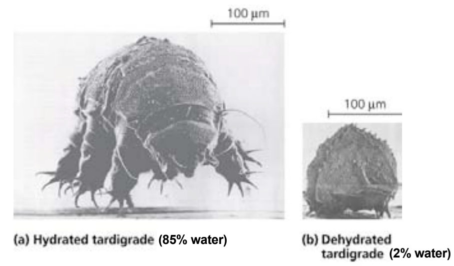
Osmoregulation & Excretion

Anhydrobiosis: Life without water?



Water is needed to maintain the structure & function of macromolecules.

How to acquire body water?

- **Drink water & dilute fluids**
- **Moisture in food**
- **Metabolic water**

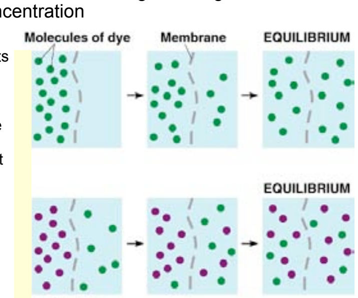
Organic food molecules + O_2 → CO_2 + $\mathbf{H_2O}$ + energy

Fat yields 2.5x as much energy and **2.5x as much water** per gram than do carbs or proteins!

REVIEW: Water and Solutes - Uptake by Cells

Passive Transport (Diffusion)

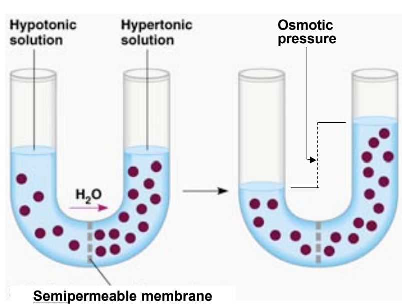
- Net movement of molecules from a region of high concentration to a region of low concentration
  - ✓ Caused by random (Brownian) movements of molecules
  - ✓ (Increase entropy)
  - ✓ Each type of molecule follows its own concentration gradient
  - ✓ At equilibrium, movement is equal in both directions



REVIEW: Water and Solutes - Uptake by Cells

Osmosis: simple diffusion of the solvent (water)

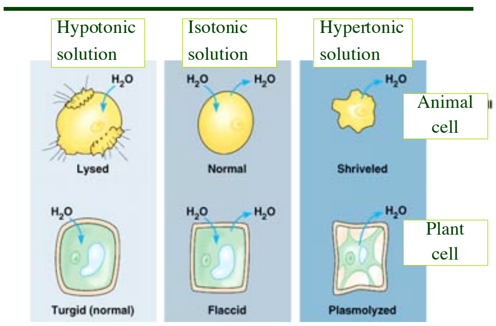
- Water diffuses according to its concentration gradient
- ↑Osm → ↓[water]
  ↓Osm → ↑[water]
- Osmosis can generate force (osmotic pressure)



REVIEW: Water and Solutes - Uptake by Cells

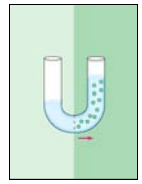
- ❖ Water moves across lipid bilayer and through **aquaporins** (membrane gate proteins)
- ❖ **Move the water by moving the solutes!**
  - Hypertonic solution: higher concentration of solutes
  - Hypotonic solution: lower concentration of solutes
  - Isotonic solution: equal solute concentrations

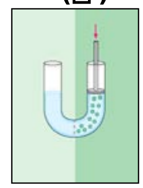
REVIEW: Water and Solutes - Uptake by Cells



REVIEW: Water and Solutes - Uptake by Cells

Water Potential (Ψ)





- Osmotic pressure pulls water to the right.
- Osmotic potential (=**solute potential [Ψ_S]**): solution on left has potential energy to push water to the right
- □Osm□ ↑ Ψ_S
- Physical pressure (= **pressure potential [Ψ_P]**): solution on right has potential energy to push water to the left
- **If Ψ_S & Ψ_P are equal but opposite□ no net flow**

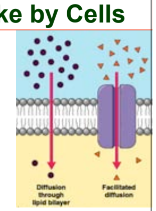
□ $\Psi = \Psi_S + \Psi_P = 0$

REVIEW: Water and Solutes - Uptake by Cells

- ❖Water moves across lipid bilayer and through aquaporins
- ❖**Move the water by moving the solutes!**
- ❖Ions and small molecules use protein channels and pumps

