Veterinary Bioscience: Cardiovascular System

WEEK 1 – STRUCTURE/FUNCTION RELATIONSHIPS IN THE HEART

LECTURER: DR LAURA DOOLEY

Laura graduated as a veterinarian from the University of Melbourne in 2007. She then worked in small animal private veterinary practice in Australia and the United Kingdom for 7 years. She subsequently completed her PhD in cardiovascular pharmacology, and a Graduate Certificate in University Teaching at the University of Melbourne. She is now a Senior Lecturer at the Melbourne Veterinary School, and teaches into the Bachelor of Science program as well as the first and second years of the Doctor of Veterinary Medicine program. She engages in educational research, and has a special interest in student support, curriculum development, and collaborative learning.

Email: laura.dooley@unimelb.edu.au

INTENDED LEARNING OUTCOMES

At the end of this lecture you should be able to:

- Describe the principal functions of a circulatory system and appreciate how the various components of such a system are structured to fulfil these functions
- Describe the organisation of the dual circulatory system in the adult mammal
- Explain the factors that determine the movement of solutes and fluid across capillary walls
- Understand the basic flow equations that describe the movement of blood through the vascular system
- Understand the basic structural and functional characteristics of the heart.

KEYWORDS

Cardiovascular system, circulation, interstitial fluid, oxygen transport, heart, blood vessels, vascular resistance, flow equation, total peripheral resistance, bulk flow, Starling's hypothesis, fluid filtration, reabsorption, systole, diastole.

LECTURE 1 – WHY HAVE A CARDIOVASCULAR SYSTEM?

INTRODUCTION

The primary function of the cardiovascular system is to facilitate rapid transport of critical molecules such as oxygen and glucose to body cells, and to remove waste products such as carbon dioxide and urea. All cells must exchange materials with their environment in order to achieve homeostasis, a fundamental requirement for maintenance of life. This body system also plays a role in control of body processes through the transport of hormones, and in thermoregulation by regulating the distribution of heat from the body core to the periphery.

The main components of the cardiovascular system are:

- **Muscular heart** - a pump that contracts and propels blood around the body
- **Arterial system** - conveys blood from the heart to the capillaries
- **Venous system** -conducts blood from the capillaries back to the heart
- **Microcirculation** – the site of exchange

The **cardiovascular system** requires a pump and tubes to circulate fluid in the body. The heart rhythmically contracts to pump blood into large arteries. Large arteries split into branches with smaller diameters and thinner walls than the parent vessel, but with every branching, the total diameter of the resulting vessels increases.

BODY FLUID COMPARTMENTS AND MOVEMENT ACROSS CAPILLARY WALLS

The body fluids are located in two main compartments; the intracellular fluid (approx. 2/3 of total body water) and the extracellular compartment (approx. 1/3 of total body water) (See 'Cells to Systems' Lecture 7 for more detail). The extracellular fluid compartment is the link between the external environment and the intracellular fluid compartment. The extracellular fluid compartment includes the blood plasma circulating within the cardiovascular system (approx. ¼ of extracellular fluid), and the interstitial fluid surrounding cells.

Most substances cross capillary walls by passive diffusion. Five factors determine diffusion rate: (i) concentration difference, (ii) surface area for exchange, (iii) diffusion distance, (iv) molecular weight of the substance and (v) permeability of the wall to the diffusing substance. The distance factor is very important, hence capillaries are designed to facilitate rapid diffusion by having a very thin wall, and a large cross-sectional area (located as close as possible to every cell in the body).

TRANSCAPILLARY FLUID MOVEMENT

Water filled channels permit fluid flow through the capillary wall. This is called **bulk flow** because various constituents move together in bulk, not as discrete diffusion of individual solutes. Fluid is constantly moving into and out of capillaries – the net fluid movement out of capillaries is referred to as **filtration**, and net fluid movement into capillaries is called **reabsorption**.

Net flow occurs because of differences between the hydrostatic and colloid osmotic pressure between plasma and interstitial fluid. Four forces influence fluid movement across the capillary wall:

- capillary blood pressure (P_c)
- plasma colloid osmotic pressure (oncotic pressure; πp)
- interstitial fluid hydrostatic pressure (P_{IF})
- interstitial fluid colloid osmotic pressure (π_{IF})

The net fluid movement at a given point across a capillary wall is given by **Starling's hypothesis**, using the equation:

$$Net\ exchange\ pressure = outward\ pressure - inward\ pressure$$
$$= [P_c + \pi_{IF}] - [\pi_p + P_{IF}]$$

Capillary blood pressure gradually decreases along the length of the capillary, so the amount of fluid filtered out decreases in the first half of the capillary length, and then increasing amounts are reabsorbed in the second half. There is a slight predominance of filtration over reabsorption overall, so not all of the fluid volume leaving the capillaries into the interstitial fluid returns directly to the capillaries. The remainder must be returned via the lymphatic system. The volume of fluid transported through the lymphatics in 24 h is approximately equal to the animal's total plasma volume. Fluid and protein enters porous blind-ending lymphatic capillaries and flow into larger lymphatic vessels back to the heart.

