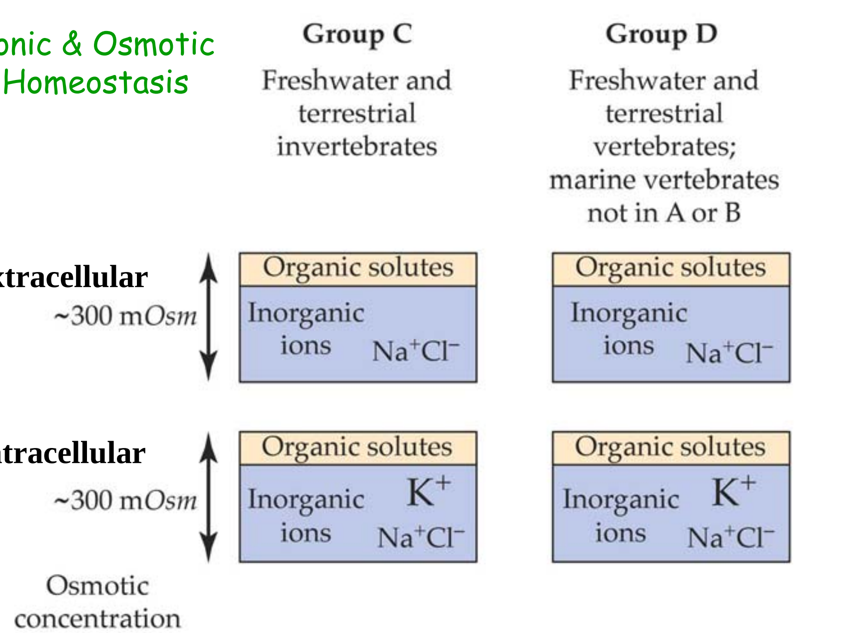
osmoregulation mechanisms in gills, salt glands, and kidneys

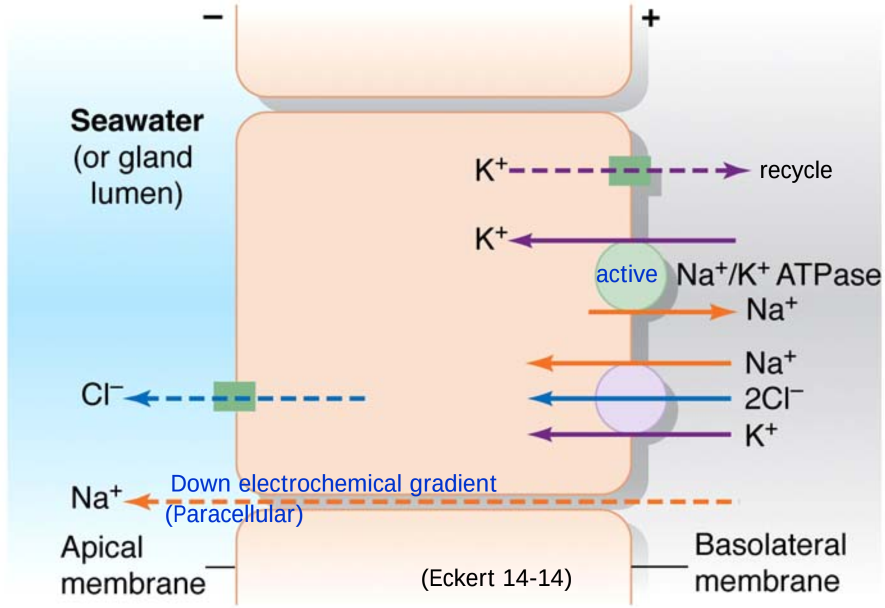
22

Ionic & Osmotic Homeostasis



ANIMAL PHYSIOLOGY, Figure 25.10 (Part 2) © 2004 Sinauer Associates, Inc.

Salt Secretion:



(Eckert 14-14)

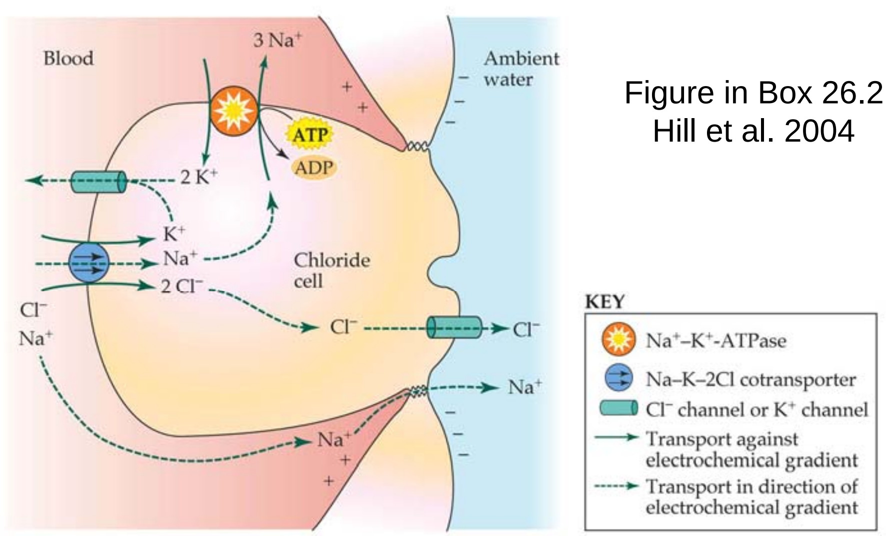


Figure in Box 26.2
Hill et al. 2004

Chloride Cell

Salt Glands

Shark rectal glands to dispose of excess NaCl

-blood hyperosmotic to seawater, but less salt
-more urea and TMAO (trimethylamine oxide)
-NaCl actively secreted

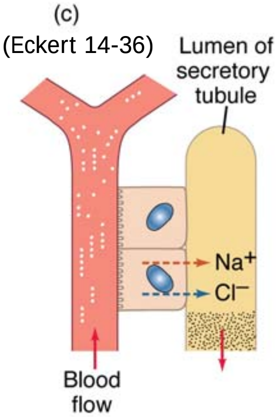
26

Shark Rectal Salt Glands

Salt-secreting cells:

-Na/K-ATPase pump in basolateral membrane
-generates gradient for Na+ by which $Na^+/2Cl^-/K^+$ cotransporter drives up $[Cl^-]$ in cell
-Cl^- across apical membrane
-Na^+ follows paracellularly down electrochemical gradient (and H_2O)
-apical membrane impermeable to urea and TMAO
-therefore iso-osmotic secretion with lots of NaCl

(c)
(Eckert 14-36)

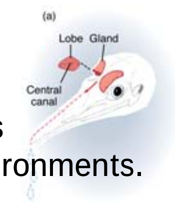


... slightly different in birds and lizards →

27

Salt Glands

(Eckert 14-36)

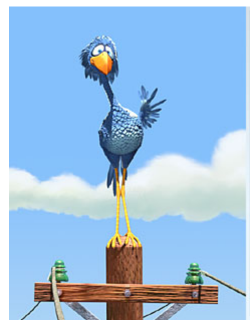


Nasal/orbital salt glands of birds and reptiles
-especially species in desert or marine environments.

Hypertonic NaCl secretions (2-3x plasma osmolarity)

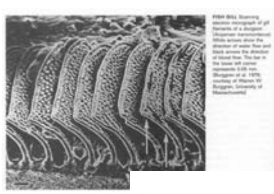
Allows some birds to drink salt water and end up with osmotically free water

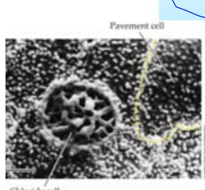
Amblyrhynchus cristatus



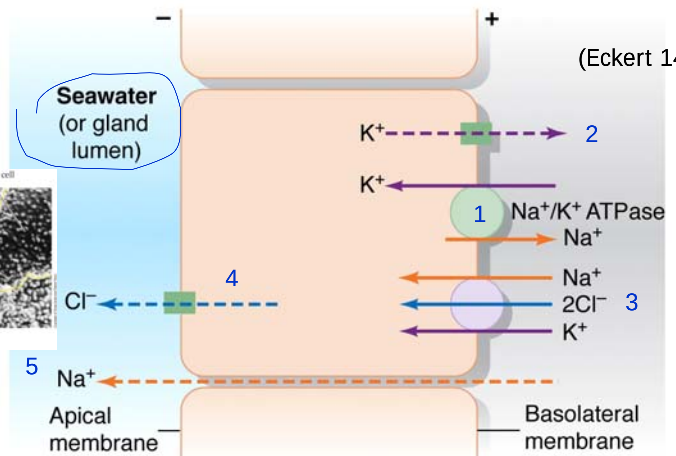
Fish Gills

Chloride cells involved in osmoregulation
-(recall lab paper on smolting)
-lots of mitochondria to power ATPases
-mechanism similar in nasal glands (birds and reptiles), and shark rectal gland





(Eckert 14-14)



