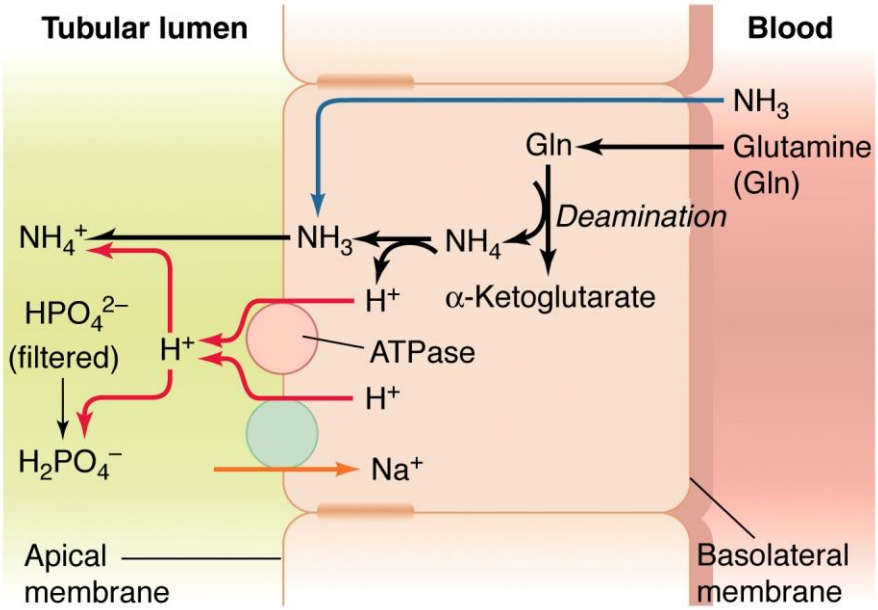
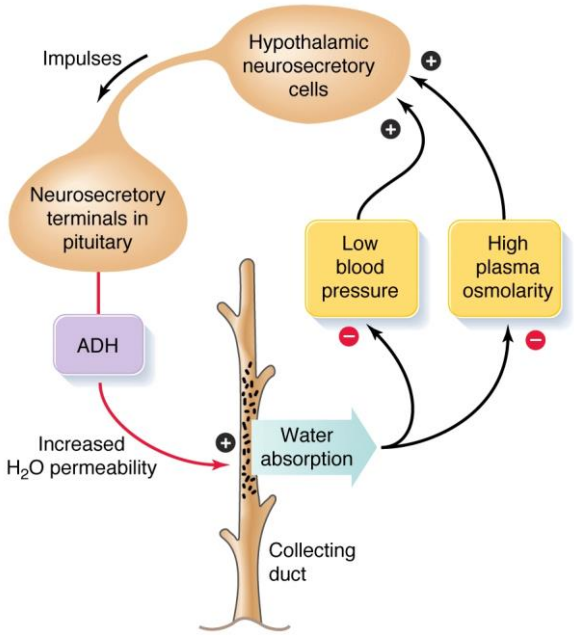
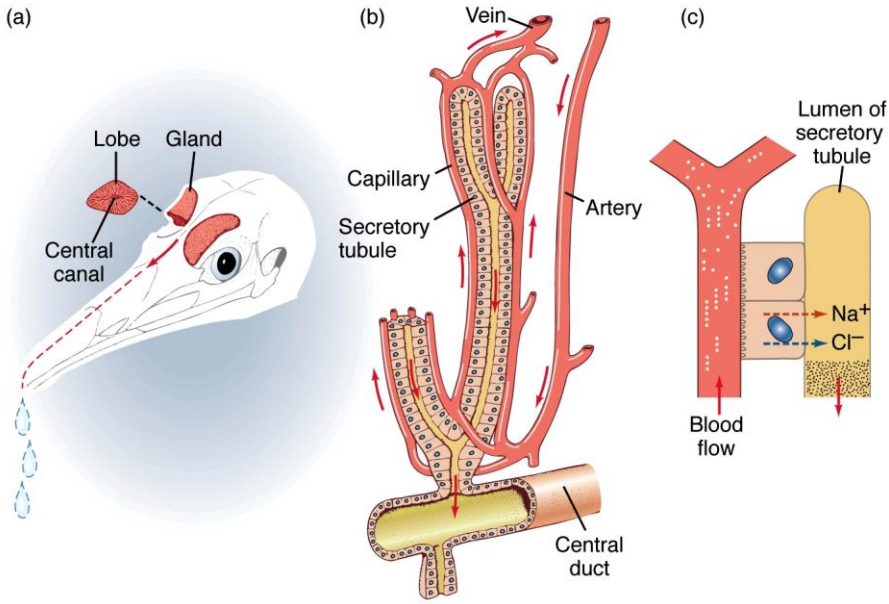
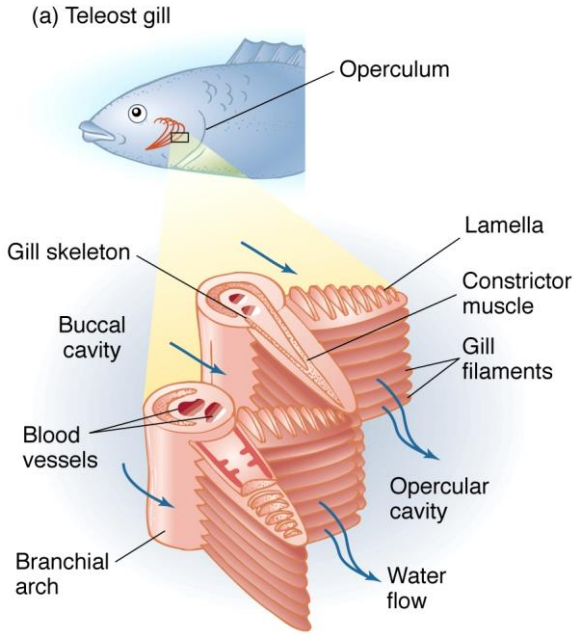
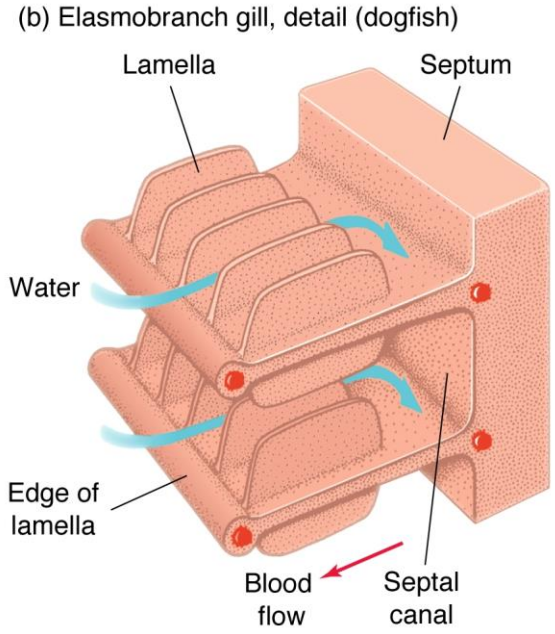
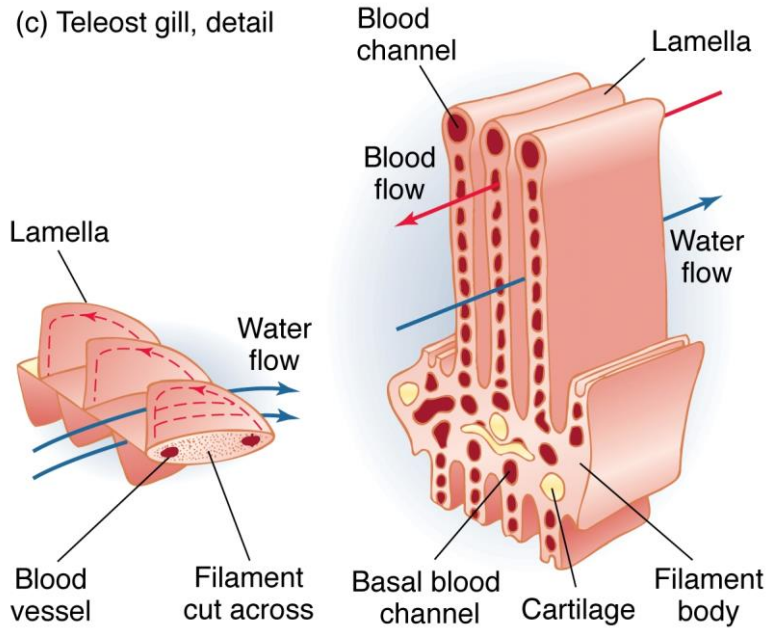

Tubular lumen
Blood
NH_3
Gln
Glutamine (Gln)
Deamination
NH_4^+
NH_3
NH_4
H^+
α-Ketoglutarate
HPO_4^{2-} (filtered)
H^+
ATPase
H^+
$H_2PO_4^-$
Na^+
Apical membrane
Basolateral membrane


Impulses
Hypothalamic neurosecretory cells
Neurosecretory terminals in pituitary
Low blood pressure
High plasma osmolarity
ADH
Increased H_2O permeability
Water absorption
Collecting duct

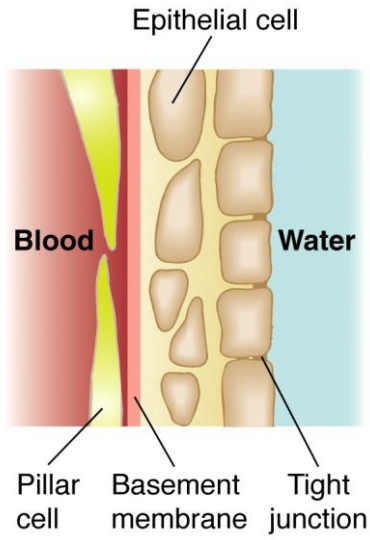

(a)
Lobe
Gland
Central canal
(b)
Vein
Capillary
Artery
Secretory tubule
Central duct
(c)
Lumen of secretory tubule
Na^+
Cl^-
Blood flow

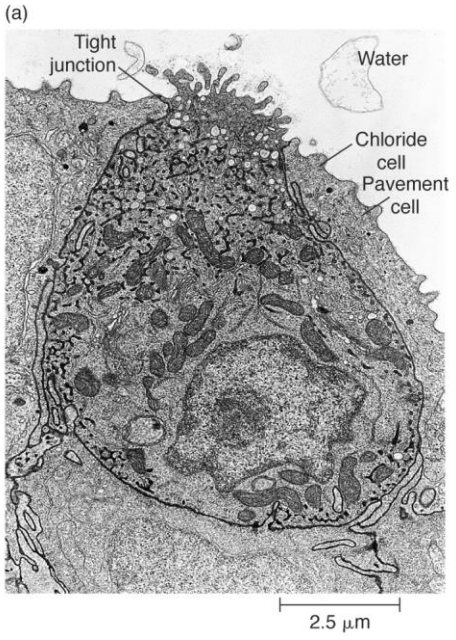

(a) Teleost gill
Operculum
Gill skeleton
Lamella
Constrictor muscle
Buccal cavity
Gill filaments
Blood vessels
Opercular cavity
Branchial arch
Water flow

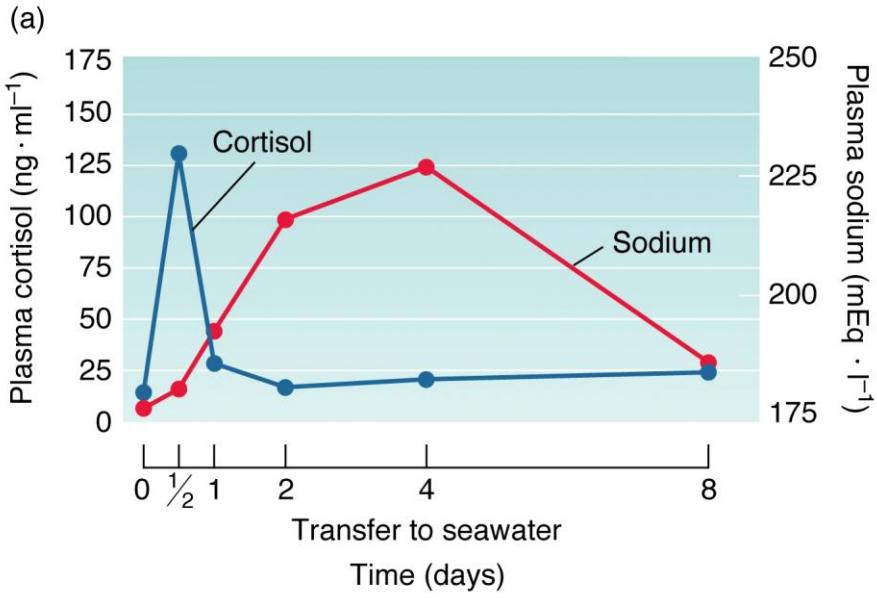

(b) Elasmobranch gill, detail (dogfish)
Lamella
Septum
Water
Edge of lamella
Blood flow
Septal canal


(c) Teleost gill, detail
Blood channel
Lamella
Blood flow
Water flow
Lamella
Water flow
Blood vessel
Filament cut across
Basal blood channel
Cartilage
Filament body

(e) Section across gill lamellar epithelium






(a)
Plasma cortisol (ng · ml⁻¹)
175
150
125
100
75
50
25
0
Cortisol
Sodium
250
225
200
175
Plasma sodium (mEq · l⁻¹)
0
½
1
2
4
8
Transfer to seawater
Time (days)

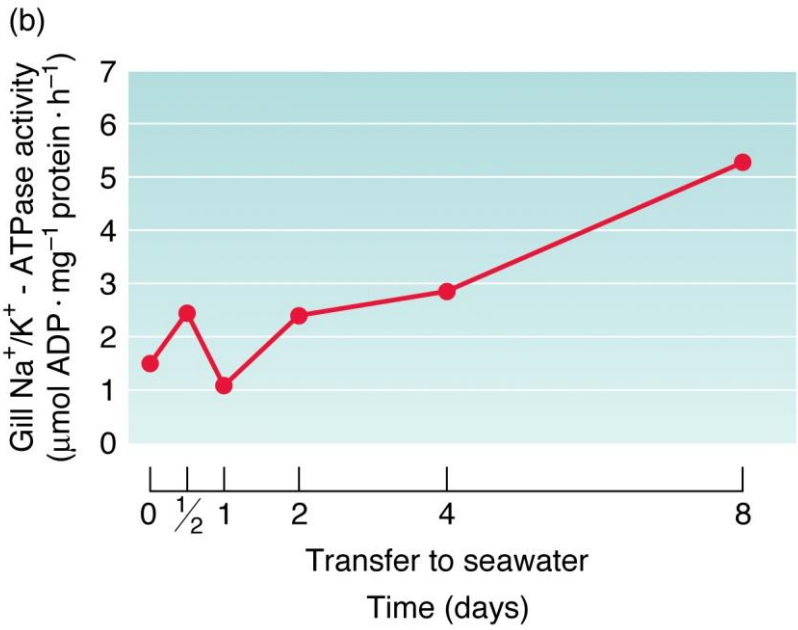

(b)
Gill Na⁺/K⁺ - ATPase activity
(µmol ADP · mg⁻¹ protein · h⁻¹)
7
6
5
4
3
2
1
0
0
½
1
2
4
8
Transfer to seawater
Time (days)

Table 14-10 Physiological acclimatizations that accompany the movement of fish to water of differing salinity

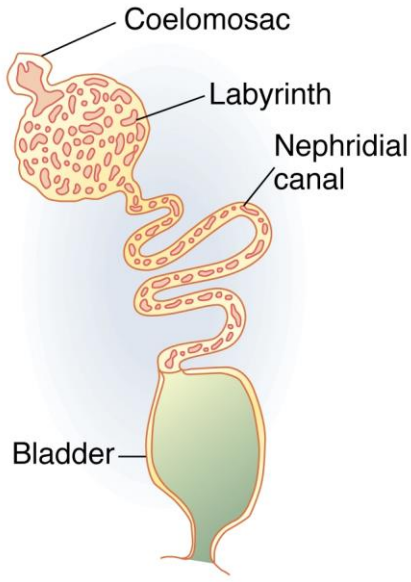
(A) From freshwater to seawater

1. The proton pump that powers active uptake of NaCl is down-regulated.
2. The rise in the flux of Na^+ into the body raises plasma Na^+, stimulating an increase in plasma cortisol and growth hormone levels.
3. Hormones induce the proliferation of chloride cells and an increase in the infolding of their basolateral membranes.
4. The changes above cause an increase in the activity of the Na^+/K^+ pump and the secretion of NaCl.
5. Plasma Na^+ levels return to normal.

