# CHAPTER 58: MAINTAINING THE INTERNAL ENVIRONMENT

## CHAPTER SYNOPSIS

The cell specialization found in complex vertebrates like humans requires extensive integrated control systems. These homeostatic processes are involved with nearly every bodily function and regulate such things as blood glucose levels and body temperature. Homeostasis occurs through various kinds of feedback loops. Negative loops attempt to return a system above or below a certain setpoint to that normal value and include regulation of blood glucose and body temperature. Positive loops accelerate changes and are exemplified by the process of childbirth.

Most marine invertebrates are simple osmoconformers; they maintain an internal concentration of ions equal to that of their environment. On the other hand, osmoregulators maintain an osmolality independent of their environment. Freshwater vertebrates have a greater internal salt concentration and must constantly exclude water. The internal salt concentration of marine specimens is roughly one-third that of the environment. They must retain water to prevent dehydration. Terrestrial animals tend to lose body water to the air through dehydration and must also conserve water.

Animals utilize various strategies to regulate water balance. Simple protists and sponges possess contractile vacuoles to exclude water. Flatworms draw fluids from their bodies into flame cells, water and metabolites are reabsorbed, excreted substances are expelled through pores in the body wall. In earthworms, the internal fluid is collected in the nephrostomes and filtered, NaCl is reabsorbed by active transport. The Malpighian tubules of insects secrete potassium ions into the gut which pull body fluids and waste past their filtering apparatus. Vertebrates use the pressure-driven filtration system of the kidney, possible only with their closed circulatory system. Certain small molecules are selectively reabsorbed in the kidneys to help conserve water.

Freshwater fish kidneys simply remove excess water that is absorbed. Marine bony fish combat dehydration by drinking enormous quantities of water as very little water is reabsorbed in the kidneys. Elasmobranchs reabsorb waste urea to make their blood isotonic with the sea, thus preventing excessive water loss and reducing the need to remove large amounts of ions. Amphibian kidneys operate much the same as those of freshwater fishes. Reptile systems are quite variable as are their habitats. Mammal and bird kidneys are able to produce urine that is more concentrated than their blood plasma, efficiently reabsorbing water from the filtrate.

Mammalian kidneys are paired organs with functionally and structurally distinct outer cortex and inner medulla. The mammalian nephron begins in the renal cortex where a mass of glomerular capillaries are surrounded by the Bowman's capsule. Glomerular filtrate passes from the capsule to the proximal convoluted tubule and into the distal convoluted tubule. One of the key characteristics of the mammalian nephron is the hair-pin-curved loop of Henle. Several nephrons empty into a single collecting duct which empties into the funnel-shaped renal pelvis. Most of the water filtered through the kidney is reabsorbed, a consequence of salt reabsorption. Glucose and amino acids are reabsorbed through active transport carriers. Other foreign molecules and waste products are actively secreted from the nephron.

Humans filter vast quantities of liquid through their kidneys. Two-thirds of the water and NaCL is immediately reabsorbed in the proximal tubule, the final third of water is reabsorbed in the collecting duct. The loop of Henle descends deeply into the hypertonic renal medulla. A countercurrent flow results where the filtrate passing through the descending limb loses water to the renal medulla because of the salts transported out of the ascending limb. The collecting tubule contains a very concentrated filtrate especially high in urea. The collecting duct is permeable to urea, which passes into the renal medulla followed by more water.

The overall solute concentration of the blood is regulated by altering the hypothalamic output of antidiuretic hormone. ADH causes the collecting ducts to become more permeable to urea. An increase in the osmolality of the blood plasma triggers a sensation of thirst and stimulates ADH secretion. The extracellular fluid in the renal medulla becomes hyperosmotic to the filtrate in the collecting duct. Therefore, even more water leaves the filtrate via osmosis and reenters the bloodstream. This dilutes the blood and returns its osmolarity to normal. Plasma salt balance is regulated by production of aldosterone by the adrenal gland. Aldosterone stimulates reabsorption of sodium in the distal convoluted tubule, decreasing the amount lost in the urine. As a result, whole body sodium increases, as does overall water retention. Atrial natriuretic hormone promotes excretion of salt and water in the urine, opposing the action of aldosterone.

## CHAPTER OBJECTIVES

ä Understand why homeostasis is a vital function of the human body.

ä Differentiate between positive and negative feedback loops. Give examples of each.

