Chapter 26: The Urinary System

Chapter Objectives

OVERVIEW OF KIDNEY FUNCTION
1. List and describe the functions of the kidneys.

NEPHRONS
2. Describe the two major portions of a nephron and the capillaries that surround a nephron.
3. In the order that fluid passes through them, list the three main sections of the renal tubule.
4. Distinguish between cortical and juxtamedullary nephrons.
5. Describe the components of the glomerular capsule.
6. Describe the location, structure, and function of the juxtaglomerular apparatus.

OVERVIEW OF RENAL PHYSIOLOGY
7. Describe three major functions carried out by nephrons and where each of these processes occurs.
8. Describe the parts of the filtration membrane and explain which parts do not allow which substances to go through.
9. List and name the forces that contribute to net filtration pressure (NFP) and explain how NFP is calculated.
10. Define glomerular filtration rate and discuss its relation to the pressures that determine net filtration pressure.
11. List three mechanisms that regulate glomerular filtration rate (GFR).
12. Discuss the myogenic mechanism and tubuloglerular feedback as contribution to renal autoregulation.
13. Explain the role of the ANS in the neural regulation of GFR.
14. Discuss the roles of angiotensin II and ANP in the regulation of GFR.

TUBULAR REABSORPTION AND SECRETION
15. Define tubular reabsorption and tubular secretion and list some of the reabsorbed and secreted substances, respectively.
16. Describe the two routes a substance being reabsorbed from the tubule lumen fluid can take before entering a peritubular capillary.
17. Explain why reabsorption of sodium ions (Na+) is particularly important.
18. Explain the role of the sodium pump in reabsorption of Na+.
20. Define and compare obligatory and facultative water absorption.
21. Discuss the role of Na\(^{+}\) symporters in reabsorption, especially of glucose.
22. Describe the role of Na\(^{+}\)/H\(^{+}\) antiporters in achieving Na\(^{+}\) reabsorption, returning filtered HCO\(_3\)\(^{-}\) and water to the peritubular capillaries, and secreting H\(^{+}\).
23. Explain how the reabsorption of Na\(^{+}\) and other solutes promotes reabsorption of water by osmosis.
24. Discuss the independent regulation of both the volume and osmolarity of body fluids in the loop of Henle.
25. Discuss the location where parathyroid hormone influences the reabsorption of Ca\(^{2+}\).
26. Describe what is secreted or reabsorbed in the distal convoluted tubules and collecting ducts.
27. List the four hormones that affect the extent of Na\(^{+}\), Cl\(^{-}\), and water reabsorption and K\(^{+}\) secretion by renal tubules.
28. Describe the three main ways angiotensin II affects renal physiology. Include the role of Aldosterone.
29. Explain the role of ADH in regulating facultative water reabsorption.
30. Discuss the role of ANP in the regulation of tubular function.

**PRODUCTION OF DILUTE AND CONCENTRATED URINE**

31. Explain how the kidneys produce dilute urine.
32. Explain how the kidneys produce concentrated urine using both the countercurrent mechanism and urea recycling.

**URINE STORAGE, TRANSPORTATION, AND ELIMINATION**

33. Describe pathway that urine travels within the kidneys, as it leaves the kidneys and as it proceeds out of the body.
34. Explain the activation of the micturition reflex.

**Chapter Lecture Notes**

Overview of Kidney Functions

Regulation of blood ionic composition

Na\(^{+}\), K\(^{+}\), Ca\(^{2+}\), Cl\(^{-}\) and phosphate ions

Regulation of blood pH, osmolarity & glucose

Regulation of blood volume
conserving or eliminating water

Regulation of blood pressure

secrating the enzyme renin

adjusting renal resistance

Release of erythropoietin & calcitriol

Excretion of wastes & foreign substances

Nephrons

The nephron is the functional unit of the kidney. (Fig 26.5)

A nephron consists of a

Renal corpuscle

glomerulus is a capillary ball

glomerular (Bowman’s) capsule is double-walled epithelial cup

Renal tubule

proximal convoluted tubule

loop of Henle (nephron loop)

descending limb – permeable to water, but impermeable to solutes

thin ascending limb

thick ascending limb - impermeable to water and solutes

distal convoluted tubule – variable permeability to water

collecting duct – variable permeability to water

distal convoluted tubules of several nephrons drain into to a single collecting duct

many collecting ducts drain into a small number of papillary ducts

papillary ducts drain urine to the renal pelvis and ureter.

Blood Vessels around the Nephron (Fig 26.5)

Glomerular capillaries are formed between the afferent & efferent arterioles

Efferent arterioles give rise to the peritubular capillaries and vasa recta
There are two types of nephrons that have differing structure and function.