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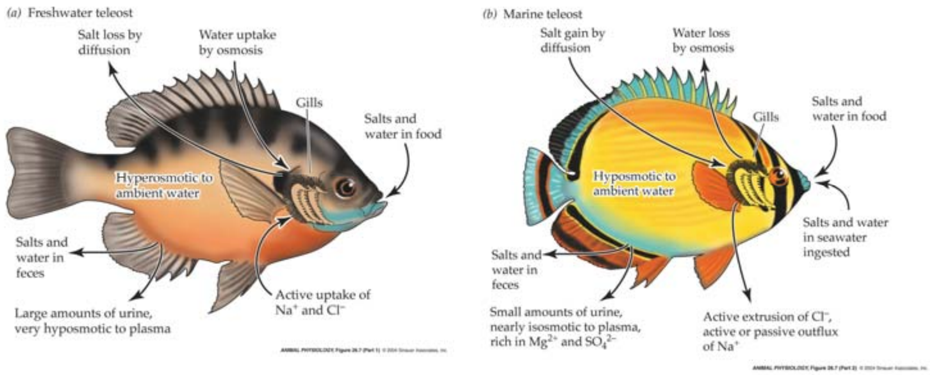
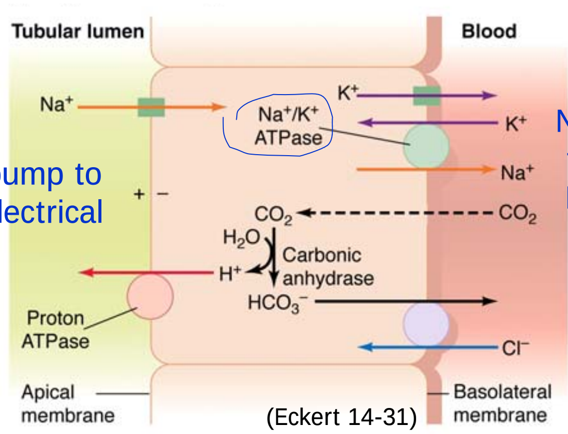


Hill et al. 2004, Fig 26.7

30

Freshwater fish:
The mechanism basically reversed to allow uptake of salt from water against concentration gradient

proton pump to create electrical gradient



(Eckert 14-31)

Na/K-ATPase to generate Na gradient

31

(recall lab paper on smolting)

Sea ←→ Freshwater

Switch between getting rid of excess salt in seawater and taking up salt in freshwater

Growth hormone and cortisol for → sea
(more active chloride cells with more Na/K-ATPase activity)

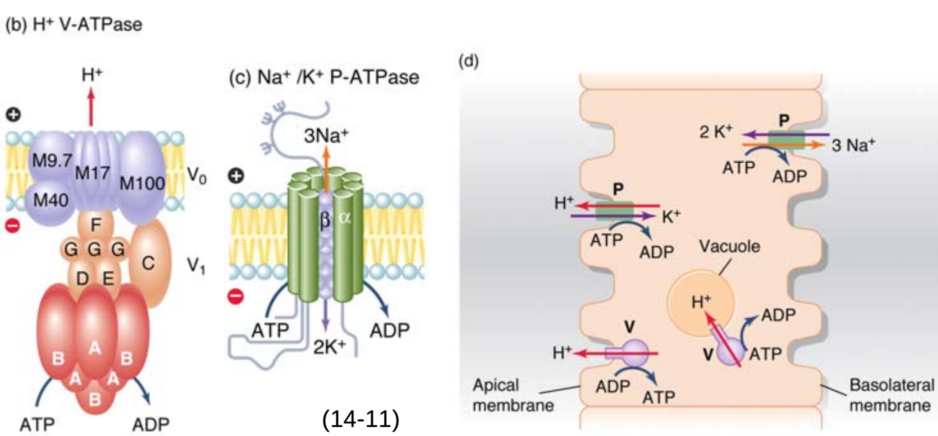
Prolactin for → freshwater

Osmoregulatory Mechanisms

Apical surface (faces lumen and outside world)

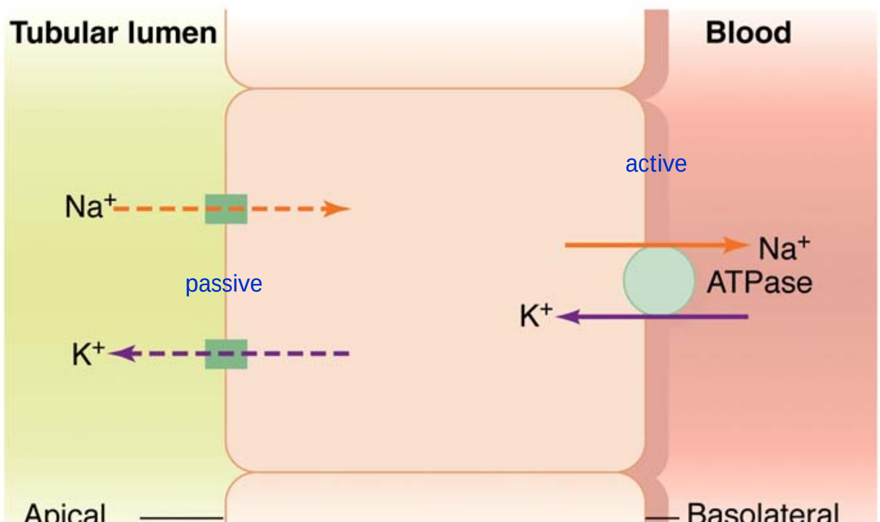
Basal surface (faces body and extracellular fluid)

- Active movement of ions/salts requires <u>ATP</u>
- Movement of <u>water follows</u> movement of ions/<u>salts</u>



(14-11)

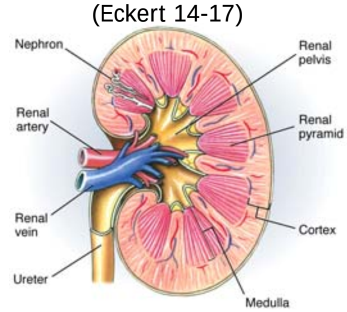
Gradients established and used...to move ions, water



(Eckert 14-12)

Mammalian Kidney

(Eckert 14-17)



Kidney Functions:

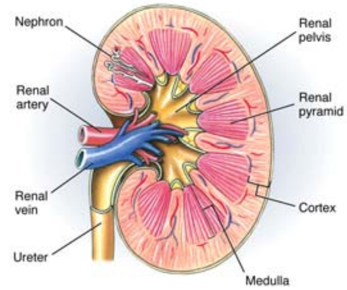
-Osmoregulation
-Blood volume regulation
-Maintain proper ion concentrations
-Dispose of metabolic waste products
-pH regulation (at ~ 7.4)
-Dispose of toxins and foreign substances

How does the kidney accomplish this?

Mammalian Kidney

-Paired
-1% body mass
-20% blood flow

(Eckert 14-17)

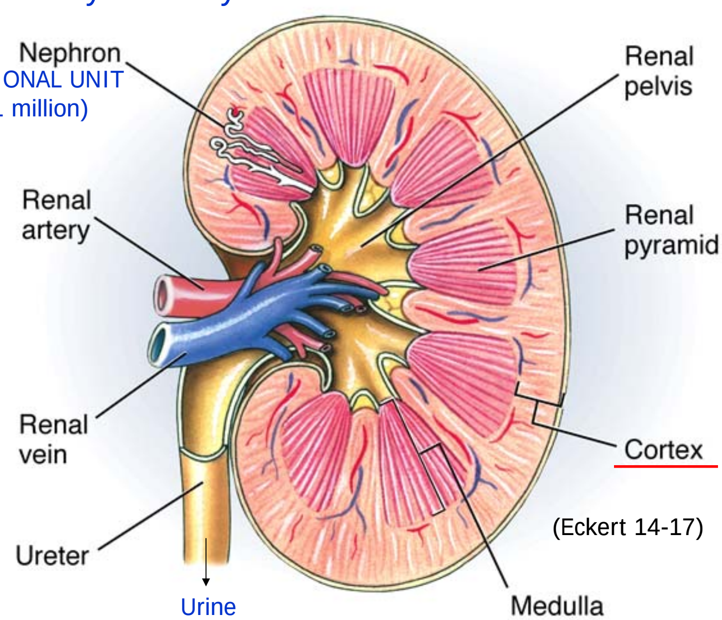


-urine contains:
 water
 metabolic byproducts (e.g., urea)
 excess salts etc.