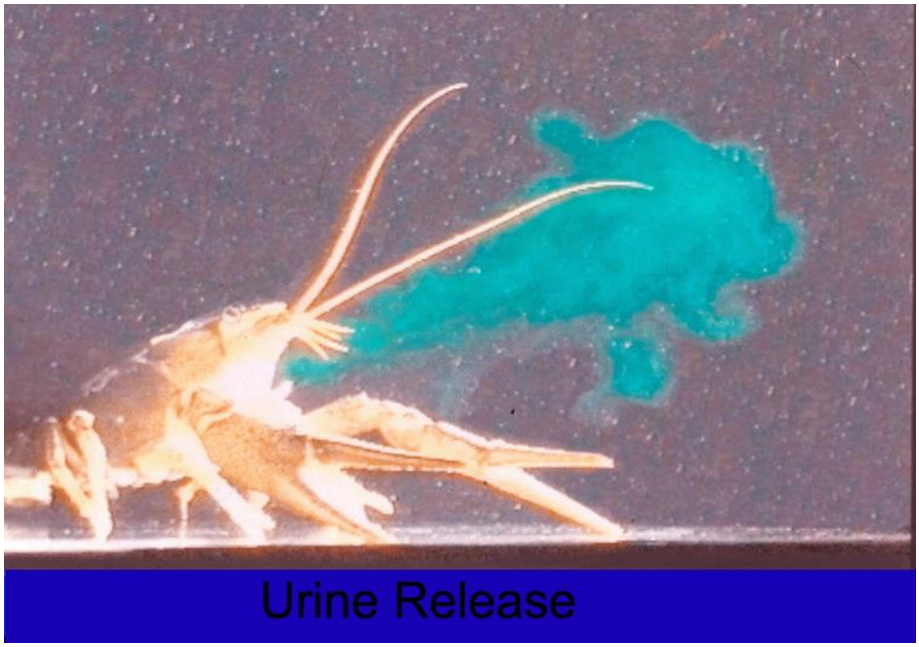
Table 14-10 Physiological acclimatizations that accompany the movement of fish to water of differing salinity

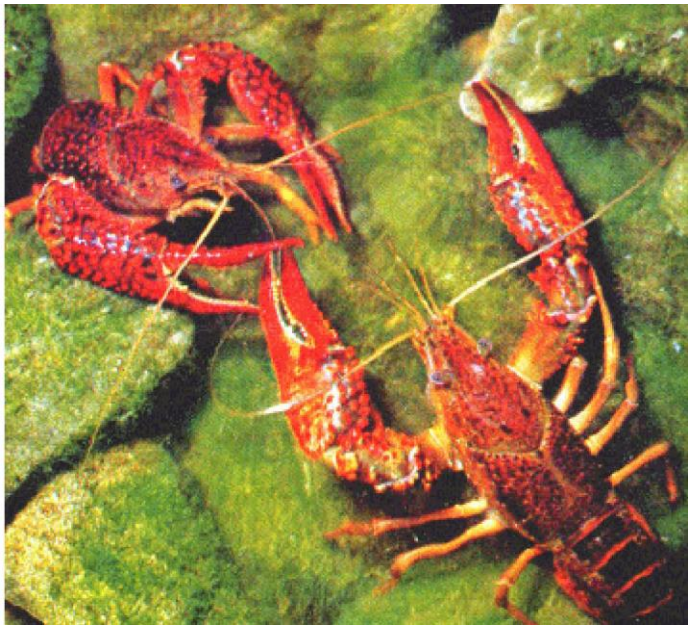
(B) From seawater to freshwater

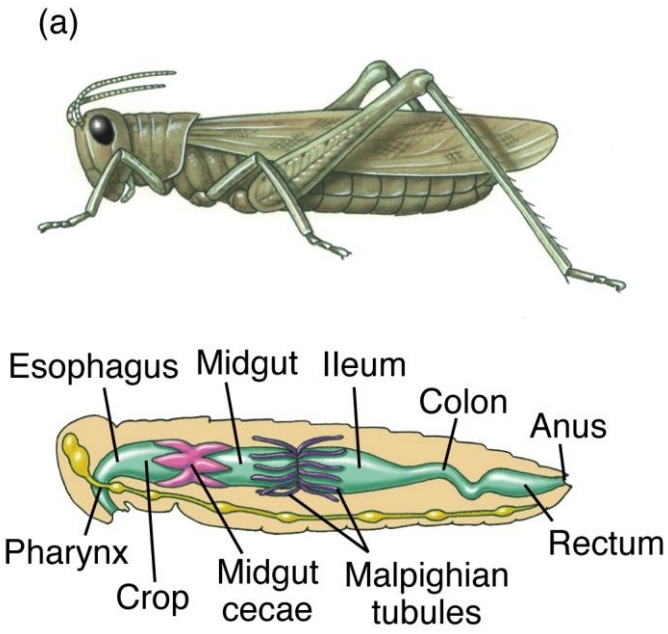
1. The paracellular gaps between chloride and accessory cells close in response to low external Na^+ levels, causing NaCl efflux to fall rapidly.
2. Plasma prolactin levels increase.
3. Prolactin causes the number of chloride cells to decrease and the apical pits to disappear.
4. As a result, the activity of the Na^+/K^+ pump falls.
5. Up-regulation of the proton pump returns the fish to the freshwater condition.



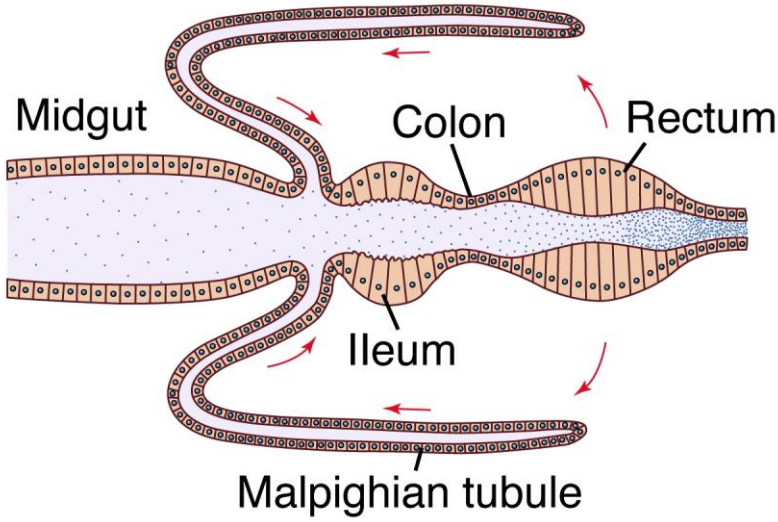
Crayfish antennal gland

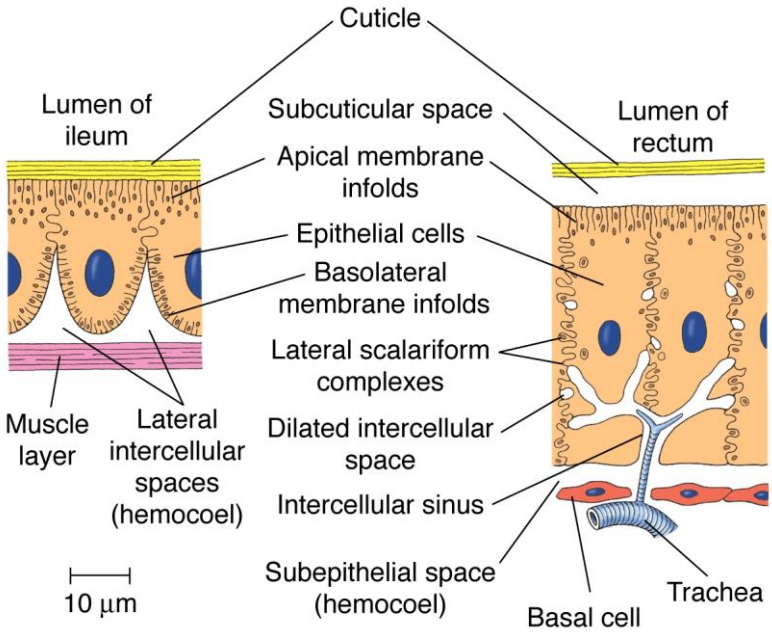


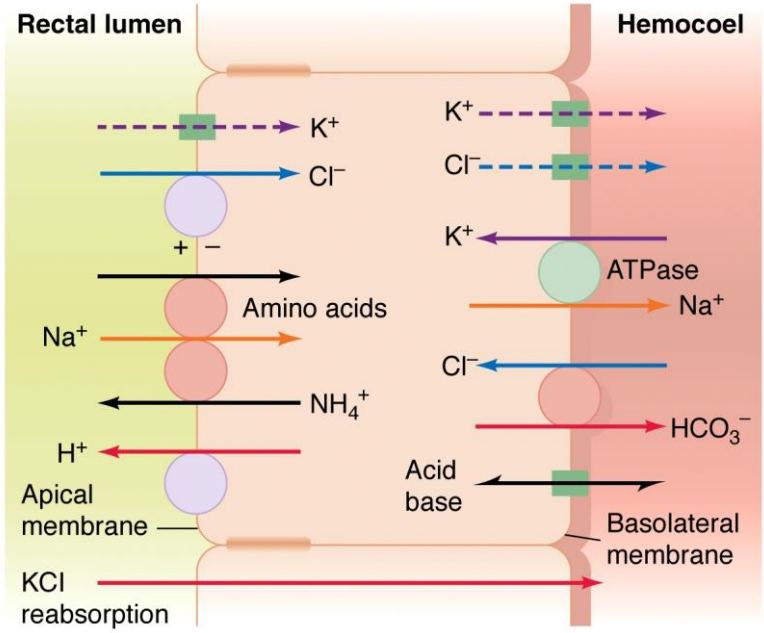


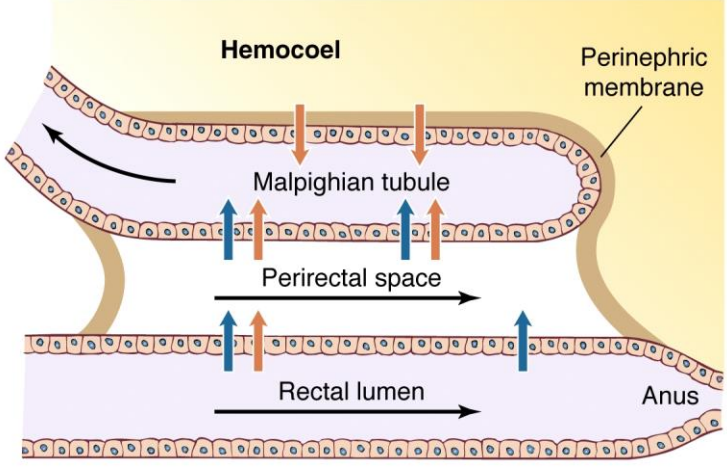

(a)
Esophagus
Midgut
Ileum
Colon
Anus
Pharynx
Crop
Midgut cecae
Malpighian tubules
Rectum

(b)

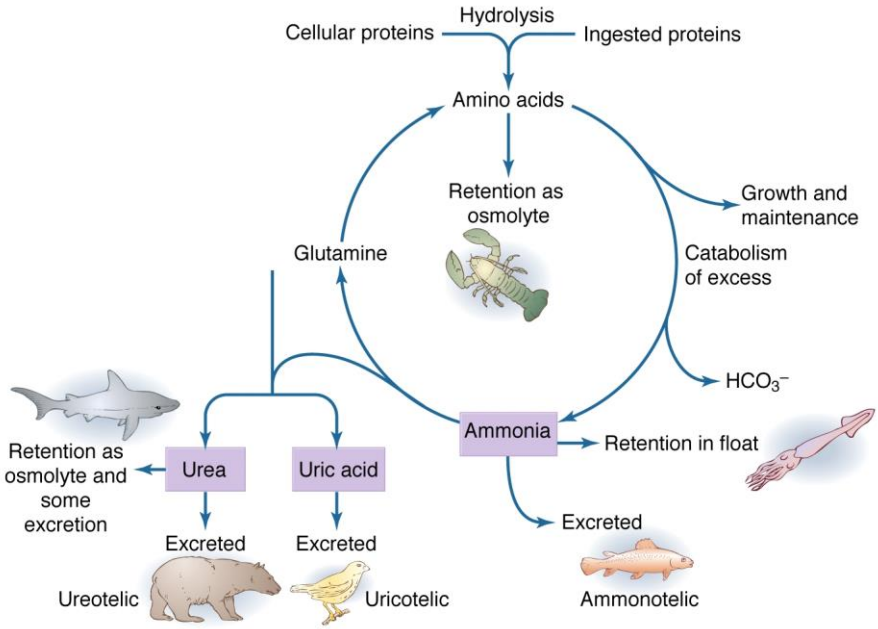

Midgut
Colon
Rectum
Ileum
Malpighian tubule

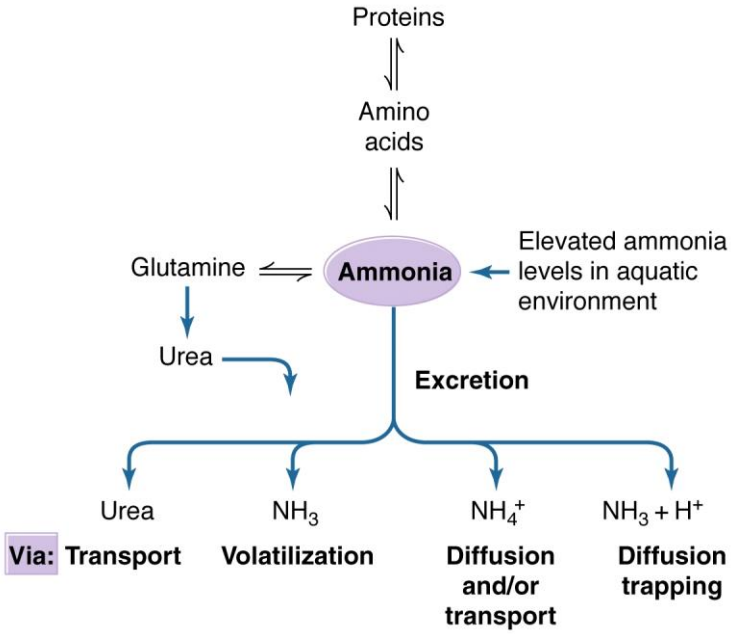

Cuticle
Lumen of ileum
Subcuticular space
Lumen of rectum
Apical membrane infolds
Epithelial cells
Basolateral membrane infolds
Lateral scalariform complexes
Dilated intercellular space
Intercellular sinus
Muscle layer
Lateral intercellular spaces (hemocoel)
10 µm
Subepithelial space (hemocoel)
Basal cell
Trachea

