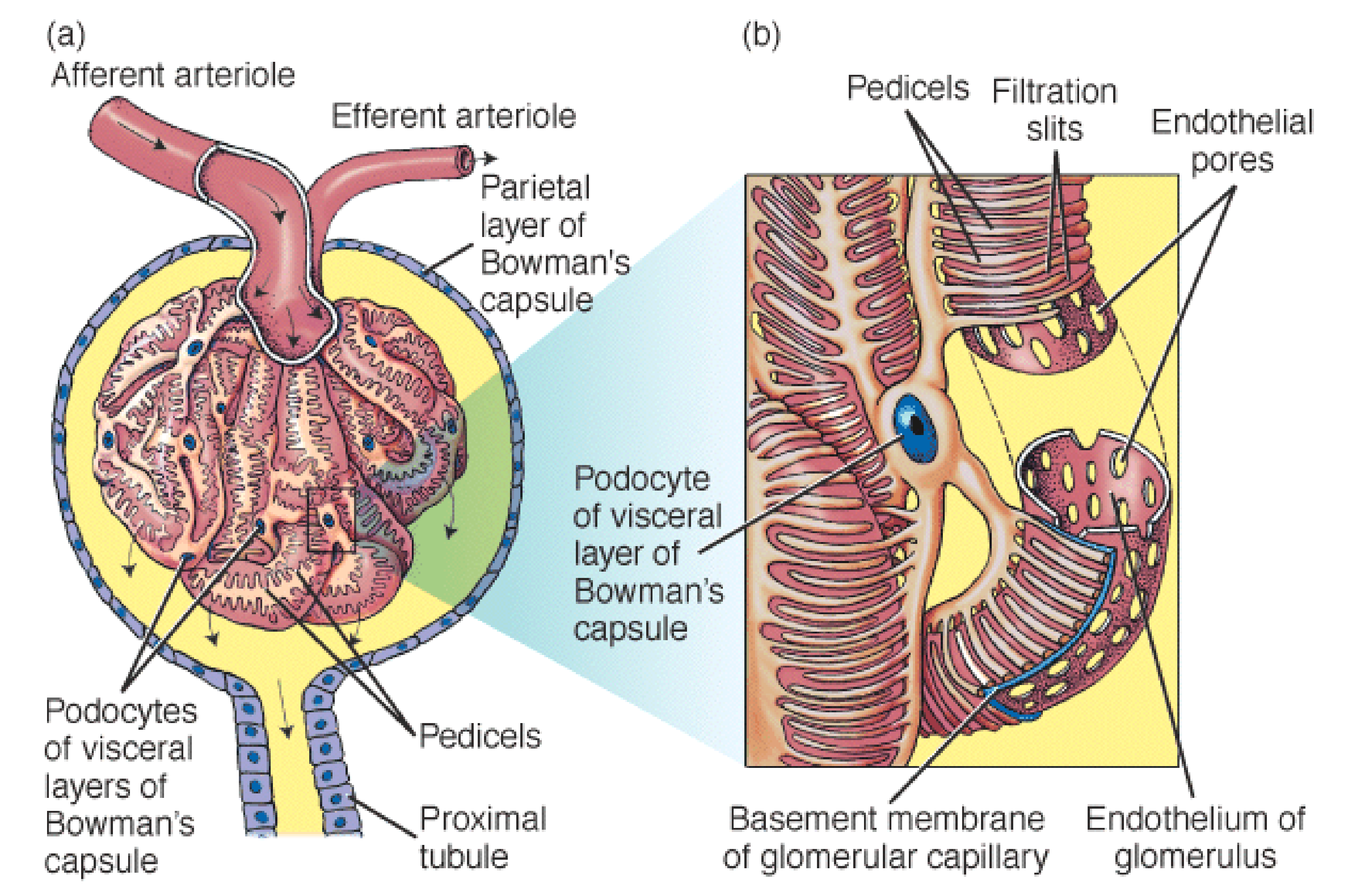


Bowman's Capsule
Proximal convoluted tubule (PCT)
glomerulus
Renal artery
Collecting duct
Afferent arteriole
Efferent arteriole
Distal convoluted tubule (DCT)
Renal vein
Loop of Henle
Vasa recta

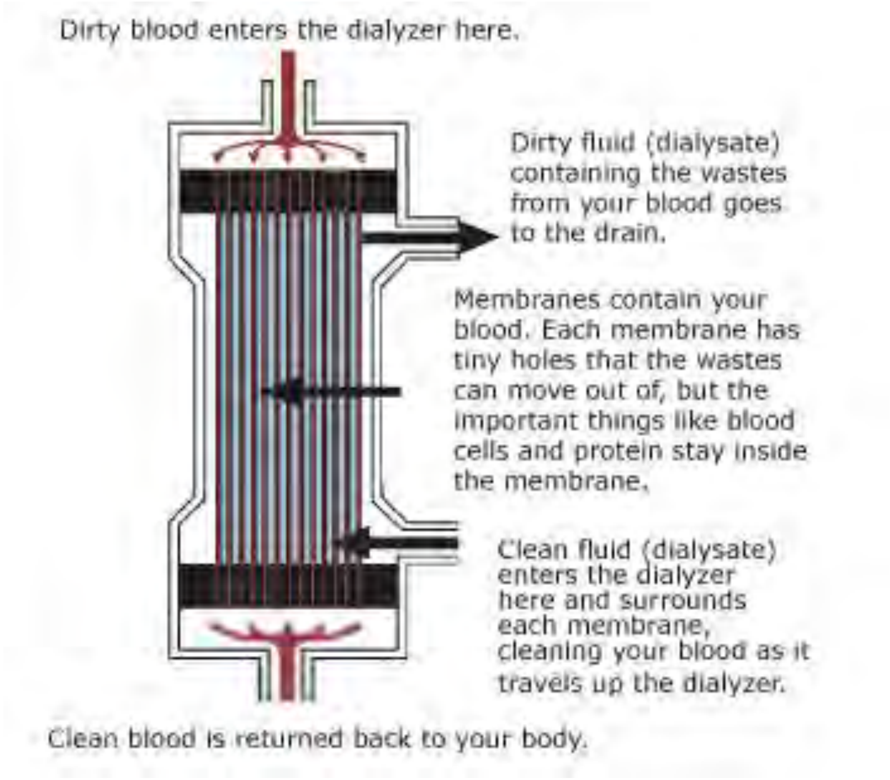
Filtration at the glomerulus: Anatomy



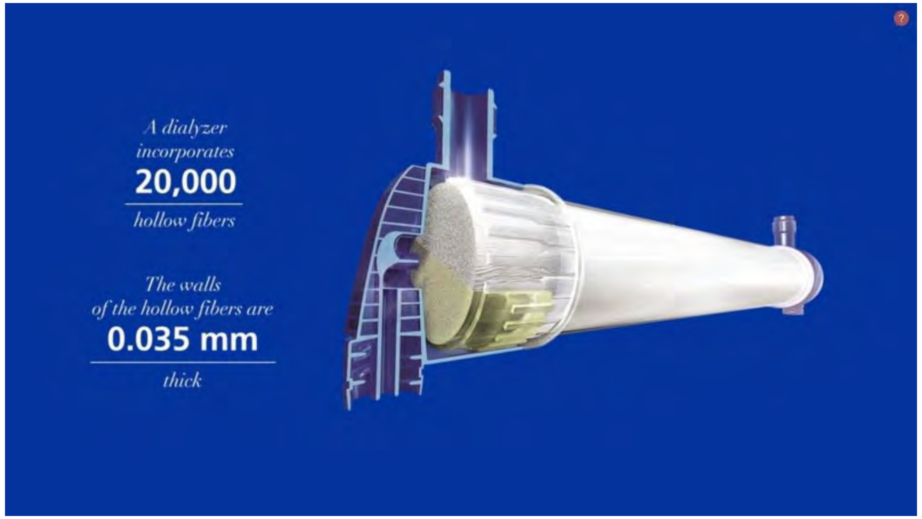




Kidney Dialysis



UNDERSTANDING
HEMODIALYSIS



Filtration at the glomerulus: physiology

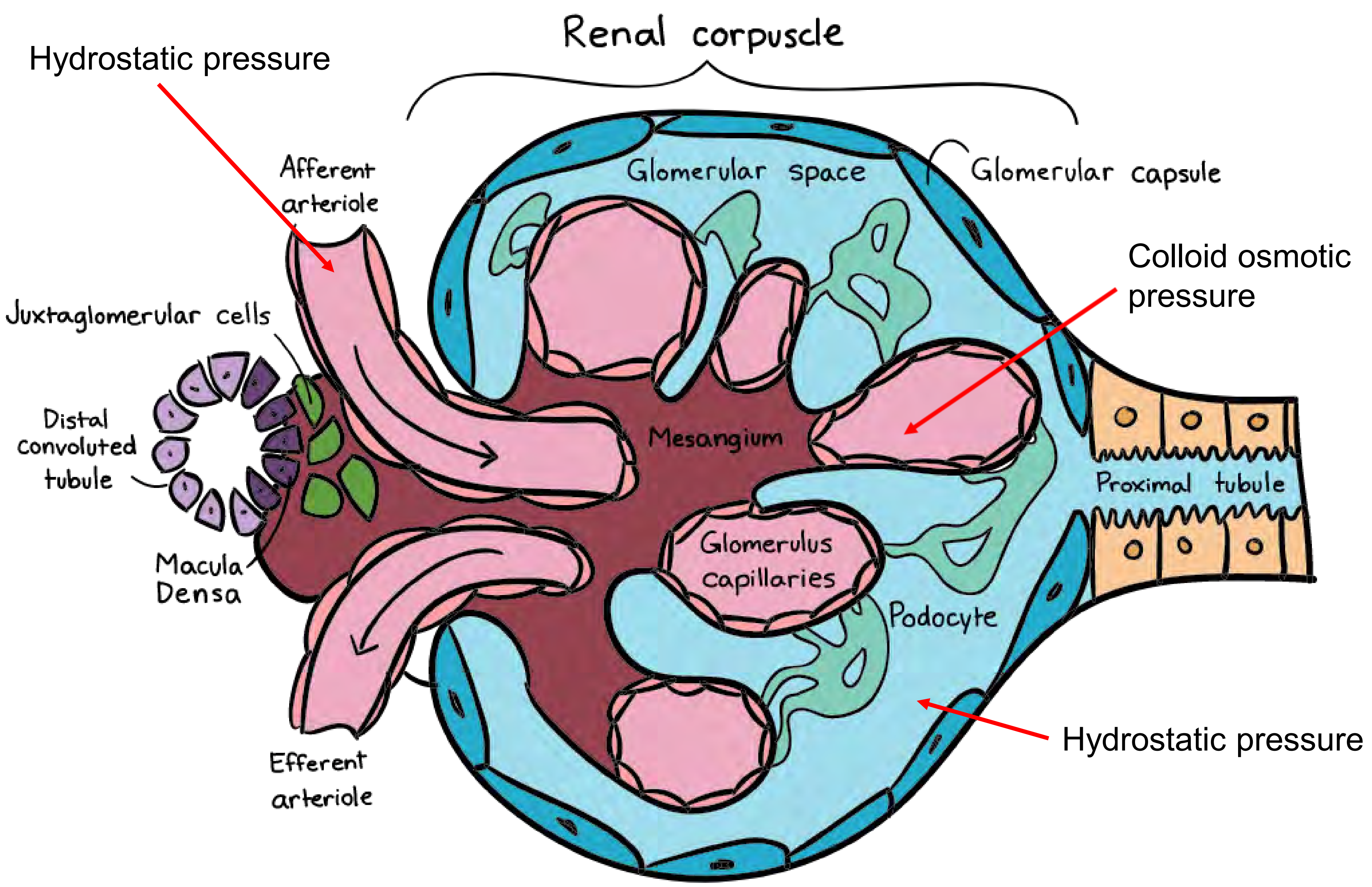
Hydrostatic pressure in glomerulus: 55mmHg