ä Pick one example of a negative homeostatic regulating process and explain how this system maintains physiological normalcy.

ä Compare osmoconformer and osmoregulator water balance.

ä Compare the excretory systems of flatworms, earthworms, and insects.

ä Describe the structure of a typical vertebrate nephron, the process of filtration and indicate which regions are associated with reabsorption or secretion.

ä Compare the efficiency of water reabsorption in freshwater, bony marine, and cartilaginous fishes; amphibians, reptiles, birds, and mammals.

ä Describe the internal structure of a typical mammalian kidney.

ä Understand the process of filtration in the human kidney especially as it relates to the materials that enter and leave proximal tubule and the loop of Henle.

ä Compare the osmotic condition of the renal cortex to the renal medulla and understand how it affects reabsorption of water.

ä Discuss hypothalamic and adrenal regulation of kidney function.

## KEY TERMS

allantoin
ammonia
antidiuretic hormone (ADH)
collecting duct
distal convoluted tubule
flame cell
glomerular filtrate
glomerulus
homeostasis
hypertonic
hypotonic
integrating center
isotonic
loop of Henle
nephron
nitrogenous waste
osmoconformer
osmolality
osmotic pressure
proximal convoluted tubule
renal cortex
renal medulla
sensor
urea
ureter
uric acid
urinary bladder
vasopressin

## CHAPTER OUTLINE

**58.0 Introduction**

I. VERTEBRATE PHYSIOLOGY REFLECTS THEIR ORIGIN IN AN AQUATIC ENVIRONMENT

A. Body Water Must Be Regulated for Survival

B. Regulatory Mechanisms Help Animals Exploit Their Environment fig 58.1

**58.1 The regulatory systems of the body maintain homeostasis**

I. THE NEED TO MAINTAIN HOMEOSTASIS

A. Cell Specialization Requires Limited Extracellular Conditions
   1. Homeostasis definition: Dynamic consistency of the internal environment
   2. Conditions are not constant but fluctuate within narrow limits
   3. Necessary for life and regulatory mechanisms

B. Negative Feedback Loops
   1. Sensors measure condition of internal environment fig 58.2
      a. Monitor extracellular conditions
      b. Relay information to integrating center
   2. Sensors detect deviations from setpoint
      a. Setpoint like temperature setting on house thermostat
      b. Body set points for temperature, blood glucose, tension on tendon
      c. Sensors monitor control variable, send data to integrating center
         1) Receives signals from many different sensors
         2) Usually particular location in brain or spinal cord
         3) May also be cells of endocrine glands
      d. Integrating center compares value to set point
      e. Center increases or decreases activity of effector to adjust
   3. Thermostat analogy
      a. Set thermostat (integrating center) at 70°F
      b. Temperature rises above this set point, sensor (thermometer) detects deviation
      c. Thermostat activates effector, air conditioner
      d. Effector acts to reverse deviation from set point
   4. Similar reaction with regard to human body temperature fig 58.3
      a. Temperature exceeds set point of 37°C, sensor in brain detects deviation
      b. Integrating center in brain acts, sensors stimulate effectors
      c. Effectors include sweat glands, lower body temperature
   5. Effectors "defend" body against deviations, regulation is in a negative direction
      a. Continue with house temperature analogy
      b. Air conditioner ultimately reduces temperature of house below set point
      c. Air conditioner turned off
      d. Effector turned on by high temperature, produces negative change
      e. Change causes effector to be turned off
      f. Constancy is maintained

C. Regulating Body Temperature
   1. Humans, mammals, and birds are endothermic
   2. Maintain constant temperature independent of environment
   3. Neurons detect temperature increase over 37°C (98.6°F)
      a. Input to hypothalamus
      b. Triggers mechanisms to dissipate heat
      c. Induces sweating, dilation of blood vessels in skin, and other reactions
      d. Responses counter rise in body temperature
   4. Decrease in body temperature
      a. Induces shivering and constriction of skin blood vessels
      b. Raises body temperature, corrects challenge to homeostasis
   5. Other vertebrates are ectothermic
      a. Body temperature dependent on environmental temperature
      b. Many ectotherms maintain a degree of body temperature homeostasis
      c. Large fishes maintain parts of body at higher temperature than water

d. Reptiles maintain temperature by behavior
   1) Place selves in sun or shade
   2) Gives selves "fever" by seeking warmer locations
6. Invertebrate temperature control
   a. Use behavior, not feedback regulation
   b. Butterflies orient selves to maximize absorption of sunlight
   c. Moths use shivering reflex to warm thoracic flight muscles — fig 58.4