A cortical nephron usually has its glomerulus in the outer portion of the cortex and a short loop of Henle that penetrates only into the outer region of the medulla (Fig 26.5a)

80-85% of nephrons are cortical nephrons

A juxtamedullary nephron usually has its glomerulus deep in the cortex close to the medulla; its long loop of Henle stretches through the medulla and almost reaches the renal papilla (Fig 26.5b)

15-20% of nephrons are juxtamedullary nephrons

Allow excretion of dilute or concentrated urine

Histology of the Glomerular Capsule

Glomerular (Bowman’s) capsule

The glomerular capsule consists of visceral and parietal layers (Fig 26.6)

The visceral layer consists of modified simple squamous epithelial cells called podocytes

The parietal layer consists of simple squamous epithelium and forms the outer wall of the capsule

Fluid filtered from the glomerular capillaries enters the capsular space, the space between the two layers of the glomerular capsule.

Juxtaglomerular Apparatus

Structure where afferent arteriole makes contact with ascending limb of loop of Henle (Fig 26.6)

macula densa is thickened part of ascending limb

juxtaglomerular cells are modified muscle cells in arteriole

the JGA helps regulate blood pressure and the rate of blood filtration by the kidneys

Overview of Renal Physiology

Nephrons and collecting ducts perform 3 basic processes (Fig 26.7)

glomerular filtration

a portion of the blood plasma is filtered into the glomerular capsule
Location - renal corpuscle

tubular reabsorption

water & useful substances are reabsorbed into the blood

Location – renal tubules and collecting duct

tubular secretion

wastes are removed from the blood & secreted into urine

Location – renal tubules and collecting duct

Glomerular Filtration

Glomerular filtrate - the fluid that enters the capsular space (Fig 26.20)

48 Gallons/day filtrate reabsorbed to 1-2 qt. urine

Filtration fraction - the fraction of plasma in the afferent arterioles that becomes filtrate

Filtration fraction is ~20% of plasma

Filtration enhanced by:

thinness of membrane

large surface area of glomerular capillaries

glomerular capillary blood pressure is high due to small size of efferent arteriole

Endothelial-capsular membrane - the filtering unit of a nephron (Fig 26.8)

glomerular endothelium

stops all cells and platelets

glomerular basement membrane

stops large plasma proteins

slit membranes between pedicels of podocytes

stops medium plasma proteins

The principle of filtration - force fluids and solutes through a membrane by pressure

is similar in glomerular capillaries as in capillaries elsewhere in the body.

Net Filtration Pressure
Glomerular filtration depends on three main pressures

Promotes filtration

Glomerular blood hydrostatic pressure (GBHP)

GBHP is higher (55 – 60 mmHg) than BHP (35 mmHg at arteriole end) in a standard capillary due to the relatively small diameter of the efferent arteriole compared with the diameter of the afferent arteriole

Opposes filtration

Capsular hydrostatic pressure (CHP)

back pressure caused by fluid that has entered the capsular space

15 mmHg

Blood colloid osmotic pressure (BCOP)

Pressure exerted by plasma proteins, which are not able to be filtered

30 mmHg

Net Filtration Pressure (NFP) = GBHP - (CHP + BCOP)

10 mmHg = 55 mmHg – (15 mmHg + 30 mmHg)

Glomerular Filtration Rate

Glomerular Filtration Rate (GFR) = Amount of filtrate formed in all renal corpuscles of both kidneys / minute

average adult male rate is 125 mL/min

Changes in net filtration pressure affects GFR

filtration stops if GBHP drops to 45mm Hg

functions normally with mean arterial pressures 80-180

Regulation of GFR

The mechanisms that regulate GFR adjust blood flow into and out of the glomerulus and alter the glomerular capillary surface area available for filtration. (Table 26.2)

The three principal mechanisms that control GFR are
Renal autoregulation

Mechanisms that maintain a constant GFR despite changes in arterial BP

myogenic mechanism

systemic increases in BP, stretch the afferent arteriole

smooth muscle contraction reduces the diameter of the arteriole returning the GFR to
its previous level in seconds
tubuloglomerular feedback (Fig 26.10)

elevated systemic BP raises the GFR so that fluid flows too rapidly through the renal
tubule & Na⁺, Cl⁻ and water are not reabsorbed

macula densa detects that difference & releases a vasoconstrictor from the
juxtaglomerular apparatus

afferent arterioles constrict & reduce GFR

Neural regulation

Blood vessels of the kidney are supplied by sympathetic fibers that cause

vasoconstriction of afferent arterioles

At rest, renal blood vessels are maximally dilated because sympathetic activity is

minimal

renal autoregulation prevails

With moderate sympathetic stimulation, both afferent & efferent arterioles constrict
equally

decreasing GFR equally

With extreme sympathetic stimulation (exercise or hemorrhage), vasoconstriction of
afferent arterioles reduces GFR

lowers urine output & permits blood flow to other tissues

Hormonal regulation

Atrial natriuretic peptide (ANP) increases GFR
stretching of the atria that occurs with an increase in blood volume causes ANP release
relaxes glomerular mesangial cells, cells between the glomerular capillaries, increasing capillary surface area and increasing GFR
Angiotensin II reduces GFR
potent vasoconstrictor that narrows both afferent & efferent arterioles reducing GFR