- **Hydrostatic pressure in Bowman's capsule:** 15mmHg

=Net hydrostatic pressure driving filtration: 40mmHg

-Colloid osmotic pressure (COP) in plasma: 30mmHg

=Net pressure driving filtration: 10mmHg


Renal corpuscle
Hydrostatic pressure
Afferent arteriole
Glomerular space
Glomerular capsule
Juxtaglomerular cells
Colloid osmotic pressure
Distal convoluted tubule
Mesangium
Proximal tubule
Glomerulus capillaries
Macula Densa
Podocyte
Hydrostatic pressure
Efferent arteriole

Tubular resorption and secretion

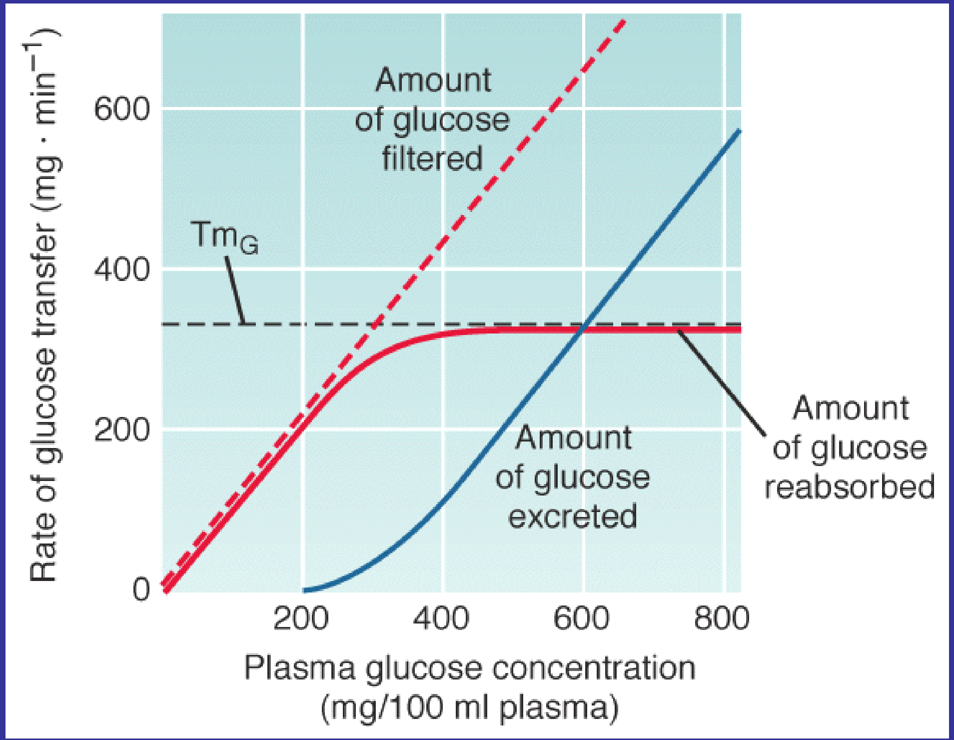
- **The filtrate has the same composition as the blood except for proteins and RBCs (hence the reverse COP)**
- **The function of the PCT and DCT is to resorb those chemicals wanted by the body and to secrete those not wanted.**
- **Renal clearance for any substance is defined as the volume of blood cleared of that substance by the kidney per unit time.**

Filtration and Absorption Values for a Typical Person

Substance (units per day)	Amount Filtered	Amount Resorbed	Amount Excreted	% Recovery from Filtrate
Glucose (gms)	180	180	0	100
HCO_3^- (mEq)	4,320	4,318	2	>99.9
Sodium (mEq)	25,560	25,410	150	99.4
Chloride (mEq)	19,440	19,260	180	99.1
Potassium (mEq)	756	664	92	87.8
Urea (gm)	46.8	23.4	23.4	50
Creatinine (gm)	1.8	0	1.8	0

Resorption and transport maximum

- Substances are filtered into the glomerulus in the same concentration that they are in the plasma.
- Substances that are actively resorbed will be removed from the nephron until the concentration in the filtrate exceeds the ability of the transport mechanism(s) to resorb them.
- This is the transport maximum.

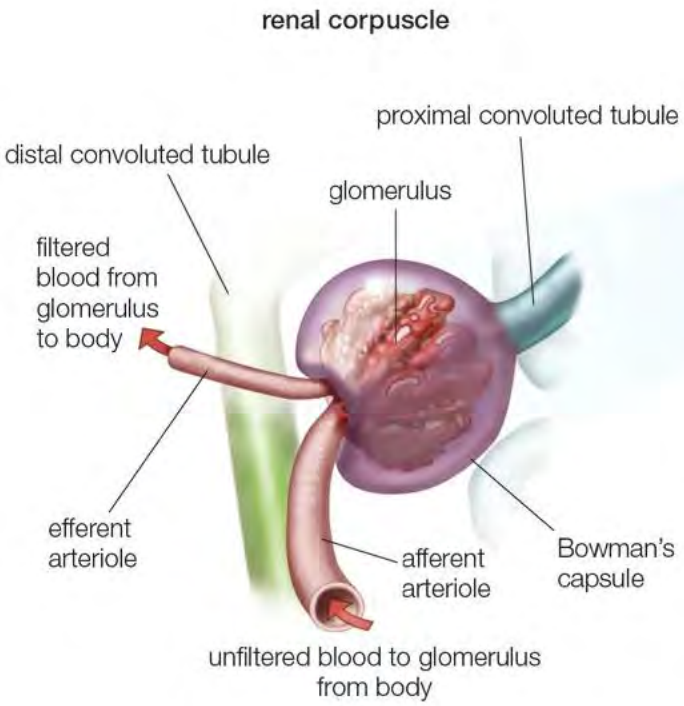


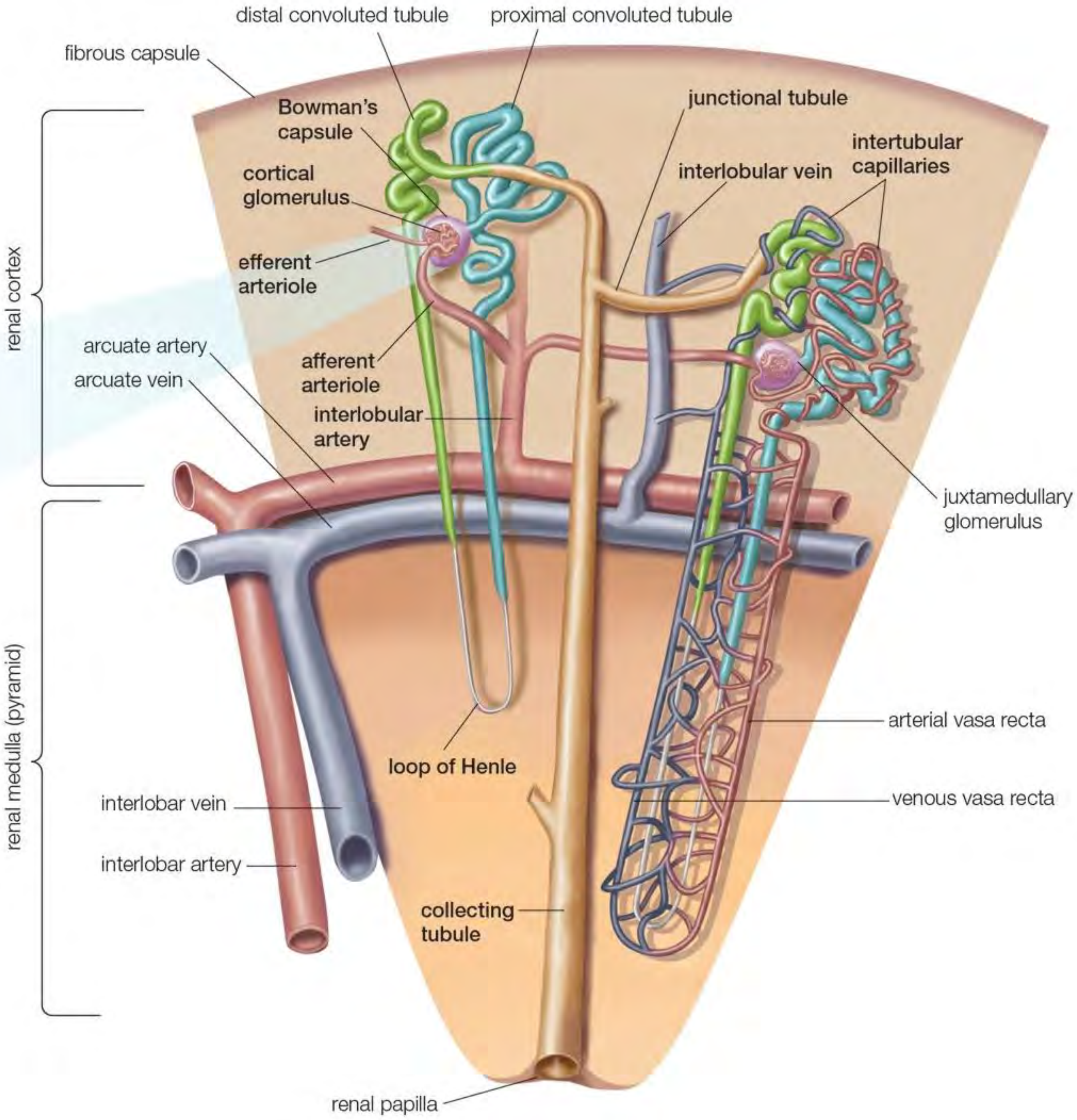
Some transport maxima

Substance	Transport maximum	
Glucose	320	mg/min
Phosphate	0.1	mM/min
Sulfate	0.06	mM/min
Amino Acids	1.5	mM/min
Vitamin C	1.77	mg/min
Urate	15	mg/min
Plasma protein	30	mg/min
Lactate	75	mg/min
Hemoglobin	1	mg/min