D. Regulating Blood Glucose
1. Large amount of glucose in body after carbohydrate meal — fig 58.5
2. Temporary rise in blood glucose concentration
3. Glucose level exceeds normal value, detected by islets of Langerhans
4. Islets secrete insulin hormone
5. Stimulates uptake of glucose by muscles, liver, adipose cells
   a. Muscles and liver convert glucose to glycogen
   b. Adipose cells convert glucose to fat
6. Islets act as sensor, integrating center, and effector
7. Blood glucose levels lowered, energy stored for later use

## II. ANTAGONISTIC EFFECTORS AND POSITIVE FEEDBACK

A. Antagonistic Effectors
1. Negative feedback mechanisms oppose each other to produce fine control
2. Commonly called "push-pull" control
   a. Increasing activity of one effector causes decreasing activity of another
   b. Affords finer degree of control than simple on/off in just one system
3. Return to analogy of maintaining room temperature
   a. Simple control by heater or air conditioner on or off
   b. More stable conditions using both kinds of effectors — fig 58.6
   c. Heater turned on when air conditioner turned off, vice versa
4. Antagonistic control of body temperature and blood glucose
   a. Insulin lowers blood glucose after meal
   b. Other hormones raise levels between meals, especially during exercise
5. Heart rate maintained by similar antagonistic effectors
   a. One group of nerve fibers increase heart rate
   b. Another group slows heart rate

B. Positive Feedback Loops
1. In positive feedback the disturbance is accentuated
2. Perturbations cause effector to drive controlled variable even farther from set point
3. Analogous to spark that ignites an explosion
4. Example: Blood clotting
   a. One factor activates another
   b. Produces cascade that leads to formation of a clot
5. Example: Contractions of uterus during childbirth — fig 58.7
   a. Stretching of uterus by fetus stimulates contraction
   b. Stimulates further stretching, more contraction
   c. Final result: Fetus expelled from uterus
6. Positive feedback systems are part of larger mechanism that maintains homeostasis

## 58.2 The extracellular fluid concentration is constant in most vertebrates

### I. OSMOLALITY AND OSMOTIC BALANCE

A. Maintaining Osmotic Balance
1. Water in body distributed into intercellular and extracellular compartments fig 58.8
    a. Extracellular compartment takes water from or gives water to environment
    b. Also must exchange inorganic ions
2. Exchanges occur across epithelial cells and in kidney filtration
3. Vertebrate homeostasis compares total and specific ion concentrations
    a. Sodium is major cation, chloride major anion in extracellular fluids
    b. Calcium and magnesium also have important functions, must be maintained

B. Osmolality and Osmotic Pressure
1. Osmosis is diffusion of water across membrane
    a. Occurs from more dilute solution to less dilute solution
    b. From lower solute concentration to higher solute concentration
2. Osmolality is the measurement of solute concentration in a solution
    a. Moles of solute per kilogram of water
    b. Two solutions with same osmotic concentration are isosmotic
    c. Solution with lower osmolality is hypoosmotic
    d. Solution with higher osmolality is hyperosmotic
3. Osmotic pressure measures tendency of solution to take in water
    a. Two solutions separated by semipermeable membrane
        1) One solution hyperosmotic to other
        2) Water moves via osmosis to hyperosmotic solution
    b. Hyperosmotic solution also called hypertonic, has higher osmotic pressure
    c. Cell placed in hypertonic solution loses water to surrounding solution
        1) Solution has higher osmotic pressure than cell cytoplasm
        2) Cell will shrink
    d. Cell in a hypotonic solution will gain water, expand
    e. Cell in isosmotic solution will show no net water movement
        1) Isosmotic solution also called isotonic
        2) Isotonic solutions include normal saline and 5% dextrose

