Vertebrate Relationships & Basic Structure

Objectives

1) To explain the structures that are characteristic of vertebrates, discuss the relationship of vertebrates to other members of the animal kingdom, & describe the systems that make vertebrates functional animals.

2) To understand the fundamentals of vertebrate design in order to appreciate the changes that have occurred during their evolution, & to trace homologies between primitive vertebrates & derived ones.

2.1 Vertebrates in Relation to Other Animals

1) Vertebrates are in subphylum **Vertebrata** of phylum **Chordata**.

2) Also in phylum Chordata: the **tunicates** (subphylum **Urochordata**) & **cephalochordates** (subphylum **Cephalochordata**).

- Tunicates are *more primitive* than cephalochordates & vertebrates, which are linked by several derived features.

3) **Shared derived features of chordates:** a notochord; a dorsal hollow nerve cord; a segmented, muscular postanal tail, and an endostyle.

- **Endostyle:** a ciliated, glandular groove on the floor of the pharynx that secretes mucus for trapping food particles during filter feeding. It is homologous with the thyroid gland of vertebrates, an endocrine gland involved with regulating metabolism.

4) Although chordates are all bilaterally symmetrical animals, they also share an additional type of left-to-right asymmetry within the body that is determined by the same genetic mechanism.

- **E.g.** the positioning of the heart, and most of the liver, on the left-hand side.
- Rare individuals have this situation in an opposite condition.

5) Chordates are characterised by a pharynx containing gill slit which is used for filter feeding in non-vertebrate chordate & for respiration in the aquatic vertebrates such as fishes. But these features also seen in some other deuterostomes.

6) Relationship of chordates to other kinds of animals is revealed by anatomical, biochemical, and embryological characters as well as by the fossil records.

7) **Figure 2-1** shows the relationships of animal phyla.

- **Vertebrates** superficially resemble other active animals, such as insects, in having a distinct head end, jointed legs, & bilateral symmetry.
- However, phylum Chordata is closely related to phylum **Echinodermata** which are marine forms without distinct heads & with pentaradial symmetry as adults.

8) The chordates, echinoderms, hemichordates, and xenoturbellids are linked as **deuterostomes** by several unique embryonic features, such as egg cleavage & larval form.

9) **Xenoturbellids** are small marine wormlike animals. **Hemichordates** are considered the sister group of chordates because both groups have pharyngeal slits & an endostyle-like structure. This is considered a primitive deuterostome feature. Hemichordates:

    1. Small phylum of marine animals.
    2. Includes the earthworm-like acorn worms & the fernlike pterobranchs.

10) Modern echinoderms lack pharyngeal slits but some extinct echinoderms may have had them. Also, primitive echinoderms may have had bilaterally symmetry, meaning that the fivefold symmetry of modern echinoderms may be a derived character of that lineage.

11) Recent information groups echinoderms & hemichordates as the **Ambulacraria**

To consider how deuterostomes are related to other animals, start at the bottom of the tree and work upward:

1) All animals (**metazoans**) are multicellular; share common embryonic & reproductive features:
    1. Embryo initially forms a hollow ball of cells (the **blastula**).
    2. Sex cells formed in special organs.
    3. Motile sperms with tails

2) Animals more derived than sponges have a nervous system, and their bodies are made of distinct layers of cells formed during **gastrulation**. Gastrulation occurs when the blastula folds in upon itself, producing two distinct cell layers & an inner gut with an opening to the outside.
    1. Outer cell layer = **ectoderm**
    2. Inner layer = **endoderm**

3) Cnidaria (jellyfishes & related animals) have these two layers of body tissue (**diploblastic**).

4) Animals more derived than jellyfishes & their kin have an additional, middle cell layer of **mesoderm**, making them **triploblastic**.
    1. Triploblasts also have a gut that opens at both ends (i.e. with mouth & anus).

2. Bilaterally symmetrical with an anterior head at some point in their life.
3. Muscles are formed from the mesoderm & the adults use these muscles to move.
4. Larval stages move by cilia.

5) The **coelom**, an inner body cavity that forms as a split within the mesoderm, is another derived character of most (but not all) triploblastic animals.

6) Coelomate animals are split into two groups on the basis of how the mouth & anus form. When the blastula folds in on itself to form a **gastrula**, it leaves an opening to the outside called the **blastopore**.

7) In **jellyfish** the blastopore is the only opening into the body & it serves as both mouth & anus. But during the embryonic development of coelomates, a second opening develops.

8) In the lineage called **protostomes**, the blastopore (first opening in embryo) becomes the mouth, whereas in deuterostomes the second opening becomes the mouth & the blastopore becomes the anus.

9) Coelom formation during development differs between protostomes & deuterostomes.