-from ureter to urinary bladder
 (smooth muscle, sphincter, inhibition)
-out via urethra during micturition

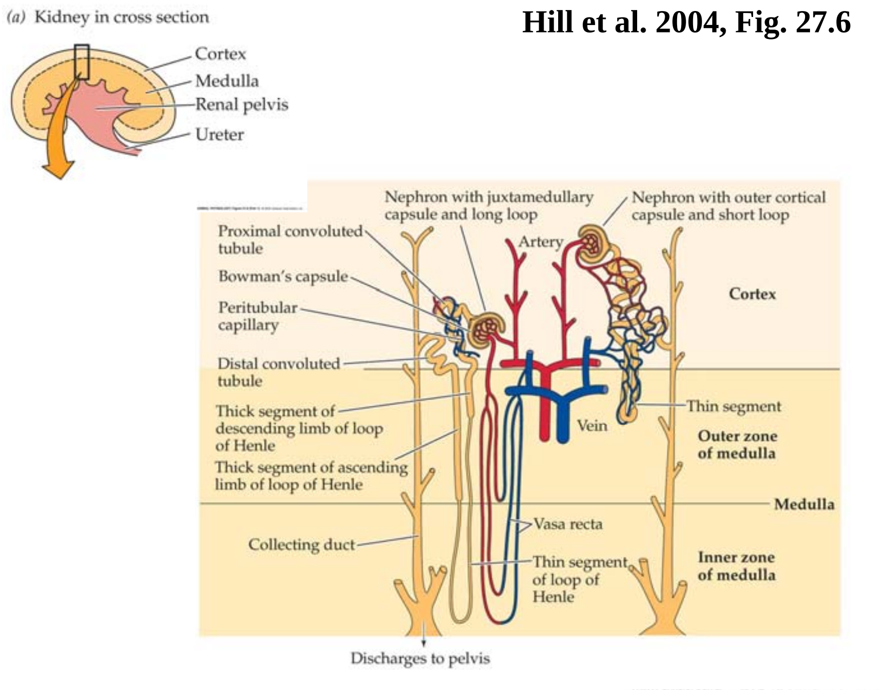
36

Mammalian Kidney Anatomy



(Eckert 14-17)

Hill et al. 2004, Fig. 27.6

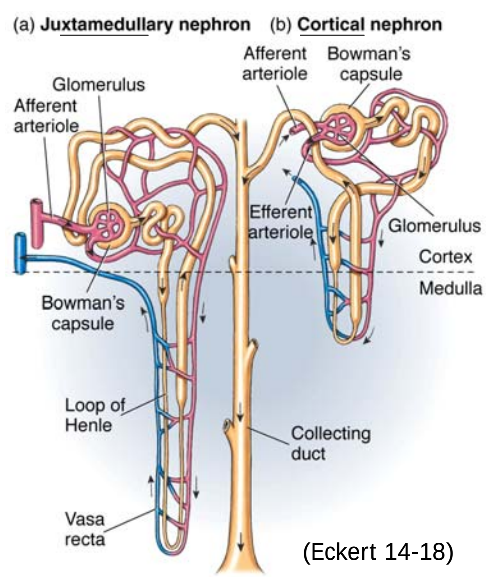


Nephron Anatomy

1 -Proximal tubule
2 -Loop of Henle
  -descending
  -ascending
3 -Distal tubule

-numerous nephrons empty into collecting duct

-collecting ducts empty into renal pelvis



(Eckert 14-18)

Nephron Anatomy

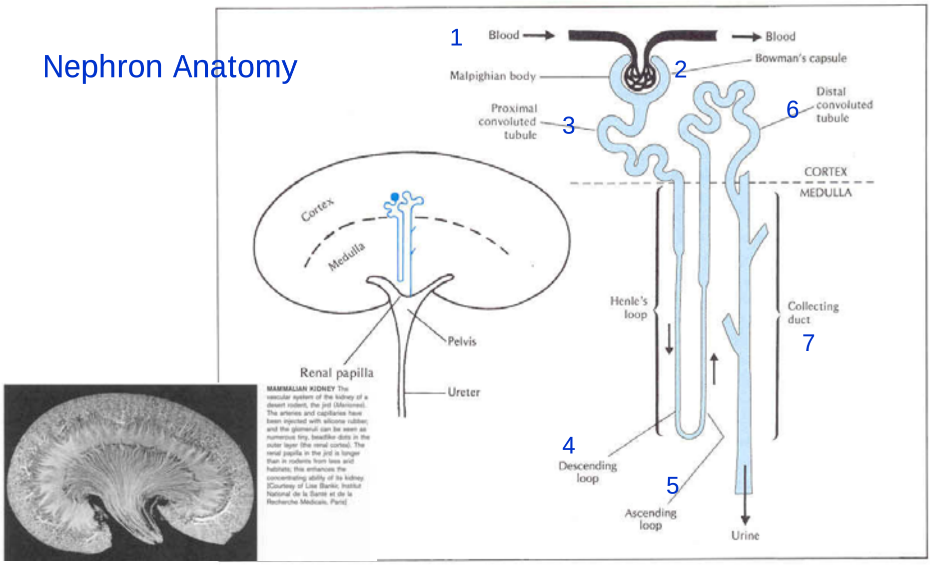
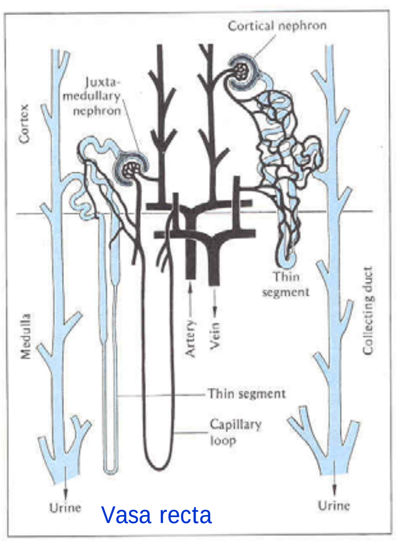


Figure 9.8 Diagram of a mammalian kidney. The kidney contains a large number, up to several million, of single nephrons. Only one nephron is indicated in this diagram and is shown enlarged to the right. The outer layer of the kidney, the *cortex*, contains the *Malpighian bodies* and the proximal and the distal convoluted tubules. The capillary network within the Malpighian body is known as the *glomerulus*. The inner portion, the *medulla*, contains *Henle's loops* and *collecting ducts*.

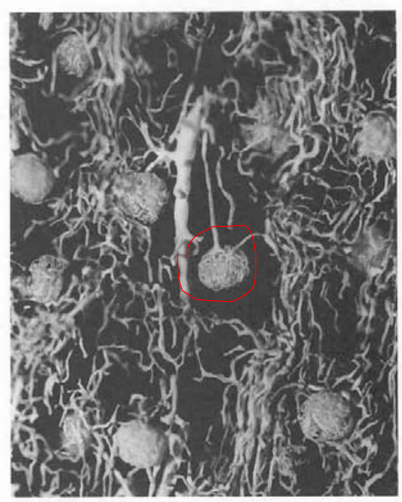
The urine is initially formed by ultrafiltration in the Malpighian bodies. The filtered fluid is modified and greatly reduced in volume as it passes down the renal tubule and into the collecting ducts. These empty the urine into the renal *pelvis*, from where it is conveyed via the *ureter* to the bladder.

Knut Schmidt_Nielsen 1997



Countercurrent exchange

Figure 9.11 Diagram ... one "long-looped" (locate ... edulla and therefore called ... looped" (or cortical) nephron. ... ralleled by a loop formed by the blood capillary. The short-looped nephron is surrounded by a capillary network. Most mammalian kidneys contain a mixture of the two types of nephrons, but some species have only one or the other kind. [Smith 1951]



DOG KIDNEY Close-up view of glomeruli from a dog kidney after arterial injection of silicone rubber. The glomerulus in the center of the photo shows the slightly thicker vessel leading into the glomerulus and the somewhat thinner vessel leaving it. The diameter of these vessels is about 15 to 20 μm; the diameter of the glomerulus is about 150 μm. [Courtesy of A. Clifford Barger, Harvard University]

Knut Schmidt_Nielsen 1997

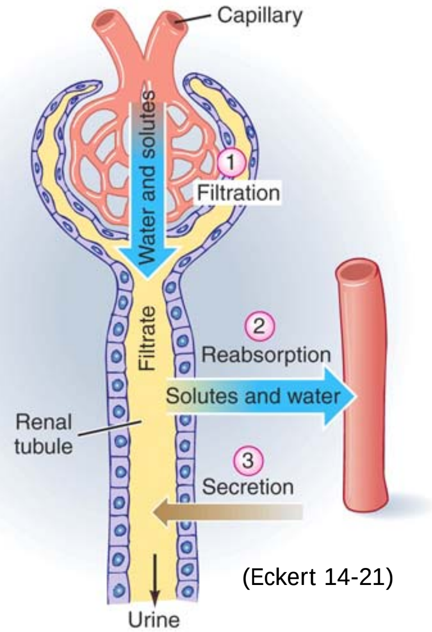
Kidney Processes- overview

1. FILTRATION
   blood --> filtrate

2. REABSORPTION
   filtrate --> blood

3. SECRETION
   blood --> filtrate

All 3 involved in final
Urine Composition



(Eckert 14-21)

Mosm = x1000 U/P

Animal	Urine maximum osmotic concentration (Osm liter^{-1})	Urine/plasma concentration ratio
Beaver[a]	0.52	2
Pig[a]	1.1	3
Human[b]	1.4	4
White rat[b]	2.9	9
Cat[b]	3.1	10
Kangaroo rat[b]	5.5 *Dipodomys*	14
Sand rat[b]	6.3	17
Hopping mouse[c]	9.4	25

[a] B. Schmidt-Nielsen and O'Dell (1961).
[b] K. Schmidt-Nielsen (1964).
[c] MacMillen and Lee (1967).