Balance Sheet

- Kidneys are perfused by about 500mL of plasma per minute, or 720 liters per day.
- Thus the entire 5 liters of blood passes through the kidneys 144 time per day.
- Kidneys produce about 180 liters of filtrate per day.
- With a typical 5 liters of blood, this means that the blood plasma is completely filtered into the kidney 36 times per day.
- Typical urine output is close to 1 liter per day.
- Thus about 99% of the filtrate is resorbed.

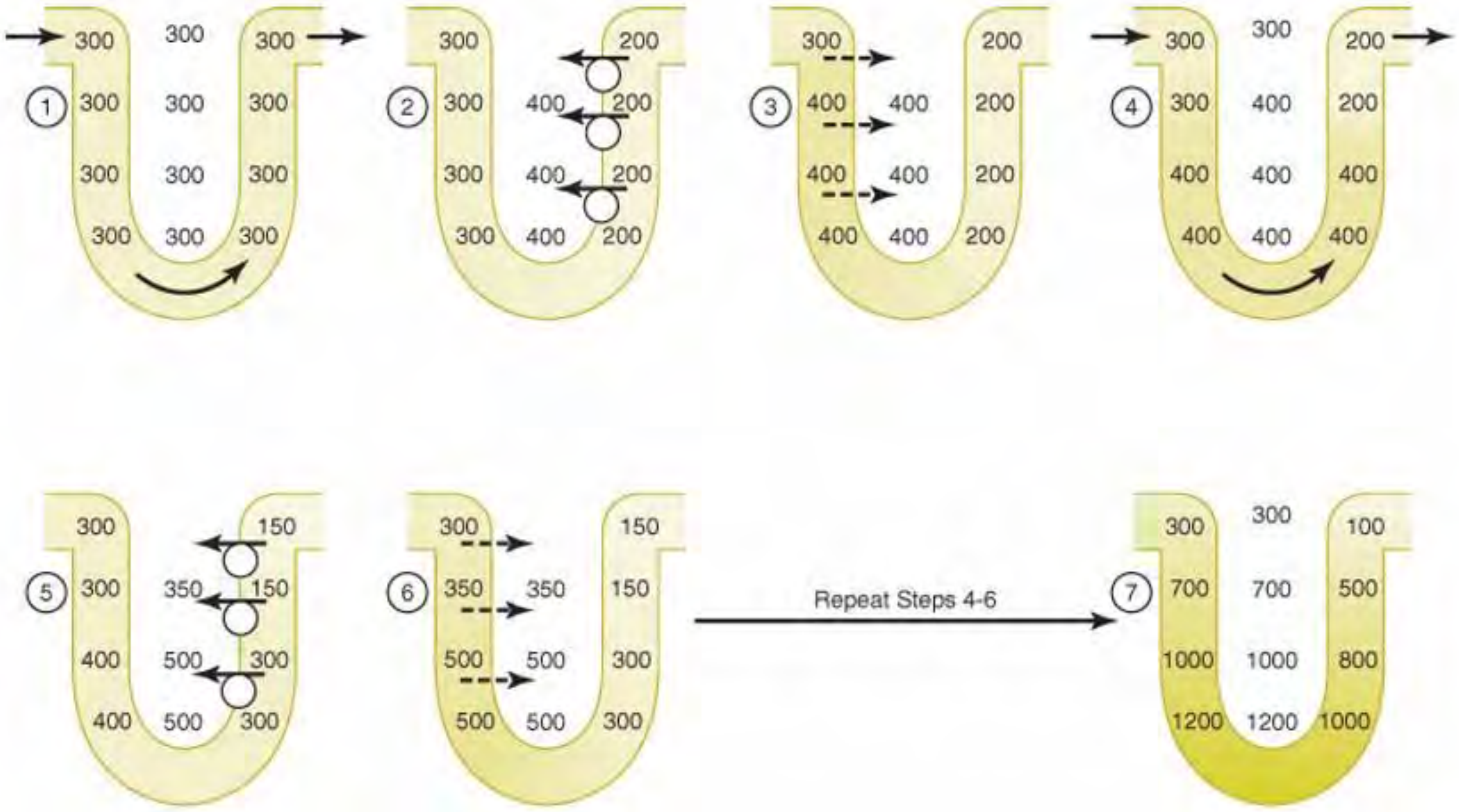

renal corpuscle
proximal convoluted tubule
distal convoluted tubule
glomerulus
filtered blood from glomerulus to body
efferent arteriole
afferent arteriole
Bowman's capsule
unfiltered blood to glomerulus from body


distal convoluted tubule
proximal convoluted tubule
fibrous capsule
Bowman's capsule
junctional tubule
intertubular capillaries
cortical glomerulus
interlobular vein
renal cortex
efferent arteriole
arcuate artery
arcuate vein
afferent arteriole
interlobular artery
juxtamedullary glomerulus
renal medulla (pyramid)
arterial vasa recta
loop of Henle
venous vasa recta
interlobar vein
interlobar artery
collecting tubule
renal papilla

Producing an Osmotic Gradient in the Kidney: the loop of Henle Countercurrent Mechanism

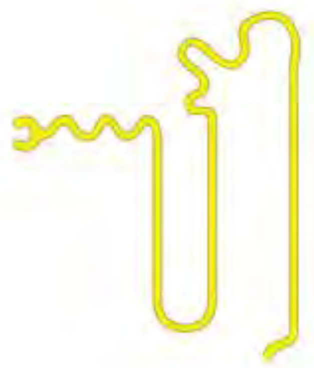
Descending tubule is permeable to water but not to Na^+

Ascending tubule is impermeable to water but actively pumps Na^+



Values in mOsm/L

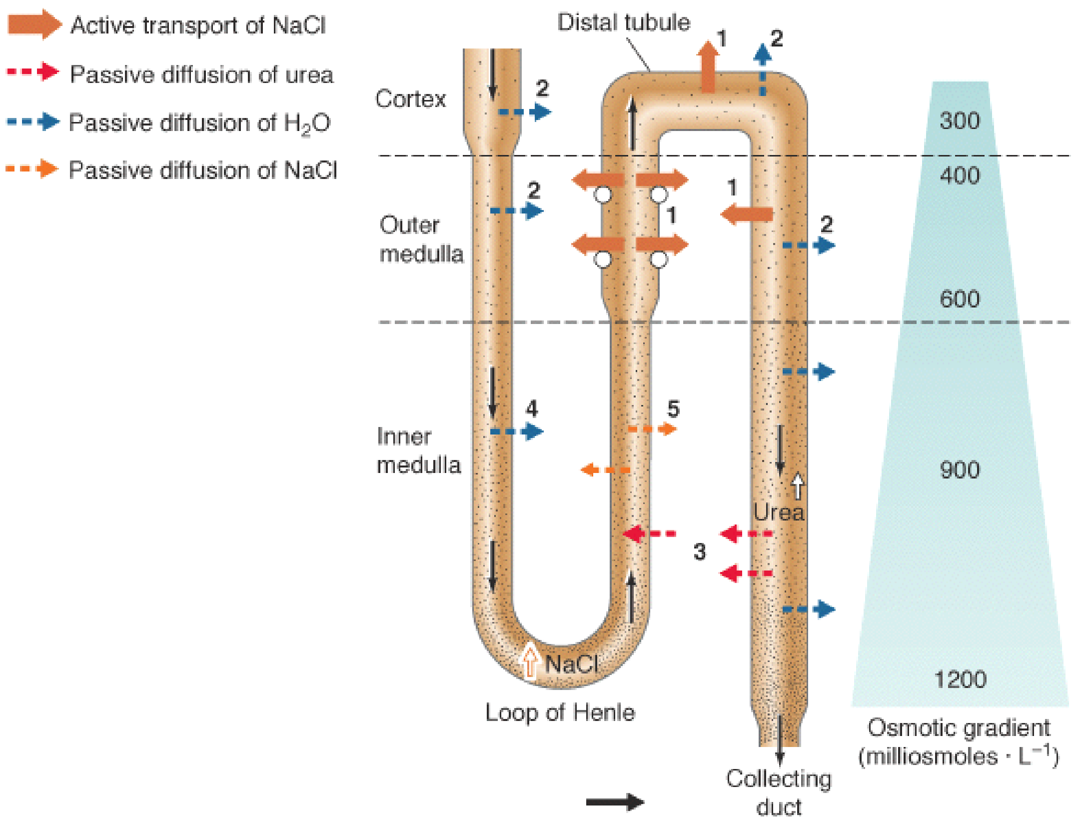
Formation of the cortical gradient



Water recovery mechanism: the collecting duct

The osmotic gradient set up by the loop of Henle is used to extract water from the collecting duct as it descends.