10) Mollusks, arthropods, annelids, and many other phyla are *protostomes*. Chordates, hemichordates, and echinoderms are *deuterostomes*.

Nonvertebrate Chordates

- The two groups of **extant** nonvertebrate chordates are small, **marine** animals.

Urochordates

1) **Tunicates** (subphylum **Urochordata**) are filter feeders with a basketlike perforated pharynx.

2) The majority are sedentary as adults.

3) Most adult tunicates (sea squirts) bear little similarity to cephalochordates & vertebrates, but their tadpole-like, free-swimming **larvae** look more like chordates.

4) **Figure 2-2 (a), (b):** shows the relationships of animal phyla.

5) **Tunicate larvae** have a notochord, a dorsal hollow nerve cord, & a muscular postanal tail that moves in a fishlike swimming pattern.

6) A popular theory was that the earliest chordates would have been like tunicates & then cephalochordates & vertebrates evolved from an ancestor that resembled a tunicate larva.

7) However, the ancestral chordate was probably a free-swimming wormlike creature that used gill slits for filter feeding.

Cephalochordates

- Subphylum **Cephalochordata** contains small, superficially fishlike marine animals <5 cm long.
- **Figure 2-2 (c):** The lancelet, commonly known as **amphioxus** (means "sharp at both ends").

1) Burrowing, sedentary animals as adults. In a few species, the adults retain the active, free-swimming behaviour of the larvae.
2) Notable *characteristic* of amphioxus is its fishlike locomotion that results from **myomeres**.
3) Myomeres are blocks of striated muscle fibers arranged along both sides of the body.
4) Tunicate larvae have banded muscles in their tails but don't have distinct myomeres.
5) Sequential contraction of myomeres bends the body from side to side resulting in forward or backward **propulsion**.
6) **Notochord** acts as an incompressible elastic rod, extending the *full length of the body* & preventing the body from shortening when the myomeres contract. The vertebrate notochord ends midway through the head region.

1- **Figure 2-2 (c)** shows some details of the **internal structure** of amphioxus.

1) Amphioxus & vertebrates differ in the use of the pharyngeal slits.
2) Amphioxus has no gill tissue associated with these slits; it is small enough that oxygen uptake & CO_2 loss occur by **diffusion** over the body surface.
3) Instead, the gill slits are used for filter feeding. Water is moved over the gill slits by cilia on the **gill bars** between the slits, aided by the **buccal** (mouth region) **cirri** & the **wheel organ**, while the **velum** is a flap helping to control the one-way flow of water.
4) In addition to the **coelom** (internal body cavity) seen in all chordates, amphioxus has an **atrium** (external body cavity) seen in tunicates & hemichordates but absent from vertebrates.
5) Atrium works in coordination with other structures to control the **flow of water** (and the passage of substances through the pharynx.

2.2 Definition of a Vertebrate

Main Features of Vertebrates

1) The term *vertebrate* is derived from the vertebrae that make up the spinal column (backbone).

2) In land vertebrates, the vertebrae form around the notochord during development & encircle the nerve cord.

3) *Bony* **vertebral column** replaces the original notochord after the embryonic period. Vertebrae are made of *cartilage* in many fishes.

4) **Cranium** (skull) surrounding the brain.

5) Prominent **head** containing complex sense organs.

6) Not all animals in subphylum Vertebrata have vertebrae, **e.g.** jawless vertebrates & hagfishes.

7) Not all vertebrates have vertebrae e.g. the jawless vertebrates, hagfishes.

8) Fully formed vertebrae, with a **centrum** surrounding the notochord, are *found only in* **gnathostomes** (jawed vertebrates)

Two embryonic features account for many differences between vertebrates & other chordates:

I. *Hox* gene complex (*homeobox* genes)

1) *Hox* genes don't directly code for specific features; they regulate the expression of a hierarchy of other genes that control the shape of the body, especially *development along the body axis*.

2) Jellyfishes have one or two *Hox* genes; more derived metazoans have up to 13.

3) **Vertebrates** are unique in having undergone the duplication of the entire *Hox* complex.

4) More complex/developed animals have a greater amount of genetic material. Other theories explain the complexity in terms of having more microRNAs.

II. Development of Neural Crest

1) Type of tissue that forms many new structures in vertebrates, **esp.** in the head region.

2) Most important feature in the origin of the vertebrate body plan.

3) Represents a fourth germ layer which is unique to vertebrates (**quadroblastic**).

4) **Neural crest cells** originate from the **neural plate**, the embryonic structure which makes the nerve cord, and they later migrate throughout the body to form other structures.

5) Similar cell population can be found in the **amphioxus**, but here the cells do not migrate & do not change into different cell types.

6) Neural crest gives rise to the **sensory organs** of vertebrates.