Table 9.2 The maximum concentrating of various mammals is correlated with the animal, desert animals having the h concentrations and fresh-water animals

Filtration plus secretion

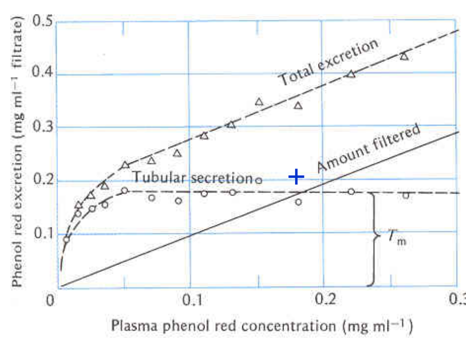


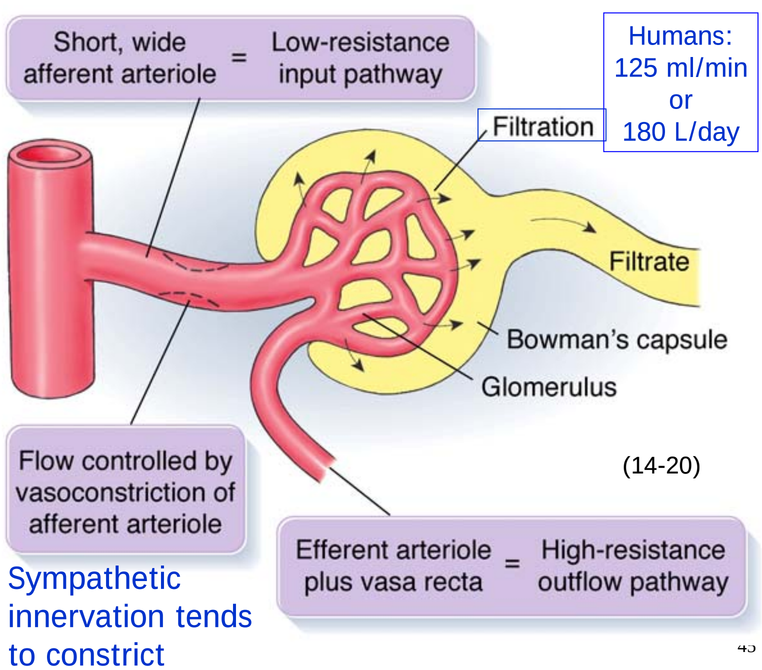
Figure 9.10 Excretion of phenol red by the bullfrog. The amount filtered increases in proportion to the plasma concentration. In addition, phenol red is added to the urine by active tubular transport, increasing the amount in the urine. The amount added by tubular secretion remains constant at plasma concentrations above 0.05 mg per milliliter; this indicates that the tubular maximum for phenol red has been reached. [Forster 1940]

Knut Schmidt_Nielsen 1997

U/P ratio	Implications for excretion: Effects on water excretion	Implications for excretion: Effects on solute excretion	Effects on composition of blood plasma
U/P = 1 (isosmotic urine)	Water is excreted in the same relation to solutes as prevails in the blood plasma.	Solutes are excreted in the same relation to water as prevails in the blood plasma.	The formation of urine leaves the ratio of solutes to water in the blood plasma unchanged, thus does not alter the plasma osmotic pressure.
U/P < 1 (hyposmotic urine)	Water is preferentially excreted. Urine contains more water relative to solutes than plasma.	Solutes are preferentially held back from excretion. Urine contains less solutes relative to water than plasma.	The ratio of solutes to water in the plasma is shifted upward. The osmotic pressure of the plasma is raised.
U/P > 1 (hyperosmotic urine)	Water is preferentially held back from excretion. Urine contains less water relative to solutes than plasma.	Solutes are preferentially excreted. Urine contains more solutes relative to water than plasma.	The ratio of solutes to water in the plasma is shifted downward. The osmotic pressure of the plasma is lowered.

Hill et al. 2004, Fig 25.7

44



45

Filtration:

Bowman's capsule

3 layers

1. Glomerular endothelial cells
   - -100x leakier than other capillary walls
2. Basement membrane
   - -negatively charged glycoproteins
   - -repel plasma proteins by charge
3. Epithelial cells
   - -podocytes create slits

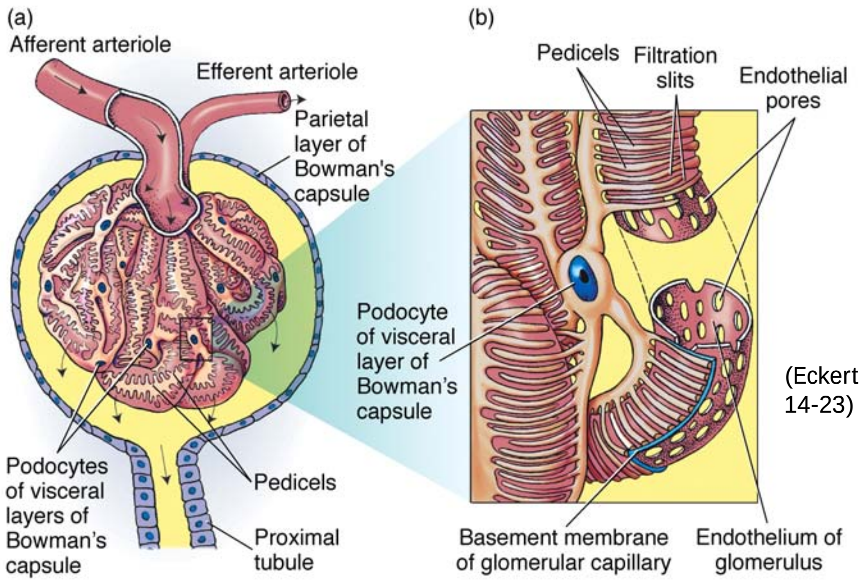
Filtrate = protein-free and cell-free plasma

Glomerular Filtration Rate (GFR)

Humans: 125 ml/min or 180 L/day (60x plasma vol.)

46

Bowman's capsule



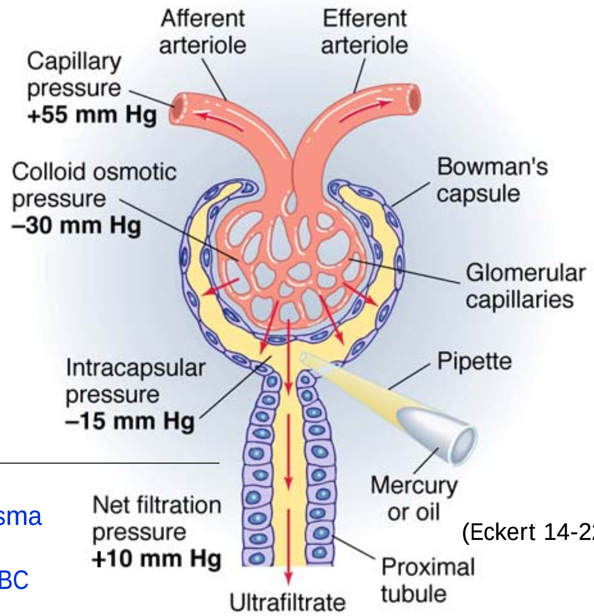
(Eckert 14-23)

47

Bowman's capsule

proteins and larger molecules remain

About 20% of the plasma and solutes that enter glomerulus end up in BC



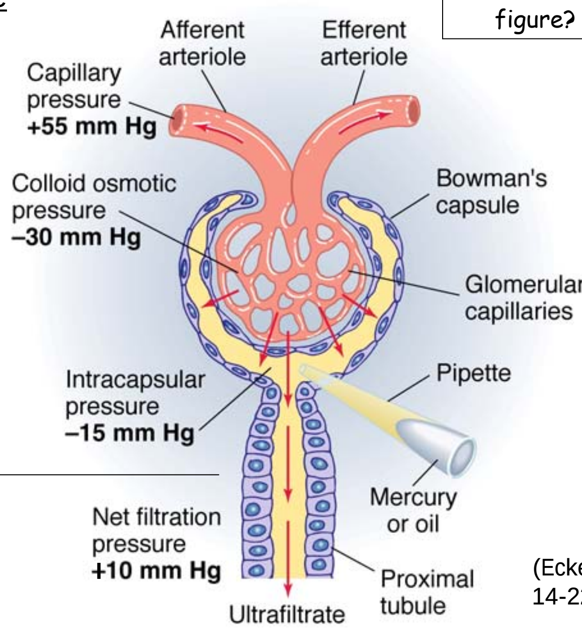
(Eckert 14-22)

Bowman's capsule

Errors on this figure?

1. Starvation Implications?

2. Kidney Stone Implications?



(Eckert 14-22)

Filtration Regulation:

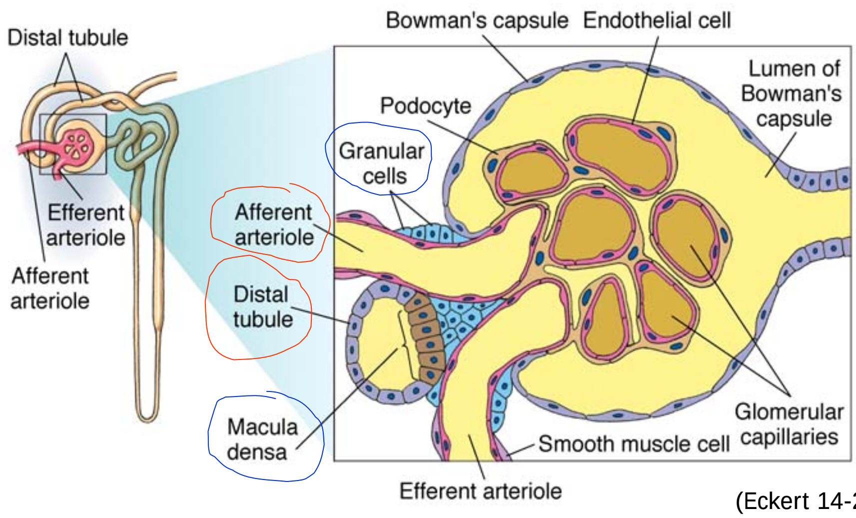
1. Myogenic props. of afferent arteriole resist stretch

2. Secretions from cells of juxtaglomerular apparatus
(where distal tubule passes near bowman's capsule)

-Macula densa cells (distal tubule)
-monitor osmolarity and flow in distal tubule
-paracrine hormonal activity on afferent arteriole

-Granular or juxtaglomerular cells (afferent arteriole)
-release renin which alters blood pressure…

50



(Eckert 14-24)

51

Filtration Regulation:

Renin (from granular cells) released in response to
-low renal BP,
-low solute [ ] in distal tubule,
-or sympathetic activation

Renin leads to activation of Angiotensin II which
causes systemic vasoconstriction to inc. BP
stimulates aldosterone from adrenal cortex
vasopressin (ADH) from post. pit.
(these promote salt, water reabsorption)

3. Sympathetic innervation (reduce GFR)
-afferent vasoconstriction
-decreased space between podocytes

52

Renal Clearance:

Volume of plasma cleared of a substance by the kidney.