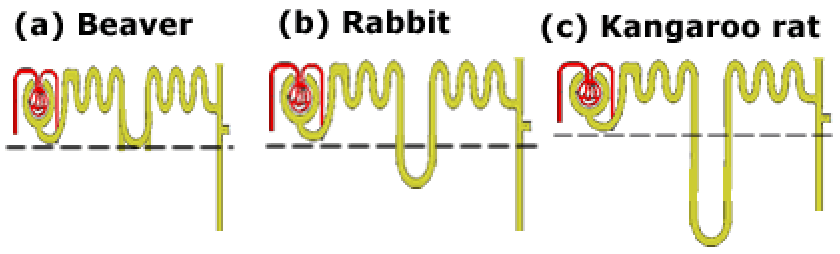
Control of water resorption relies on control of permeability of the descending collecting duct.

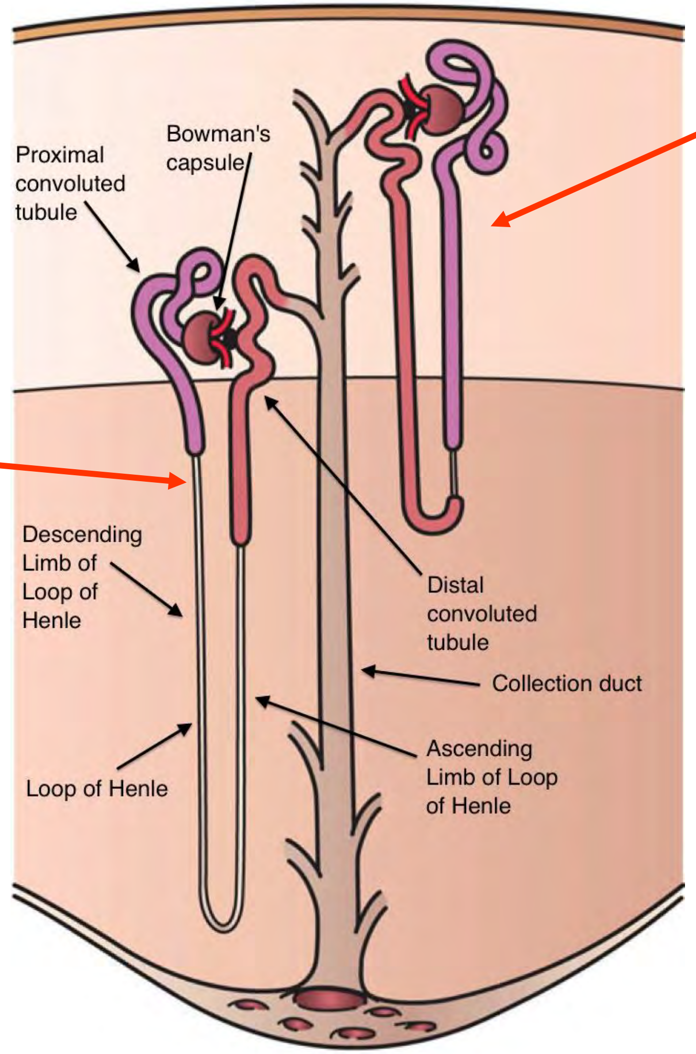


Loop of Henle distribution

Juxtamedullary nephron

Cortical Nephron

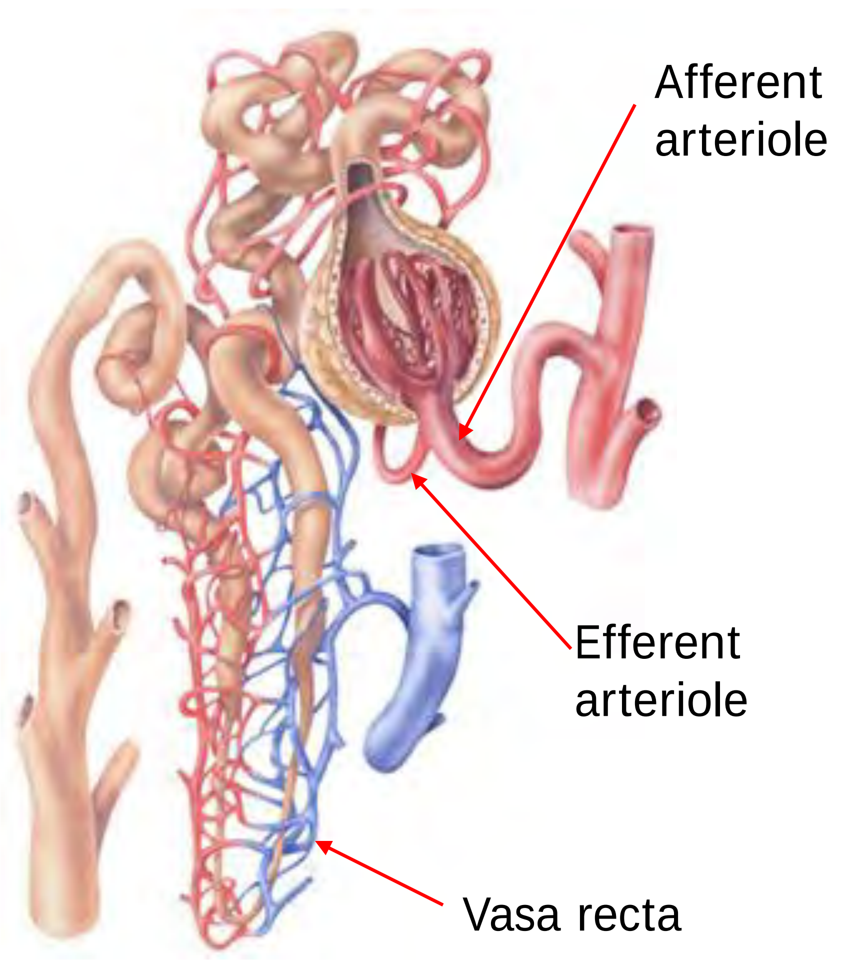




Juxtamedullary nephrons are only found in birds and mammals.

Urine concentrating mechanism: the vasa recta

- **Blood leaving the glomerulus is at a low hydrostatic pressure.**
- **It enters the descending vasa recta.**
- **As it descends through the cortex of the kidney it loses water and becomes more hyperosmotic.**
- **As it then ascends it picks up water and becomes less hyperosmotic**
- **Because of the high rate of flow, equilibrium is not fully established, and the blood leaving the vasa recta has more water than that entering it.**
- **This keeps the kidney gradient intact and returns the water to general circulation.**

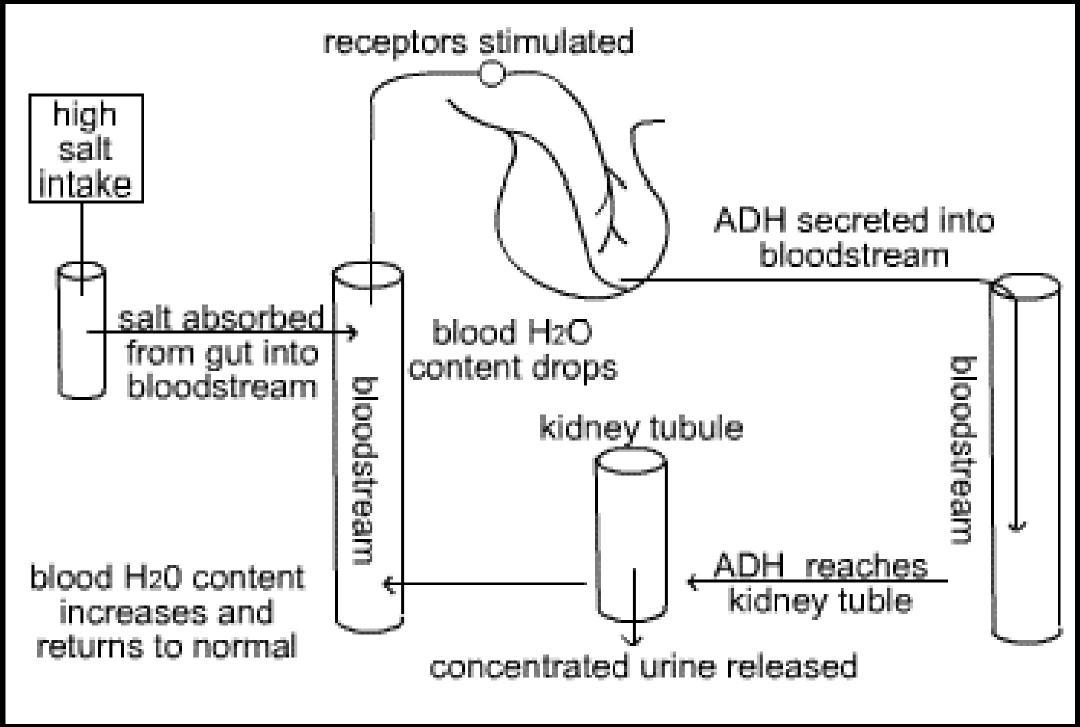


Water resorption in the human kidney

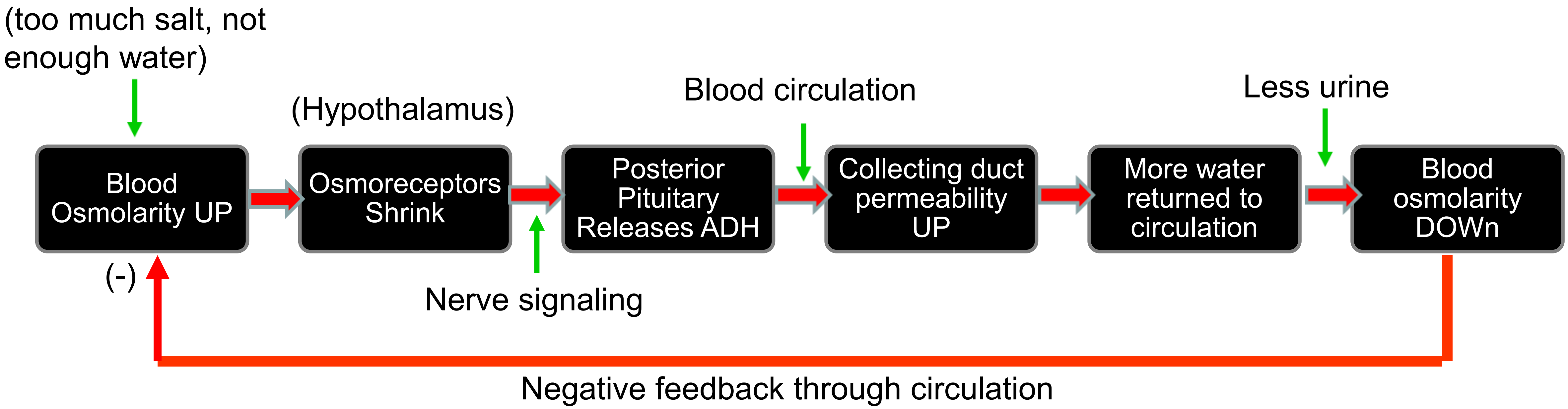
Location	Flow (mL/min)			% absorbed
	In	Out	Change	
Proximal tubule	125	25	100	80
Loop of Henle	25	18	7	6
Distal tubule	18	6	12	9
Collecting duct	6	4	2	4
Total				99