7) **Brain** of vertebrates is larger than the brains of primitive chordates & has three parts: forebrain, midbrain, and hindbrain.

8) Brain of amphioxus is not obviously divided but it may be *homologous* to the vertebrate brain, except for the front part of the forebrain (the **telencephalon**).

2.3 Basic Vertebrate Structure

Table 2.1 & Figure 2-4 contrast the **basic/primitive vertebrate** condition with that of a **non-vertebrate chordate** such as amphioxus.

Aim is to give a general introduction to the basics of vertebrate design.

1) **Larger** & more **active** than non-vertebrate chordates.
2) Have more **specialized systems** that carry out physiological processes at a greater rate.
3) More **developed** head, jaws, and muscular pharynx & bigger brain and more sensory organs.
4) **Mobile** animals that move using muscles & a skeleton.
5) Tough but flexible external **body covering**.
6) **Bone** & other mineralized tissues.

Embryology

1) Shows how systems develop & how adult body function is related to the early stages of life.
2) Vertebrates develop from a single fertilized cell (the **zygote**).
3) Remember that **invertebrates** develop from cell lineages whose fate is predetermined while **vertebrates** are more flexible & use the interaction between cells to form new cells and tissues during their development.

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4) Outermost germ layer (**ectoderm**) forms the adult superficial layers of skin (**epidermis**).
5) Innermost layer (**endoderm**) forms the rest of the digestive tract's lining as well as the lining of glands associated with the gut.
6) Middle layer (**mesoderm**) forms everything else: muscles, skeleton, connective tissues, and circulatory & urogenital systems.
7) Later in development there is a split within the solid mesoderm layer, forming a **coelom**.
8) Coelom is the cavity containing the internal organs & it is divided into:
    1- **pleuroperitoneal cavity** (around the viscera)
    2- **pericardial cavity** (around the heart)
9) These cavities are lined by sheets of mesoderm – **peritoneum** (= **pericardium** around heart).
10) Gut is suspended in the peritoneal cavity by **mesenteries** (sheets of peritoneum).
11) **Neural crest** forms many of the sense organs in the head including some bones and muscles & the peripheral nervous system. Also forms the adrenal glands & pigment cells in the skin.

1) **Figure 2-5** shows a stage in early embryonic development where the ancestral chordate feature of **pharyngeal pouches** is present:

    1- In fish the grooves between the pouches (the **pharyngeal clefts**) perforate to become the gill slits.

    2- Whereas in land vertebrates these clefts disappear in the adult. Lining of pharyngeal pouches give rise to **glands** of the lymphatic system.

2) Dorsal hollow **nerve cord** is formed by infolding and then pinching off & isolation of ectoderm.

3) **Cells** that will form the neural crest arise next to the developing nerve cord.

4) **Figure 2-5:** Embryonic mesoderm becomes divided into three portions:

    1- **Dorsal (upper) part** of the mesoderm, lying above the gut & next to the nerve cord, forms a series of thick-walled segmental buds (**somites**) that extend from head to tail.

    2- **Ventral (lower) part** of the mesoderm, surrounding the gut & containing the coelom, is thin-walled and unsegmented; called the **lateral plate** (hypomere). Small segmental buds linking the somites & the lateral plate are called **nephrotomes**.

5) Segmental somites form the **dermis** of the skin, striated muscles, & portions of the skeleton.

6) Some of these segmental muscles migrate *ventrally* from their *dorsal* (**epaxial**) position to form the layer of striated muscles on the underside of the body (**hypaxial** muscles), and from here they form the muscles of the limbs in **tetrapods** (four-footed land vertebrates).

7) Nervous system also follows this segmented – unsegmented body design.

8) **Lateral plate** forms all the internal, nonsegmented portions of the body, **e.g.** the connective tissue, the blood vascular system, the peritoneum, and the reproductive system. It also forms the smooth muscle of the gut & the **cardiac** (heart) muscle.

9) Nephrotomes form the **kidneys** – elongated segmental structures in the primitive vertebrates.

Exceptions to *segmented vs. nonsegmented* division of vertebrate body:

1- **Locomotory muscles** derived from the somites but limb bones are derived from lateral plate.

2- Another strange feature is found in the head of vertebrates which does not follow the simple segmentation of the body. The head **mesoderm** contains only somites & no lateral plate. The somites give rise to the eye muscles.

3- Within the **brain**, the anteriormost part of forebrain & midbrain are *not segmented,* but the rest of the forebrain & hindbrain show *segmentation* during development.