(Filtration, Reabsorption, Secretion)

Inulin (=GFR) b/c neither reabsorbed nor secreted

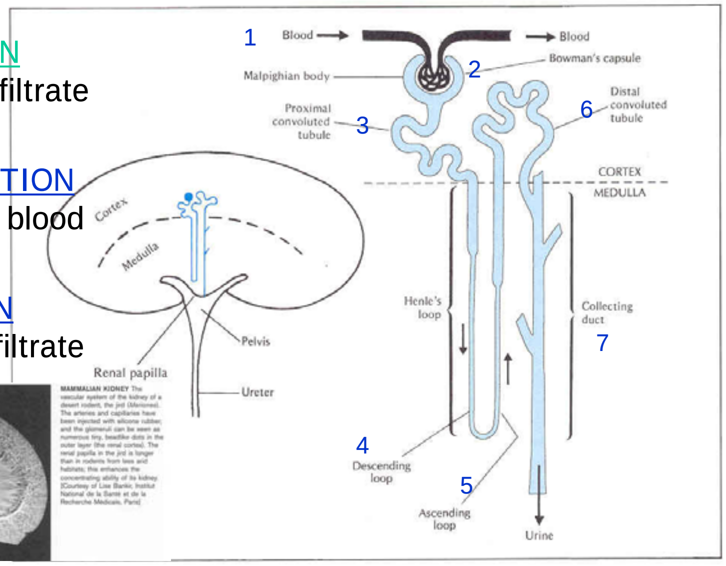
If clearance > GFR = secretion
If clearance < GFR = reabsorption

53

1. FILTRATION
blood --> filtrate

2. REABSORPTION
filtrate --> blood

3. SECRETION
blood --> filtrate



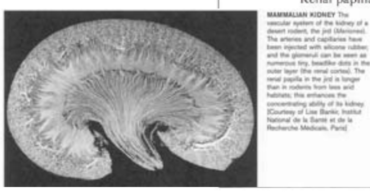


Figure 9.8 Diagram of a mammalian kidney. The kidney contains a large number, up to several million, of single nephrons. Only one nephron is indicated in this diagram and is shown enlarged to the right. The outer layer of the kidney, the *cortex*, contains the *Malpighian bodies* and the proximal and the distal convoluted tubules. The capillary network within the Malpighian body is known as the *glomerulus*. The inner portion, the *medulla*, contains *Henle's loops* and *collecting ducts*.
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Knut Schmidt_Nielsen 1997

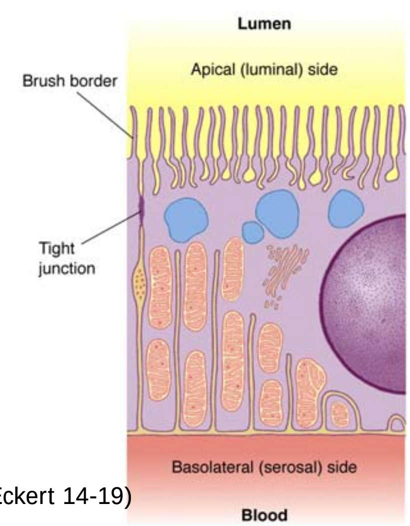
Reabsorption:

of 180 L/day filtered, ~178.5 L reabsorbed in humans

Lots of active transport of salts and other substances

Tight junctions not so tight in proximal tubule, so water can move from filtrate to plasma

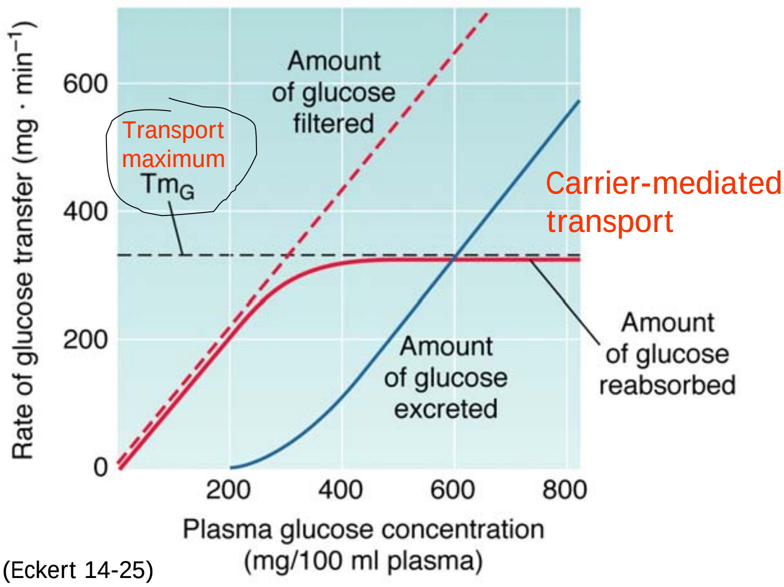
Because of reabsorption (and secretion), Renal clearance does NOT often equal GFR



(Eckert 14-19)

Reabsorption limit –
Glucose example

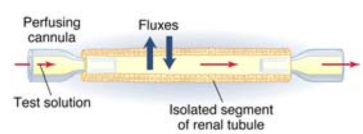
Tm at 300 mg/min/100ml plasma



(Eckert 14-25)

Reabsorption:

(Eckert 14-27)



<u>Proximal Tubule</u>

70% filtered Na^+ actively reabsorbed

(by Na^+/K^+ATPase pump in basolateral membrane)

Cl^- and water follow

75% of filtrate is reabsorbed

including glucose and amino acids (Na^+ dependent)

also, phosphates, Ca+, electrolytes as needed

Parathyroid hormone controls phosphate and Ca^+ reabsorp.

triggers calcitriol production (Vit. D) for Ca^+

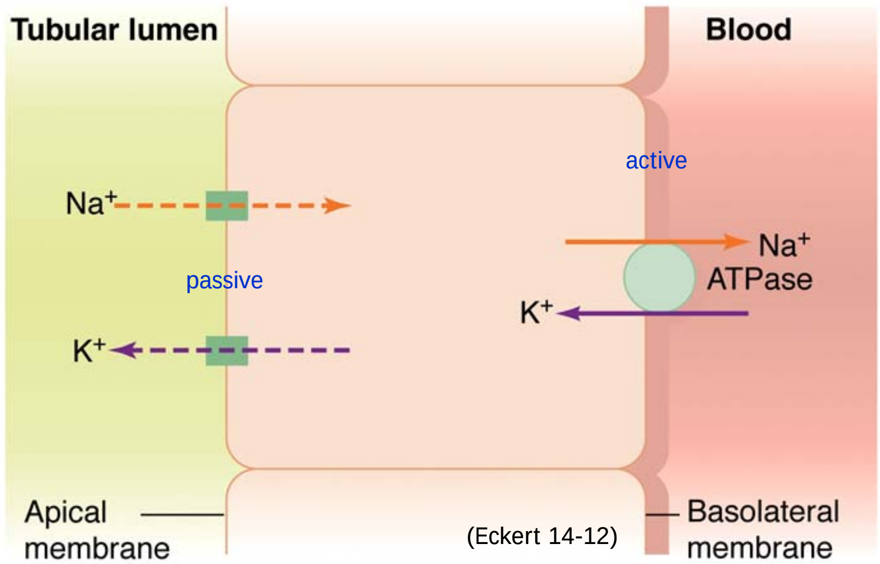
At end of proximal tubule filtrate is isoosmotic with plasma

(~300mOsm)

however, remaining substances are 4x concentrated

57

Gradients established and used:

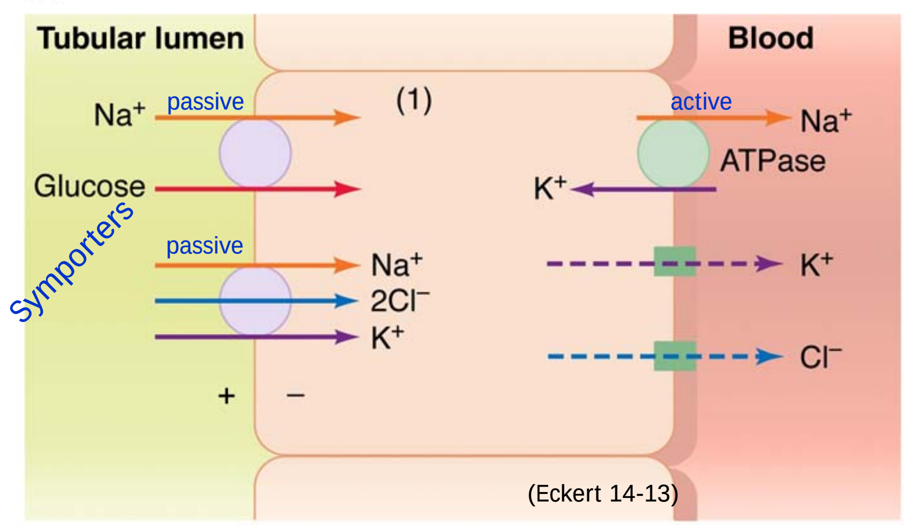


Mammalian Kidney

58

Gradients established and used:

(a)



Mammalian Kidney

59

Reabsorption:

Loop of Henle

Descending limb

- -no active NaCl transport
- -low urea and NaCl permeability
- -permeable to water

Ascending thin limb

- -no active NaCl transport
- -but permeable to NaCl
- -low urea permeablity
- -low water permeability

Ascending thick limb

- -NaCl transported out of tubule
- -low water permeability

Countercurrent multiplier

One driver of concentrating mechanism of nephron

Knut Schmidt_Nielsen 1997

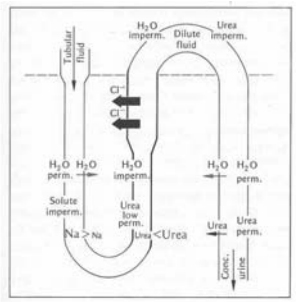
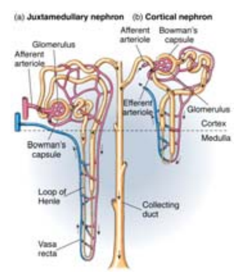


Figure 9.12 Diagram of the concentrating mechanism in the loop of Henle in the mammalian kidney during the formation of concentrated urine. Active transport of chloride ion is indicated by heavy arrows; passive flux of water and urea by light arrows. [Kokko and Tisher 1976]

Reabsorption (and Secretion): (Eckert 14-18)



Distal Tubule

- -K^+, H^+, NH_3 into tubule
- -under endocrine control
- -Na^+, Cl^-, HCO_3^- back into body
- -water follows

(Na+ reabsorption facilitated by aldosterone)

Angiotensinogen →(Renin) Ang. I →(ACE in lung) Ang. II → aldosterone from adrenal cortex

Ang. II → ADH from post. pit.

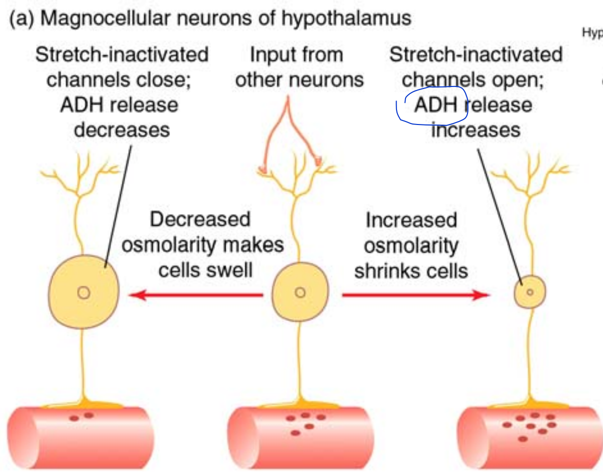
Collecting Duct

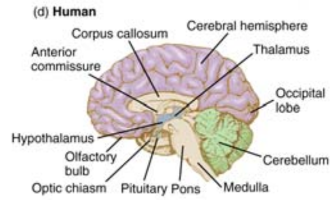
- -permeable to water
- -hormone control (ADH/vasopressin)
- -water (via aquaporins) follows osmotic gradient

- -permeable to Urea in inner medulla

Another driver of concentrating mechanism of nephron

-ADH role in water reabsorption/urine concentration





-Renin -> Ang. II
-> ADH

-Baroreceptor input (atrial and arterial)

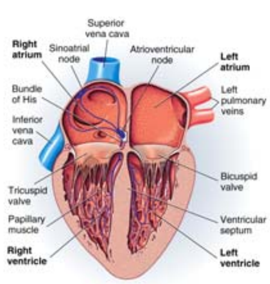
-EtoH inhibits ADH release

62

Atrial Natriuretic Peptide (ANP)

-released by atrium cells in response to stretch (elevated BP)

-opposite effect of renin-angiotensin system
-decreases sodium reabsorption
-therefore increased urine production
-ANP inhibits release of ADH, renin, aldosterone



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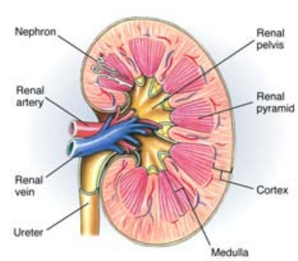
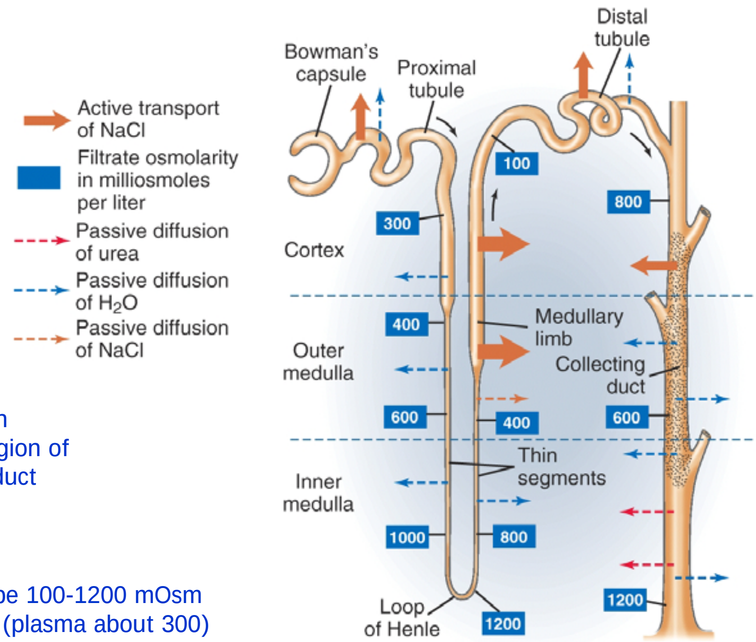


63

ADH acts in stippled region of collecting duct

Urine can be 100-1200 mOsm in humans (plasma about 300)



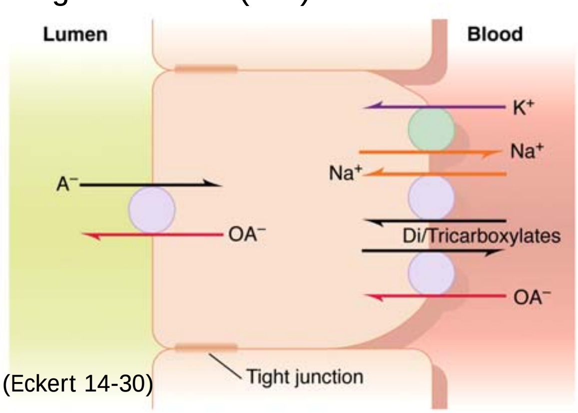
(Eckert 14-28)

Secretion:

From plasma into tubule of nephron

K+, H+, NH3, organic acids, organic bases

Organic anions (OA⁻):



(Eckert 14-30)

Liver conjugates toxins and waste to glucuronic acid

Secreted into tubule lumen and excreted

Na/K-ATPase

65

Table 14-9 Some organic ions secreted by the proximal tubule
Eckert

Anions	Cations
Endogenous	*Endogenous*
Urates	Dopamine
Hippurates	Epinephrine
Oxalate	Norepinephrine
Prostaglandins	Creatinine
cAMP	
Exogenous	*Exogenous*
Furosemide	Morphine
Bumetanide	Amiloride
Penicillin	Quinine
Aspirin	Atropine
Chlorothiazides	Isoproterenol

66

Countercurrent Exchangers (passive)

Countercurrent Multipliers (active)

See p.736 in your text

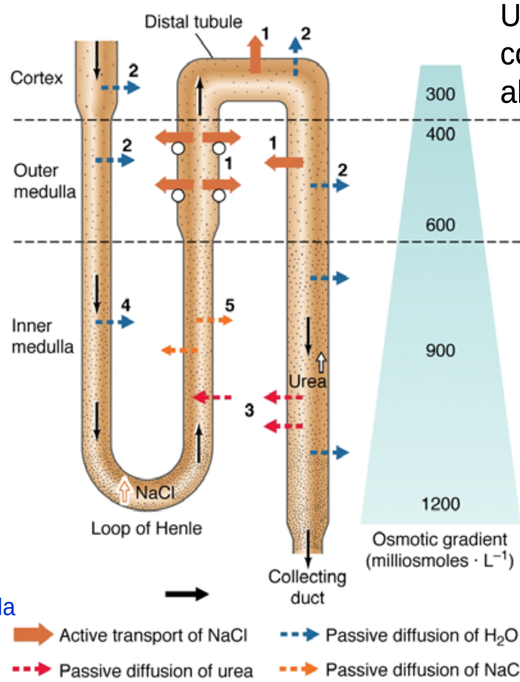
67

-Active Countercurrent Multiplier

-Dynamic

-Vasa Recta

Urine concentrating ability



Some urea “recycled”