REVIEW: Water and Solutes - Uptake by Cells

Selective permeability

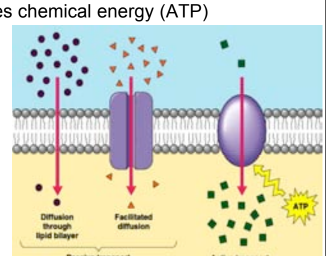


- Except for water and small nonpolar solutes, permeability of cell membranes is **selective** and **regulated**.
- Permeability determined by **transporter proteins**.
  - Channels and carriers are solute specific
  - If no transporter, than that solute cannot cross membrane
- *(Artificial membranes are only semipermeable —i.e., only discriminate based upon molecular size.)*

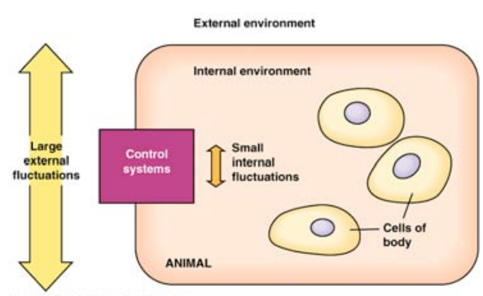
REVIEW: Water and Solutes - Uptake by Cells

Types of cellular transport

- **Passive transport**: driven by Brownian motion
  - Simple diffusion & osmosis
  - Facilitated diffusion (carrier mediated passive transport)
- **Active transport**: requires chemical energy (ATP)
  - Carrier mediated
  - Can transport against concentration gradient

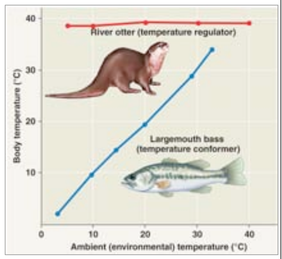


REVIEW: Homeostasis: maintaining a constant, optimal internal environment



REVIEW: Conformers & Regulators

- Conformers: allow internal environment to conform to external
- Regulators: use control mechanisms to maintain constant internal environment despite external variations
- Note: an organism may be different for different variables
  - **The same fish may be a thermoconformer and an osmoregulator**



otter & bass from same stream

Osmoregulation

The exchange of water and ions between the environment and the body fluids of an organism to maintain a constant internal environment (homeostasis).

- Balance between water gain & water loss

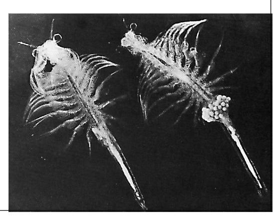
Which is related to

- Balance between electrolyte (salt) gain & loss

Osmoconformers & Osmoregulators

- **Osmoconformers** don't adjust osmolarity
- **Osmoregulators** adjust **osmolarity** by
  - pumping water in or out
  - pumping ions in or out

brine shrimp spend 30% of metabolism on osmoregulation



Osmoregulation

Osmoconformers:

- body fluids are isotonic to their environment
  - *Different* solutes, but same total Osm
    - Must maintain membrane potential of cells with certain ion gradients
- do not have to actively maintain water balance
- include most marine invertebrates

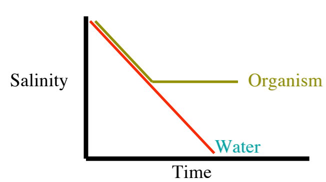
Osmoregulation

Osmoregulators:

- body fluids are **not** isotonic to their environment
- have to actively maintain water balance
- Include bony fish, marine mamms, freshwater, & terrestrial organisms

Osmoconformers & Osmoregulators

- **Stenohaline** cannot tolerate □ osmolarity
- **Euryhaline** can tolerate □
  - Estuaries, tidepools
  - some are facultative osmoregulators

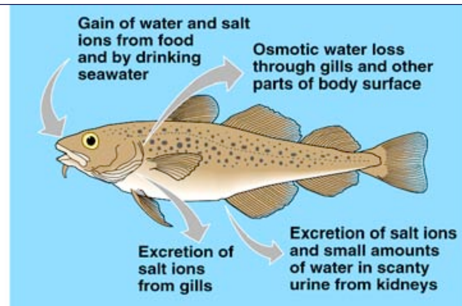


Aquatic animals — most water & salt exchange occurs in **gills**

- Large, thin exposed surface area to exchange gases
- Permeable to water

Osmoregulation: A Marine Fish

- Seawater = 3.5% NaCl (1 Osm); Body fluids = 1% (0.3 Osm)
- Across gills — salt diffuses in; water diffuses out

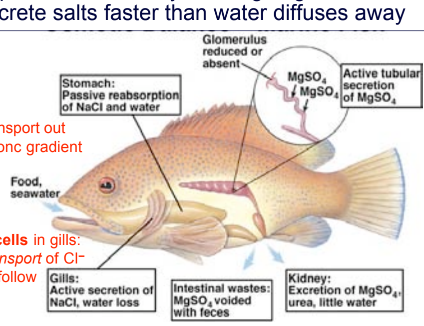


Osmoregulation: A Marine Fish

- Replace lost water by drinking large volumes
- Secrete salts faster than water diffuses away