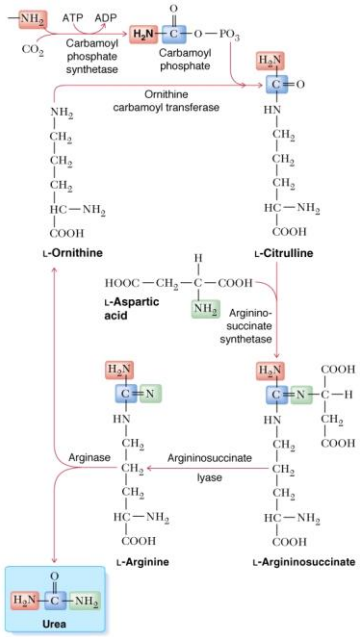


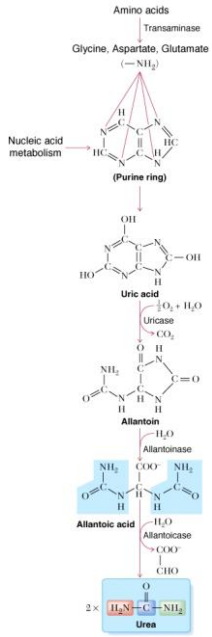


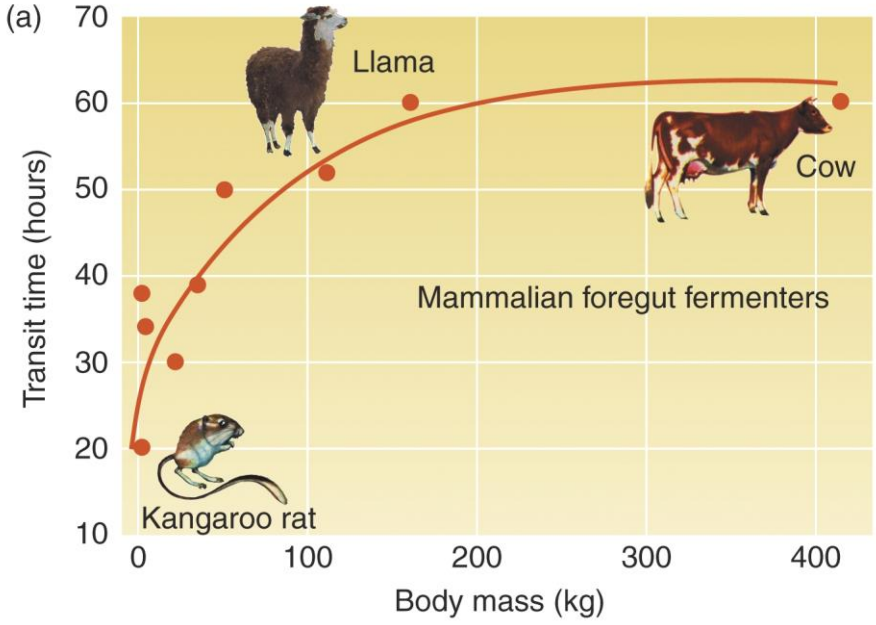
Direction of bulk water flow
Net water transfer
Net KCl transfer

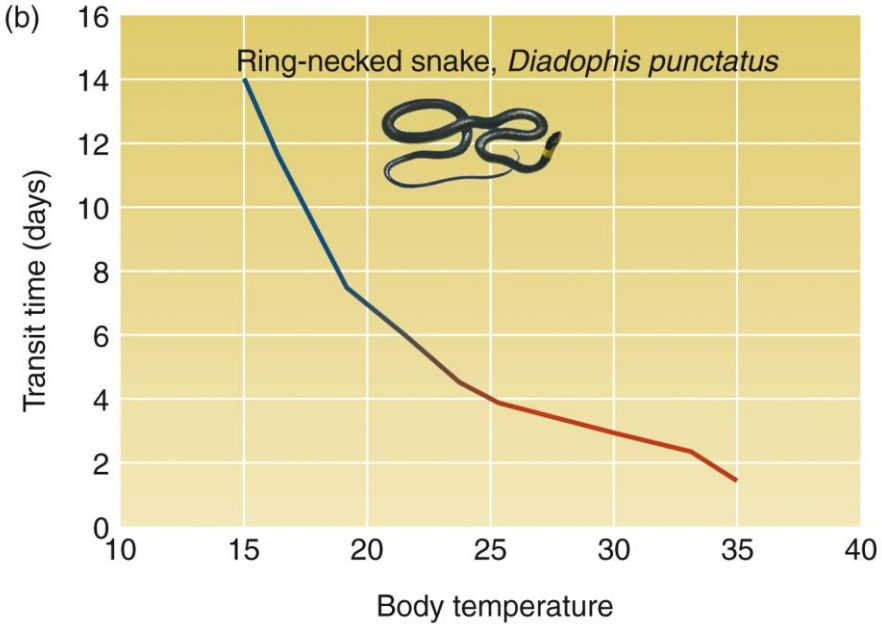

Hydrolysis
Cellular proteins
Ingested proteins
Amino acids
Retention as osmolyte
Growth and maintenance
Glutamine
Catabolism of excess
HCO_3^-
Ammonia
Retention in float
Retention as osmolyte and some excretion
Urea
Uric acid
Excreted
Excreted
Excreted
Ureotelic
Uricotelic
Ammonotelic

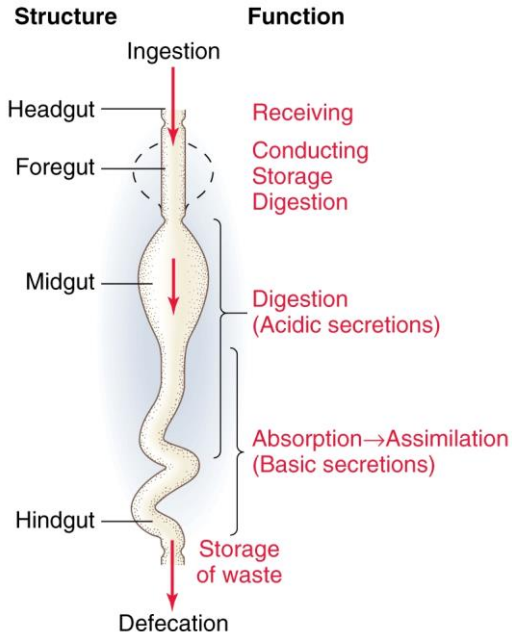

Proteins
Amino acids
Glutamine
Ammonia
Elevated ammonia levels in aquatic environment
Urea
Excretion
Urea
NH_3
NH_4^+
$NH_3 + H^+$
Via: Transport
Volatilization
Diffusion and/or transport
Diffusion trapping

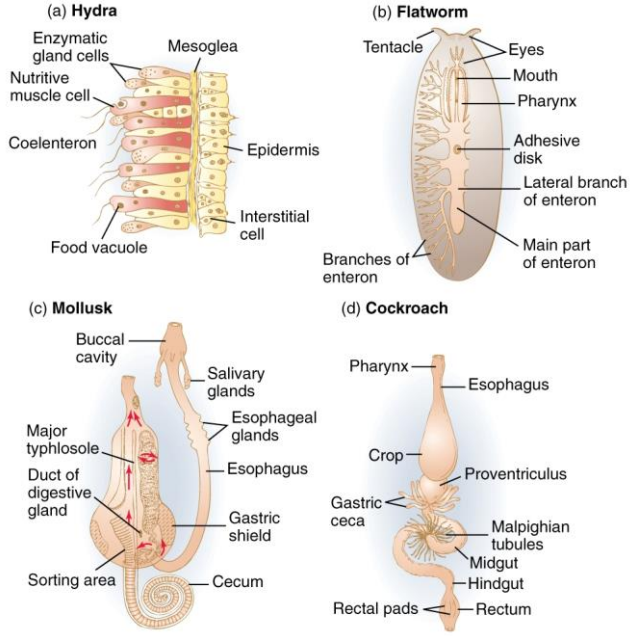

ATP
ADP
Carbamoyl phosphate synthetase
Carbamoyl phosphate
Ornithine carbamoyl transferase
L-Ornithine
L-Citrulline
L-Aspartic acid
Arginino-succinate synthetase
Arginase
Argininosuccinate lyase
L-Arginine
L-Argininosuccinate
Urea


Amino acids
Transaminase
Glycine, Aspartate, Glutamate
Nucleic acid metabolism
(Purine ring)
Uric acid
Uricase
Allantoin
Allantoinase
Allantoic acid
Allantoicase
Urea

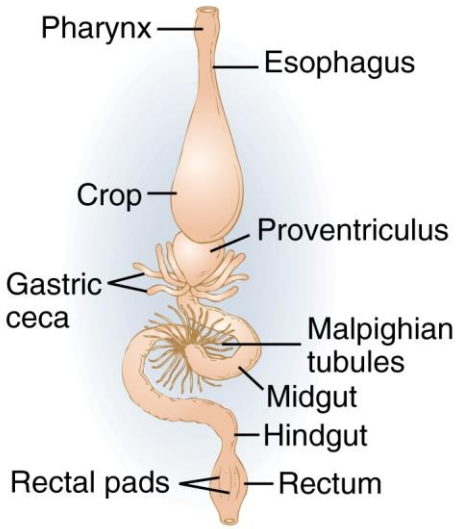

(a)
Transit time (hours)
70
60
50
40
30
20
10
0
100
200
300
400
Body mass (kg)
Llama
Cow
Mammalian foregut fermenters
Kangaroo rat

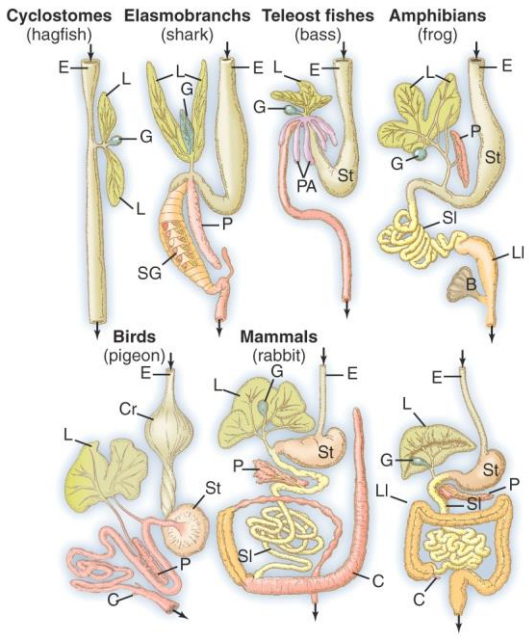

(b)
Transit time (days)
16
14
12
10
8
6
4
2
0
10
15
20
25
30
35
40
Body temperature
Ring-necked snake, *Diadophis punctatus*

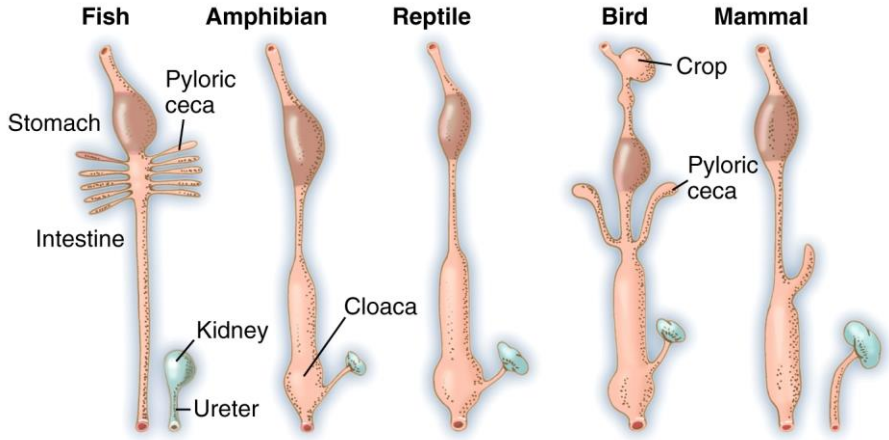

Structure
Function
Ingestion
Headgut
Foregut
Midgut
Hindgut
Receiving
Conducting
Storage
Digestion
Digestion
(Acidic secretions)
Absorption→Assimilation
(Basic secretions)
Storage
of waste
Defecation

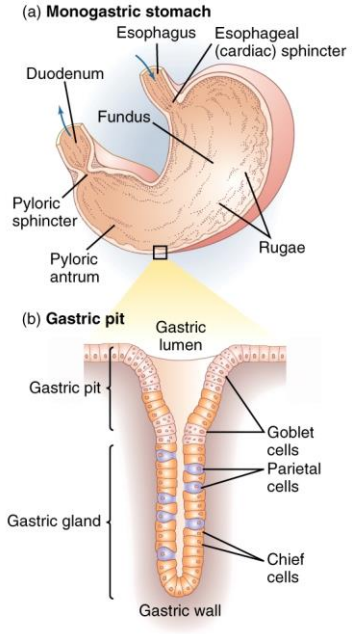

(a) Hydra
Enzymatic gland cells
Mesoglea
Nutritive muscle cell
Coelenteron
Epidermis
Interstitial cell
Food vacuole
(b) Flatworm
Tentacle
Eyes
Mouth
Pharynx
Adhesive disk
Lateral branch of enteron
Main part of enteron
Branches of enteron
(c) Mollusk
Buccal cavity
Salivary glands
Esophageal glands
Major typhlosole
Esophagus
Duct of digestive gland
Gastric shield
Sorting area
Cecum
(d) Cockroach
Pharynx
Esophagus
Crop
Proventriculus
Gastric ceca
Malpighian tubules
Midgut
Hindgut
Rectal pads
Rectum