Cortex and outer medulla

Inner medulla

(Eckert 14-34)

68

Endotherms in the COLD…

Countercurrent Heat Exchange

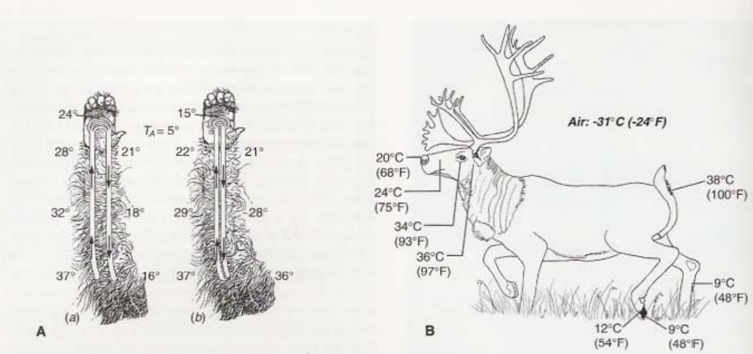
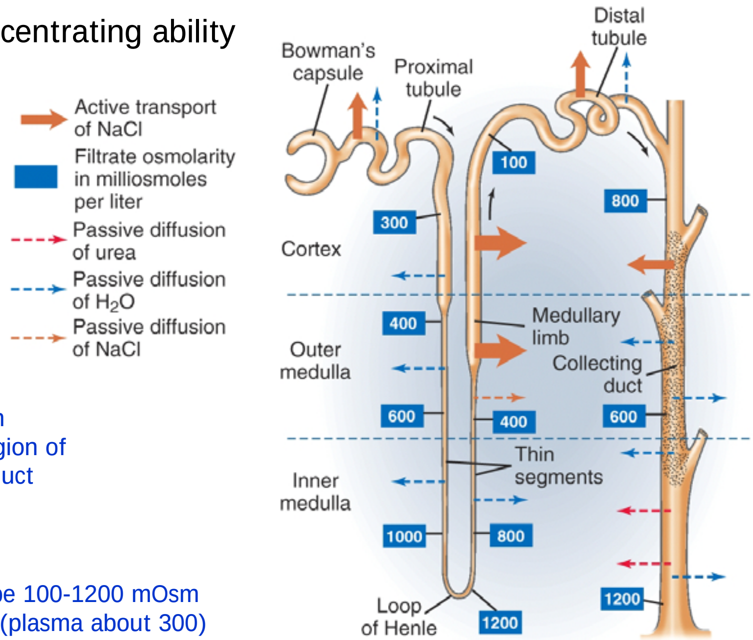


Figure 8.9 **Countercurrent heat exchange.** (A) A diagram representing the circulation in a limb of a mammal showing hypothetical temperature changes of the blood in the absence (a) and presence (b) of countercurrent heat exchange. Arrows indicate direction of blood flow. In (b), the venous blood takes up heat (thus cooling the arterial blood) all along its path of return because even as it becomes warmer and warmer, it steadily encounter arterial blood that is warmer yet. (B) Regulation of external body temperature in the caribou. Temperature regulation is accomplished in part by countercurrent heat exchange. An intricate meshwork of veins and arteries acts to keep the temperature of the legs near that of the environment so heat is not lost from the body.

(A) Source: Data from R.W. Hill and G.A. Wyse, Animal Physiology, *2nd edition, 1989, Harper & Row, New York. (B) Data from J.F. Merritt, "Animals of the Arctic" in* Arctic Life: Challenge to Survive, *(M.M. Jacobs & J.B. Richardson III, eds.), 1983, The Board of Trustees, Carnegie Institute, Pittsburgh, Pennsylvania.*

69

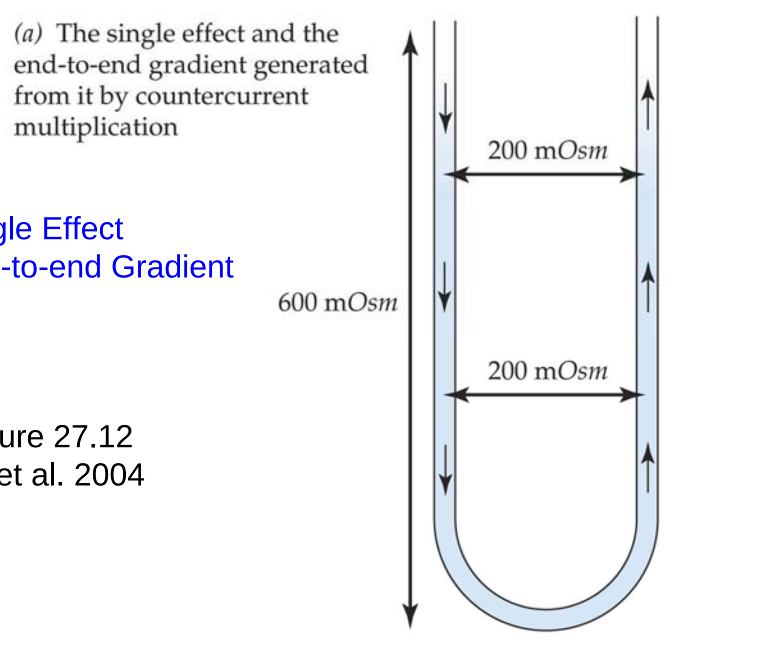
Urine concentrating ability



(Eckert 14-28)

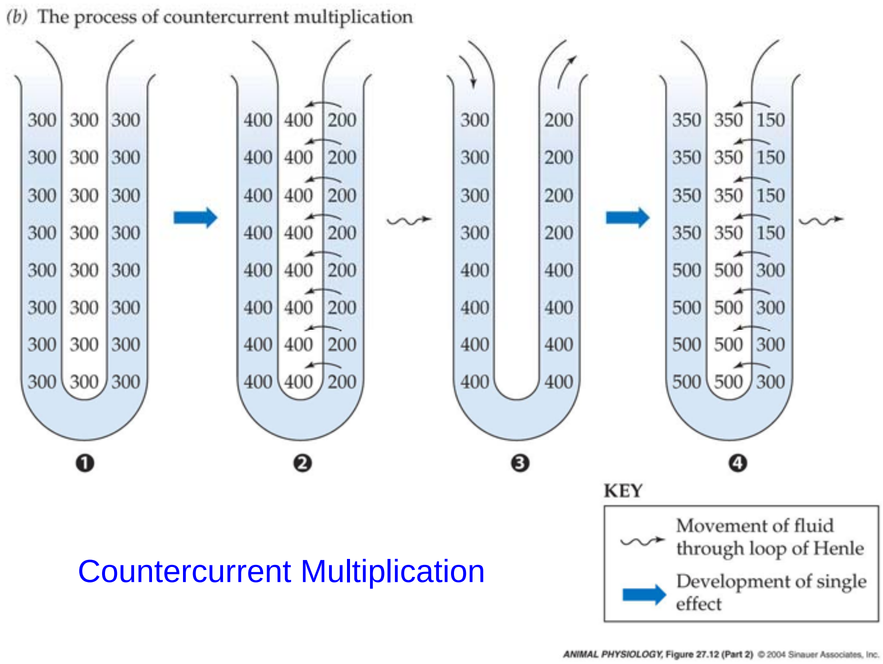
ADH acts in stippled region of collecting duct

Urine can be 100-1200 mOsm in humans (plasma about 300)

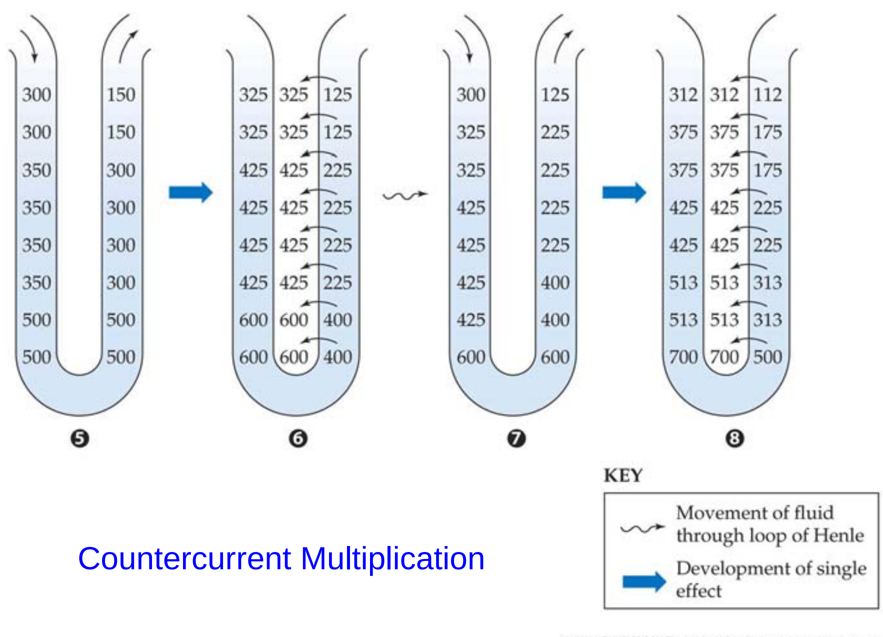


1. Single Effect
2. End-to-end Gradient

Figure 27.12
Hill et al. 2004



Countercurrent Multiplication



Countercurrent Multiplication

Same story, different picture

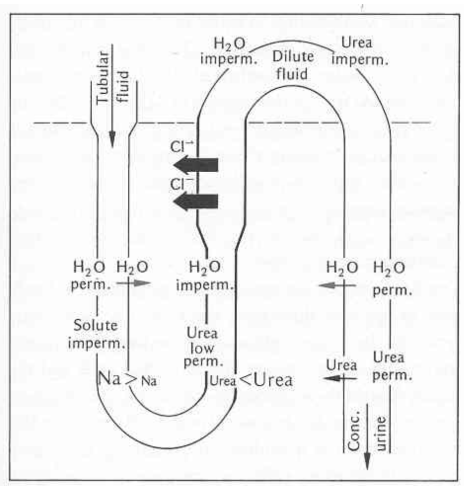


Figure 9.12 Diagram of the concentrating mechanism in the loop of Henle in the mammalian kidney during the formation of concentrated urine. Active transport of chloride ion is indicated by heavy arrows; passive flux of water and urea by light arrows. [Kokko and Tisher 1976]

