Section C: Water Balance and Waste Disposal

1. Water balance and waste disposal depend on transport epithelia.
2. An animal’s nitrogenous wastes are correlated with its phylogeny and habitat.
3. Cells require a balance between osmotic gain and loss of water.
4. Osmoregulators expend energy to control their internal osmolarity; osmoconformers are isoosmotic with their surroundings.
Introduction

- Animals must also regulate the chemical composition of its body fluids by balancing the uptake and loss of water and fluids.

- Management of the body’s water content and solute composition, osmoregulation, is largely based on controlling movements of solutes between internal fluids and the external environment.
  
  - This also regulates water movement, which follows solutes by osmosis.
  
  - Animals must also remove metabolic waste products before they accumulate to harmful levels.
• While the ultimate goal of osmoregulation is to maintain the composition of body’s cells, this is primarily accomplished indirectly by managing the composition of the internal body fluid that bathes the cells.

• In insects and other organisms with an open circulatory system, this fluid is the hemolymph.

• Vertebrates and other animals with closed circulatory systems regulate the interstitial fluid indirectly by controlling the composition of blood.

• Animals often have complex organs, such as kidneys of vertebrates, that are specialized for the maintenance of fluid composition.
1. Water balance and waste disposal depend on transport epithelia

- In most animals, osmotic regulation and metabolic waste disposal depend on the ability of a layer or layers of transport epithelium to move specific solutes in controlled amounts in particular directions.

- Some transport epithelia directly face the outside environment, while others line channels connected to the outside by an opening on the body surface.

- The cells of the epithelium are joined by impermeable tight junctions that form a barrier at the tissue-environment barrier.
• In most animals, transport epithelia are arranged into complex tubular networks with extensive surface area.

• For example, the salt secreting glands of some marine birds, such as an albatross, secrete an excretory fluid that is much more salty than the ocean.

• The counter-current system in these glands removes salt from the blood, allowing these organisms to drink sea water during their months at sea.
• The molecular structure of plasma membranes determines the kinds and directions of solutes that move across the transport epithelium.

• For example, the salt-excreting glands of the albatross remove excess sodium chloride from the blood.

• By contrast, transport epithelia in the gills of freshwater fishes actively pump salts from the dilute water passing by the gill filaments.

• Transport epithelia in excretory organs often have the dual functions of maintaining water balance and disposing of metabolic wastes.
2. An animal’s nitrogenous wastes are correlated with its phylogeny and habitat

• 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 impact on water balance.

• Nitrogenous breakdown products of proteins and nucleic acids are among the most important wastes in terms of their effect on osmoregulation.

• During their breakdown, enzymes remove nitrogen in the form of ammonia, a small and very toxic molecule.
• In general, the *kinds* of nitrogenous wastes excreted depend on an animal’s evolutionary history and habitat - especially water availability.

• The *amount* of nitrogenous waste produced is coupled to the energy budget and depends on how much and what kind of food an animal eats.
Fig. 44.13
• Animals that excrete nitrogenous wastes as ammonia need access to lots of water.
  • This is because ammonia is very soluble but can only be tolerated at very low concentrations.
  • Therefore, ammonia excretion is most common in aquatic species.
  • Many invertebrates release ammonia across the whole body surface.
  • In fishes, most of the ammonia is lost as ammonium ions (NH$_4^+$) at the gill epithelium.
    • Freshwater fishes are able to exchange NH$_4^+$ for Na$^+$ from the environment, which helps maintain Na$^+$ concentrations in body fluids.
• Ammonia excretion is much less suitable for land animals and even many marine fishes and turtles.
  • Because ammonia is so toxic, it can only be transported and excreted in large volumes of very dilute solutions.
  • Most terrestrial animals and many marine organisms (which tend to lose water to their environment by osmosis) do not have access to sufficient water.

• Instead, mammals, most adult amphibians, and many marine fishes and turtles excrete mainly urea.
  • Urea is synthesized in the liver by combining ammonia with carbon dioxide and excreted by the kidneys.
• The main advantage of urea is its low toxicity, about 100,000 times less than that of ammonia.

• Urea can be transported and stored safely at high concentrations.

• This reduces the amount of water needed for nitrogen excretion when releasing a concentrated solution of urea rather than a dilute solution of ammonia.
• The main disadvantage of urea is that animals must expend energy to produce it from ammonia.