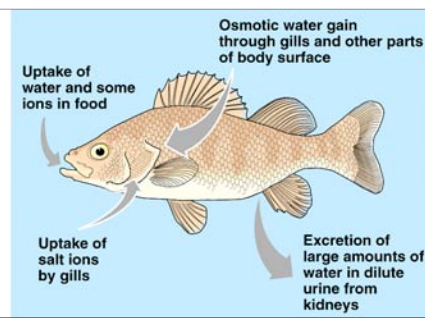
Secretion:
active transport out
against conc gradient

Chloride cells in gills:
Active transport of Cl⁻
Na⁺ ions follow



Osmoregulation: A Freshwater Fish

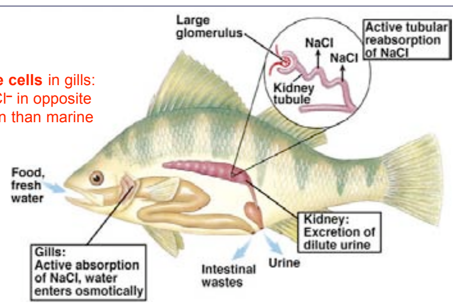
- Body fluids = 1% NaCl; Freshwater <0.01%
- Across gills — water diffuses in; salt diffuses out



Osmoregulation: A Freshwater Fish

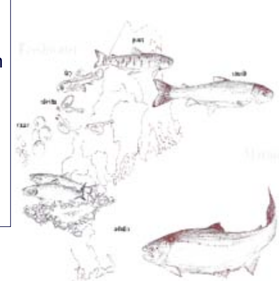
- No drinking. Consume salts & some water in food
- Dump water. Uptake salts faster than water

Chloride cells in gills:
pump Cl⁻ in opposite direction than marine fish



Osmoregulation: Euryhaline fish

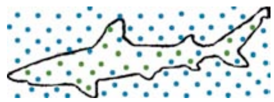
- **Anadromous**: juveniles in freshwater; adults at sea
  - Salmon, striped bass
- **Catadromous**: juveniles in saltwater; adults in fresh
  - Anguillid eels
- Must transition gills & kidneys before migrating
  - Chloride cells must reverse direction
  - **Smoltification**



Life Cycle of Atlantic Salmon
http://www.nefsc.noaa.gov/sos/spsyn/af/salmon/images/fig41_2.gif

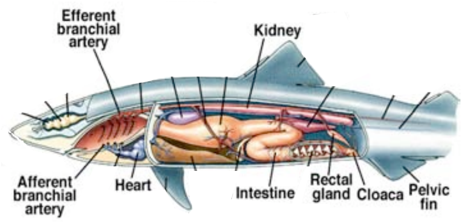
Osmoregulation: Sharks & Rays
almost osmoconformers

- Tissue salt concentration same as bony fish
- Make up the difference from seawater with **urea**
  - Need carnivorous diet for sufficient organic nitrogen
  - Use trimethylamine oxide (**TMAO**) to block toxic effect of high urea on protein structure
- Actually overcompensate: slightly hypertonic to seawater
  - Passively gain water. Do not need to drink.

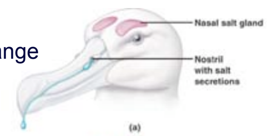
Osmoregulation: Sharks & Rays
almost osmoconformers

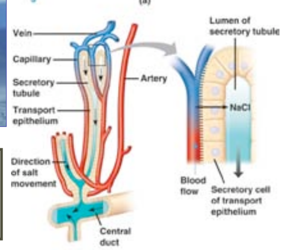
- Kidneys retain urea
- Don't need to worry about water, but must dump salt
- Chloride cells in gills, intestines, kidney & and rectal gland actively secrete



Osmoregulation: Seabirds

- **Transport epithelia** & counter-current salt exchange



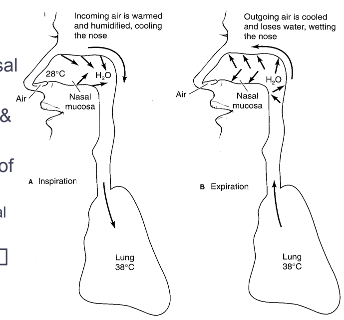
- Similar salt gland tissue in nasal passages of marine iguanas & tear glands of sea turtles