Adult Tissue Types

Five kinds of tissue in vertebrates:

1- Epithelial
2- Connective
3- Vascular (i.e. blood)
4- Muscular
5- Nervous

1) Fundamental component of most animal tissues is the fibrous protein **collagen** (mesodermal tissue) that forms:
   i. **Soft** tissues of organs
   ii. **Organic** matrix of bone
   iii. **Tough** tissue of tendons & ligaments
2) Vertebrates have a unique type of **fibrillar collagen**.
3) Collagen is stiff & does not stretch easily.
4) Collagen can be combined with the protein **elastin** which can stretch & recoil.
5) Another important fibrous protein, seen only in vertebrates, is called **keratin**, which is an **ectodermal tissue** that forms structures such as hair, scales, feathers, claws, beaks, etc.

The Integument

- External covering of vertebrates is a single organ, making up around 15–20% of the body weight. It includes the **skin** & its derivatives, **e.g.** glands, scales, and hair.
- Skin protects the body & receives stimuli.

Major Divisions of Vertebrate Skin:

1) **Epidermis** (superficial cell layer derived from embryonic ectoderm).
2) **Dermis** (unique to vertebrates; main structural layer; mesodermal & neural crest origin).
3) The dermis extends deeper into a subcutaneous tissue (**hypodermis**).

1) **Epidermis** contains secretory glands; may play important role in osmotic & volume regulation
2) **Dermis** contains collagen fibres that help to maintain its strength & shape. It contains blood vessels which are under neural & hormonal control. Also contains pigment cells (**melanocytes**) & smooth muscle fibers, & houses sensory structures & nerves in **tetrapods**.

3) **Hypodermis** contains collagenous & elastic fibers; fat-storage area in birds & mammals.

Mineralized Tissues

1) Vertebrates have a unique type of mineral called **hydroxyapatite** (calcium & phosphorous) which is resistant to acidity of the blood during anaerobic metabolism.
2) Six types of tissues (**enamel**, **dentine**, **bone**, **cartilage**, **enameloid**, and **cementum**) can be **mineralized** in vertebrates, each formed from a different cell lineage in development. Most of these are found in the mineralized condition in the adult except the cartilage.
3) **Bone** is a mineralized tissue of internal skeleton of bony fishes & tetrapods. Bones may replace cartilage in development. Bone is composed of different types of cells – **osteocytes**, which are called **osteoblasts** while they are making the bone. **Chondrocytes** form cartilage.
4) Cells that form **bone & cartilage cells** are derived from the **mesoderm** except in the region of the front of the **head** where they are derived from neural crest tissue. **Odontoblasts** that form dentine are derived from neural crest tissue. **Amyloblasts** that form enamel are derived from the ectoderm.
5) **Enamel** & **dentine** are the most mineralised tissues (99% & 90% mineral resp.), & are found in teeth of living vertebrates & in the dermal skeleton (exoskeleton) of some primitive fishes.
6) **Enameloid** is a type of vertebrate hard tissue seen in fishes.
7) **Cementum** is a type of hard tissue; bonelike substance.
8) Bone is highly vascularised. Old bone is eaten away by specialised blood cells (**osteoclasts**). New bone is formed by **steoblasts**.
9) Two types of bone in vertebrates:
    a) **Dermal bone:** formed in the skin; primitive type of vertebrate bone first seen in the fossil jawless vertebrates (**ostracoderms**).
    b) **Endochondral bone:** formed inside cartilage.
10) **Figure 2-6 (a):** Organisation of vertebrate mineralised tissue.
11) Only in the bony fishes & tetrapods is the endoskeleton composed primarily of bone.
12) Most of our skull bones are dermal bones, forming a shell around our brains.

Teeth form from **dermal papillae**, & so form only in the skin, over dermal bones. Teeth are composed of an inner layer of dentine & an outer layer of enamel or enameloid around a central pulp cavity. **Sharks scales** have a similar structure.

The Skeletomuscular System

- ❖ **Notochord** is the basic endoskeletal structure of chordates.
- ❖ Vertebrates initially added the **cranium** surrounding the brain. Later vertebrates added the **dermal** skeleton & **axial** skeleton (vertebrae, ribs, & median fin supports), and later ones still added the **appendicular** skeleton (bones of the limb skeleton & limb girdles).

The Cranial Skeleton & Musculature

1) Skull, or cranium, is formed by three basic components:

1- **Chondrocranium,** surrounding the brain.

2- **Splanchnocranium,** forming the gill supports. Also known as gill arches.

3- **Dermatocranium,** forming in skin as outer cover, not seen in earliest vertebrates.

2) In all vertebrates, the anterior elements of the **splanchnocranium** are specialized into nongill-bearing structures such as the jaws of gnathostomes (known as **pharyngeal arches**) or **branchial arches** and another name for the similar structure is **visceral arches**. Another term used for the blood vessels associated with the gills is **aortic arches**.

3) **Chondrocranium** & **splanchnocranium** are formed from neural crest tissue. Splanchnocranium is present in cephalochordates & hemichordates.