• In weighing the relative advantages of urea versus ammonia as the form of nitrogenous waste, it makes sense that many amphibians excrete mainly ammonia when they are aquatic tadpoles.

• They switch largely to urea when they are land-dwelling adults.
• Land snails, insects, birds, and many reptiles excrete **uric acid** as the main nitrogenous waste.
  • Like urea, uric acid is relatively nontoxic.
  • But unlike either ammonia or urea, uric acid is largely insoluble in water and can be excreted as a semisolid paste with very small water loss.
  • While saving even more water than urea, it is even more energetically expensive to produce.

• Uric acid and urea represent different adaptations for excreting nitrogenous wastes with minimal water loss.
• Mode of reproduction appears to have been important in choosing between these alternatives.
  
  • 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).
  
  • 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 (even urea is toxic at very high concentrations).
  
  • In these animals, uric acid precipitates out of solution and can be stored within the egg as a harmless solid left behind when the animal hatches.
• The type of nitrogenous waste also depends on habitat.
  
  • For example, terrestrial turtles (which often live in dry areas) excrete mainly uric acid, while aquatic turtles excrete both urea and ammonia.
  
  • In some species, individuals can change their nitrogenous wastes when environmental conditions change.
    
    • For example, certain tortoises that usually produce urea shift to uric acid when temperature increases and water becomes less available.
• Excretion of nitrogenous wastes is a good illustration of how response to the environment occurs on two levels.
• Over generations, evolution determines the limits of physiological responses for a species.
• During their lives individual organisms make adjustments within these evolutionary constraints.
3. Cells require a balance between osmotic gain and loss of water

- All animals face the same central problem of osmoregulation.
  - Over time, the rates of water uptake and loss must balance.
  - Animal cells - which lack cell walls - swell and burst if there is a continuous net uptake of water or shrivel and die if there is a substantial net loss of water.
• Water enters and leaves cells by osmosis, the movement of water across a selectively permeable membrane.
  
• Osmosis occurs whenever two solutions separated by a membrane differ in osmotic pressure, or osmolarity (moles of solute per liter of solution).

• The unit of measurement of osmolarity is milliosmoles per liter (mosm/L).
  
• 1 mosm/L is equivalent to a total solute concentration of $10^{-3} M$.

• The osmolarity of human blood is about 300 mosm/L, while seawater has an osmolarity of about 1,000 mosm/L.
• There is no *net* movement of water by osmosis between isoosmotic solutions, although water molecules do cross at equal rates in both directions.

• When two solutions differ in osmolarity, the one with the greater concentration of solutes is referred to as hyperosmotic and the more dilute solution is hypoosmotic.

• Water flows by osmosis from a hypoosmotic solution to a hyperosmotic one.
4. Osmoregulators expend energy to control their internal osmolarity; osmoconformers are isoosmotic with their surroundings

- There are two basic solutions to the problem of balancing water gain with water loss.
  - One - available only to marine animals - is to be isoosmotic to the surroundings as an osmoconformer.
  - Although they do not compensate for changes in external osmolarity, osmoconformers often live in water that has a very stable composition and hence have a very constant internal osmolarity.
• In contrast, an **osmoregulator** is an animal that must control its internal osmolarity, because its body fluids are not isoosmotic with the outside environment.

• An osmoregulator must discharge excess water if it lives in a hypoosmotic environment or take in water to offset osmotic loss if it inhabits a hyperosmotic environment.

• Osmoregulation enables animals to live in environments that are uninhabitable to osmoconformers, such as freshwater and terrestrial habitats.

• It also enable many marine animals to maintain internal osmolarities different from that of seawater.
Whenever animals maintain an osmolarity difference between the body and the external environment, osmoregulation has an energy cost.

- Because diffusion tends to equalize concentrations in a system, osmoregulators must expend energy to maintain the osmotic gradients via active transport.

- The energy costs depend mainly on how different an animal’s osmolarity is from its surroundings, how easily water and solutes can move across the animal’s surface, and how much membrane-transport work is required to pump solutes.

- Osmoregulation accounts for nearly 5% of the resting metabolic rate of many marine and freshwater bony fishes.
• Most animals, whether osmoconformers or osmoregulators, cannot tolerate substantial changes in external osmolarity and are said to be stenohaline.

• In contrast, euryhaline animals - which include both some osmoregulators and osmoconformers - can survive large fluctuations in external osmolarity.