Speaking of noses, …

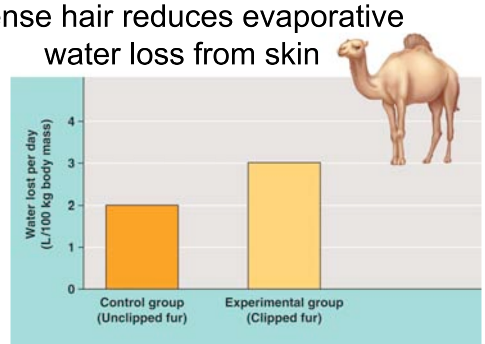
Water reclamation in mammals

Turbinals: ↑sa in nasal passages

1. Inspired air warmed & humidified
2. Evaporative cooling of nasal surface
   - May also cool cerebral blood flow
3. **Expired air cooled water reclaimed**



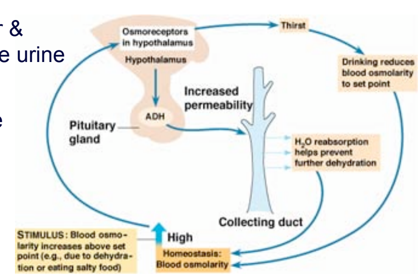
Dense hair reduces evaporative water loss from skin



Sacrifice cooling efficiency for water retention

Terrestrial animals — most regulation of water & salt exchange occurs in **excretory system**

- ↑Osm drink water & concentrate urine
- Osm dilute urine



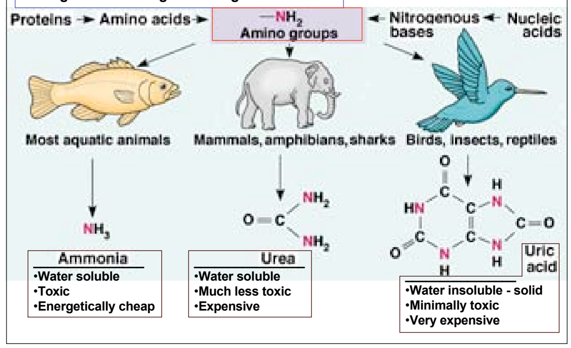
Excretory Systems

"Conditioning" the body fluids

- Water & electrolyte balance
- Maintain extracellular fluid volume (ECF)
  - Including blood plasma volume & P_B
- Remove waste products
  - esp., nitrogenous wastes
- Retain nutrients

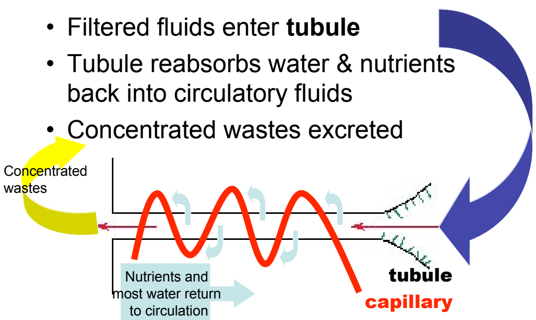
Nitrogenous wastes

- Waste by-products of metabolism
- Degradation of organic nitrogen most toxic



Excretory System Components

- Filtered fluids enter **tubule**
- Tubule reabsorbs water & nutrients back into circulatory fluids
- Concentrated wastes excreted

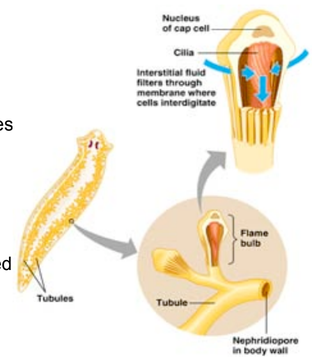


Protonephridial Excretory System

Platyhelmintes (*Planaria*)

Freshwater flatworm

- Flame bulb: cap cell (flame cell) interdigitates with tube cell
- Cap cell cilia beat
  > draw body fluid through slits
  > solutes reabsorbed
  > excess water excreted

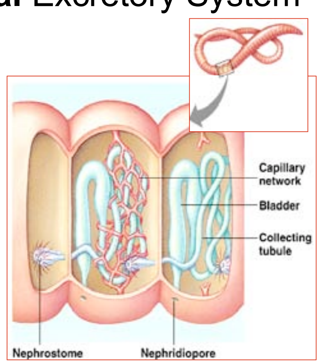


Metanephridial Excretory System

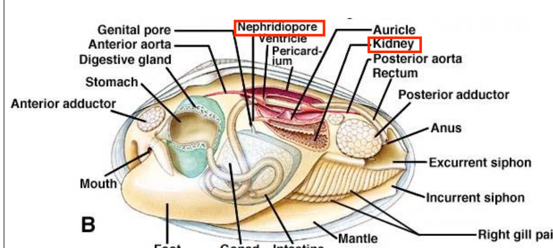
- Ciliated **nephrostome** draws interstitial fluid into tubule
- Tubule reabsorbs nutrients, most salt & water into capillary bed
- Concentrated wastes collect in bladder until excreted