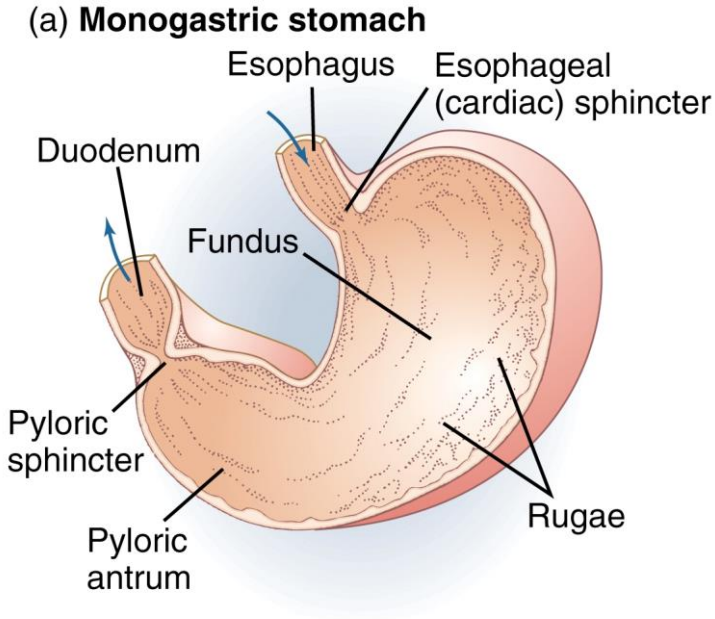
(d) **Cockroach**

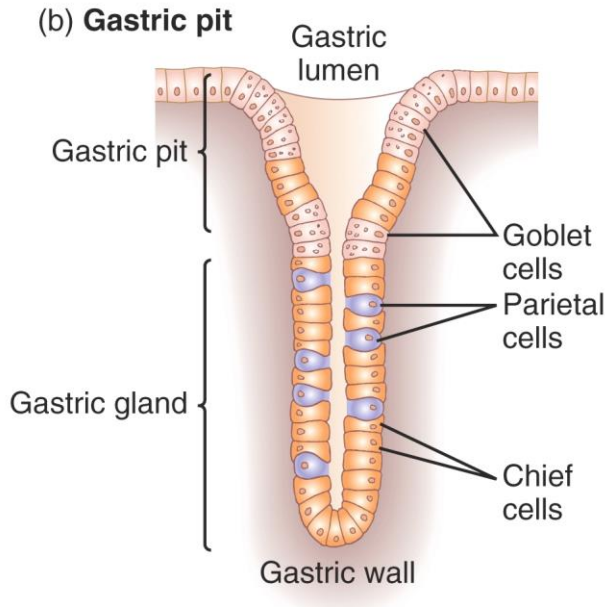

Pharynx
Esophagus
Crop
Proventriculus
Gastric ceca
Malpighian tubules
Midgut
Hindgut
Rectal pads
Rectum

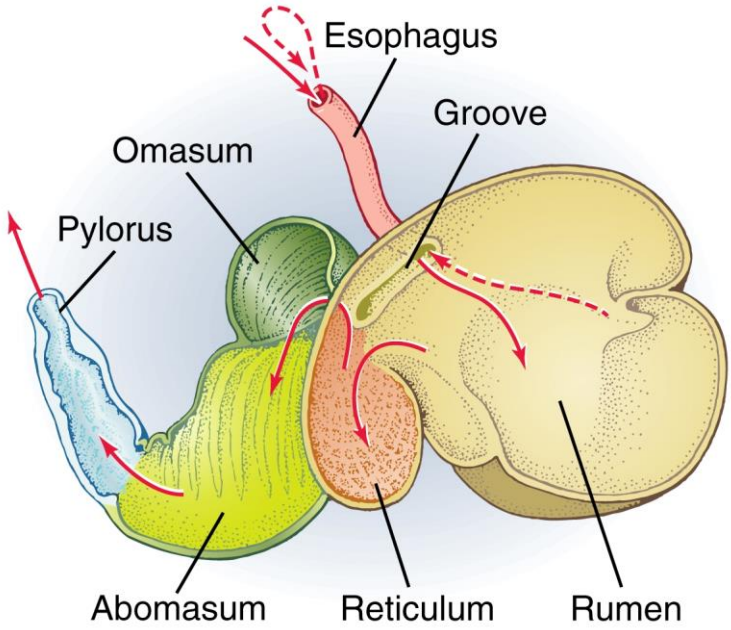

Cyclostomes (hagfish)
Elasmobranchs (shark)
Teleost fishes (bass)
Amphibians (frog)
Birds (pigeon)
Mammals (rabbit)
E
L
G
P
SG
PA
St
Sl
Ll
B
Cr
C

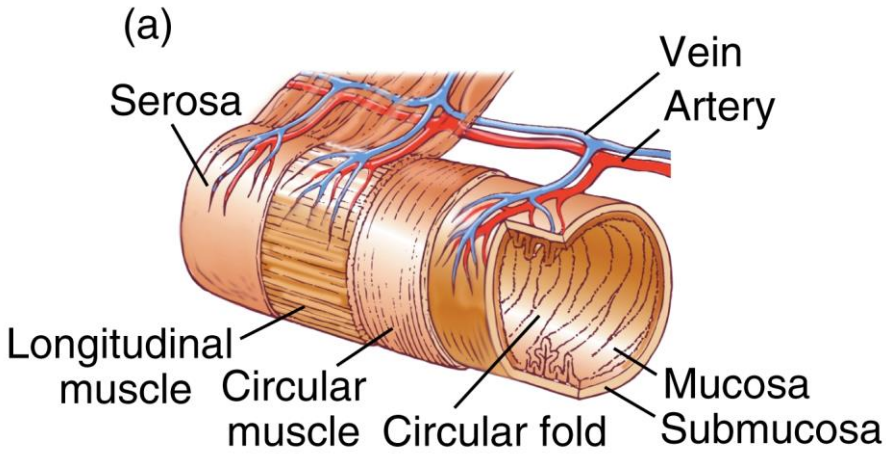

Fish
Amphibian
Reptile
Bird
Mammal
Stomach
Pyloric ceca
Intestine
Kidney
Ureter
Cloaca
Crop
Pyloric ceca

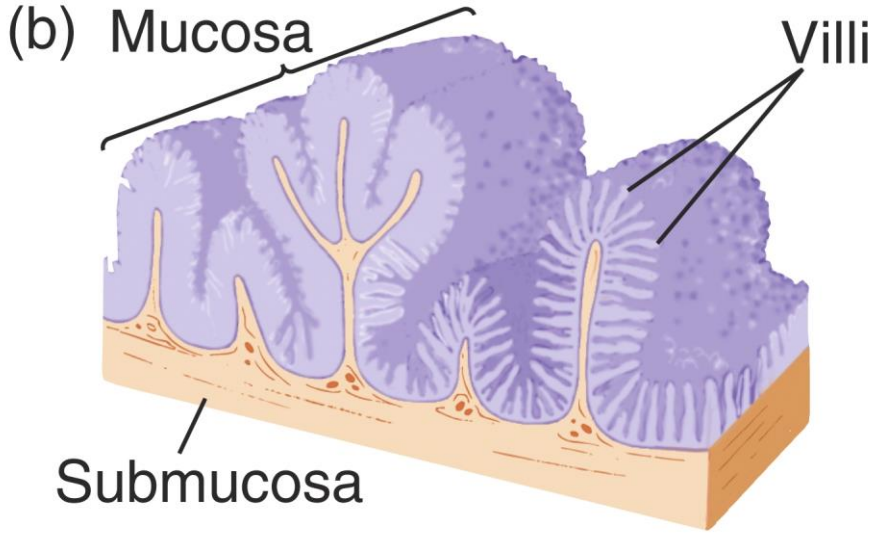

(a) Monogastric stomach
Esophagus
Esophageal (cardiac) sphincter
Duodenum
Fundus
Pyloric sphincter
Pyloric antrum
Rugae
(b) Gastric pit
Gastric lumen
Gastric pit
Goblet cells
Parietal cells
Gastric gland
Chief cells
Gastric wall

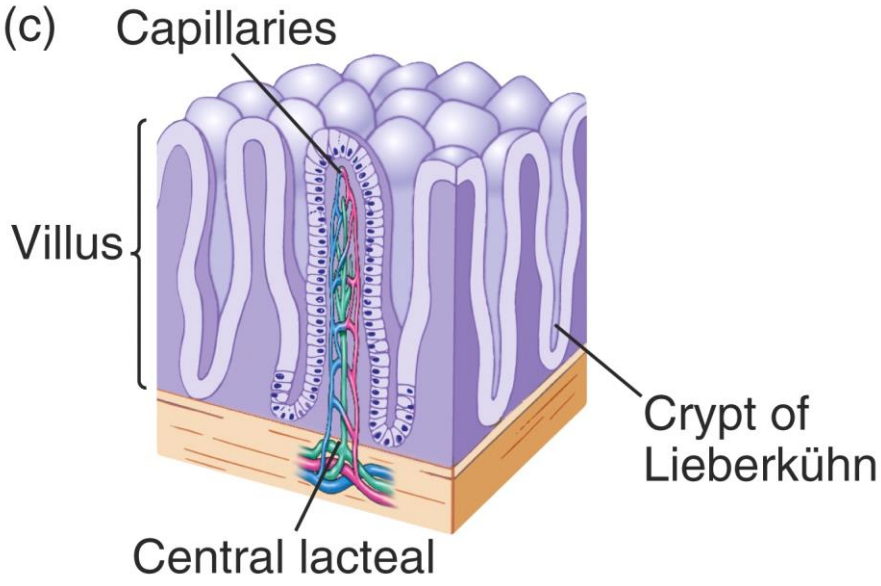

(a) Monogastric stomach
Esophagus
Esophageal (cardiac) sphincter
Duodenum
Fundus
Pyloric sphincter
Pyloric antrum
Rugae

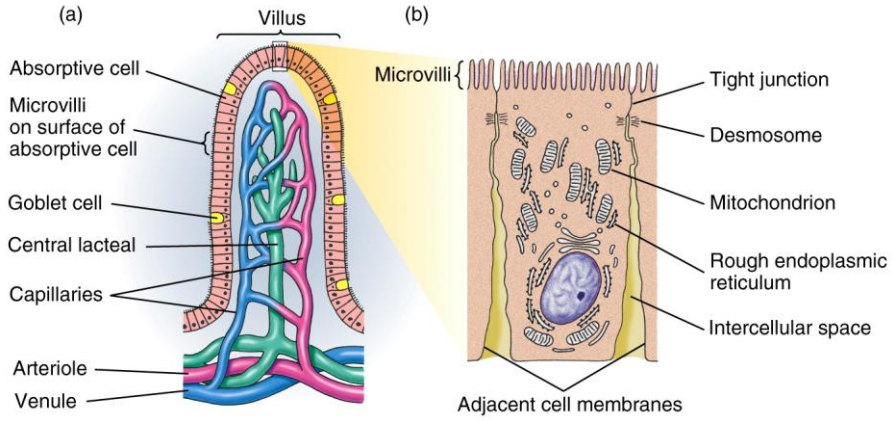

(b) Gastric pit
Gastric lumen
Gastric pit
Goblet cells
Parietal cells
Gastric gland
Chief cells
Gastric wall

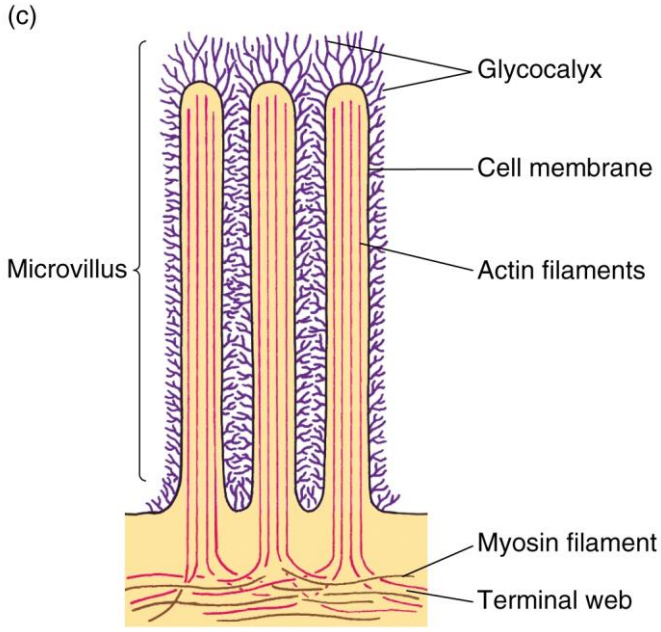

Esophagus
Groove
Omasum
Pylorus
Abomasum
Reticulum
Rumen

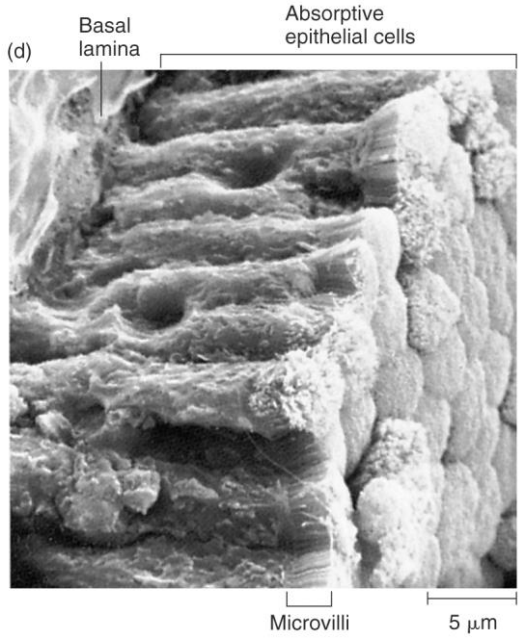

(a)
Vein
Artery
Serosa
Longitudinal muscle
Circular muscle
Circular fold
Mucosa
Submucosa

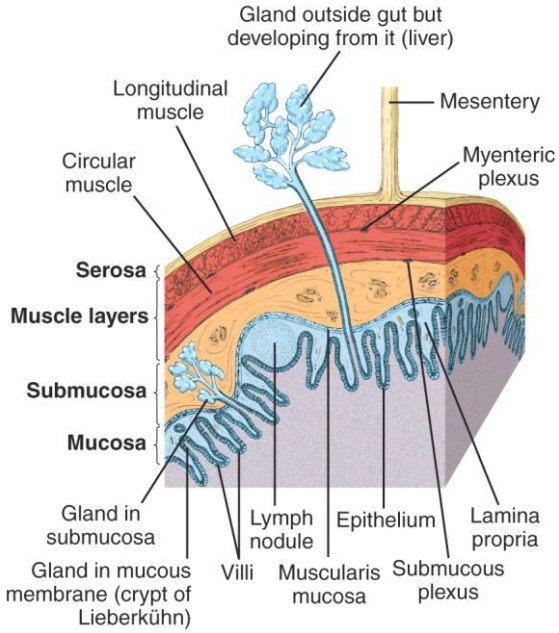

(b) Mucosa
Villi
Submucosa

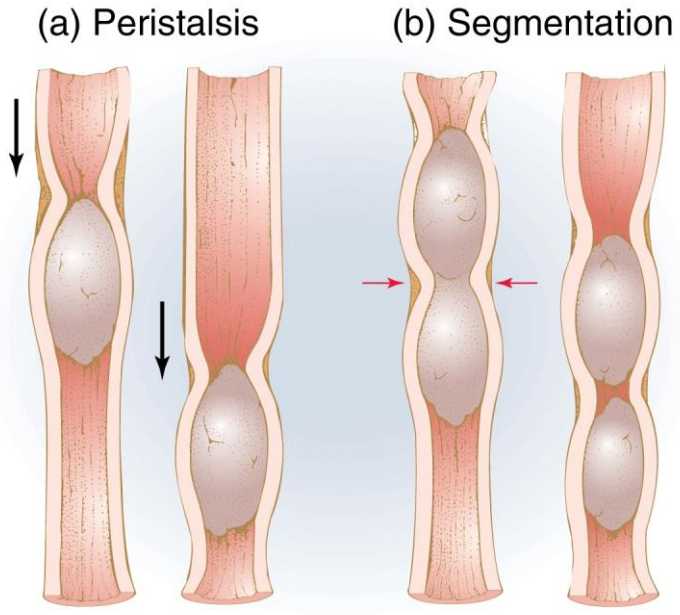

(c) Capillaries
Villus
Crypt of Lieberkühn
Central lacteal

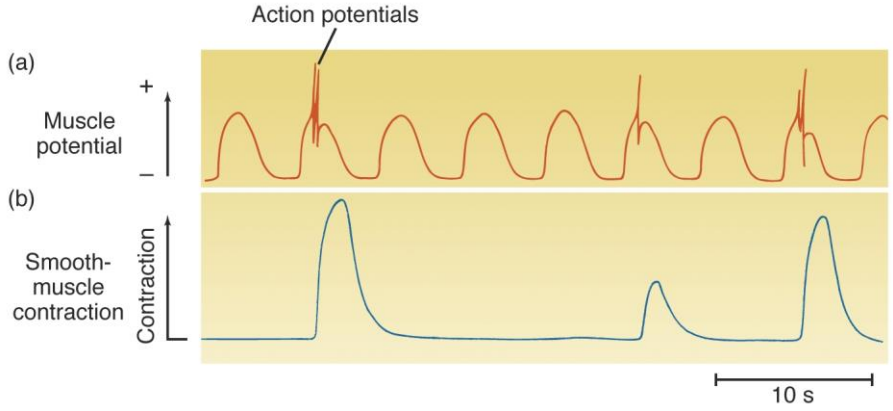

(a)
Villus
Absorptive cell
Microvilli on surface of absorptive cell
Goblet cell
Central lacteal
Capillaries
Arteriole
Venule
(b)
Microvilli
Tight junction
Desmosome
Mitochondrion
Rough endoplasmic reticulum
Intercellular space
Adjacent cell membranes

