Osmoregulation and Excretion

1. There are two basic solutions to the problem of balancing water gain with water loss.
   a. The first, available only to marine animals, is to be an **osmoconformer.** The concentration of solutes in their body fluid is equal to that of their environment. As a result, they do not gain or lose water. Osmoconformers usually live in water that has a very stable composition (*i.e.*, the ocean) and so their internal environment changes very little.
      i. Most marine invertebrates are osmoconformers.
   b. The second is to be an **osmoregulator**. These animals must control their internal osmolarity because their body fluids are not isoosmotic with the outside environment. Most vertebrates are osmoregulators – they maintain a concentration of solutes in their body fluid different from that of the environment.
      i. An osmoregulator must discharge excess water if it lives in a hypotonic environment or take in water to offset osmotic loss if it inhabits a hypertonic environment.
      ii. Because diffusion tends to equalize concentrations in a system, osmoregulators must expend energy to maintain the osmotic gradients via active transport.
         (1) Osmoregulation accounts for nearly 5% of the resting metabolic rate of many marine and freshwater bony fishes.
   c. Most animals, whether osmoconformers or osmoregulators, cannot tolerate substantial changes in internal osmolarity so they need a way to maintain the internal concentration of fluids.
   d. Marine vertebrates and some marine invertebrates are osmoregulators. For most of these animals, the ocean is a strongly dehydrating environment because it is much saltier than internal fluids, and water is lost from their bodies by osmosis.
      i. Marine bony fishes are hypoosmotic to seawater and constantly lose water by osmosis and gain salt by diffusion and from the food they eat.
      ii. The fishes balance water loss by drinking seawater and actively transporting chloride ions out through their skin and gills. Sodium ions follow passively.
      iii. They produce very little urine.
   e. In contrast to marine organisms, freshwater animals are constantly gaining water by osmosis and losing salts by diffusion.
      i. This happens because the osmolarity of their internal fluids is much higher than that of their surroundings.
      ii. They solve this problem by excreting large amounts of very dilute urine. They replace lost ions by active transport of ions across the gills from the water into the blood.
         (1) Some fishes, like salmon, migrate between seawater and freshwater and must undergo dramatic and rapid changes in osmoregulation.
         (2) While in the ocean, salmon osmoregulate as other marine fishes do, by drinking seawater and excreting excess salt from the gills.
         (3) When they migrate to fresh water, salmon cease drinking, begin to produce lots of dilute urine, and their gills start taking up salt from the dilute environment - the same as fishes that spend their entire lives in fresh water.
   f. Dehydration is fatal for most animals, but some aquatic invertebrates living in temporary ponds and films of water around soil particles can lose almost all their body water and survive in a dormant state, called **anhydrobiosis,** when their habitats dry up.
      i. Some anhydrobiotic organisms, like insects that survive freezing in winter, contain large amounts of sugars that protect their cell membranes when they dry out.

2. Diverse excretory systems have evolved but most share the common characteristic of relying on a system of tubes to collect waste and excrete it.
    a. Flatworms have an excretory system consisting of a branching network of dead-end tubules. These contain cilia that move water and solutes from the **interstitial fluid** (the fluid surrounding cells) into the tubule system. The urine in the tubules exits through openings.
    b. Each segment of an annelid worm has a pair of tubes that collect body fluids from the body cavity and release the fluid to the outside.
    c. Insects and other terrestrial arthropods have organs that remove nitrogenous wastes and also function in osmoregulation. These tubes collect waste from the body fluid and open into the digestive system.
    d. The kidneys of vertebrates usually function in both osmoregulation and excretion and also small tubes to filter blood.

3. The threat of desiccation is a major regulatory problem facing terrestrial plants and animals. Adaptations that reduce water loss are key to survival on land.
    a. Most terrestrial animals have body coverings that help prevent dehydration. These include waxy layers in insect exoskeletons, the shells of land snails, and the several layers of dead skin cells of most terrestrial vertebrates.
    b. Being nocturnal also reduces evaporative water loss.
    c. Despite these adaptations, most terrestrial animals lose considerable water from moist surfaces in their respiratory surface, in urine and feces, and across the skin.
        i. Land animals balance their water budgets by drinking and eating moist foods and by using metabolic water from aerobic respiration.
        ii. Some animals are so well adapted for minimizing water loss that they can survive in deserts without drinking by using the water produced during cellular respiration.
        iii. Efficient kidneys allow the excretion of concentrated urine to get rid of waste.