4) **Dermatocranium** is made from dermal bone (**membrane bone**) formed *in the membrane* & not by cartilage.

5) **Figures 2-8 and 2-9** show the form & early evolution of the cranium of vertebrates.

Muscles of the head of vertebrates

- Two types of **striated muscles** in the head:

1) Extrinsic eye muscles

2) Branchiomeric muscles.

- ❖ **Six muscles** (seven in lampreys) in each eye rotate the eyeball in all vertebrates except hagfishes. These muscles are innervated by somatic motor nerves.

- **Branchiomeric muscles** are used to suck water into the mouth during feeding & respiration. Branchiomeric muscles are innervated by nerves from the brain that exit dorsally.

The Axial Skeleton & Musculature

1) Notochord is the main axial support of all chordates.
2) It is made up of large, closely spaced cells with fluid filled **vacuoles**.
3) Notochord is wrapped in a **fibrous sheath** that is the site of attachment for segmental muscles & connective tissues.
4) In all vertebrates, the notochord extends from the **pituitary gland** to the tip of the tail.
5) Original form of notochord is lost in adult tetrapods but portions remain as intervertebral discs.
6) **Axial muscles** are made up of folded myomeres.
7) **Figure 2-10:** Chordate body muscles (myomeres)
8) Sequential muscle blocks overlap & produces **undulation movement**.
9) In amphioxus, myomeres have simple **V shape** whereas in vertebrates they have a **W shape**.
10) Myomeres of jawed vertebrates are divided into **epaxial** (dorsal) and **hypaxial** (ventral) portions by a sheet of fibrous tissue (the **horizontal septum**).
11) **Segmental axial muscle** is clearly visible in fishes as zigzag blocks, each block representing a myomere. It is less clear in tetrapods.

Locomotion

1) Many small aquatic animals, especially larval forms, move by using **cilia**. Larger chordates use the serial contraction of **segmental muscle bands**.
2) Notochord **stiffens** the body so it **bends** from side to side as the muscles contract. Most fishes use this type of locomotion.
3) The paired fins of jawed fishes are used for **steering**, **braking**, and **providing lift**, but not for propulsion except in few fishes.

Energy Acquisition & Support of Metabolism

Feeding & Digestion

1) Feeding includes getting food into the **oral chamber** (the mouth), **oral** or **pharyngeal processing** (generally chewing), and **swallowing**.
2) Digestion includes the breakdown of complex compounds into small molecules that are absorbed across the gut wall.

3) Vertebrate ancestors used **filter** type of feeding from water, as **amphioxus** and **larval lampreys** still do. Most vertebrates are **particulate feeders**; take in food as bite-size pieces.

4) They have a *larger* **gut volume** than amphioxus & **gut muscles** that move food by peristalsis.

5) Vertebrates digest food by secreting **digestive enzymes** produced by the liver & pancreas into the gut, while amphioxus digests food within the gut cells themselves.

6) **Pancreas** also secretes the hormone **insulin** which regulates blood sugar levels.

7) In primitive vertebrates (amphioxus) there is no stomach, no division of the intestine into small & large portions, and no distinct rectum.

8) Intestine opens to the **cloaca**, a common opening for urinary, reproductive, & digestive systems.

Respiration & Ventilation

1) Ancestral chordates relied on simple oxygen & CO_2 diffusion across a thin skin (**cutaneous respiration**) as in amphioxus.

2) Cutaneous respiration is important for many vertebrates (e.g. **modern amphibians**). But larger body sizes require a complex system for obtaining oxygen

3) **Gills** are effective in water, whereas **lungs** work better in air. Both structures have large (*increase the*) surface areas for respiration.

Cardiovascular System

Blood is important because it carries **respiratory gases**, **nutrients**, **metabolites**, & **waste products** to and from the cells. Blood stabilises the internal environment & carries hormones

1) Blood is composed of **liquid plasma**, **erythrocytes**, and **leucocytes**. **Thrombocytes** are present in all vertebrates except mammals, which have platelets.

2) Blood flows in a **closed** circulatory system; arteries & veins are connected by capillaries.

3) Arteries carry blood **away** from the heart, and veins return blood **to** the heart.

   Figure 2-11: Diagrammatic plan of vertebrate cardiovascular circuit.

4) **Blood pressure** is higher in the arteries which have thicker walls.

5) Capillaries are sites of (gas, nutrient, and waste product) **exchange** between blood & tissues.

6) Capillaries form **dense beds** in metabolically active tissues. Blood flow through capillary beds is regulated by **precapillary sphincter muscles**.

7) Arterioles and venules can be connected directly by **anastomoses**.