C. Osmoconformers and Osmoregulators
1. Most marine invertebrates are osmoconformers
    a. Osmotic concentration of body fluid equals that of seawater
    b. Extracellular fluids are isotonic to seawater
    c. No osmotic gradient, no net movement of water
2. Marine invertebrates are in osmotic equilibrium with environment
3. Comparison of marine vertebrates
    a. Hagfish are only strict osmoconformers
    b. Sharks, other chondrichthyes are semi-osmoconformers
        1) Are isotonic to seawater
        2) Blood level of NaCl lower than seawater
        3) Difference made up by retaining blood urea at high concentration
    c. All other vertebrates are osmoregulators
4. Osmoregulators maintain a constant osmotic concentration independent of environment
    a. Permits exploitation of variety of ecological niches
    b. Requires constant adjustment
5. Freshwater vertebrates
    a. Maintain higher salt concentration in body than in environment
    b. Hypertonic to the environment, water tends to enter body

c. Must prevent water from entering and exclude excess that does enter
d. Lose inorganic ions to environment, actively transport back in

6. Marine vertebrates
   a. Are hypotonic to the environment
   b. Body osmolality one-third that of seawater
   c. Must retain water to prevent dehydration
   d. Drink seawater, eliminate excess through kidneys and gills
7. Terrestrial vertebrates
   a. Bodies have a higher concentration of water than surrounding air
   b. Tend to lose water to evaporation from skin and lungs
   c. Have excretory systems that help retain water

## II. OSMOREGULATORY ORGANS

### A. How Osmoregulation Is Achieved

1. Simple protists and sponges
   a. Removal of water or salts coupled to removal of metabolic wastes
   b. Possess contractile vacuoles
2. Other multicellular animals use excretory tubule systems to expel fluids and wastes

### B. Excretory Systems of Invertebrates

1. Flatworms have protonephridia — fig 58.9
   a. Branch through body into bulblike flame cells
   b. Structures open to outside, not inside of body
   c. Cilia in flame cell draws fluid in from body
   d. Water and metabolites reabsorbed
   e. Excreted substances expelled through excretory pores
2. Earthworms have metanephridia — fig 58.10
   a. Tubules open to inside and outside of body
   b. Obtain fluid from inside of body via nephrostomes
      1) Fluid is filtered, formed under pressure, and passed through small openings
      2) Molecules larger than certain size are excluded
   c. Fluid is isotonic to coelom, NaCl removed by active transport system
   d. Process called reabsorption
      1) Transport out of tubule, into surrounding body fluids
      2) Salt reabsorbed from filtrate, urine is more dilute than body fluid (hypotonic)
3. Kidneys of mollusks and crustacean antennal glands have same function
4. Insects possess Malpighian tubules — fig 58.11
   a. Extension of digestive tract branching off hindgut
   b. Urine not formed by filtration, no pressure difference
   c. Waste molecules, potassium ions secreted into tubules by active transport
      1) Secretion process is opposite of filtration
      2) Ions or molecules transported from body fluid to tubule
   d. Osmotic gradient pulls water into tubules from open circulatory system
   e. Water and potassium reabsorbed through epithelium in hindgut
   f. Small molecules and waste products excreted from rectum with feces
   g. Extremely efficient means of water conservation
5. Vertebrates utilize pressure-driven filtration system
   a. Filtrate contains waste products and water
   b. Also includes valuable small molecules like glucose, amino acids, vitamins
   c. Small molecules and water reabsorbed from tubules into blood, wastes remain
   d. Additional wastes may be secreted by tubules into filtrate
   e. Final filtrate excreted as urine

6. Vertebrate selective reabsorption provides great flexibility
   a. Filter out almost everything, expend energy to reabsorb important molecules
   b. Various groups reabsorb different molecules
   c. Beneficial in particular habitats

## III. EVOLUTION OF THE VERTEBRATE KIDNEY

### A. Basic Design Retained in All Vertebrate Forms
1. Kidney is complex organ, composed of repeating nephron units — fig 58.12
2. Blood pressure forces blood fluid past glomerulus filter
   a. Red blood cells, proteins, large molecules stay in blood
   b. Water, small molecules, wastes pass through into bent part of nephron tube
   c. Useful sugars and ions recovered by active transport
   d. Water, metabolic wastes left behind in fluid urine
3. Glomerular filtrate is initially isotonic to blood
   a. Can produce isotonic urine if ions are reabsorbed
   b. Can produce hypotonic urine, more dilute
4. Only birds and mammals can produce hypertonic urine, more concentrated than blood