Annelid worm

- Pair of metanephridia in each segment
- Nephrostome draws from adjacent segment
- Excretion via **nephropore**



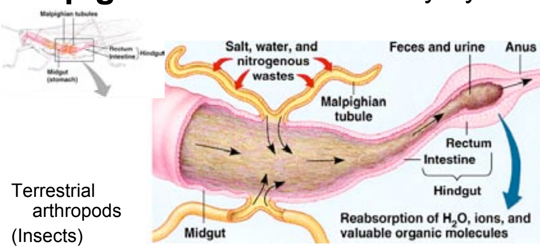
Metanephridial Excretory System



Mollusc (clam)

- Hemolymph drawn into tubules consolidated into **kidney**
- Excretion via one common **nephropore**

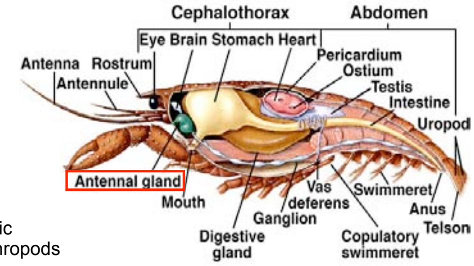
Malpighian Tubule Excretory System



Terrestrial arthropods (Insects)

- Wastes secreted from hemolymph into tubules. Water follows > flushes into gut
- Nitrogenous waste precipitated as uric acid. Water & salts reabsorbed in hind gut
- Almost solid feces+wastes excreted

supplemental Excretory System



Aquatic arthropods (Crustaceans)

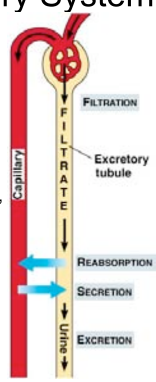
- Most water/salt balance and ammonia excretion in **gills**
- Additional excretion from **antennal gland**

Vertebrate **Renal** Excretory System

Nephron: functional unit of the vertebrate **kidney**

- Tubule + associated capillary beds

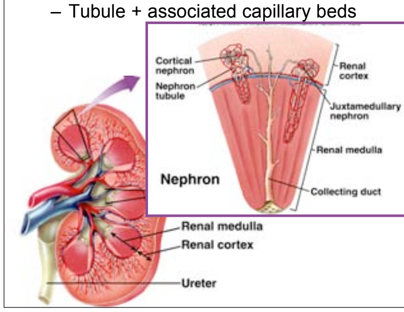
- **Filtration**: P_B pushes plasma water & small (non-protein) solutes from first capillary bed into tubule
- **Reabsorption**: vital components (nutrients, most salt & water) actively/specifically transported back into second capillary bed
- **Secretion**: specific wastes or salt actively/specifically transported from second capillary bed into tubule filtrate
  - ↑**F** and/or ↑**S** ↑excretion
  - ↑**R** excretion

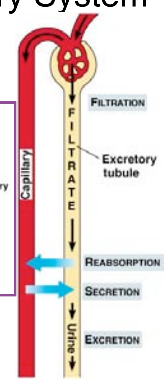


Mammal **Renal** Excretory System

Nephron: functional unit of the vertebrate **kidney**

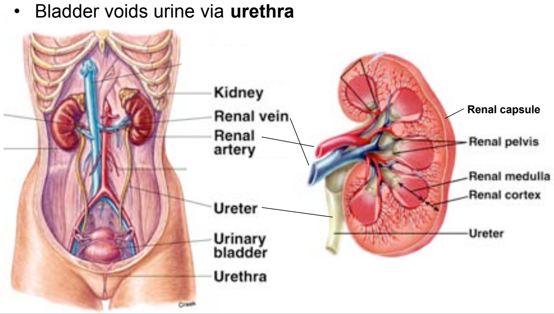
- Tubule + associated capillary beds



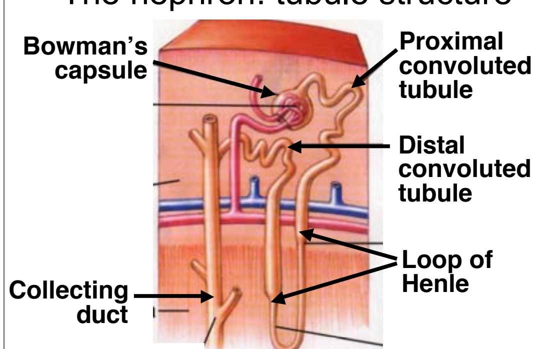


Human **Renal** Excretory System

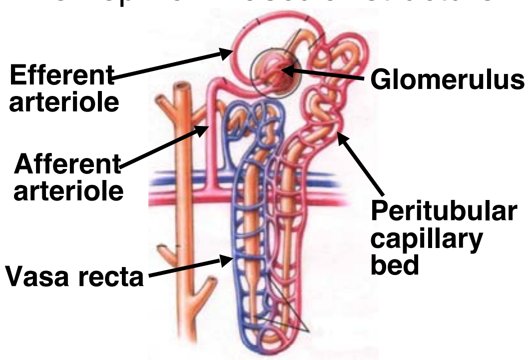
- 20% of systemic blood circulation flows through kidney
- Urine flows via **ureter** from each kidney to **bladder**
- Bladder voids urine via **urethra**