8) When **metabolic activity** of a tissue increases (**e.g.** when a muscle becomes active), waste products stimulate precapillary sphincters to **dilate**, increasing blood flow to that tissue.

9) Blood vessels that lie between two capillary beds are called **portal vessels** such as the **hepatic portal vein**.

10) Absorbed substances are transported to the **liver** for detoxification, and some nutrients are processed.

11) Most vertebrates also have a **renal portal vein** between the trunk and kidneys. The renal portal system is not well developed in jawless vertebrates & has been lost in mammals.

Vertebrate Heart

1) Vertebrate heart is a muscular tube folded on itself & is primitively constricted into three sequential chambers: **sinus venosus**, **atrium**, and **ventricle**.

2) **Sinus venosus** is a thin-walled sac with few cardiac muscle fibers. It is filled by pressure in the veins, aided by **pulsatile** reductions in pressure in the **pericardial cavity** surrounding the heart as the heart beats.

3) **Suction** produced by muscular contraction draws blood **anteriorly** into the atrium, which has valves at each end that prevent backflow.

4) **Ventricle** is thick-walled, and the muscular walls have an **intrinsic pulsatile rhythm** (*except in hagfishes*) which can be speeded up or slowed down by the nervous system.

5) Contraction of the ventricle forces the blood into the **ventral aorta**.

6) Mammals no longer have a distinct structure identifiable as the sinus venosus; it is incorporated into the right atrium wall as the **sinoatrial node** that controls the heartbeat.

7) Basic vertebrate **circulatory plan** consists of a heart that pumps blood into the **ventral aorta**.

Figure 2-12: The form and early evolution of the heart & aortic arches of vertebrates.

8) Around six **aortic arches** supply each side of the head & branch from the ventral aorta. This is the same as in fishes where the aortic arches lead to the gills for oxygenation.

9) **Dorsal aorta** is paired above the gills, and the anterior portions run forward to the head as the **carotid arteries**. Behind the gills, the two vessels unite into a **single** dorsal aorta that carries blood posteriorly.

10) Dorsal aorta is flanked by paired **cardinal veins** that return blood to the heart.

11) **Anterior cardinal veins** (the **jugular veins**) draining the head & **posterior cardinal veins** draining the body unite on each side in a common cardinal vein that enters the atrium.

12) In the lungfishes and tetrapods, the posterior cardinal vein is replaced by a single vessel called the posterior vena cava (*new edition*).

13) Blood is also returned separately to the heart from the gut & liver via **hepatic portal system**.

Excretory & Reproductive Systems

1) E&R systems are formed from the **nephrotome** or **intermediate mesoderm**, which forms the **embryonic nephric ridge** (**Figure 2-12**).

2) **Kidneys** are segmental whereas the **gonads** are unsegmented.

3) Gonads derived from mesoderm but gametes in the endoderm then travel to the gonads.

See Figure 2-5

4) **Archinephric duct** drains urine from kidney to cloaca & from there to the outside world.

5) In jawed vertebrates this duct is also used for the release of **sperm** by the testes.

6) Kidneys dispose of **nitrogenous waste** & regulate water and minerals – especially sodium, chloride, calcium, magnesium, potassium, bicarbonate, & phosphate.

7) In **tetrapods** the kidneys are responsible for all these functions, but in fishes and amphibians the gills and skin help as well.

Kidney of Fishes

1) Kidney of **fishes** is a long, segmental structure along the entire length of the dorsal body wall.

2) In all vertebrate embryos, the kidney is composed of three portions: **pronephros, mesonephros, and metanephros** (**Figure 2-13**).

3) Pronephros is functional only in **embryos** of living vertebrates & possibly in **adult hagfishes**.

4) **Opisthonephric kidney** of adult fishes & amphibians includes mesonephros & metanephros.

5) Bean-shaped **metanephric kidney** seen in adult amniotes includes only the metanephros, drained by a new tube, the **ureter**.

Ultrafiltration

1) Basic units of kidney are microscopic structures called **nephrons**.

2) Vertebrate kidneys work by **ultrafiltration**: High blood pressure forces water, ions, & molecules through gaps in capillary walls.

3) Non-vertebrate chordates lack true kidneys.

4) Amphioxus has excretory cells **(solenocytes)** associated with the pharyngeal blood vessels that empty into the atrium, and waste is discharged via the **atriopore**.

5) Solenocytes of amphioxus may be homologous with the **podocytes** of vertebrate nephron.