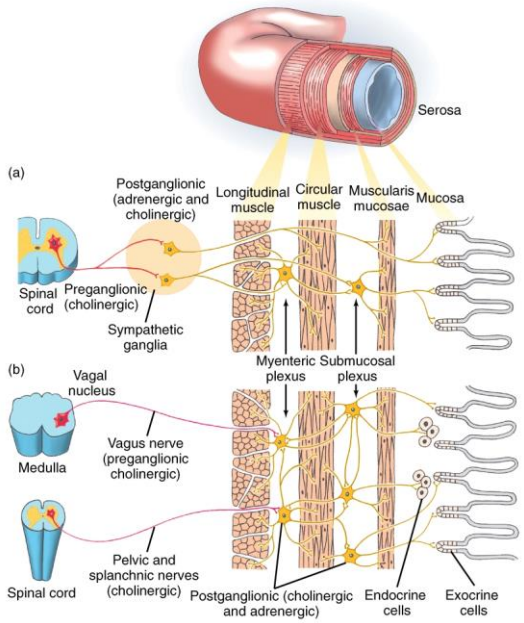

(c)
Glycocalyx
Cell membrane
Microvillus
Actin filaments
Myosin filament
Terminal web

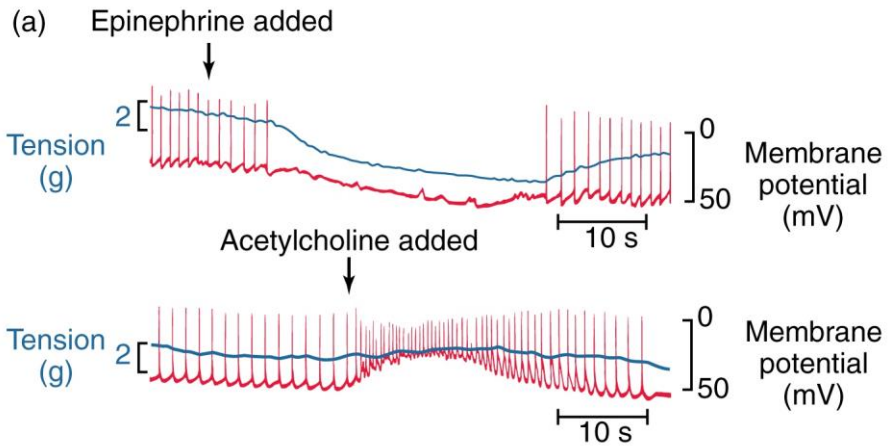

(d)
Basal lamina
Absorptive epithelial cells
Microvilli
5 μm

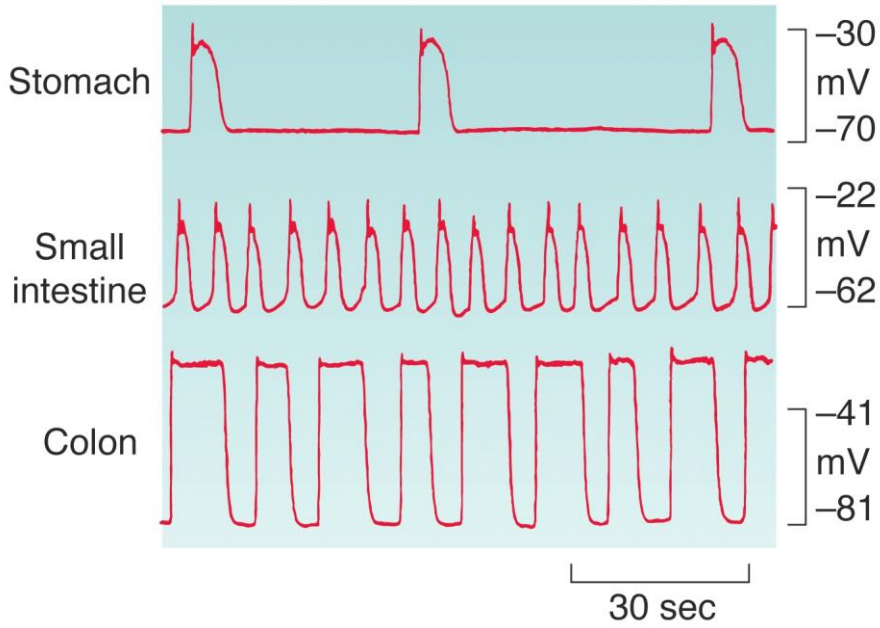

Gland outside gut but developing from it (liver)
Longitudinal muscle
Mesentery
Circular muscle
Myenteric plexus
Serosa
Muscle layers
Submucosa
Mucosa
Gland in submucosa
Lymph nodule
Epithelium
Lamina propria
Gland in mucous membrane (crypt of Lieberkühn)
Villi
Muscularis mucosa
Submucous plexus

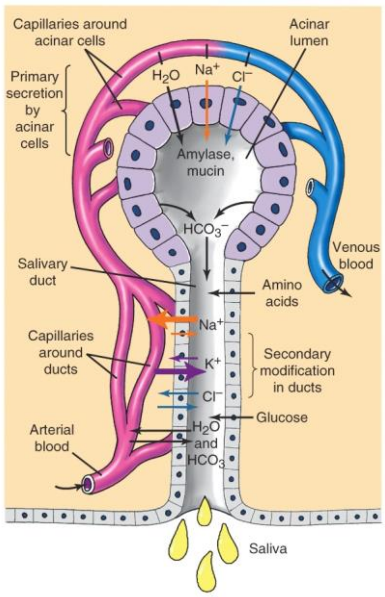

(a) Peristalsis
(b) Segmentation


Action potentials
(a)
Muscle potential
+
–
(b)
Smooth-muscle contraction
Contraction
10 s

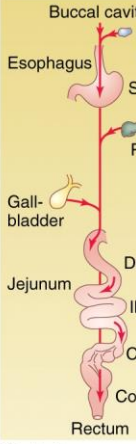

Serosa
(a)
Postganglionic (adrenergic and cholinergic)
Longitudinal muscle
Circular muscle
Muscularis mucosae
Mucosa
Spinal cord
Preganglionic (cholinergic)
Sympathetic ganglia
Myenteric plexus
Submucosal plexus
(b)
Vagal nucleus
Medulla
Vagus nerve (preganglionic cholinergic)
Spinal cord
Pelvic and splanchnic nerves (cholinergic)
Postganglionic (cholinergic and adrenergic)
Endocrine cells
Exocrine cells


(a) Epinephrine added
Tension (g)
2
0
50
Membrane potential (mV)
10 s
Acetylcholine added
Tension (g)
2
0
50
Membrane potential (mV)
10 s


Stomach
–30
mV
–70
Small intestine
–22
mV
–62
Colon
–41
mV
–81
30 sec


Capillaries around acinar cells
Acinar lumen
Primary secretion by acinar cells
H_2O
Na^+
Cl^-
Amylase, mucin
HCO_3^-
Venous blood
Salivary duct
Amino acids
Na^+
Capillaries around ducts
K^+
Secondary modification in ducts
Cl^-
Glucose
Arterial blood
H_2O and HCO_3^-
Saliva

Region	Secretion	Daily amount (L)	pH	Composition*
Buccal cavity, Salivary glands	Saliva	1+	6.5	Amylase, bicarbonate
Esophagus, Stomach	Gastric juice	1—3	1.5	Pepsinogen, HCl, rennin in infants, intrinsic factor
Pancreas	Pancreatic juice	1	7—8	Trypsinogen, chymotrypsinogen, carboxy- and aminopeptidase, lipase, amylase, maltase, nucleases, bicarbonate
Gall-bladder	Bile	1	7—8	Fats and fatty acids, bile salts and pigments, cholesterol
Duodenum, Jejunum, Ileum, Cecum, Colon, Rectum	Succus entericus	1	7—8	Enterokinase, carboxy- and aminopeptidases, maltase, lactase, sucrase, lipase, nucleases



*Excluding mucus and water, which together make up some 95% of the actual secretion.

Table 15-1 Action of the major enzymes secreted in the mouth, stomach, pancreas, and small intestine

Enzyme	Site of action	Substrate	Products of action
Mouth			
Salivary α-amylase	Mouth	Starch	Disaccharides (few)
Stomach			
Pepsinogen:pepsin	Stomach	Proteins	Large peptides
Pancreas			
Pancreatic α-amylase	Small intestine	Starch	Disaccharides
Trypsinogen:trypsin	Small intestine	Proteins	Large peptides
Chymotrypsin	Small intestine	Proteins	Large peptides
Elastase	Small intestine	Elastin	Large peptides
Carboxypeptidases	Small intestine	Large peptides	Small peptides (oligopeptides)
Aminopeptidases	Small intestine	Large peptides	Oligopeptides
Lipase	Small intestine	Triglycerides	Monoglycerides, fatty acids, glycerol
Nucleases	Small intestine	Nucleic acids	Nucleotides
Small intestine			
Enterokinase	Small intestine	Trypsinogen	Trypsin
Disaccharidases	Small intestine*	Disaccharides	Monosaccharides
Peptidases	Small intestine*	Oligopeptides	Amino acids
Nucleotidases	Small intestine*	Nucleotides	Nucleosidases, phosphoric acid
Nucleosidases	Small intestine*	Nucleosides	Sugars, purines, pyrimidines

*Intracellular

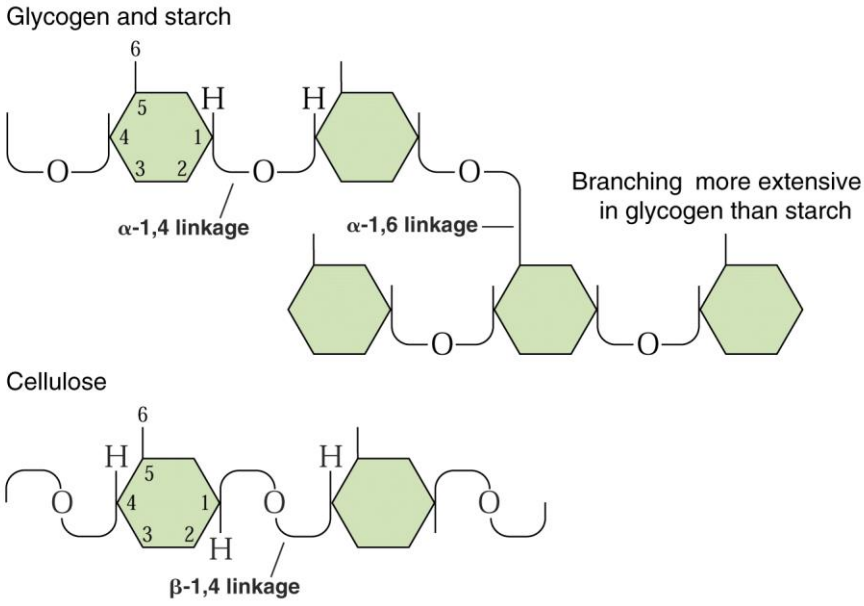
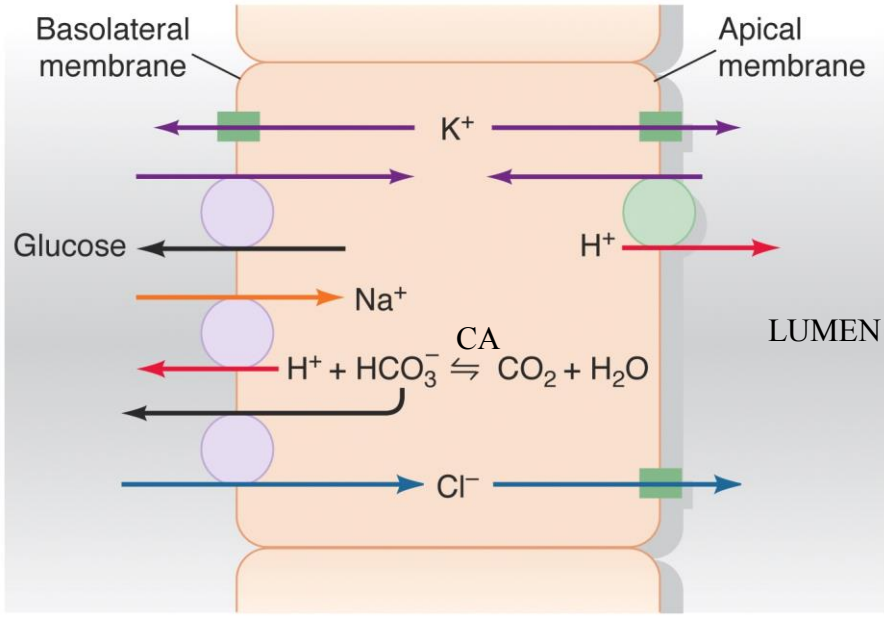
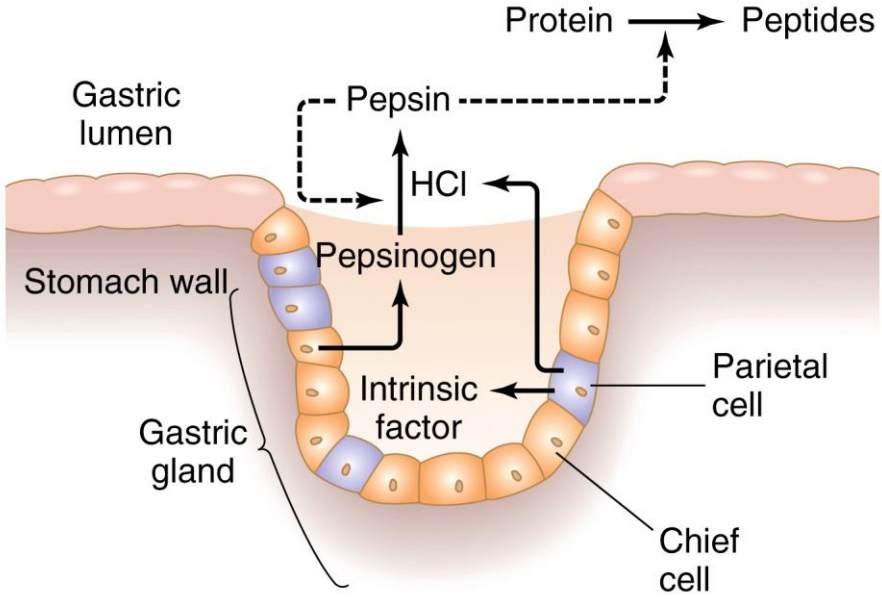