4. Water balance and waste disposal.
    a. Because most metabolic wastes must be dissolved in water when they are removed from the body, the type and quantity of waste products may have a large effect on water balance.
    b. When animals digest proteins, the amino acids (which contain nitrogen) must be metabolized.
        i. During their breakdown, enzymes remove nitrogen in the form of **ammonia,** a small and very toxic molecule.
        ii. In order to excrete nitrogenous waste as ammonia, animals need to be able to dilute it with lots of water.
            (1) Because it must be diluted with so much water, ammonia excretion is most common in aquatic species.
            (2) This is why freshwater fish produce such a large volume of dilute urine.
        iii. Ammonia excretion is not an option for most marine and land animals.
            (1) Most terrestrial animals and many marine organisms (which tend to lose water to their environment by osmosis) do not have access to sufficient water to be able to dilute ammonia.
            (2) Instead, mammals, most adult amphibians, sharks, and some marine bony fishes and turtles excrete mainly **urea.**
                (a) Urea is synthesized in the liver by combining ammonia with carbon dioxide and is excreted by the kidneys.
                (b) The main advantage of urea is its low toxicity, about 100,000 times less than that of ammonia. This means urea can be transported and

stored safely at high concentrations, reducing the amount of water needed for nitrogen excretion.

(c) The main disadvantage of urea is that animals must expend energy to produce it from ammonia.

(3) Land snails, insects, birds, and many reptiles excrete **uric acid** as the main nitrogenous waste.

(a) Like urea, uric acid is relatively nontoxic.

(b) But unlike either ammonia or urea, uric acid is largely insoluble in water and can be excreted as a semisolid paste with very little water loss.

(c) While saving even more water than urea, the compromise is that it is even more energetically expensive to produce.

c. Mode of reproduction appears to have been important in choosing among these alternatives.

i. Soluble wastes can diffuse out of a shell-less amphibian egg (ammonia) or be carried away by the mother's blood in a mammalian embryo (urea).

ii. However, the shelled eggs of birds and reptiles are not permeable to liquids, which means that soluble nitrogenous wastes trapped within the egg could accumulate to dangerous levels.

iii. Uric acid precipitates out of solution and can be stored within the egg as a harmless solid left behind when the animal hatches.

5. Most excretory systems produce urine by refining a filtrate derived from body fluids. While excretory systems are diverse, nearly all produce urine in a process that involves three general several steps.

a. In **filtration**, blood pressure forces fluid from the blood through a selectively permeable membrane. The fluid is called the **filtrate** (*i.e.*, the fluid that will become urine). Filtration is mostly nonselective.

b. During **reabsorption**, useful molecules from the filtrate are recovered and returned to the blood, some by active transport.

c. Any wastes that remain in the blood are added to the filtrate by selective **secretion,** which also uses active transport.

d. The filtrate is excreted as urine.

6. Mammals have a pair of bean-shaped kidneys, each one being supplied with blood by a **renal artery** and drained by a **renal vein**. Although the kidneys are only about 1% of your body weight, they get about 20% of your blood flow.

a. Urine exits each kidney through a duct called the **ureter,** and both ureters drain through a common **urinary bladder.** During urination, urine is expelled from the urinary bladder through a tube called the **urethra,** which empties to the outside near the vagina in females or through the penis in males.

b. The kidneys are packed with microscopic tubes called **nephrons** that are surrounded by capillaries. Each human kidney contains about a million nephrons, with a total tube length of about 80 km.

c. Each nephron consists of a single long tube and a ball of capillaries, called the **glomerulus**.

d. The tube begins with a ball-shaped swelling called **Bowman's capsule** that surrounds the glomerulus.

e. Blood enters the kidney from the renal artery which then branches into smaller and smaller vessels until reaching the capillaries of the glomerulus. As blood passes into the capillaries of the glomerulus, blood pressure forces water and small molecules out of the blood into

Bowman's capsule.