Tubular Reabsorption & Secretion

Normal GFR is so high that volume of filtrate in capsular space in half an hour is greater than the total plasma volume
Nephron must reabsorb 99% of the filtrate (Table 26.3)
Another important function of nephrons is tubular secretion
Reabsorption Routes
A substance being reabsorbed can move between adjacent tubule cells or through an individual tubule cell before entering a peritubular capillary. (Fig 26.11)
Paracellular reabsorption - 50% of reabsorbed material moves between cells by diffusion in some parts of tubule
Transcellular reabsorption - material moves through both the apical and basal membranes of the tubule cell by passive and active transport

Transport Mechanisms
Transport across membranes can be either active or passive.
Passive mechanisms
simple diffusion
facilitated diffusion
osmosis
filtration
Primary active transport - energy derived from ATP is used to “pump” a substance across a membrane.

Secondary active transport - energy stored in an ion’s electrochemical gradient drives another substance across the membrane.

Apical and basolateral membranes of tubule cells have different types of transport proteins.

Reabsorption of Na\(^+\) is important.

Several transport systems exist to reabsorb Na\(^+\).

Na\(^+\)/K\(^+\) ATPase pumps sodium from tubule cell cytosol through the basolateral membrane only (Fig 26.11).

Water is only reabsorbed by osmosis.

Obligatory water reabsorption - water is “obliged” to follow the solutes being reabsorbed.

Facultative water reabsorption – reabsorption of water in the late distal convoluted tubule and collecting duct under the control of antidiuretic hormone (ADH).

Reabsorption and Secretion in the Proximal Convoluted Tubule.

Sodium levels are kept low in PCT cells due to Na\(^+\)/K\(^+\) pump in basolateral membranes.

The majority of solute and water reabsorption from filtered fluid occurs in the PCT and most reabsorption involves Na\(^+\) (Fig 26.20).

Normally, 100% of filtered glucose, amino acids, lactic acid, water-soluble vitamins, and other nutrients are reabsorbed in the first half of the PCT by Na\(^+\) symporters (Fig 26.12).

Na\(^+\)/H\(^+\) antiporters achieve additional Na\(^+\) reabsorption, HCO\(_3\)\(^-\) reabsorption, and water reabsorption (Fig 26.13).

PCT cells continually produce the H\(^+\) needed to keep the antiporters running by combining CO\(_2\) with water to produce H\(_2\)CO\(_3\) which dissociates into H\(^+\) and HCO\(_3\)\(^-\).

Caffeine inhibits Na\(^+\) reabsorption.

Na\(^+\)/H\(^+\) antiporters also achieve H\(^+\) secretion.
Diffusion of Cl\(^-\) into interstitial fluid via the paracellular route leaves tubular fluid more positive than interstitial fluid. This electrical potential difference promotes passive paracellular reabsorption of Na\(^+\), K\(^+\), Ca\(^{2+}\), and Mg\(^{2+}\) (Fig 26.14).

Reabsorption of Na\(^+\) and other solutes creates an osmotic gradient that promotes reabsorption of water by osmosis.

PCT and descending loop of Henle are especially permeable to water due to numerous aquaporin-1 channels (membrane transport pores for water).

NH\(_4\)\(^+\) can substitute for H\(^+\) aboard Na\(^+\)/H\(^+\) antiporters and be secreted into tubular fluid.

Urea and ammonia in the blood are both filtered at the glomerulus and secreted by the proximal convoluted tubule cells into the tubules.

Reabsorption in the Loop of Henle

Thick limb of loop of Henle has Na\(^+\)-K\(^+\)-Cl\(^-\) symporters that reabsorb these ions.

Because K\(^+\) leakage channels return much of the K\(^+\) back into tubular fluid, the main effect of the Na\(^+\)-K\(^+\)-Cl\(^-\) symporters is reabsorption of Na\(^+\) and Cl\(^-\) plus the interstitial fluid and blood are negatively charged (Fig 26.15).

Cations passively move to the vasa recta, the peritubular capillaries around the Loop of Henle.

Filtered water is reabsorbed in the descending limb, but little or no water is reabsorbed in the ascending limb.

No transport molecules for water.

Ions continue to be reabsorbed.

Tubular fluid osmolarity (ratio of solutes to water) increases as it goes down the descending limb and decreases in the thick ascending limbs (Fig 26.20).

Reabsorption in the DCT

As fluid flows along the DCT, reabsorption of Na\(^+\) and Cl\(^-\) continues due to Na\(^+\)-Cl\(^-\) symporters.