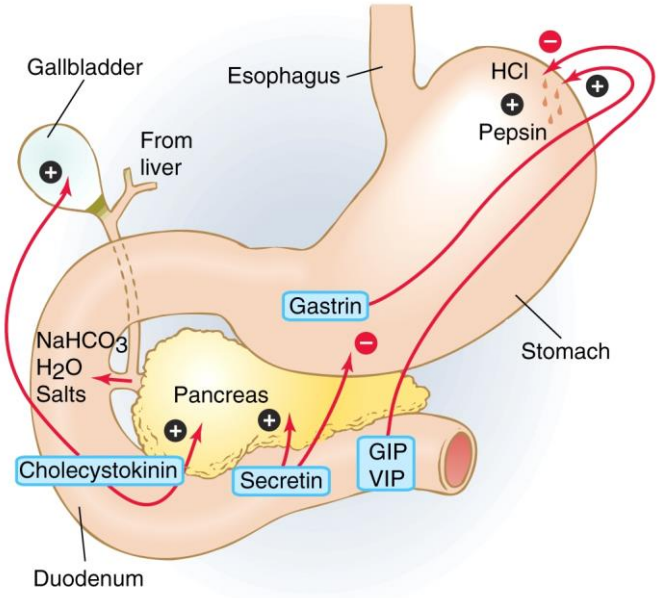
Table 15-2 The major gastrointestinal peptide hormones

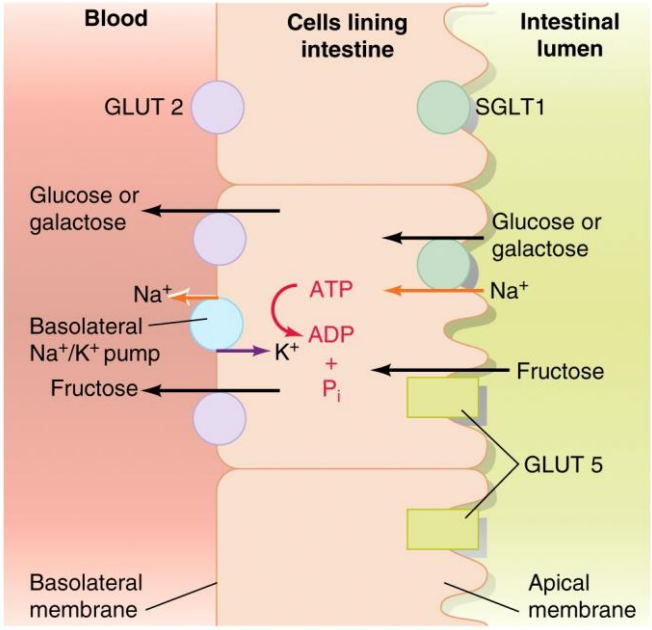
Hormone	Tissues of origin	Target tissue	Primary action	Stimulus to secretion
Gastrin	Stomach and duodenum	Secretory cells and muscles of stomach	HCl production and secretion; stimulation of gastric motility	Vagus nerve activity; peptides and proteins in stomach
Cholecystokinin (CCK)*	Upper small intestine	Gallbladder	Contraction of gallbladder	Fatty acids and amino acids in duodenum
		Pancreas	Pancreatic juice secretion	
Secretin*	Duodenum	Pancreas, secretory cells, and muscles of stomach	Water and $NaHCO_3$ secretion; inhibition of gastric motility	Food and strong acid in stomach and small intestine
Gastric inhibitory peptide (GIP)	Upper small intestine	Gastric mucosa and musculature	Inhibition of gastric secretion and motility	Monosaccharides and fats in duodenum
Bulbogastrone	Upper small intestine	Stomach	Inhibition of gastric secretion and motility	Acid in duodenum
Vasoactive intestinal peptide (VIP)*	Duodenum	Stomach, intestine	Increase of blood flow; secretion of thin pancreatic fluid; inhibition of gastric secretion	Fats in duodenum
Enteroglucagon	Duodenum	Jejunum, pancreas	Inhibition of motility and secretion	Carbohydrates in duodenum
Enkephalin*	Small intestine	Stomach, pancreas, intestine	Stimulation of HCl secretion; inhibition of pancreatic enzyme secretion and intestinal motility	Basic conditions in stomach and intestine
Somatostatin*	Small intestine	Stomach, pancreas, intestine, splanchnic arterioles	Inhibition of HCl secretion, pancreatic secretion, intestinal motility, and visceral blood flow	Acid in lumen of stomach

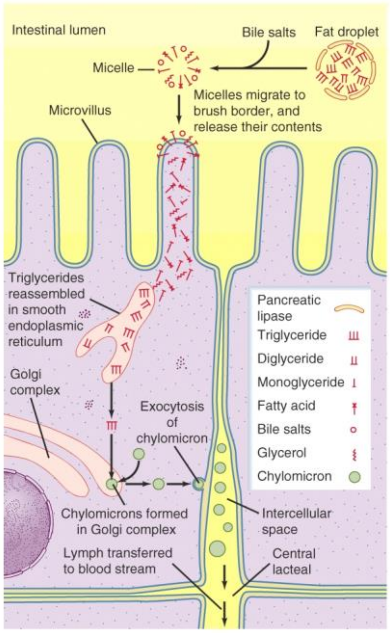
*These peptides are also found in central nervous tissue as neuropeptides. Additional unlisted neuropeptides identified in both brain and gut tissue include substance P, neurotensin, bombesin, insulin, pancreatic polypeptide, and ACTH.


Basolateral membrane
Apical membrane
K+
Glucose
H+
Na+
LUMEN
CA
H+ + HCO3− ⇋ CO2 + H2O
Cl−


Protein
Peptides
Gastric lumen
Pepsin
HCl
Pepsinogen
Stomach wall
Parietal cell
Intrinsic factor
Gastric gland
Chief cell


Gallbladder
Esophagus
HCl
Pepsin
From liver
Gastrin
Stomach
NaHCO3
H2O
Salts
Pancreas
Cholecystokinin
Secretin
GIP
VIP
Duodenum


Blood
Cells lining intestine
Intestinal lumen
GLUT 2
SGLT1
Glucose or galactose
Glucose or galactose
Na+
ATP
Na+
Basolateral Na+/K+ pump
ADP + Pi
K+
Fructose
Fructose
GLUT 5
Basolateral membrane
Apical membrane


Intestinal lumen
Bile salts
Fat droplet
Micelle
Micelles migrate to brush border, and release their contents
Microvillus
Triglycerides reassembled in smooth endoplasmic reticulum
Golgi complex
Exocytosis of chylomicron
Pancreatic lipase
Triglyceride
Diglyceride
Monoglyceride
Fatty acid
Bile salts
Glycerol
Chylomicron
Chylomicrons formed in Golgi complex
Intercellular space
Lymph transferred to blood stream
Central lacteal

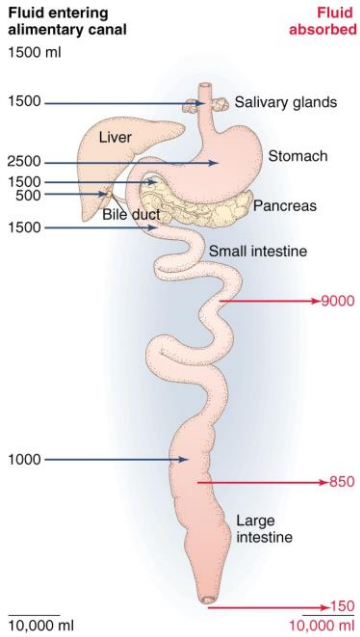

Fluid entering alimentary canal
1500 ml
Fluid absorbed
1500
Salivary glands
Liver
2500
Stomach
1500
500
Pancreas
Bile duct
1500
Small intestine
9000
1000
850
Large intestine
150
10,000 ml
10,000 ml

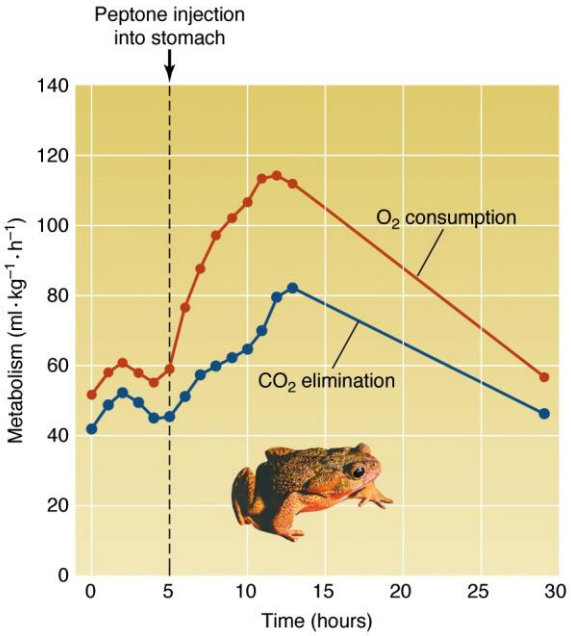
Table 15-3 **Some mammalian vitamins**

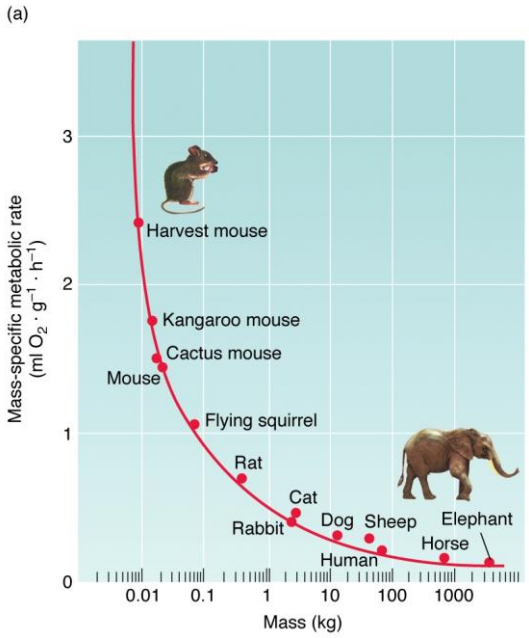
Vitamin	Major dietary sources; solubility*	Uptake; storage	Function in mammals†	Deficiency symptoms
Ascorbic acid (C)	Citrus fruits; WS	Absorbed from gut; little storage	Vital element for collagen; antioxidant	Scurvy (failure to form connective tissue)
Biotin	Egg yolk, tomatoes, liver, synthesis by intestinal flora; WS	Absorbed from gut	Protein and fatty acid synthesis; CO_2 fixation; transamination	Scaly dermatitis, muscle pains, weakness
Cyanocobalamin (B_{12})	Liver, kidney, brain, fish, eggs, synthesis by intestinal flora; WS	Absorbed from gut; stored in liver, kidney, brain	Nucleoprotein synthesis; formation of erythrocytes	Pernicious anemia, malformed erythrocytes
Folic acid (folacin, pteroylglutamic acid)	Meats; WS	Absorbed from gut; utilized as acquired	Nucleoprotein synthesis; formation of erythrocytes	Failure of erythrocytes to mature, anemia
Niacin	Lean meat, liver, whole grains; WS	Absorbed from gut; distributed to all tissues	Coenzyme in hydrogen transport (NAD, NADP)	Pellagra, skin lesions, digestive disturbances, dementia
Pantothenic acid	Many foods; WS	Absorbed from gut; stored in all tissues	Constituent of coenzyme A (CoA)	Neuromotor, cardiovascular disorders
Pyridoxine (B_6)	Whole grains, traces in many foods; WS	Absorbed from gut; half appears in urine	Coenzyme for amino and fatty acid metabolism	Dermatitis, nervous disorders
Riboflavin (B_2)	Milk, eggs, lean meat, liver, whole grains; WS	Absorbed from gut; stored in kidney, liver, heart	Flavoproteins in oxidative phosphorylation	Photophobia, fissuring of the skin
Thiamine (B_1)	Brain, liver, kidney, heart, whole grains, nuts, beans, potatoes	Absorbed from gut; stored in liver, brain, kidney	Formation of cocarboxylase enzyme involved in decarboxylation (citric acid cycle)	Stoppage of CH_2O metabolism at pyruvate, beriberi, neuritis, heart failure

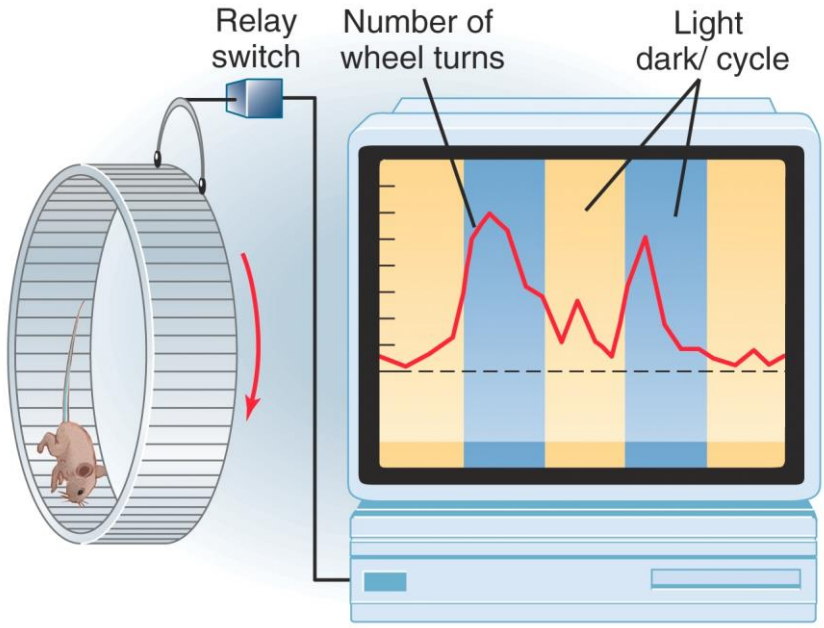
*FS = fat-soluble; WS = water-soluble.
†Most vitamins have numerous functions; the functions listed are a mere sampling.