i. The capillaries of the glomerulus are permeable to water and small solutes like salt but not to blood cells or large molecules like proteins.

ii. The filtrate in Bowman's capsule contains salt, glucose, amino acids, vitamins, urea, and other small molecules.

f. From Bowman's capsule, the filtrate passes through three regions of the nephron: the **proximal tubule**; the **loop of Henle**, a hairpin turn with a descending limb and an ascending limb; and the **distal tubule**.

i. The distal tubule empties into a **collecting duct,** which receives filtrate from many nephrons.

ii. The many collecting ducts empty into the **renal pelvis,** which drains into a duct called the **ureter**. The filtrate, which we might now call urine, exits each kidney through the ureter, and both ureters drain to the **urinary bladder**.

iii. During urination, urine is expelled from the urinary bladder through a tube called the **urethra,** which empties to the outside near the vagina in females or through the penis in males.

g. The nephrons and collecting ducts reabsorb nearly all of the sugar, vitamins, and other nutrients from the initial filtrate and about 99% of the water. In humans, between 1000 and 2000 L of blood passes through the kidneys each day. About 180 L of water leaves the blood but most is reabsorbed, and only about 1.5 L of urine is produced.

h. Secretion and reabsorption in the proximal tubule change the volume, composition and concentration of the filtrate.

i. Drugs and other poisons that have been processed in the liver are removed from the blood and enter the filtrate and valuable nutrients like glucose, amino acids, and ions, are actively or passively absorbed from the filtrate.

ii. One of the most important functions of the **proximal tubule** is reabsorption of most of the NaCl and water from the filtrate.

(1) Salt is transported out of the filtrate and water follows by osmosis.

iii. As the filtrate flows through the proximal tubule, large amounts of water *and* salt are reabsorbed. The volume of the filtrate decreases substantially, but its osmolarity remains about the same.

i. Reabsorption of water continues as the filtrate moves into the **descending limb of the loop of Henle**.

i. The descending limb is permeable to water but not to salt.

ii. The concentration of the interstitial fluid increases from the outer cortex to the inner medulla. As the filtrate flows from the cortex to the medulla in the descending limb of the loop of Henle, water leaves the tubule by osmosis.

iii. The osmolarity of the filtrate increases as solutes, like NaCl, become more concentrated.

iv. The highest molarity occurs at the bend of the loop of Henle so there is a lot of diffusion of salt out of the loop as the filtrate enters the ascending limb.

v. The descending limb produces progressively saltier filtrate. The high salt concentration maintains a high osmolarity in the interstitial fluid of the renal medulla.

j. The permeability of the **ascending limb of the loop of Henle** is reversed – it is permeable to salt but not water.

i. As filtrate moves through the ascending limb, NaCl diffuses out of the filtrate increasing the concentration of the interstitial fluid in the medulla.

ii. More salt is removed from the filtrate by active transport as it continues through the ascending limb.

iii. By losing salt but not water, the filtrate becomes more dilute as it moves up the ascending limb of the loop.

k. The **distal tubule** helps to regulate the K^+ and NaCl concentrations in body fluids by adjusting the amount of these ions secreted into and reabsorbed from the filtrate.

i. The proximal and distal tubules also help regulate the pH of blood by controlling the secretion of H^+ and the reabsorption of bicarbonate (HCO_3^-).

l. By actively reabsorbing NaCl, the **collecting duct** helps determine how much salt is actually excreted in the urine.

i. Although the permeability of the collecting duct is controlled by hormones, it is generally permeable to water but not to salt.

ii. As filtrate moves through the collecting duct it becomes increasingly concentrated as it loses more and more water by osmosis to the hyperosmotic interstitial fluid.

iii. The urea becomes so concentrated in the collecting duct that some of it diffuses out of the duct and into the interstitial fluid.

iv. The NaCl and urea maintain the high osmolarity of the interstitial fluid in the medulla.

v. This high osmolarity enables the mammalian kidney to conserve water by excreting urine that is hyperosmotic to general body fluids. The human kidney can excrete urine that is 4x the concentration of blood.