Regulation of the kidney: ADH

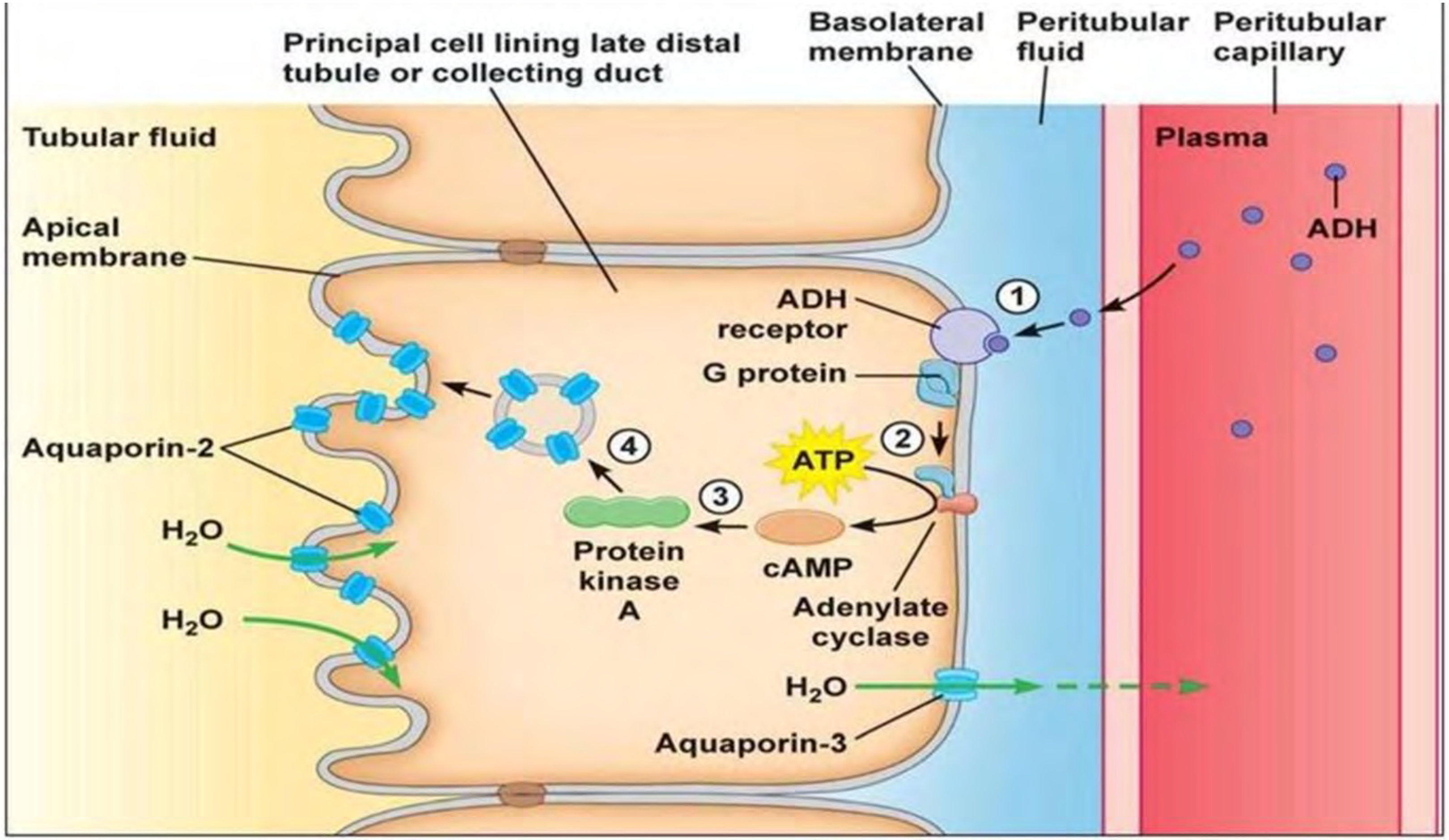
Hypothalamic osmoreceptors respond to blood osmolarity. When they shrink (blood osmolarity up) they fire action potentials which travel down the posterior pituitary and release antidiuretic hormone (vasopressin, also known as ADH). The ADH causes the walls of the collecting duct to become more permeable to water (increases the number of active water channels), thus allowing more water resorption and producing a more concentrated urine.



The ADH Control System



Cellular Mechanism of ADH



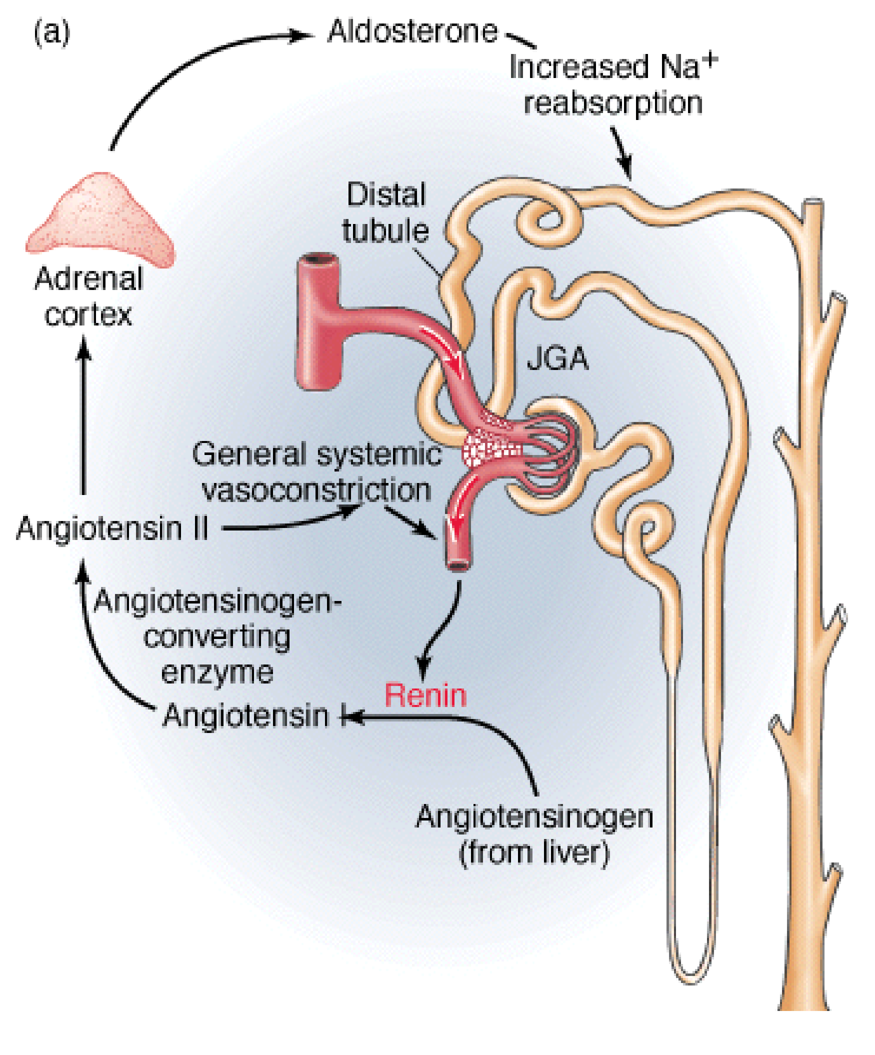
Regulation of the kidney: aldosterone

Cells in the juxtaglomerular apparatus (JGA) respond to low afferent arteriolar pressure and to low plasma sodium content (a measure of blood osmolarity) by secreting renin.

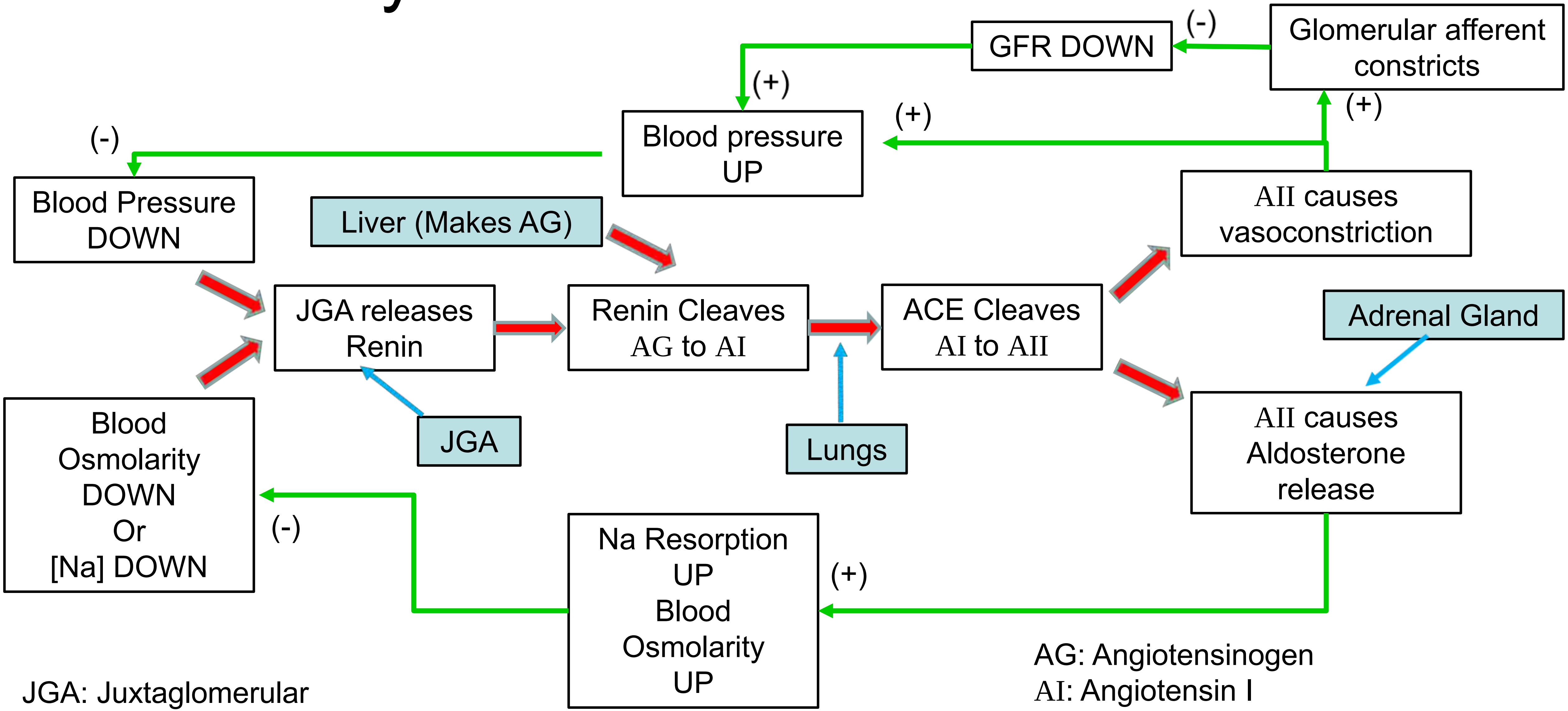
Renin catalyses the cleavage of circulating angiotensinogen into the active angiotensin I (AI).