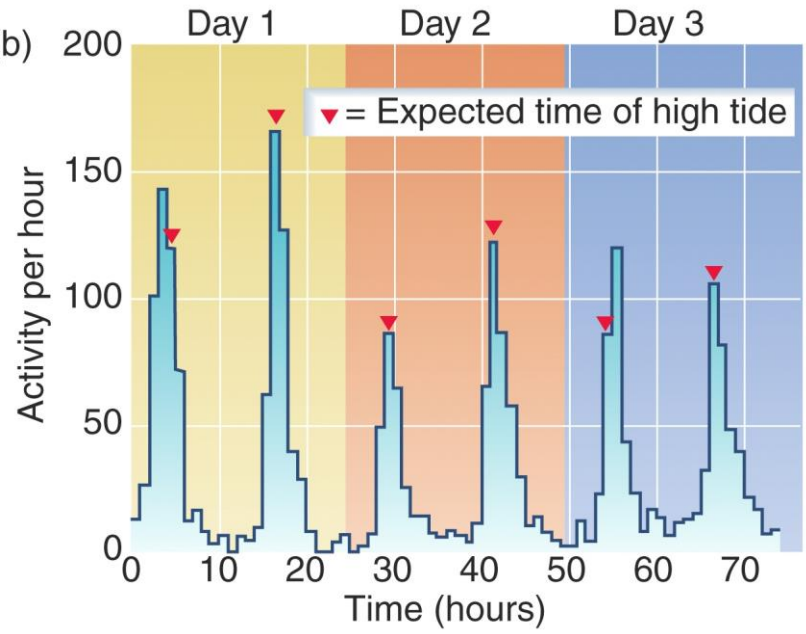
Table 16-1 Heat production and respiratory quotient for the three major food types

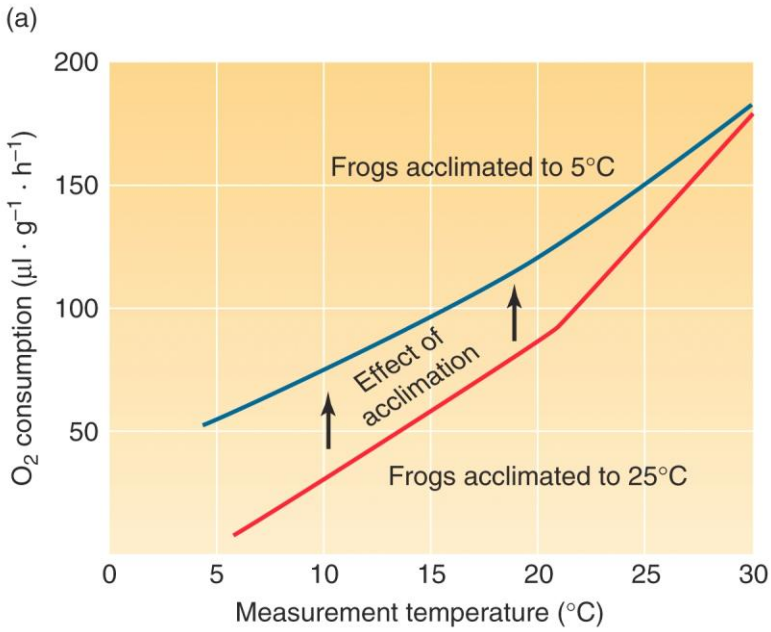
	Heat Production (kJ)			
	Per gram of food	Per liter of CO_2 produced	Per liter of O_2 consumed	R_Q
Carbohydrates	17.1	21.1	21.1	1.00
Fats	38.9	19.8	27.9	0.71
Proteins (to urea)	17.6	18.6	23.3	0.80

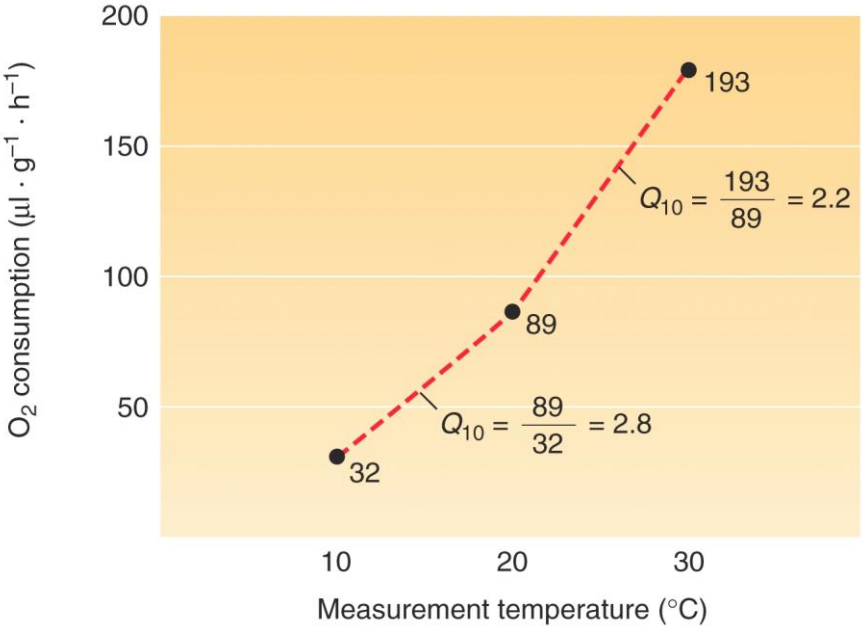

Peptone injection into stomach
140
120
100
80
60
40
20
0
Metabolism (ml · kg⁻¹ · h⁻¹)
O2 consumption
CO2 elimination
0
5
10
15
20
25
30
Time (hours)

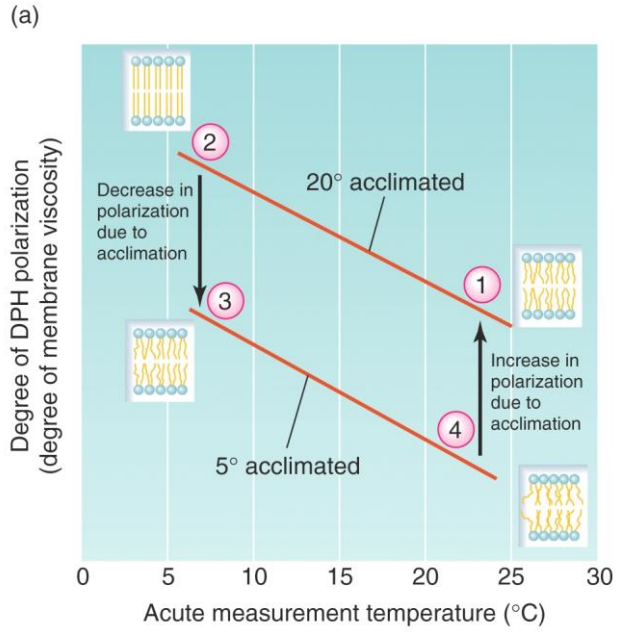

(a)
3
2
1
0
Mass-specific metabolic rate (ml O2 · g⁻¹ · h⁻¹)
Harvest mouse
Kangaroo mouse
Cactus mouse
Mouse
Flying squirrel
Rat
Cat
Rabbit
Dog
Sheep
Elephant
Horse
Human
0.01
0.1
1
10
100
1000
Mass (kg)

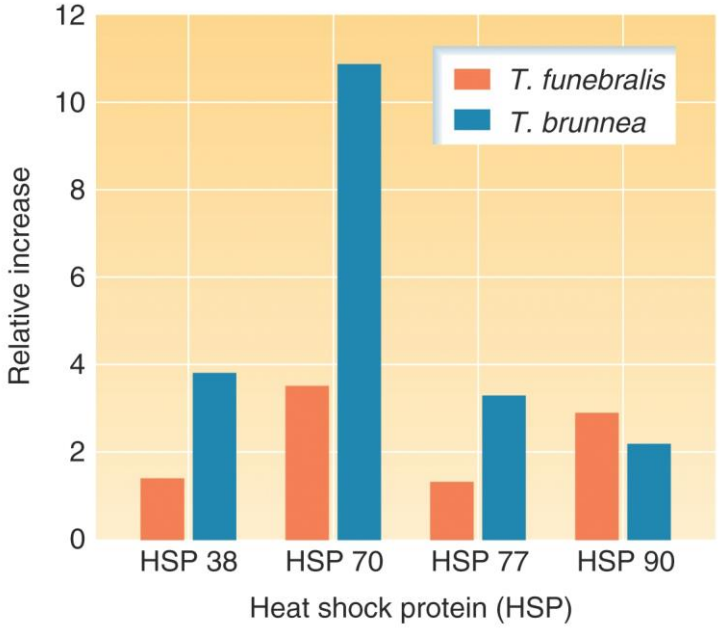

Relay switch
Number of wheel turns
Light dark/ cycle

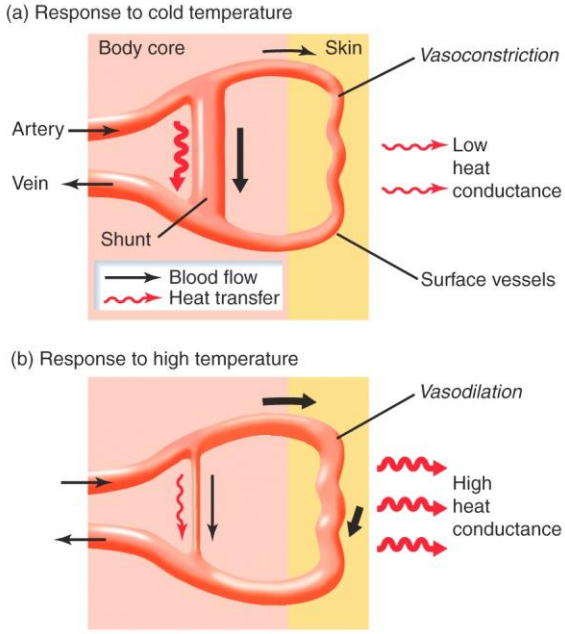

(b)
Day 1
Day 2
Day 3
▼= Expected time of high tide
Activity per hour
200
150
100
50
0
0
10
20
30
40
50
60
70
Time (hours)

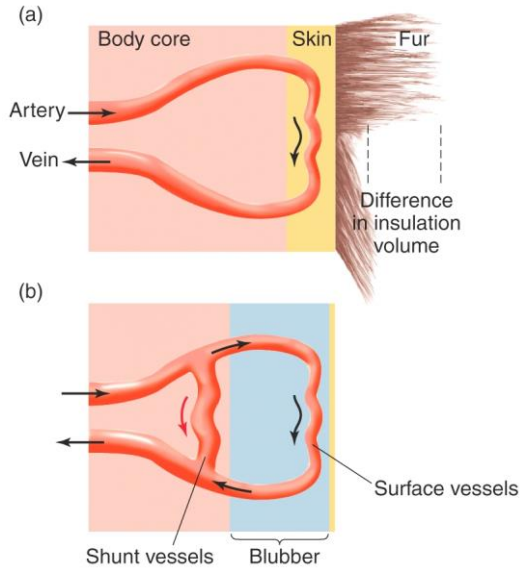

(a)
200
150
100
50
O_2 consumption ($\mu l \cdot g^{-1} \cdot h^{-1}$)
Frogs acclimated to 5°C
Effect of acclimation
Frogs acclimated to 25°C
0
5
10
15
20
25
30
Measurement temperature (°C)

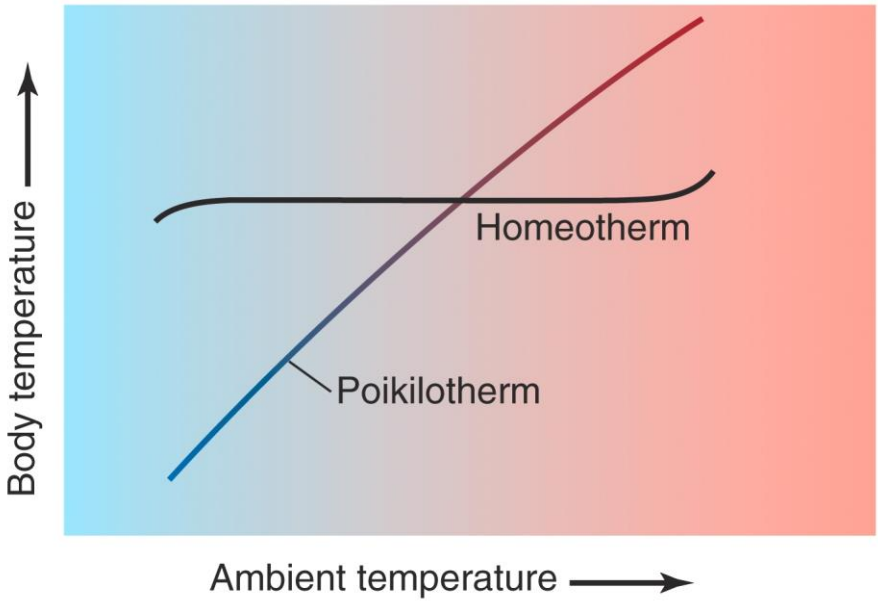

200
150
100
50
O_2 consumption ($\mu l \cdot g^{-1} \cdot h^{-1}$)
193
$Q_{10} = \frac{193}{89} = 2.2$
89
$Q_{10} = \frac{89}{32} = 2.8$
32
10
20
30
Measurement temperature (°C)

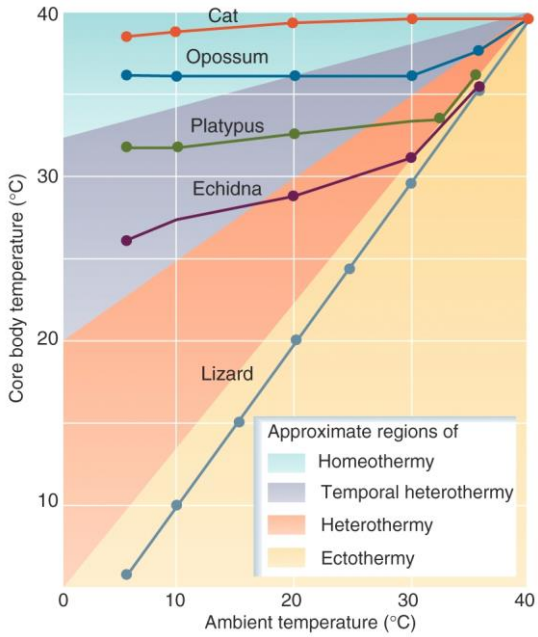

(a)
Degree of DPH polarization (degree of membrane viscosity)
2
20° acclimated
Decrease in polarization due to acclimation
1
3
Increase in polarization due to acclimation
4
5° acclimated
0
5
10
15
20
25
30
Acute measurement temperature (°C)

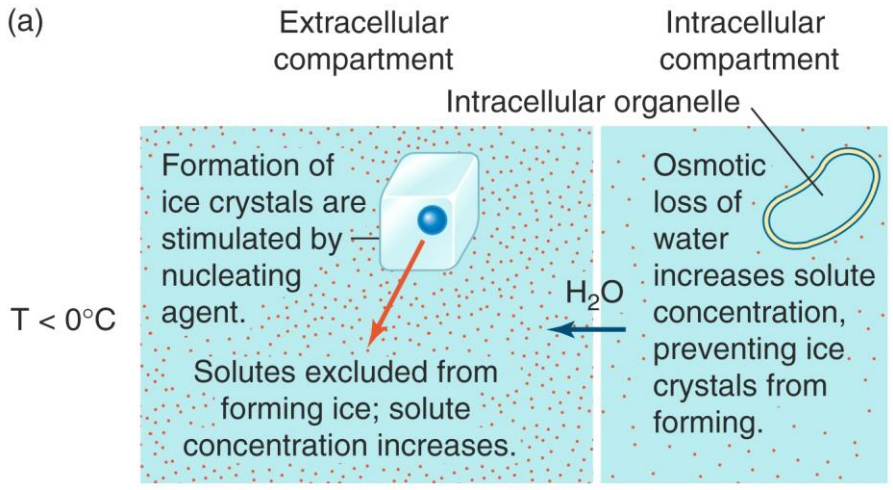

12
10
8
6
4
2
0
Relative increase
T. funebralis
T. brunnea
HSP 38
HSP 70
HSP 77
HSP 90
Heat shock protein (HSP)