### B. Freshwater Fishes
1. Vertebrate kidneys evolved in bony freshwater fish
2. Fish body fluids have greater osmotic concentration than surrounding water
   a. Water tends to enter body from environment
   b. Solutes tend to leave body and enter environment
3. How fish address problems
   a. Do not drink water and excrete large volume of dilute urine
   b. Reabsorb ions across nephron tubules from filtrate back into blood
   c. Actively transport ions across gills from surrounding water into blood

### C. Marine Bony Fishes — fig 58.13
1. Bony marine fish probably evolved from freshwater ancestors
2. Faced new problems, body fluids hypotonic compared to surrounding seawater
   a. Water tends to leave body by osmosis across gills, lose water in urine
   b. Marine fish compensate by drinking large amounts of seawater
3. Excretion of ions
   a. Divalent $Ca^{++}$, $Mg^{++}$, remain in digestive tract, eliminated in anus
   b. Some absorbed into blood, as are monovalent ions $K^{+}$, $Na^{+}$, and $Cl^{-}$
   c. Most monovalent ions actively transported out of blood across gills
   d. Divalent ions secreted into nephron tubules, excreted in urine
4. Excreted urine is isotonic to body fluids
   a. More concentrated than freshwater fish
   b. Less concentrated than birds and mammals

### D. Cartilaginous Fishes
1. Elasmobranchs solve osmotic problem differently than bony fishes
2. Kidneys reabsorb the metabolic waste urea
   a. Have a blood urea concentration 100 times greater than mammals
   b. Thus blood is isotonic with surrounding sea
3. No net water movement, water loss prevented
   a. Do not drink excessive amounts of sea water
   b. Kidneys and gills do not need to remove large quantities of ions
   c. Enzymes and tissues tolerant of high urea

E. Amphibians and Reptiles
   1. Amphibian kidneys operate identically to freshwater fish
      a. Spend significant portion of lives in water, stay in wet places on land
      b. Produce very dilute urine
      c. Compensate for $Na^+$ loss by transporting it across skin from surrounding water
   2. Reptile kidneys are varied with habitat
      a. Freshwater varieties have kidneys similar to fish and amphibians
      b. Marine forms have kidneys similar to freshwater forms
         1) Lose water and take in salts
         2) Drink seawater and excrete isotonic urine
         3) Eliminate salt via salt glands on head — fig 58.14
      c. Terrestrial forms reabsorb most of salt and water from filtrate
         1) Conserves blood volume in dry environments
         2) Urine cannot be more concentrated than blood plasma
         3) Additional water reabsorbed when urine enters cloaca

F. Mammals and Birds
   1. Produce urine with greater osmotic concentration than body fluids
      a. Can excrete wastes in smaller volume of water, water retained in body
      b. Human kidneys can produce 4.2 times more concentrate urine
      c. Kidneys of some desert animals very concentrated
         1) Camel= 8 times
         2) Gerbil = 14 times
         3) Pocket mouse = 22 times
         4) Efficiency in kangaroo rat so efficient it never has to drink water — fig 58.15
   2. Loop of Henle results in production of hyperosmotic urine — fig 58.18
      a. Found only in birds and mammals
      b. Nephron with long loop descends into medulla, produces concentrated urine
      c. Mammals have some long and some short looped nephrons
      d. Birds have mostly short looped nephrons
         1) Produce urine only twice as concentrated as blood
         2) Marine birds drink sea water, excrete salt from salt glands near eyes — fig 58.16
         3) Moderately hypertonic urine delivered to cloaca
         4) Additional water may be reabsorbed there

**58.3 The functions of the vertebrate kidney are performed by nephrons**

I. THE MAMMALIAN KIDNEY

A. Basic Structure of the Kidney — fig 58.17
   1. Paired organs located in lower back region
      a. Receives blood from renal artery, produces urine
      b. Urine drains through ureter to urinary bladder
   2. Internal structure of kidney
      a. Mouth or ureter formes funnel-like renal pelvis
      b. Cup-shaped extensions receive urine from renal tissue
      c. Renal tissue composed of outer renal cortex and inner renal medulla

B. Nephron Structure and Filtration
   1. Functional unit is the nephron — fig 51.17
      a. Each kidney contains one million nephrons
      b. Juxtamedullary nephrons have long loops, descend deep into medulla
      c. Cortical nephrons have shorter loops