Reproduction

1) Reproduction is the means by which **gametes** are produced, released, and combined with opposite sex cells to produce a fertilised zygote.
2) Vertebrates usually have two sexes although **unisexual species** occur among fishes, amphibians, and lizards.
3) **Gonads** are paired & usually lie on the posterior body wall, behind the **peritoneum**.
4) It is only among mammals that the **testes** are found outside the body in a **scrotum**.
5) Ovaries contain large primary sex cells (**follicles**). As they mature, the follicular cell layer becomes larger, nurturing the developing egg (**ovum**), stimulating yolk development in the egg, and producing the hormone **estrogen**.
6) When the eggs **mature**, the follicle ruptures, releasing the completed egg (**ovulation**).
7) **Testes** are composed of **seminiferous tubules** where sperm develop, and are nourished by the supporting or **Sertoli cells**. Testes also produce the hormone **testosterone**.

Reproduction – primitive vs. jawed vertebrates

1) In primitive vertebrates, there is *no special tube or duct* for the passage of gametes. Instead, the sperm or eggs erupt from the gonad & move through the **coelom** to pores that open to the base of the **archinephric ducts**.
2) In jawed vertebrates (fish), however, the gametes are transported to the **cloaca** via specialized, paired ducts from each gonad.
    - In **males**, sperm are released directly into the archinephric ducts that drain the kidneys in **non–amniotes** & **embryonic amniotes**.
    - In **females**, egg is still released into **coelom**, but is then transported via the **oviduct.**
3) Oviducts produce **egg yolk** and **shell**; oviducts can enlarge to form **uterus** or paired **uteri** in which eggs are stored or young develop.
4) Vertebrates may **deposit** eggs that develop outside the body or **retain** the eggs within the mother's body until embryonic development is complete.
5) **Shelled eggs** must be fertilised in the oviduct before the shell and albumen are deposited.
6) **Oviparous** (vertebrates that lay shelled eggs) & **viviparous** vertebrates must have an organ by which sperm are inserted into female's reproductive tract.

Coordination & Integration

- Nervous & endocrine systems respond to conditions inside & outside an animal.
- Together, they control the actions of organs & muscles.

General Features of the Nervous System

Neurons (individual cells) are basic units of nervous system:

1) In jawed vertebrates, neuron axons (*extensions*) are encased in a fatty insulating coat (**myelin sheath**) which increases the conduction velocity of the nerve impulse.

Figure 2-14: Generalised vertebrate neurons.

2) Collections of axons in the peripheral nervous system (**PNS** = in the body) are called **nerves**; within central nervous system (**CNS** = within the brain & nerve cord) they are called **tracts**.

3) Group of **cell bodies** (portion of nerve cell that contains the nucleus) in the PNS = **ganglion**.

4) Neurons communicate with other neurons via short processes called **dendrites.**

5) **Nerve cord** (= spinal cord) is composed of a hollow tube with the cell bodies (grey matter) on the inside & the myelin–covered axons (white matter) on the outside.

6) Nerves of PNS are segmentally arranged, exiting from the spinal cord between the vertebrae.

7) Spinal cord receives **sensory inputs**, integrates them with CNS, and sends **impulses** that cause muscles to contract.

8) Vertebrates are unique among animals in having a dual type of nervous system:

1. **Somatic** nervous system (**voluntary** NS)
2. **Visceral** nervous system (**involuntary** NS)

9) **Somatic nervous system** innervates structures derived from the segmented portion (the somite) of the mesoderm such as limb muscles.

10) **Visceral nervous system** innervates the smooth & cardiac muscles that we cannot move consciously e.g. the gut and heart muscles.

11) **Each spinal nerve complex is made up of four types of fibers:**

1- **Somatic motor fibers** to the body.

2- **Somatic sensory fibers** from the body wall.

3- **Visceral motor fibers** to the muscles and glands of the gut & to blood vessels.

4- **Visceral sensory fibers** from the gut wall & blood vessels.

12) Motor portion of visceral nervous system is called **autonomic nervous system**. In mammals, this system becomes divided into two: **sympathetic** nervous system (*to speed things up*) & **parasympathetic** nervous system (*to slow things down*).

13) Vertebrates also have cranial nerves that emerge directly from the brain (cranial nerves). These are 10 pairs in primitive vertebrates and 12 paires in the amniotes. Some of these nerves such as the olfactory nerve I and the optic nerve II are not true nerves. They are outgrowths of the brain.

14) Cranial nerves emerge directly from the brain.

1. 10 pairs in **primitive** vertebrates
2. 12 pairs in **amniotes**
3. Some of these nerves (**e.g.** the **olfactory nerve, I** & the **optic nerve, II**) are not true nerves, but outgrowths of the brain.

15) Vagus nerve (cranial nerve X) extends through all but the most posterior part of the trunk, carrying the **visceral motor fibers** to the organs. Vagus nerve is independent of spinal cord.

Brain Anatomy & Evolution

- All chordates have a brain as a thickening of the front end of the notochord (*new edition*).
- Brain of all vertebrates is a tripartite (three-part) structure.