Knut Schmidt_Nielsen 1997

74

Non-mammalian kidneys:

-Only birds also have loops of henle

-Freshwater fish with more and larger glomeruli to make lots of dilute urine

-Some marine fish without glomeruli or bowman's capsule – urine formed by secretion, ammonia secreted by gills

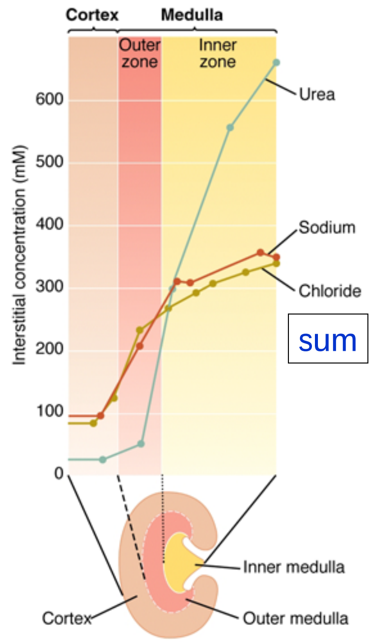
-Osmoregulation also via extrarenal organs

75

Urine concentrating ability

1200 mOsm in humans
9000 mOsm on kangaroo rats
9600 mOsm in *Perognathus* (mouse)

-Length of loops of henle
-Corticomedullary
  concentration gradient



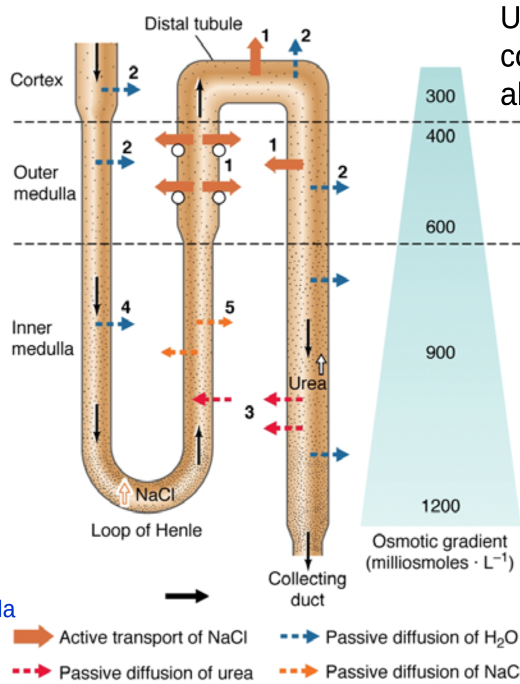
(Eckert 14-33)

76

-Active Countercurrent Multiplier

-Dynamic

-Vasa Recta



Urine concentrating ability

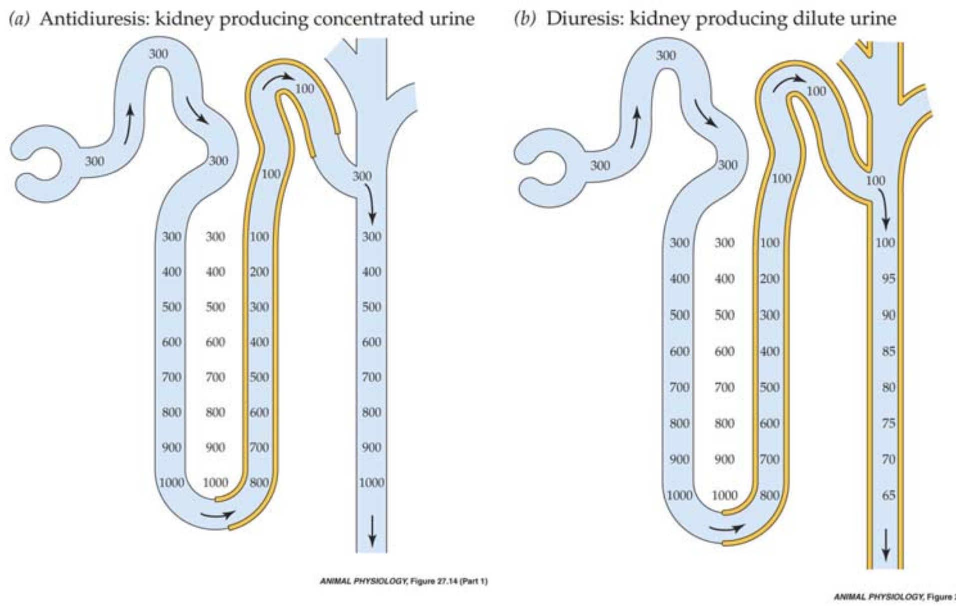
Some urea "recycled"

Cortex and outer medulla

Inner medulla

(Eckert 14-34)

77

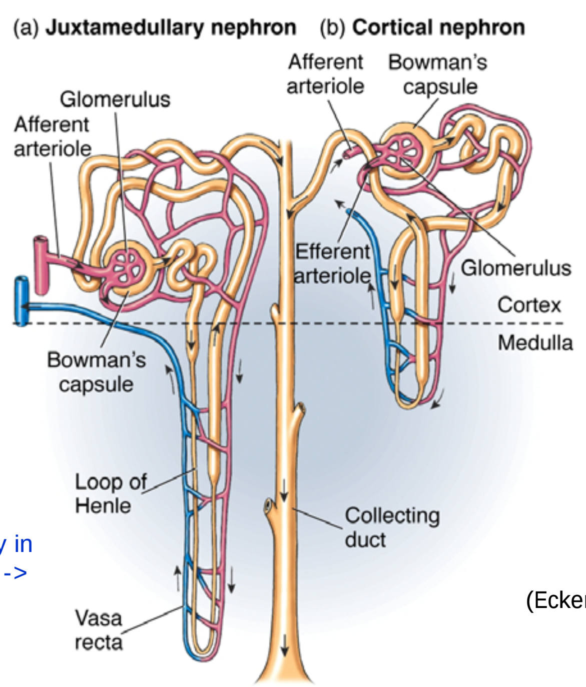


Hill et al. 2004, Fig. 27.14

78

Urine concentrating ability

-Vasa Recta

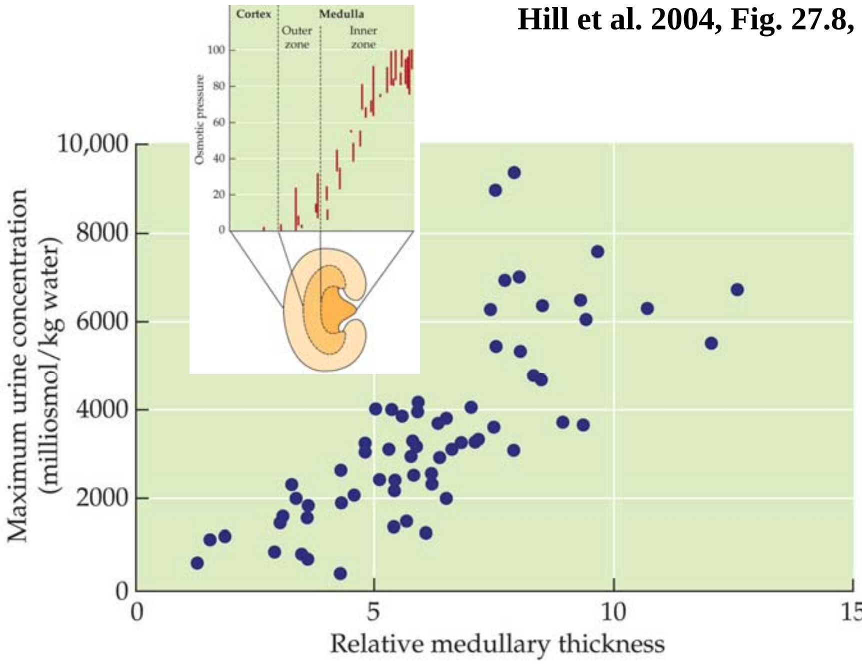


-Loops of Henle only in Mammals and Birds -> Hyperosmotic Urine

(Eckert 14-18)

79

Hill et al. 2004, Fig. 27.8, 13



Hill et al. 2004, Fig. 27.9