2. Each nephron has tubular and vascular component fig 58.18
   a. Afferent arteriole carries blood to tuft of capillaries called glomerulus
      1) Blood filtered by pressure forcing blood through capillary walls
      2) Blood cells and large plasma proteins cannot pass through
      3) Large amounts of water and dissolved molecules form glomerular filtrate
   b. Filtrate enters first part of tubular component, Bowman's capsule
      1) Capsule surrounds glomerulus like soft balloon surrounds embedded fist
      2) Capsule has slits through which fluid passes to nephron tubules
   c. Filtrate then enters proximal convoluted tubule located in cortex
   d. Fluid moves into medulla and back via loop of Henle
      1) Loop of Henle only found in birds and mammals
      2) Allow them to concentrate urine
   e. Fluid then goes to distal convoluted tubule in cortex
   f. Fluid drains into collecting duct that descends into medulla
   g. Merges with other collecting ducts in the renal pelvis, dumps urine
   h. Unfiltered products return to vascular system via efferent arteriole
      1) Forms second vascular bed, peritubular capillaries, surrounding tubules
      2) Only capillary bed drained by arteriole rather then venule
      3) Only time second arteriole delivers blood to second capillary bed
   i. Peritubular capillaries involved in reabsorption and secretion

C. Reabsorption and Secretion
1. Most of water and dissolved solutes entering filtrate returns to blood fig 58.19
   a. In human, 2,000 liters of blood passes through kidneys per day
   b. 180 liters of water leaves blood, enters filtrate
   c. Most reabsorbed, only 1 to 2 liters becomes urine
2. Reabsorption of water a consequence of salt reabsorption
3. Reabsorption of glucose, amino acids driven by active transport carriers
   a. Maximum rate of transport reached when carriers are saturated
   b. Renal glucose saturation = 180 milligrams of glucose per 100 milliliters of blood
   c. If blood glucose is higher, extra will be lost in urine
      1) Occurs in untreated diabetes mellitus
      2) Glucose in urine is hallmark of disease
4. Secretion of foreign molecules and waste products
   a. Involves transport of molecules across membranes of capillaries and kidney tubules
   b. Similar to reabsorption but in opposite direction
   c. Elimination may be rapid
   d. Reason why penicillin must be administered in high doses

D. Excretion
1. Potentially harmful substances eliminated via the kidney
2. Urine also contains nitrogenous wastes
   a. Example urea and uric acid
   b. Products of amino acid and nucleic acid catabolism
3. May also contain excess $K^+$, $H^+$, and other ions
   a. High $H^+$ concentration helps maintain blood pH in narrow range
   b. Excretion of water maintains blood volume and pressure

E. Critical Function of Kidney Is Homeostasis
1. Maintain constancy of internal environment
2. Disease in kidney can alter this function
   a. Increase in blood nitrogenous waste products
   b. Disturb electrolyte and acid-base balance
   c. Failure in regulation of blood pressure

## II. TRANSPORT PROCESSES IN THE MAMMALIAN NEPHRON

A. Humans Produce Large Quantities of Glomerular Filtrate
   1. 180 liters produced per day, volume of fluid lost if nor reabsorbed
   2. Water can only pass via osmosis, cannot occur between two isotonic solutions
   3. Special mechanism creates gradient between filtrate and blood

B. Proximal Tubule
   1. Two-thirds of NaCl and water in capsule reabsorbed immediately in proximal tubule
      a. Driven by active transport of $Na^+$ out of filtrate, into blood vessels
      b. $Cl^-$ follows $Na^+$ passively by electrical attraction
      c. Water follows both because of osmosis
      d. Filtrate is still isotonic to blood plasma
   2. One-third of volume remains, equals 60 liters of fluid
      a. Additional water must be reabsorbed
      b. Occurs mostly across wall of collecting duct
      c. Interstitial fluid in renal medulla is hypertonic to fluid in collecting ducts
      d. Water drawn out of collecting duct by osmosis
      e. Remaining fluid is hypertonic