Figure 2-15: The vertebrate brain

1) **Telencephalon** (front part of forebrain) & olfactory receptors are new features of vertebrates.

2) In the most primitive condition, **forebrain** is associated with sense of smell, the **midbrain** with vision, and **hindbrain** with balance and detection of vibrations (i.e. hearing). These portions of the brain are associated with the **nasal**, **optic**, and **otic** capsules of the **chondrocranium**, respectively (see **Figure 2-8**).

3) **Hindbrain** has two portions:

- Posterior – **myelencephalon** (or medulla oblongata); controls functions such as respiration and acts as a relay station for receptor cells from inner ear.
- Anterior – **metencephalon** develops the **cerebellum** only in jawed vertebrates.

4) Cerebellum controls motor activities.

5) **Midbrain** develops in conjunction with the eyes & receives input from the **optic nerve**.

6) **Forebrain** also has two parts: the posterior part is **diencephalon**. The **pituitary gland** is a ventral outgrowth of the diencephalon. The floor of diencephalon (the **hypothalamus)** & the

pituitary gland form the primary center for neural–hormonal coordination and integration. Another endocrine gland, the **pineal organ**, is a dorsal outgrowth of the diencephalon. Its original function may have been photoreception. Many early tetrapods had a hole in the skull over the pineal gland to admit **light** (still seen in some reptiles).

7) Anterior region of adult forebrain, the **telencephalon**, develops in association with the **olfactory capsules**. In different vertebrates, the telencephalon enlarges to form **cerebrum**. Tetrapods develop an area in the cerebrum called **neocortex** which becomes a site for sensory integration.

8) **Bony fishes** also evolved a larger, more complex **telencephalon** but by a different way. Sharks & hagfishes have also independently evolved large forebrains, although a large **cerebrum** is primarily a feature of tetrapods (birds and mammals in *new edition*).

The Sense Organs

1) Water and air have very different physical properties, and the **sensory systems** of aquatic & terrestrial vertebrates are correspondingly different.

2) The senses of **smell** and **taste** involve detection of dissolved molecules by specialized receptors. These two senses are interlinked but innervated in different ways.

3) Smell is a **somatic sensory system** – sensing items at a distance, with the sensations being received in the **forebrain**. Taste is a **visceral sensory system** – sensing items on direct contact, with the sensations being received initially in the **hindbrain**.

4) Vertebrate eye receptor originates from the brain. The **retina** is an outgrowth of the brain & contains two types of light–sensitive cells, **cones** and **rods**, which differ in their morphology, photo-chemistry, and neural connections.

5) **Electroreception** is the *capacity to perceive electrical impulses generated by the muscles of other organisms*; form of distance reception. Seen today in fishes.

6) **Inner ear** originally detected an animal's position in space, and it retains that function today in both aquatic & terrestrial vertebrates. Also used for hearing in tetrapods and some fishes.

7) Basic sensory cell in the inner ear is the **hair cell**, which detects the movement of fluid resulting from a **change of position** or the **impact of sound waves**.

8) Hair cells aggregate into **neuromast organs** which detect water movement around the body.

9) Inner ear contains the **vestibular apparatus** which includes the organs of balance and, in tetrapods only, the **cochlea** (organ of hearing). Vestibular apparatus is enclosed within the **otic capsule** of the skull, and contains a fluid called **endolymph.**

10) Lower parts of vestibular apparatus, the **sacculus** and **utriculus**, house sensory organs called **maculae**, which contain tiny crystals of calcium carbonate on hair cells. Sensations from the macculae tell the animal which way is up & detect **linear acceleration**.

11) Upper part of vestibular apparatus contains **semicircular canals**. Sensory areas at the end of each canal (**ampullae**) detect angular acceleration through **cristae**, hair cells embedded in a jellylike substance.

12) **Jawed vertebrates** have three semicircular canals on each side of the head. **Hagfishes** have one, and **lampreys** have two.

Figure 2-16: Design of the vestibular apparatus in fishes.

The Endocrine System

1) Transfers information from one part of the body to another via the release of **hormones**.

2) Hormones are produced in **endocrine glands e.g.** the pituitary, thyroid, thymus, & adrenals, and by **organs** such as the gonads, kidneys, and gastrointestinal tract.

3) Endocrine system regulates energy use, storage, and release.

The Immune System (new edition)

1) **Vertebrate** immune system is different from **invertebrates**; it is adaptive.

2) While all animals have innate responses to pathogens, vertebrates have additionally lymphocytes (antigen recognition).

3) Immune system is different in **jawless** & **jawed** vertebrates. Gnathostomes have lymphocytes; lampreys and hagfishes have **leucine-rich** repeat molecules and they lack a thymus gland which produces lymphocytes.