• For example, various species of salmon migrate back and forth between freshwater and marine organisms.

• The food fish, tilapia, is an extreme example, capable of adjusting to any salt concentration between freshwater and 2,000 mosm/L, twice that of seawater.
• Most marine invertebrates are osmoconformers, as are the hagfishes.

• Their osmolarity is the same as seawater.

• However, they differ considerably from seawater in their concentrations of most specific solutes.

• Thus, even an animal that conforms to the osmolarity of its surroundings does regulate its internal composition.
• Except for hagfishes, marine vertebrates are osmoregulators.

• Marine fishes (class Osteichthys) constantly lose water through their skin and gills.

• To balance this, these fishes obtain water in food and by drinking large amounts of seawater and they excrete ions by active transport out of the gills.

• They produce very little urine.

(a) Osmoregulation in a saltwater fish

Fig. 44.14a
• Marine sharks and most other cartilaginous fishes (class Chondrichthyes) use a different osmoregulatory “strategy.”

• Like bony fishes, salts diffuse into the body from seawater and these salts are removed by the kidneys, a special organ called the rectal gland, or in feces.

• Unlike bony fishes, marine sharks do not experience a continuous osmotic loss because high concentrations of urea and trimethylamine oxide (TMAO) in body fluids lead to an osmolarity slightly higher than seawater.

  • TMAO protects proteins from damage by urea.

  • Consequently, water slowly enters the shark’s body by osmosis and in food, and is removed in urine.
• In contrast to marine organisms, freshwater animals are constantly gaining water by osmosis and losing salts by diffusion.

• Freshwater protists such as *Amoeba* and *Paramecium* have contractile vacuoles that pump out excess water.

• Many freshwater animals, including fishes, maintain water balance by excreting large amounts of very dilute urine, regaining lost salts in food, and by active uptake of salts from their surroundings.

Fig. 44.14b
Salmon and other euryhaline fishes that migrate between seawater and freshwater undergo dramatic and rapid changes in osmoregulatory status.

- While in the ocean, salmon osmoregulate like other marine fishes by drinking seawater and excreting excess salt from the gills.

- When they migrate to freshwater, salmon cease drinking, begin to produce lots of dilute urine, and their gills start taking up salt from the dilute environment - just like fishes that spend their entire lives in freshwater.
• Dehydration dooms 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.

• For example, tardigrades, or water bears, contain about 85% of their weight in water when hydrated but can dehydrate to less than 2% water and survive in an inactive state for a decade until revived by water.
Anhydrobiotic animals must have adaptations that keep their cell membranes intact.

While the mechanism that tardigrades use is still under investigation, researchers do know that anhydrobiotic nematodes contain large amount of sugars, especially the disaccharide trehalose.

Trehalose, a dimer of glucose, seems to protect cells by replacing water associated with membranes and proteins.

Many insects that survive freezing in the winter also utilize trehalose as a membrane protectant.
• The threat of desiccation is perhaps the largest regulatory problem confronting terrestrial plants and animals.
  • Humans die if they lose about 12% of their body water.
• Adaptations that reduce water loss are key to survival on land.
  • Most terrestrial animals have body coverings that help prevent dehydration.
  • These include waxy layers in insect exoskeletons, the shells of land snails, and the multiple layers of dead, keratinized skin cells.
  • Being nocturnal also reduces evaporative water loss.
• Despite these adaptations, most terrestrial animals lose considerable water from moist surfaces in their gas exchange organs, in urine and feces, and across the skin.

• Land animals balance their water budgets by drinking and eating moist foods and by using metabolic water from aerobic respiration.
• Some animals are so well adapted for minimizing water loss that they can survive in deserts without drinking.
  • For example, kangaroo rats lose so little water that they can recover 90% of the loss from metabolic water and gain the remaining 10% in their diet of seeds.
  • These and many other desert animals do not drink.
Fig. 44.16

Water balance in a kangaroo rat (60mL=100%)

- Ingested in food (6)
- Derived from metabolism (54)

Water balance in a human (2,500mL=100%)

- Derived from metabolism (250)
- Ingested in liquid (1,500)
- Ingested in food (750)

Water gain (mL/day)

Water loss (mL/day)

- Feces (2.6)
- Evaporation (900)
- Feces (100)
- Urine (13.5)
- Evaporation (43.9)
- Urine (1,500)

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