Angiotensin Converting Enzyme (ACE), found on the vascular endothelium (especially in the lungs) cleaves the AI to angiotensin II (AII).

AII raises blood pressure and blood osmolarity by, among other things, vasoconstriction of the arterioles and increasing Na absorption in the DCT via the release of aldosterone.



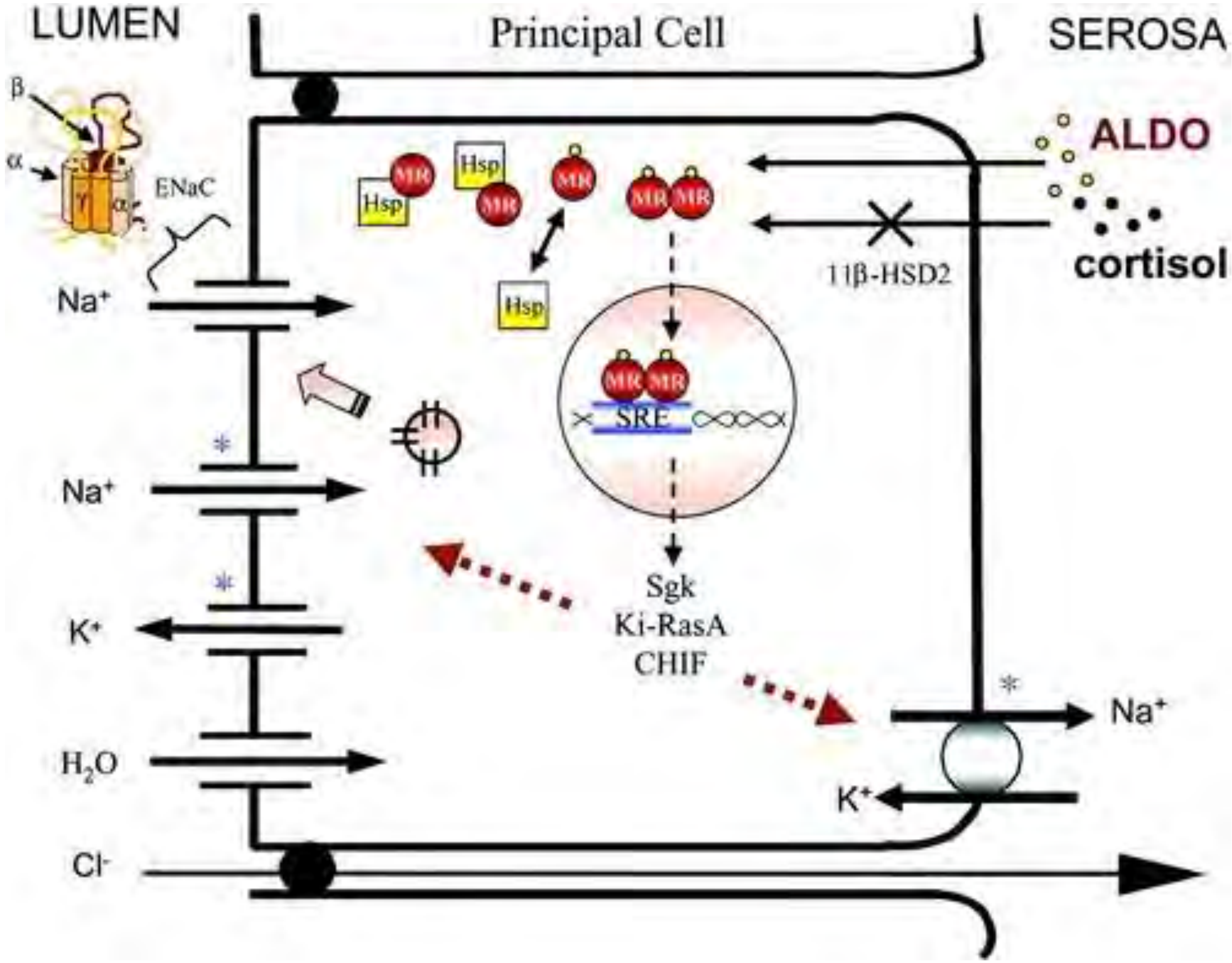
Juxtaglomerular Apparatus/Aldosterone Control Cycle



JGA: Juxtaglomerular Apparatus

AG: Angiotensinogen
AI: Angiotensin I
AII: Angiotensin II

Cellular Mechanism of Aldosterone



Regulation of the kidney: Atrial natriuritic peptide

Atrial natriuritic hormone (ANP) is released by the right atrium of the heart in response to increased venous pressure (or increased Na content.)

It acts to lower blood pressure by

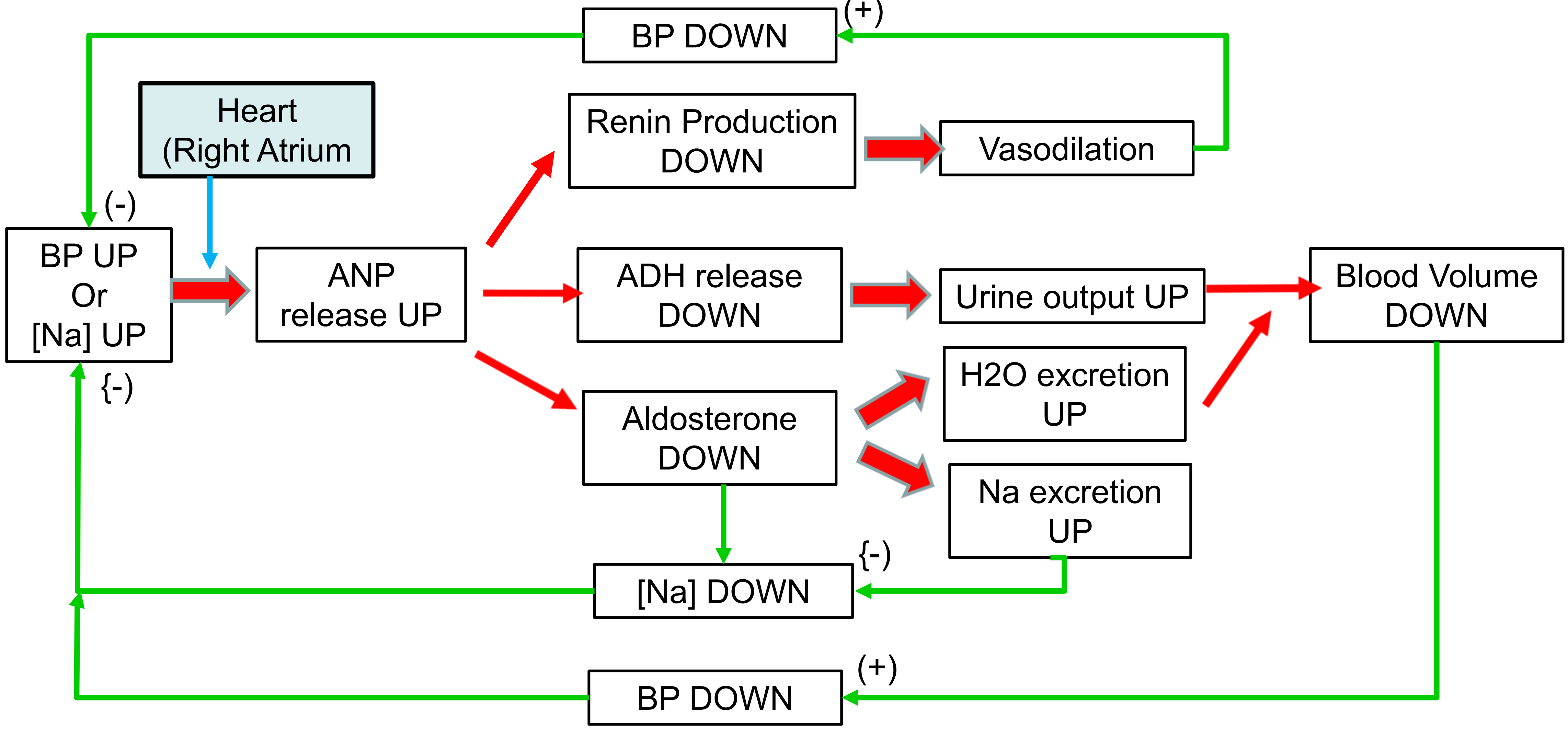
(1) inhibiting the production of renin by the JGA;

(2) inhibiting the release of ADH from the pituitary;