7. By changing the amount of water eliminated or conserved, blood volume and blood pressure can be regulated by the kidneys. This is done by hormonal control of the kidney using negative feedback.

a. One hormone important in regulating water balance is **antidiuretic hormone (ADH)**.

i. ADH is produced in the hypothalamus and stored in the pituitary gland, which lies just below the hypothalamus.

ii. Cells in the hypothalamus monitor the osmolarity of the blood. When the body loses water, the concentration of the blood increases. ADH is released into the bloodstream and reaches the kidney.

iii. ADH causes the distal tubules and collecting ducts to become more permeable to water, increasing the amount of water reabsorbed and reducing urine volume. This helps prevent further water loss.

iv. As the osmolarity of the blood decreases less ADH is secreted.

v. Notice that ADH can only reduce water loss. Lost water can only be replaced by eating or drinking.

vi. When a person drinks lots of water, blood osmolarity goes down and very little ADH is released. This decreases the permeability of the distal tubules and collecting ducts, so less water is reabsorbed, and dilute urine is produced.

(1) Some molecules, like alcohol, are **diuretics**. They interfere with the action of ADH, causing excessive urination, water loss and dehydration.

b. The **renin-angiotensin-aldosterone system (RAAS)** is another mechanism that helps maintain homeostasis.

i. The **juxtaglomerular apparatus (JGA)** is a patch of tissue near the glomerulus that monitors blood pressure.

ii. When blood pressure drops, the JGA release the enzyme renin which converts a blood protein called angiotensinogen to **angiotensin II.**

iii. Angiotensin II increases blood pressure by constricting arterioles, decreasing blood flow to many capillaries, including those of the kidney.

iv. It also stimulates the proximal tubules to reabsorb more NaCl and water which reduces the amount of salt and water excreted. As a result blood pressure and volume increase.

v. It also stimulates the adrenal glands, located on top of the kidneys, to release a hormone called **aldosterone**. This hormone causes the distal tubules to reabsorb more Na^+ and water, increasing blood volume and pressure.

vi. It might seem like RAAS would be unnecessary because ADH is able to reduce water loss but RAAS responds to a different problem.

(1) ADH is released in response to an increase in blood osmolarity, like if you are dehydrated from water loss or not drinking enough water.

(2) If you were to lose both salt *and* water – as you would if you had severe diarrhea - blood volume and pressure would decrease but osmolarity would not. ADH would not help.

(3) The RAAS will detect the decrease in blood volume and pressure and respond by increasing water and Na^+ reabsorption.

8. There are many diseases that affect the kidneys including infections, blockages, and physical trauma.

a. For most people, kidney damage occurs slowly over many years, most often due to diabetes or high blood pressure. This is called chronic kidney disease (CKD).

i. The causes of CKD include Type 1 or type 2 diabetes, high blood pressure, prolonged obstruction of the urinary tract from an enlarged prostate, kidney stones or some cancers and recurrent kidney infection.

ii. The risk factors include diabetes, high blood pressure, heart disease, smoking, obesity, high cholesterol, being African-American, Native American or Asian-American, having a family history of kidney disease, and being age 65 or older. A diet low in sodium, potassium and protein helps to avoid kidney disease.

iii. Early CKD has no symptoms so a patient won't feel different until the condition becomes advanced. Kidney disease is treatable if detected early but if it is ignored can lead to kidney failure.

iv. If the kidneys are no longer able to adequately filter blood, the patient must be put on dialysis, a treatment that filters the blood for them.

b. Kidney stones (renal lithiasis, nephrolithiasis) are small, hard mineral deposits that form inside your kidneys. The stones are made of mineral and acid salts.

i. Kidney stones are caused when your urine becomes too concentrated and contains too much of certain crystal-forming ions and minerals. The minerals crystalize and stick together.

ii. Passing kidney stones can be quite painful, but the stones usually cause no permanent damage. Small stones are treated by drinking 2-3 L of water each day to flush the stone naturally. Larger stones may be broken up with ultrasound so that the small pieces can be passed. In the case of very large stones they must be surgically removed.

iii. A kidney stone may not cause symptoms until it moves around within the kidney or passes into the ureter. Symptoms include severe pain in the side and back that can spread to the abdomen and groin, pain during urination, blood in the urine, frequent urination, especially with small amounts of urine.