C. Loop of Henle
   1. Reabsorption dependent on hypertonic renal medulla
      a. More hypertonic medulla will create greater osmotic gradient
      b. Steeper gradient will cause more water reabsorption
   2. Loop of Henle creates hypertonic conditions in renal medulla — fig 58.20
   3. Ascending limb of loop actively extrudes $Na^+$, $Cl^-$ follows
      a. Mechanism different from process in proximal tubule
      b. Ascending limb not permeable to water
      c. $Na^+$ exits, fluid in ascending limb gets more dilute, hypotonic
      d. Surrounding tissue becomes more concentrated, hypertonic
   4. NaCl pumped out of ascending limb trapped in interstitial fluid
      a. Blood vessels in medulla have loops called vasa recta
      b. NaCl diffuses from blood leaving medulla to blood entering medulla
      c. Vasa recta functions in countercurrent exchange of NaCl
      d. Keeps NaCl within interstitial fluid of medulla, keeps it hypertonic
   5. Descending limb is permeable to water
      a. Water leaves by osmosis as fluid descends into hypertonic medulla
      b. Water enters blood vessels of vasa recta, carried to general circulation
   6. Loss of water from descending limb multiplies concentration
      a. Longer loop of Henle increases interaction between descending and ascending loops
      b. Increases concentration possible
      c. Concentration in human kidney multiplied four-fold (300 to 1,200 milliosmoles)
   7. Serves as countercurrent multiplier
      a. Fluid flows in opposite directions in two limbs of loop of Henle
      b. Creates hypertonic renal medulla
      c. Primarily results from NaCl accumulation, urea also contributes
         1) Descending limb and collecting duct are permeable to urea
         2) Urea leaves nephron by diffusion

D. Distal Tubule and Collecting Duct
   1. Filtrate in distal tubule is hypotonic
      a. NaCl pumped out at ascending limb
      b. Concentration is 100 milliosmoles
   2. Collecting duct plunges into renal medulla, osmotic gradient draws out water

3. Permeability of collecting duct altered by antidiuretic hormone (ADH), vasopressin
   a. Posterior pituitary secretes more ADH to conserve water
   b. Increases number of water channels in plasma membrane of collecting duct cells
   c. Increases permeability to water
   d. More water reabsorbed, less excreted in urine, creates hypertonic urine

E. Additional Homeostatic Events Occur in Kidneys
1. Kidneys also regulate electrolyte balance by reabsorption and secretion fig 58.21
   a. Reabsorb $K^+$ in proximal tubule
   b. Secrete it in distal convoluted tubule
2. Kidneys maintain acid-base balance
   a. Excrete $H^+$ into urine
   b. Reabsorb bicarbonate $HCO_3^-$

III. AMMONIA, UREA, AND URIC ACID

A. Animals Catabolize Nitrogen-Containing Compounds
1. Include amino acids and nucleic acids
2. Produce nitrogenous wastes that must be eliminated fig 58.22
3. Metabolism of amino and nucleic acids
   a. Amino group removed, combined with $H^+$ to form ammonia in liver
   b. Ammonia is toxic, must be transported in very dilute solution
4. Adaptations of various vertebrates
   a. No problem for freshwater fish or tadpoles
      1) Most elimination via diffusion across gills
      2) Also produce copious amounts of urine
   b. Elasmobranchs, adult amphibians, mammals produce urea
      1) Less toxic form
      2) Water-soluble, excreted in large amounts in urine
   c. Reptiles, birds, insects excrete uric acid
      1) Slightly soluble in water
      2) Uric acid precipitates, can be excreted in small amounts of liquid
         a) Product is insoluble in water, crystallizes
         b) Excreted as semi-solid paste called guano
      3) Metabolic wastes can build up in shell as embryo grows
         a) Lengthy, energy requiring process
         b) Precipitate cannot affect embryo even though it is still within egg
   d. Mammals also produce some uric acid
      1) Waste of purine nucleotide degradation
      2) Most mammals have uricase enzyme that converts uric acid into allantoin
      3) Lacking in humans, apes, dalmatian dog
         a) Must excrete uric acid directly
         b) Excessive uric acid accumulation in joints called gout

**58.4 The kidney is regulated by hormones**

I. HORMONES CONTROL HOMEOSTATIC FUNCTIONS

A. Regulate Osmotic Concentration of Urine Via Water Excretion
1. Blood volume, blood pressure maintained by action of kidneys
   a. Excrete hypertonic urine when body needs to conserve water
   b. Excretes hypotonic urine when too much water has been ingested
2. Regulate plasma $Na^+$ and $K^+$ concentrations, also blood pH
3. Coordinated primarily via actions of hormones