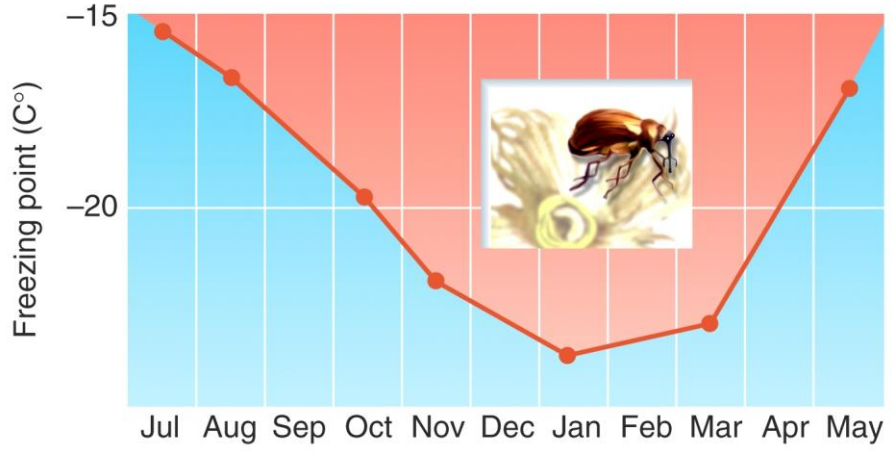

(a) Response to cold temperature
Body core
Skin
Vasoconstriction
Artery
Vein
Low heat conductance
Shunt
Blood flow
Heat transfer
Surface vessels
(b) Response to high temperature
Vasodilation
High heat conductance

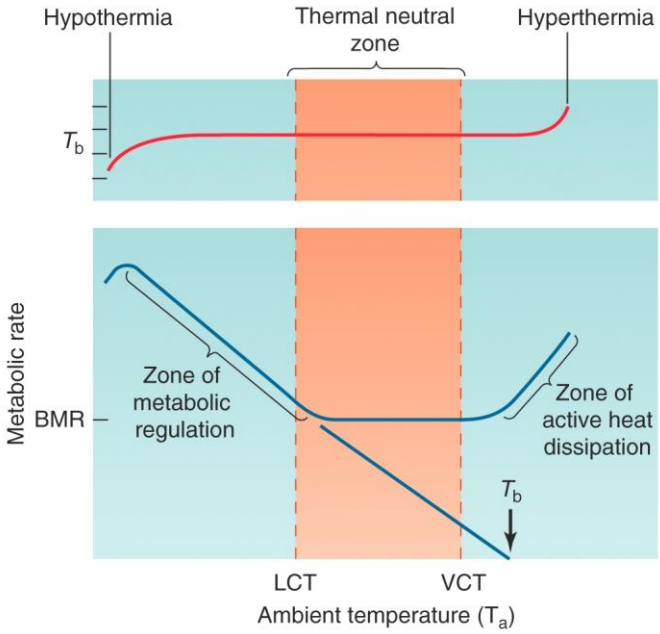

(a)
Body core
Skin
Fur
Artery
Vein
Difference in insulation volume
(b)
Surface vessels
Shunt vessels
Blubber

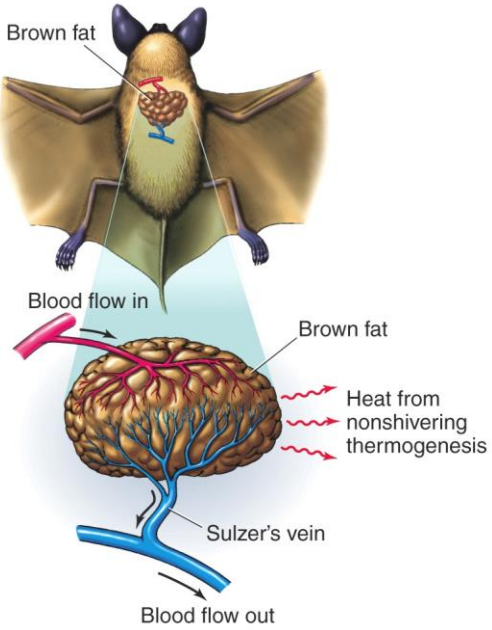

Body temperature
Homeotherm
Poikilotherm
Ambient temperature

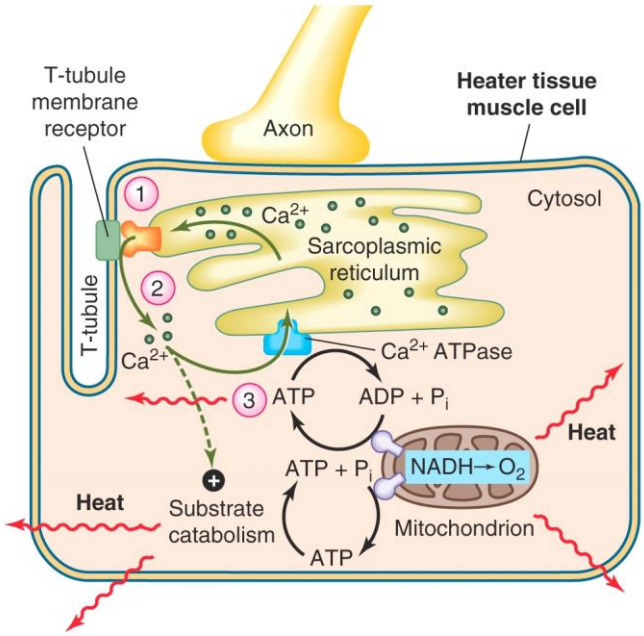

Cat
Opossum
Platypus
Echidna
Lizard
Approximate regions of
Homeothermy
Temporal heterothermy
Heterothermy
Ectothermy
Core body temperature (°C)
Ambient temperature (°C)
40
30
20
10
0
10
20
30
40

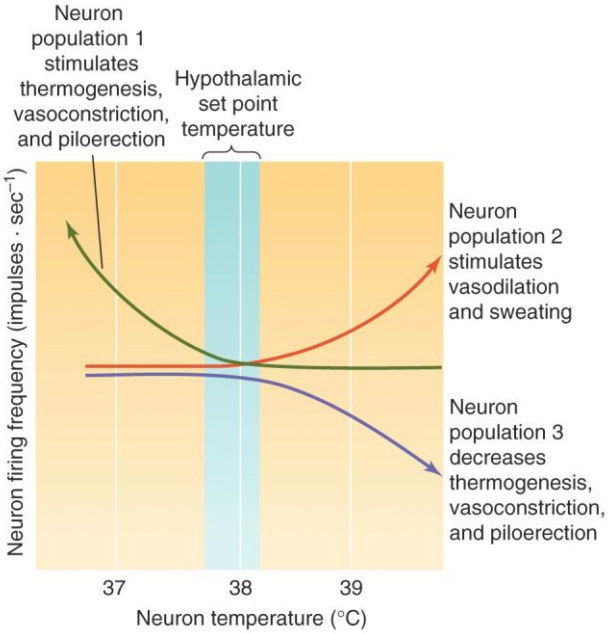

(a)
Extracellular compartment
Intracellular compartment
Intracellular organelle
Formation of ice crystals are stimulated by nucleating agent.
Osmotic loss of water increases solute concentration, preventing ice crystals from forming.
T < 0°C
H_2O
Solutes excluded from forming ice; solute concentration increases.

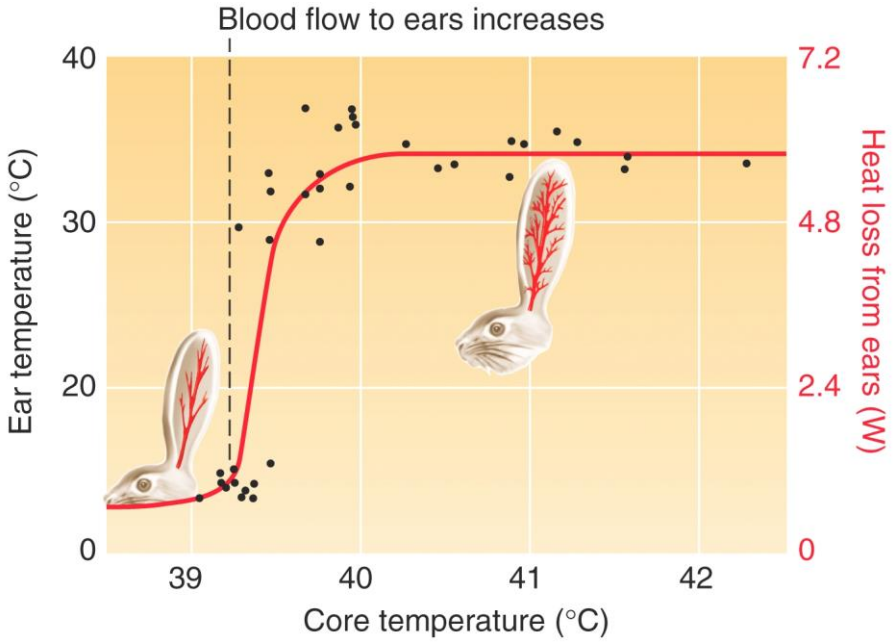

Freezing point (C°)
–15
–20
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May

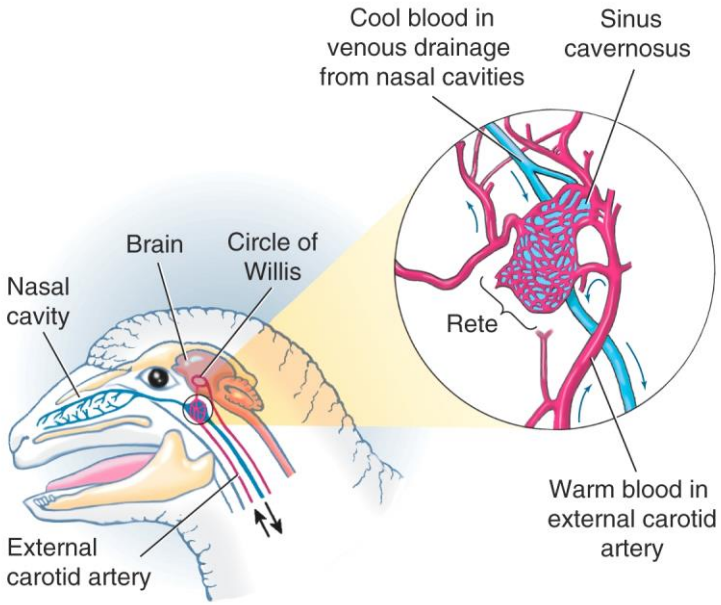

Hypothermia
Thermal neutral zone
Hyperthermia
T_b
Metabolic rate
BMR
Zone of metabolic regulation
Zone of active heat dissipation
T_b
LCT
VCT
Ambient temperature (T_a)

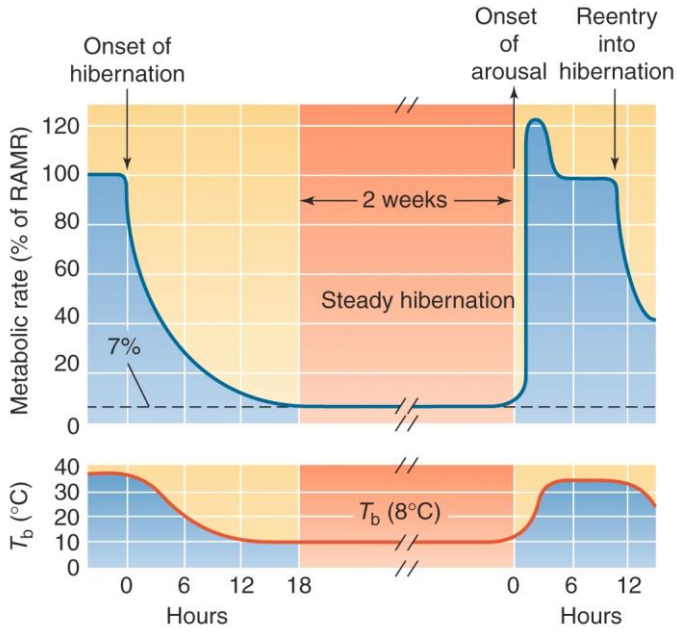

Brown fat
Blood flow in
Brown fat
Heat from nonshivering thermogenesis
Sulzer's vein
Blood flow out


T-tubule membrane receptor
Axon
Heater tissue muscle cell
Cytosol
1
Ca^{2+}
Sarcoplasmic reticulum
2
T-tubule
Ca^{2+}
Ca^{2+} ATPase
3
ATP
ADP + P_i
Heat
ATP + P_i
$NADH \rightarrow O_2$
Heat
Substrate catabolism
Mitochondrion
ATP

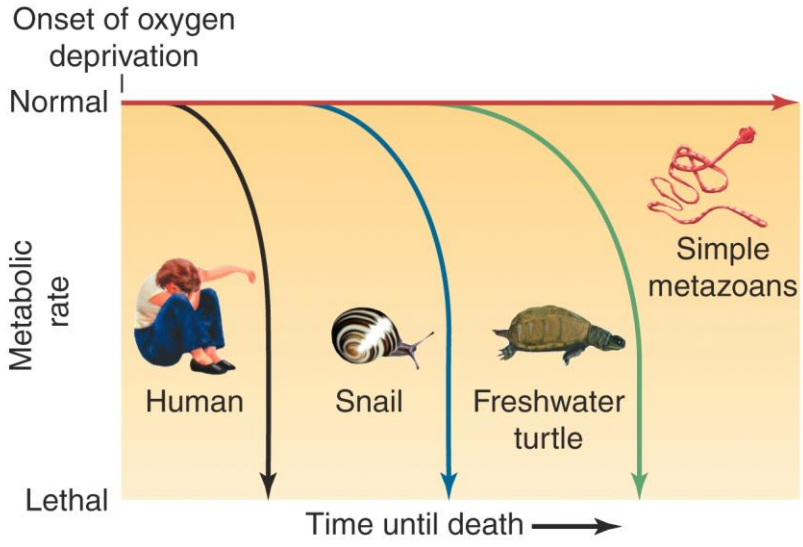

Neuron population 1 stimulates thermogenesis, vasoconstriction, and piloerection
Hypothalamic set point temperature
Neuron firing frequency (impulses · sec^{-1})
Neuron population 2 stimulates vasodilation and sweating
Neuron population 3 decreases thermogenesis, vasoconstriction, and piloerection
37
38
39
Neuron temperature (°C)


Blood flow to ears increases
Ear temperature (°C)
40
30
20
0
39
40
41
42
Core temperature (°C)
7.2
4.8
2.4
0
Heat loss from ears (W)


Cool blood in venous drainage from nasal cavities
Sinus cavernosus
Brain
Circle of Willis
Nasal cavity
Rete
Warm blood in external carotid artery
External carotid artery


Onset of hibernation
Onset of arousal
Reentry into hibernation
Metabolic rate (% of RAMR)
120
100
80
60
40
20
0
2 weeks
Steady hibernation
7%
T_b (°C)
40
30
20
10
0
T_b (8°C)
0
6
12
18
Hours
0
6
12
Hours

(b)


Onset of oxygen deprivation
Normal
Metabolic rate
Lethal
Human
Snail
Freshwater turtle
Simple metazoans
Time until death