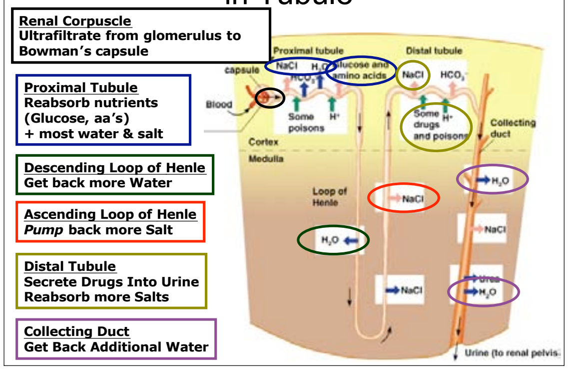
The nephron: tubule structure



The nephron: vascular structure

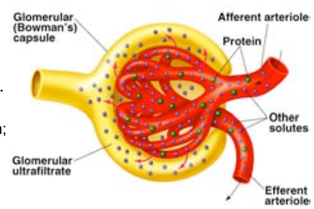


Filtration, Reabsorption & Secretion in Tubule

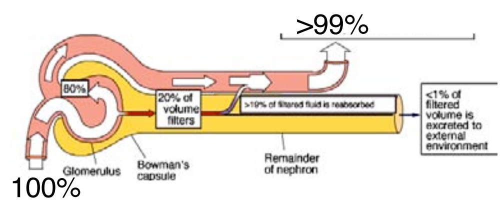


Glomerular Ultrafiltrate

- Fluid in glomerular capsule is called **ultrafiltrate**.
  - Glomerular filtration:
    - Mechanism of producing ultrafiltrate under hydrostatic pressure of the blood.
      - Process similar to the formation of tissue fluid by other capillary beds.
- Glomerular filtration rate (GFR):
  - Volume of filtrate produced by both kidneys each minute.
    - Averages ~120ml/min (115 ml/min. in women; 125 ml/min. in men.)

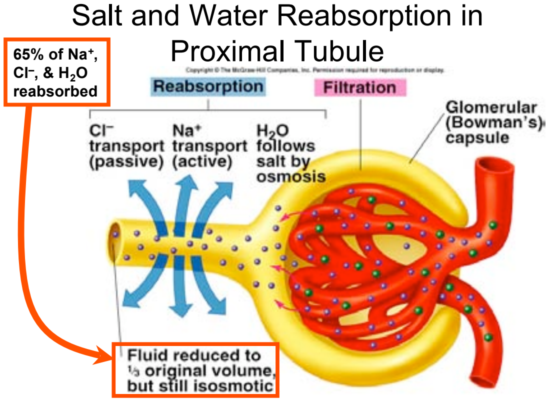


Glomerular Filtration

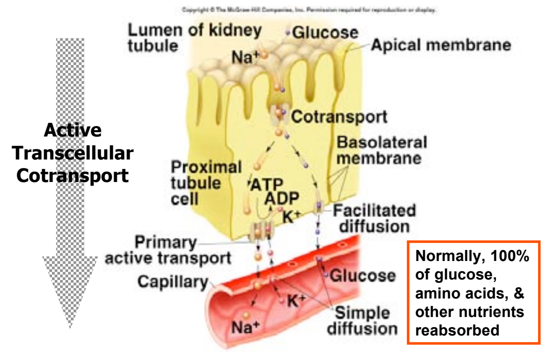


- 20% of plasma that enters glomerulus is filtered into nephron
- Kidneys filter 180 liters of fluid per day, but produce only ~1.5 liter of urine
- Minimum of 400 ml/day urine necessary to excrete metabolic wastes (obligatory water loss).