B. Antidiuretic Hormone
   1. Hypothalamus produces antidiuretic hormone, secreted by posterior pituitary
      a. Increase in osmolality of blood plasma stimulates its production
      b. Osmoreceptors in hypothalamus respond to elevated osmolality
      c. Trigger sensation of thirst, stimulate ADH secretion fig 58.23
   2. Actions of ADH
      a. Makes kidney collecting ducts more permeable to water
         1) Water channels exist in membranes of intracellular vesicles of epithelium
         2) ADH stimulates fusion of vesicle membrane with plasma membrane
         3) With reduction of ADH, membrane pinches in to form new vesicles
         4) Membrane thus becomes less permeable to water
      b. Extracellular fluid in medulla is hypertonic to collecting duct filtrate
         1) Water leaves filtrate by osmosis
         2) Reabsorbed into blood
   3. Urine output related to ADH production
      a. Maximal ADH results in 600 ml concentrated urine produced
      b. Lack of any ADH causes diabetes insipidus
         1) Creates large volume of dilute urine
         2) Causes severe dehydration, dangerously low blood pressure

C. Aldosterone and Atrial Natriuretic Hormone
   1. $Na^+$ ions are major solutes in blood
   2. If $Na^+$ decreased, blood osmolality also decreased
      a. Inhibits ADH secretion
      b. More water excreted in urine as less is reabsorbed
      c. Blood volume decreases, lowers blood pressure, may be lethal
      d. Salt necessary for life, animals seek salt in nature
   3. Kidneys compensate for $Na^+$ decrease via aldosterone secreted by adrenal cortex
      a. Stimulates reabsorption of $Na^+$ at distal convoluted tubule
      b. Thus decreases amount of $Na^+$ lost in the urine
      c. Reabsorption of $Na^+$ followed by $Cl^-$ and then water
      d. Net effect to retain both salt and water
      e. Maintains blood volume and pressure
   4. Homeostasis maintained by renin-angiotensin-aldosterone system
      a. Secretion of aldosterone with $Na^+$ decrease is indirect
      b. Fall in $Na^+$ accompanied by decreased blood volume
      c. Reduced blood flow past juxtaglomerular apparatus in kidney fig 58.26
      d. Juxtaglomerular apparatus secretes renin into blood
         1) Renin catalyzes production of angiotensin I from angiotensinogen
         2) Angiotensin I converted into angiotensin II
      e. Actions of angiotensin II
         1) Stimulates blood vessels to constrict
         2) Stimulates adrenal cortex to produce aldosterone
   5. Aldosterone also promotes secretion of $K^+$ into distal convoluted tubule
      a. Lowers blood $K^+$ level
      b. Helps maintain $K^+$ constant with changing amounts in diet
   6. Lack of aldosterone is lethal
      a. Excessive loss of salt and water
      b. Buildup of $K^+$ in blood
   7. Action of aldosterone opposed by atrial natriuretic hormone (ANH)
      a. Secreted by right atrium of heart
      b. Occurs in response to increased blood flow that stretches atrium
      c. Aldosterone secretion reduced, atrial naturetic hormone secretion increased
      d. Promotes excretion of salt and water in urine, lowers blood volume

# INSTRUCTIONAL STRATEGY

## PRESENTATION ASSISTANCE:

This is a difficult topic for beginning students to understand. Set the stage, introduce the characters, then begin the play. Describe the gross anatomy of a mammalian kidney including the osmotic differences between the cortex and the medulla. Then indicate the location of the various parts of the nephron: capsule, proximal and distal convoluted tubules, descending and ascending limbs of the loop of Henle, collecting duct, and associated blood vessels. Finally put everything together by following a drop of blood and its filtrate through the capsule, into the nephron and out the collecting duct.

Most students have experienced the effects of caffeine and ethanol on their urine output and will be interested in the physiology that regulates urine output.

Compare the operation of a dialysis machine to that of a normal kidney. Discuss why artificial dialysis is necessary relative to increased levels of blood urea nitrogen (BUN) and creatinine.

The kidneys excrete many metabolic toxins and drugs, penicillin and tetracycline for example. Excess vitamin C is also dumped here (and turns the urine bright orange). Many of these compounds can cause damage to the renal tubule when used for too long.

## VISUAL RESOURCES:

Obtain various samples of vertebrate kidneys from the butcher or slaughter house. Few kidneys resemble the "kidney bean" structures possessed by those animals a student typically dissects.

Set up a simple dialysis experiment to proceed as you lecture.