Na\(^+\) and Cl\(^-\) then reabsorbed into peritubular capillaries (Fig 26.20).

The DCT serves as the major site where parathyroid hormone stimulates reabsorption of Ca\(^{2+}\).
DCT is not very permeable to water so the solutes are reabsorbed with little accompanying water.

Reabsorption and Secretion in the Collecting Duct

By end of DCT, 95% of solutes & water have been reabsorbed and returned to the bloodstream

Cells in the collecting duct make the final adjustments (Fig 26.16)

- Na\(^+\) reabsorbed
- K\(^+\) may be secreted or reabsorbed depending upon blood concentration
- Bicarbonate ions are reabsorbed and H\(^+\) secreted

Hormonal Regulation of Urine Excretion

Rate of excretion of any substance = rate of filtration + rate of secretion - rate of reabsorption

Hormones affect Na\(^+\), Cl\(^-\) & water reabsorption and K\(^+\) secretion in the tubules (Table 26.4)

- renin-angiotensin-aldosterone
  - angiotensin II decreases GFR by vasoconstricting afferent arteriole
  - angiotensin II enhances absorption of Na\(^+\) by activating the Na\(^+\)/H\(^+\) antiporters in the PCT
  - aldosterone stimulates the principal cells in the collecting duct to reabsorb more Na\(^+\) and Cl\(^-\) and secrete K\(^+\) which causes the collecting duct to reabsorb more water
  - increases blood volume by increasing water reabsorption
  - decreases urine output

- atrial natriuretic peptide
  - inhibits reabsorption of Na\(^+\) and water in PCT & suppresses secretion of aldosterone & ADH
  - increase excretion of Na\(^+\) which increases urine output and decreases blood volume

- antidiuretic hormone (Fig 26.17)
  - Increases water permeability of collecting duct - regulates facultative water reabsorption
  - Stimulates the insertion of aquaporin-2 channels into the membrane of a collecting duct
  - water molecules move more rapidly
When osmolarity of plasma & interstitial fluid decreases, more ADH is secreted and facultative water reabsorption increases.

The rate at which water is lost from the body depends mainly on ADH, when ADH levels are very low, the kidneys produce dilute urine and excrete excess water; in other words, renal tubules absorb more solutes than water.

Alcohol inhibits secretion of ADH

Formation of Dilute Urine

Dilute = having fewer solutes than plasma (300 mOsm/liter). (Fig 26.18)

Water is reabsorbed in descending limb increasing the osmolarity of the tubular fluid, but as ions are reabsorbed in thick ascending limb of loop of the fluid becomes more dilute than plasma

can be 4x as dilute as plasma

The collecting duct does not reabsorb water if ADH is low and urine stays dilute

Formation of Concentrated Urine

Urine can be up to 4 times greater osmolarity than plasma (Fig 26.19)

Long loop juxtamedullary nephrons make that possible

Countercurrent multiplication and exchange

The descending and ascending limb of the nephron loop run countercurrent to one another – opposite directions

The vasa recta is running countercurrent to the tubules

The ions being reabsorbed by the ascending limb are picked up by the vasa recta and transported to the deepest portion of the medulla

The buildup of ions encourages water to be reabsorbed in the descending limb

The net effect is to establish an osmotic gradient in the renal medulla – lower osmolarity near the cortex and much higher in the deepest part of the medulla

Urea recycling
The descending limb and thin ascending limb are permeable to urea and it will enter the tubular fluid (secreted).

The thick ascending limb is impermeable to urea and the urea will remain in the tubules until it can leave near the end of the collecting duct.

Contributes to osmotic gradient.

Formation of concentrated urine occurs when ADH levels are high.

Water will be reabsorbed by the collecting duct by facultative reabsorption.

The osmolarity gradient established by the countercurrent mechanism and urea recycling drives the movement of water out of the collecting duct once aquaporin-2 molecules are inserted.

The urine becomes more and more concentrated as more water leaves.

It is possible to remove water from urine to that extent, if interstitial fluid surrounding the loop of Henle has high osmolarity.

Urine Storage, Transportation and Elimination

Urine flow pathway

Nephrons → collecting ducts → papillary ducts → minor calyces → major calyces → renal pelvis → ureters → urinary bladder → urethra

Micturition Reflex

Micturition or urination (voiding)

Stretch receptors signal spinal cord and brain

when volume exceeds 200-400 mL

Impulses sent to micturition center in sacral spinal cord (S2 and S3) & reflex is triggered

parasympathetic fibers cause detrusor muscle in the urinary bladder to contract, external & internal sphincter muscles to relax

Filling causes a sensation of fullness that initiates a desire to urinate before the reflex actually occurs.
conscious control of external sphincter

cerebral cortex can initiate micturition or delay its occurrence for a limited period of time