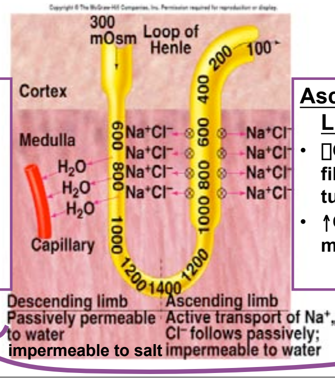
Salt and Water Reabsorption in Proximal Tubule



Reabsorption of Circulating Energy Substrates in Proximal Tubule



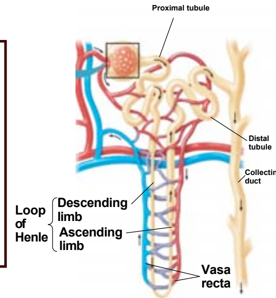
Loop of Henle — countercurrent multiplier



Decending Limb
- ↑Osm of filtrate in tubule
- ↓volume of filtrate in tubule

Ascending Limb
- ↓Osm of filtrate in tubule
- ↑Osm of medulla

Loop of Henle & the Vasa Recta — countercurrent exchange

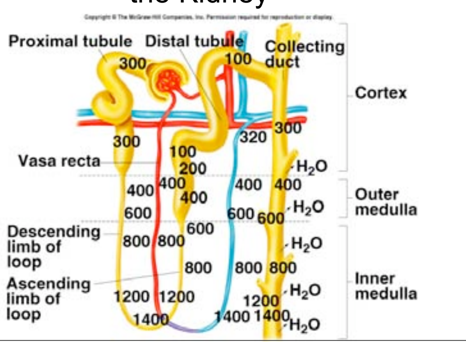


Ascending Vessel
- Collects H_2O from Decending Limb
- ↓ Osm & ↑ volume of plasma

Decending Vessel
- Collects NaCl from Ascending Limb
- ↑Osm of plasma

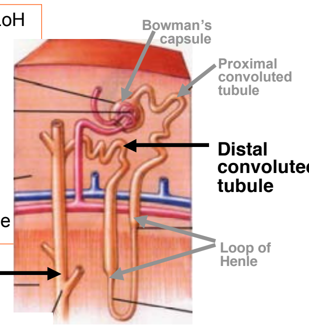
After PCT & LoH, 90% of NaCl & 85% of H_2O reabsorbed

Osmolality of Different Regions of the Kidney



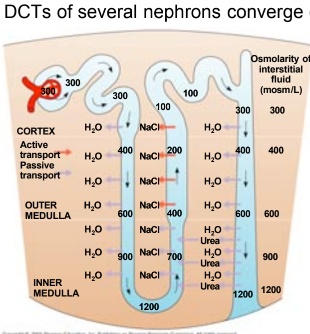
Distal Convoluted Tubule & cortical region of Collecting Duct

- Filtrate hypotonic from LoH
- Continue active Na^+ transport & Cl^- cotransport
- 98–100% of filtered NaCl now reabsorbed
  - Actual amount regulated by **aldosterone** hormone



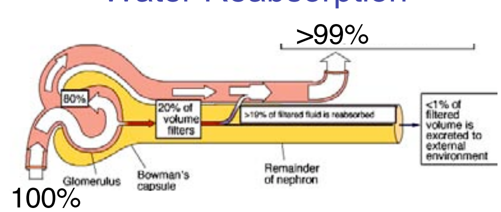
Collecting Duct

DCTs of several nephrons converge on each collecting duct



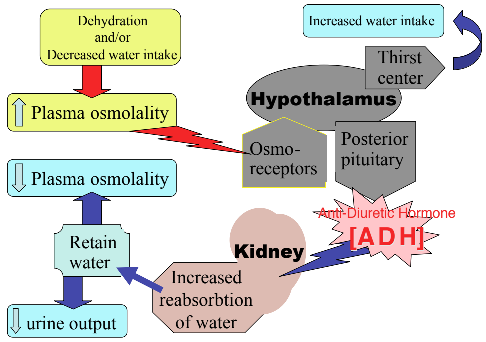
- Filtrate travels through collecting duct back through medulla
- Becomes isotonic to medulla by losing water
- Some urea diffuses out → adds to medulla Osm
- Rate of water reabsorption depends on # of **aquaporins** in tubule membrane
- # of aquaporins regulated by **antidiuretic hormone (ADH)**

Water Reabsorption

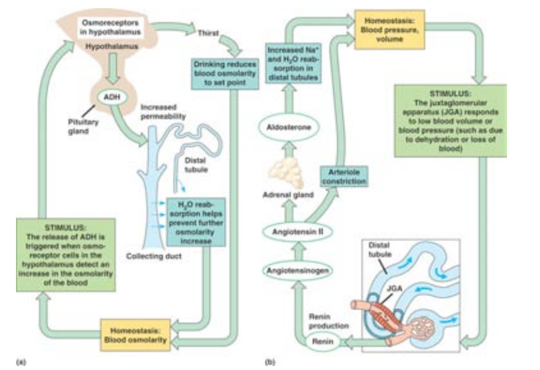


Kidneys filter 180 liters of fluid per day, …
- No ADH → 99.2% of filtered H2O reabsorbed
  - … but produce only ~1.5 liter of urine
- Maximum ADH → 99.8% of filtered H2O reabsorbed
  - Minimum of 400 ml/day urine necessary to excrete metabolic wastes (obligatory water loss).