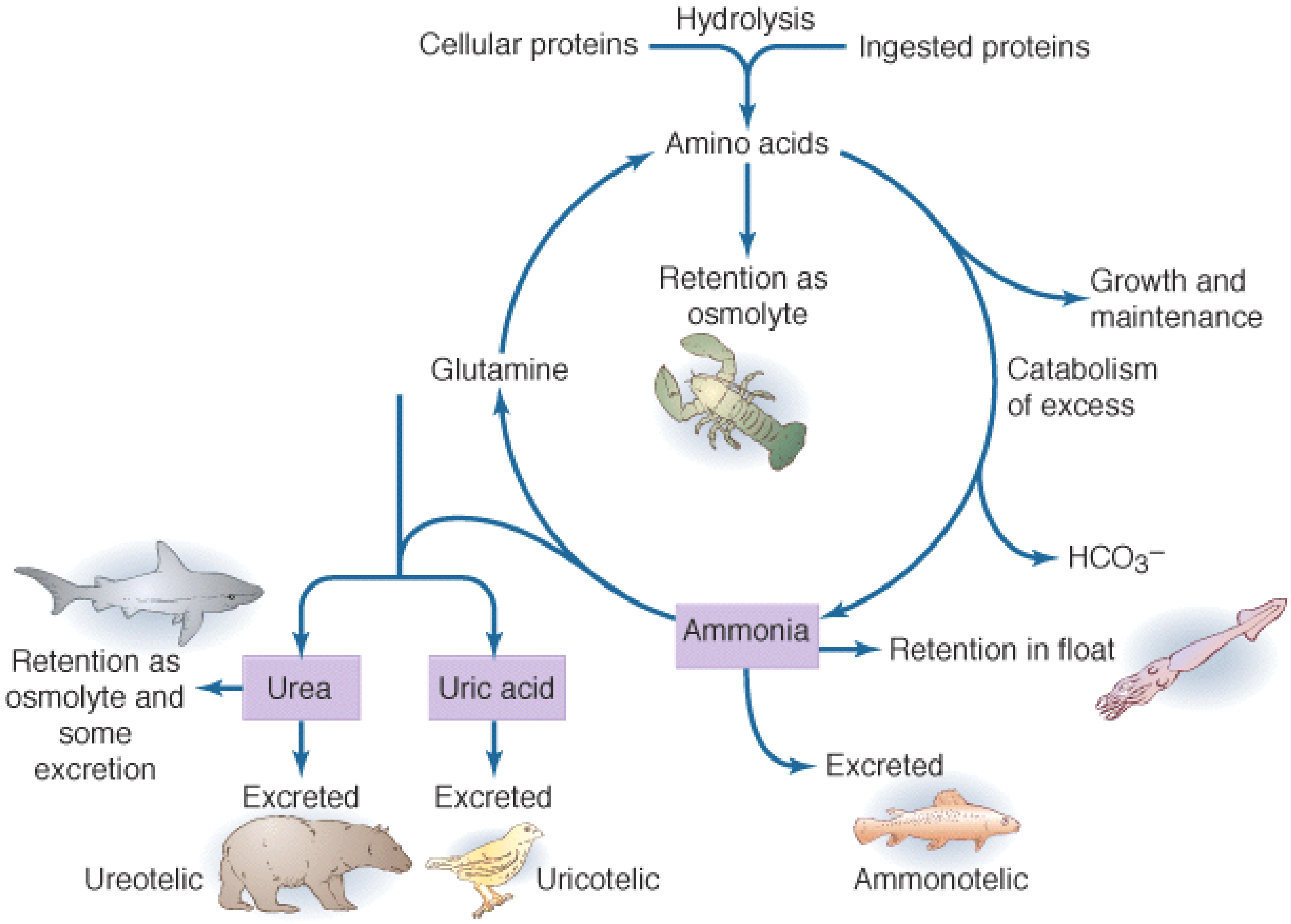
(3) inhibiting the production of aldosterone by the adrenal cortex;

(4) lowering arteriolar resistance, venous resistance and cardiac output.

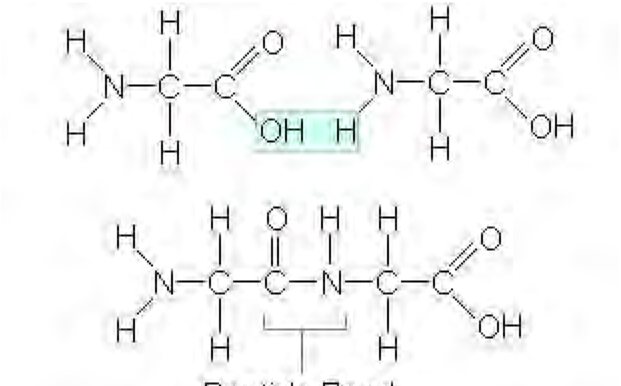
Atrial Naturitic Peptide (ANP) Cycle



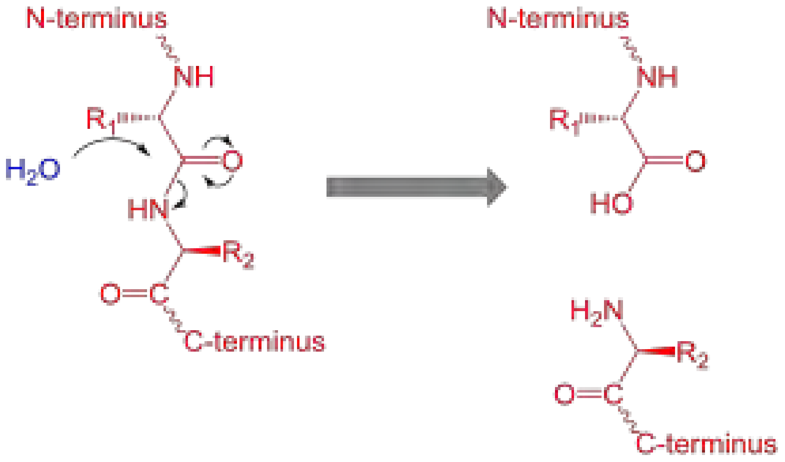
Nitrogen excretion



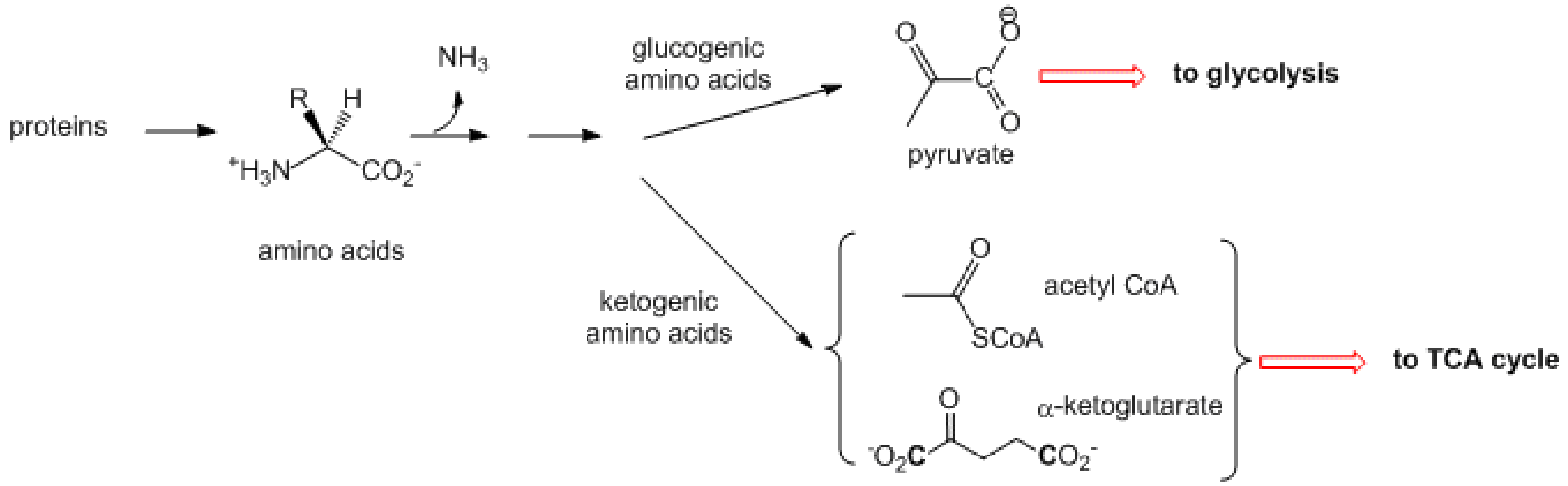
Source of Nitrogen: Protein Catabolism



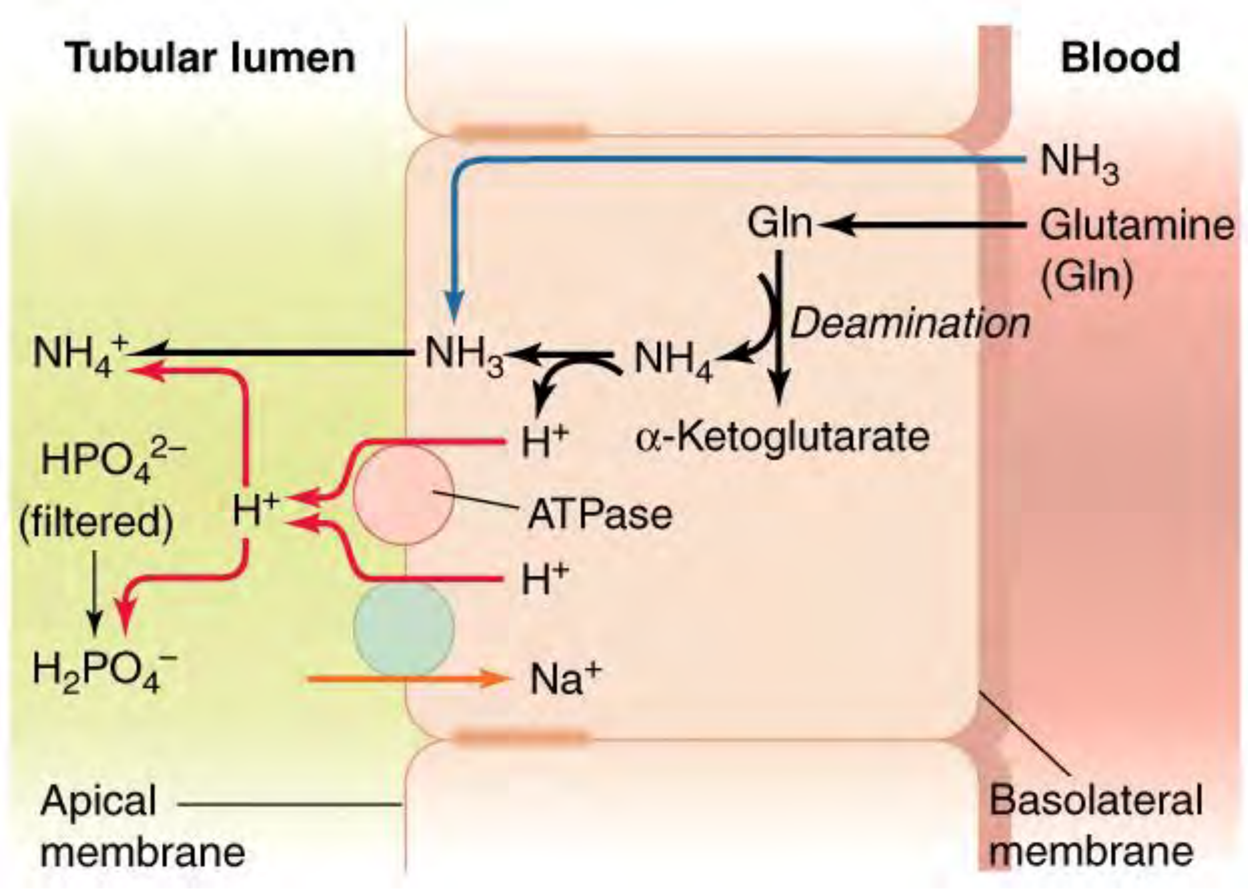
A molecule of water is removed from two glycine amino acids to form a peptide bond.