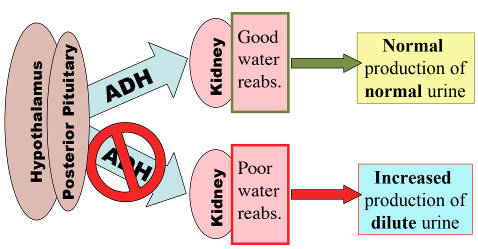
Regulation of plasma osmolarity



Adjusting the Urine □ Adjusting the Blood

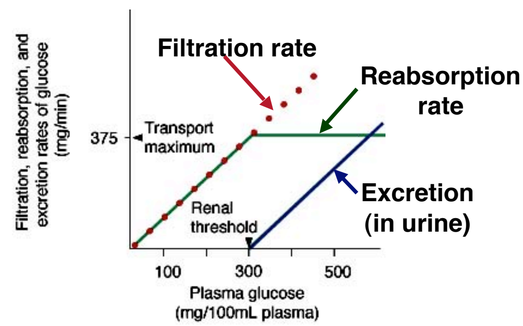


ADH Insufficiency



Diabetes insipidus

Glucose handling by nephron



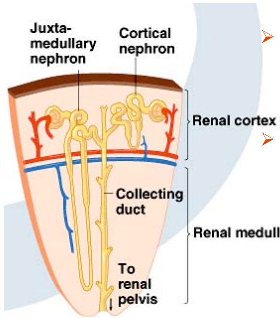
Glucosuria: glucose in urine

- Glucose completely reabsorbed under normal conditions
- ***Diabetes mellitis***: insulin deficiency causes blood glucose levels to exceed renal threshold (more than can be reabsorbed)
- Excess **glucose excreted in urine**
- Glucose in urine osmotically holds more water in urine

"Diabetes" = increased urine output

Type	Etiology	Primary effect	Symptom	Urine Osm
Diabetes insipidus	insufficient ADH action	renal tubule water permeability impaired	**increased urine output**	dilute; "bland urine"
Diabetes mellitus	insufficient insulin action	elevated osmotic pressure of renal filtrate	**increased urine output**	high [glucose]; "sweet urine"

Two kinds of nephrons



- ~85% of nephrons in human kidney are cortical nephrons.
  - short Loops of Henle
- Cortical nephrons use the osmotic gradient created by juxtamedullary nephrons.

Living in extreme environments — no fresh water

Marine Mammals

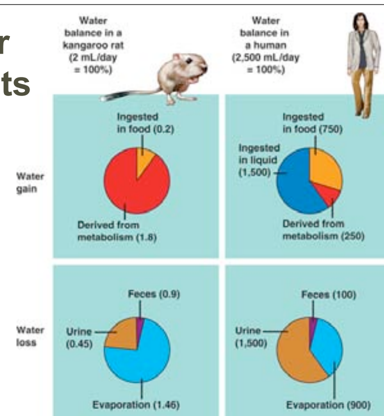
- Higher proportion of juxtamedullary nephrons with very long Loops of Henle
  - ↑Osm of renal medulla ↑Osm of urine
- Can drink seawater and dump salt for net water gain
  - Human would take 135 ml of urine to dump salt from 100 ml seawater net water loss
  - Dolphin takes only 65 ml urine to dump salt from 100 ml seawater net water gain

Living in extreme environments — no fresh water

Desert Mammals — **Kangaroo Rat**

- Forage at night;
  hide in humid burrow in daytime
- Extensive nasal turbinates
- Large kidney with higher proportion of juxtamedullary nephrons with very long Loops of Henle
  - ↑Osm of renal medulla ↑Osm of urine
- Does not drink! — **Metabolic water**
- Eats almost exclusively seeds with high oil content
  - ↑fat ↑water & energy yield
  - protein nitrogenous wastes
  - no need to produce much urine

Water Budgets



Avian **Renal** Excretory System

- Drink little — Cannot afford the weight of excess water
- Juxtamedullary nephrons only have short Loops
- urine only slightly hypertonic to tissues
- But since nitrogenous wastes excreted as solid paste of uric acid, no need to produce much urine
- Water reabsorbed in cloaca
  - Transport epithelia

Reptilian **Renal** Excretory System

- Ectothermic — hot habitats
- Cortical nephrons only!
  - **no** Loops of Henle
  - (only in mamms & birds)
- urine only isotonic to tissues
- But since nitrogenous wastes excreted as solid paste of uric acid, no need to produce much urine
- Water reabsorbed in cloaca