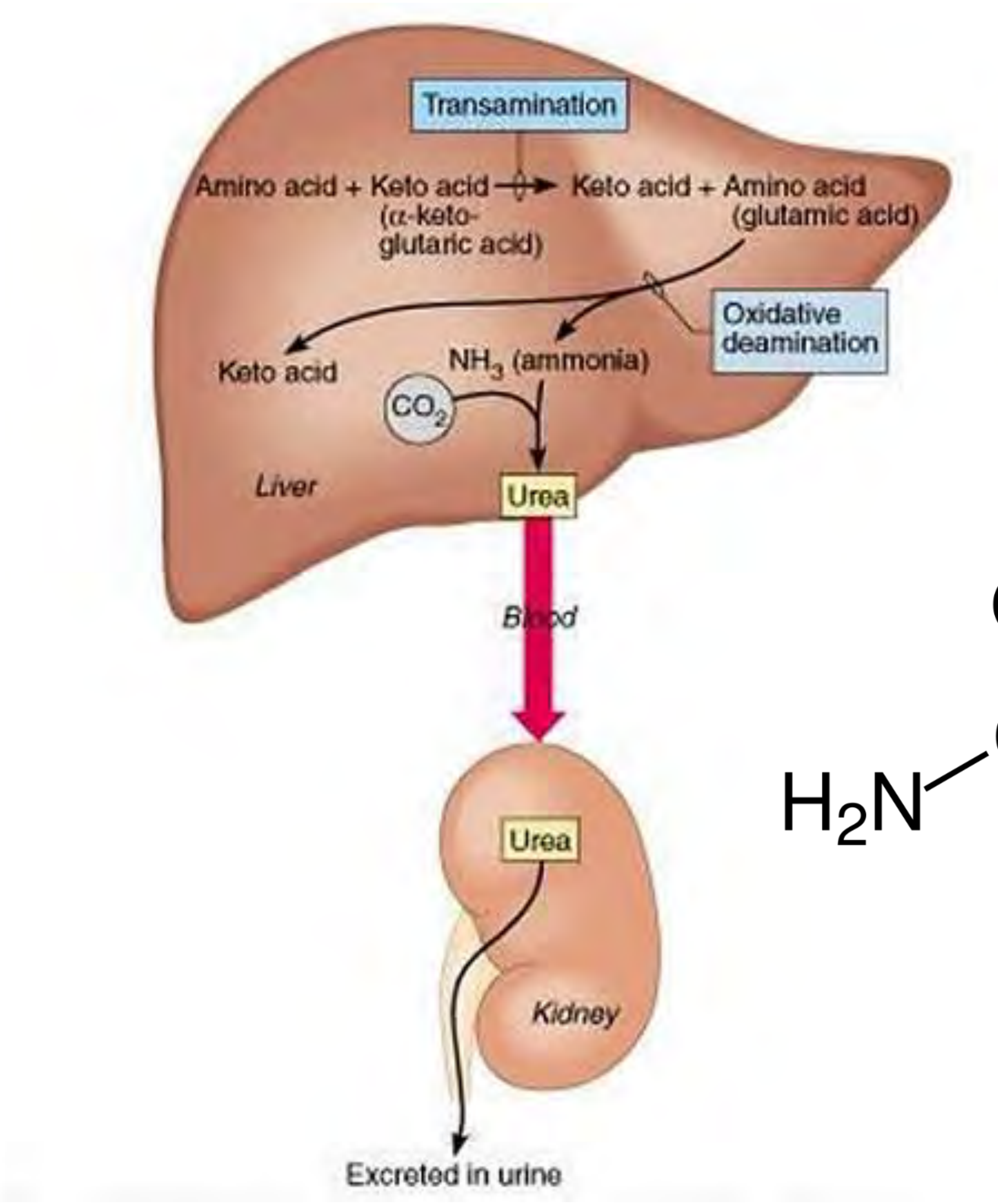
PROTEIN DEGRADATION

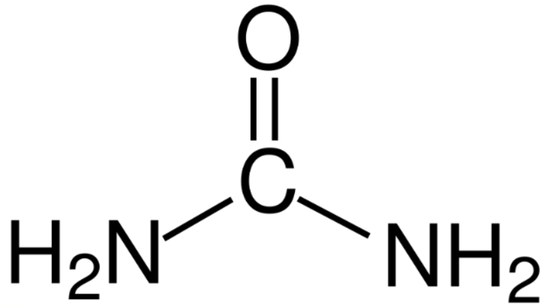


Nitrogen Excretion in Kidney Distal Tubule

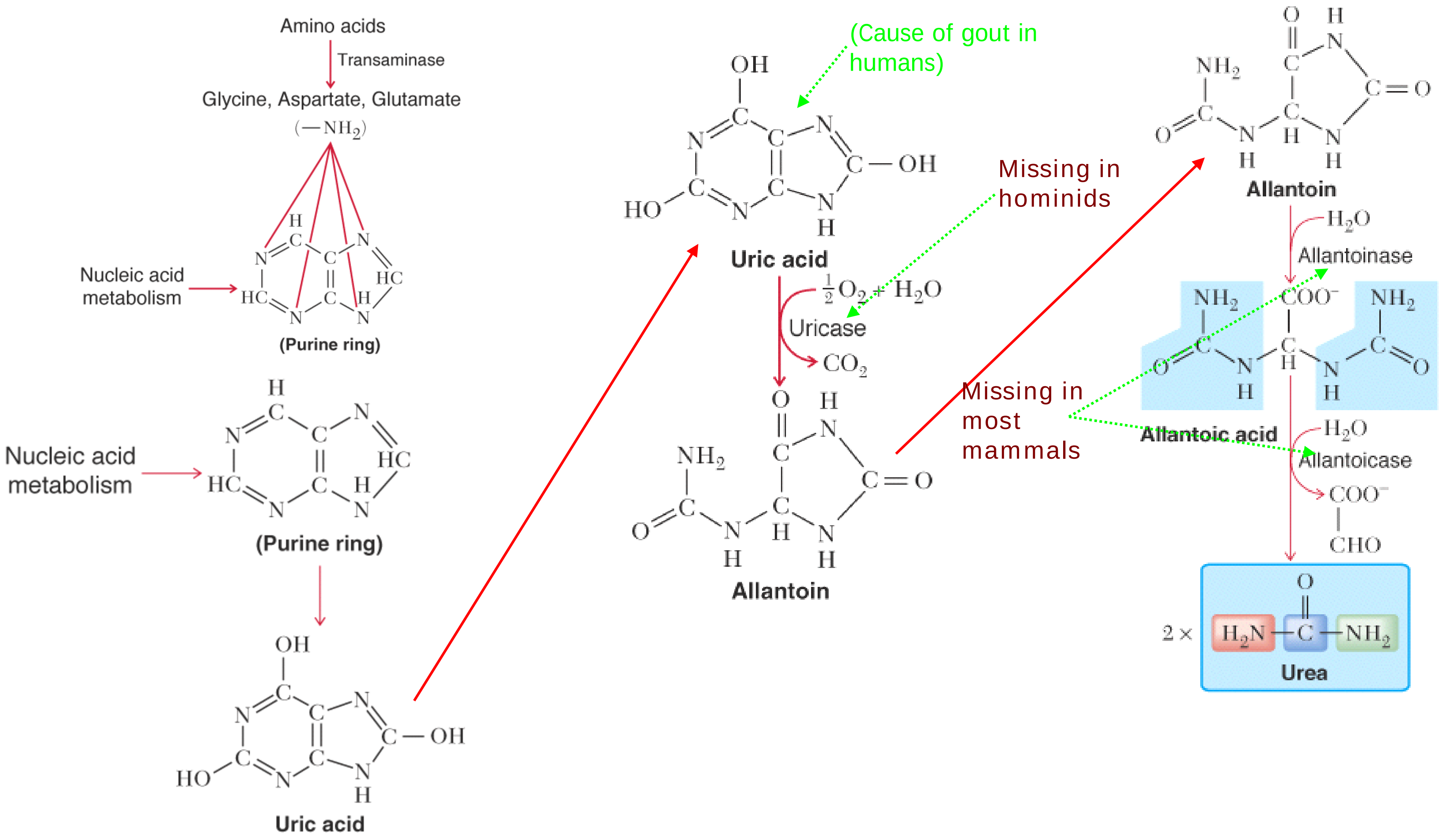


Primary Nitrogen Excretion in Humans: Urea





Comparative Purine Metabolism



Uric Acid and Gout

Drugs Affecting the Kidney

Clinical Pharmacology & Therapeutics *online*

DRUGS AND MEDICINES

Professor Simon Maxwell

https://www.pharmacologyeducation.org/drugs/renal-system