MAKING BLOOD FLOW

Flow of liquid through a tube occurs when there is a pressure difference between inlet and outlet ends of a tube. **Pressure difference** is the driving force for the flow. Because friction develops between moving fluid and the stationary walls of the tube, vessels tend to resist fluid movement in them. **Vascular resistance** is a measure of how difficult it is to make blood flow through a tube, i.e. the pressure required to move a given volume over a certain period of time.

THIS IS THE BASIC FLOW EQUATION:

$$Flow = \frac{Pressure\ Difference}{Resistance}$$

Or:

$$Q = \frac{\Delta P}{R}$$

Where Q = flow rate (volume/time); ΔP = Pressure difference (mmHg); and R = resistance (mmHg x time/vol)

Therefore, there are only two ways that blood flow through any organ can be changed: by changing the pressure difference across its vascular bed or by changing its vascular resistance.

DETERMINANTS OF RESISTANCE

Poiseuille's Law states that:

$$Resistance\ to\ flow\ in\ a\ tube = \frac{8\ \times viscosity\ (V) \times length\ of\ tube\ (L)}{\pi \times internal\ radius\ (r)^4\ of\ tube}$$

Combining these in the basic flow equation:

$$Flow\ rate\ (Q) = \frac{\Delta P \pi r^4}{8LV}$$

Therefore, blood flow depends on:

- **Pressure difference** – gradient of pressure across the vessels
- **Total peripheral resistance** – small changes in internal radius have a powerful effect on flow. When the radius (or diameter) of a blood vessel doubles, the flow increases by 16 fold! (r^4).
- **Viscosity** – this is not a variable that is easily changed, but it may influence vascular resistance.

NETWORKS OF VESSELS

Vessels in series: Considering the cardiovascular system as a whole, different types and sizes of vessels are arranged sequentially, in series. In a closed system, blood flow (volume per unit time) must be equal in each segment. However, pressure will decrease along the network, with a portion of the overall pressure drop occurring within each component element. The largest portion of the overall pressure drop will occur in the part having the greatest resistance to flow. This occurs in the arterioles (tiny arteries feeding into the capillary beds).

Vessels in parallel: Since each organ or region of the body has its own arteries (branching off the aorta), vascular beds are therefore arranged in parallel. This also applies within each organ vascular bed as well – i.e. capillary beds have many individual capillary vessels arranged in parallel.

Ohm's Law defines resistance for parallel networks as:

$$\frac{1}{Rp} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots etc$$

Therefore, total flow:

$$(Q\ total) = \frac{\Delta P}{R_p}$$

This means that the overall resistance for any parallel network will always be less than the resistance of any of the elements of the network. Also, blood flow to a particular organ can be altered (by adjusting the resistance of the arterioles) without greatly affecting pressures and flows in other organs.

THE PUMPING SYSTEM

The pumping action of the **heart** as it contracts maintains the pressure difference that enables blood flow to occur. The mammalian heart is a double pump - the left and right sides of the heart function as pumps "in series" for separate circulations (the **dual circulation**):

a) Systemic Circulation - high pressure/high resistance
b) Pulmonary Circulation - low pressure/low resistance

Each pump consists of a **ventricle** – a closed chamber surrounded by a thick muscle wall. It has valves designed to allow flow in only one direction. Contraction of cardiac muscle increases the pressure within the ventricle, causing the blood to flow from the heart to the blood vessels – this is called **systole**. When the ventricular muscle relaxes, pressure within the ventricle falls below that in the atrium, the AV valve opens and the ventricle fills with blood. This is called **diastole**.

Three features of the heart are very important for effective functioning: conductivity, contractility and autorhythmicity. These features are a characteristic of all cardiac muscle cells. However, the coordination of activity of all cardiac muscle cells is possible because these cells are electrically connected by gap junctions, and also muscle cells in certain areas are specifically adapted to control the frequency of excitation, pathway of conduction and rate of impulse propagation through various parts of the heart.

With thanks to Prof Liz Tudor for drafting these notes

FURTHER READING

Aaronson PI & Ward JPT, The Cardiovascular System at a Glance 4th Edition. 2014. Ch's 9-12

Berne RM & Levy MN, Cardiovascular Physiology, 6th Edition, 2008

Mohrman DE & Heller, Cardiovascular Physiology. McGraw Hill 9th Edition, 2018. **eBook available in unimelb library**.
Sherwood, L, Human Physiology from Cells to Systems, 8th Edition 2013.

Rhoades RA & Bell DR Medical Physiology: Principles for Clinical Medicine 5th Edition 2017 Klein BG, Cunningham's Textbook of Veterinary Physiology, Elsevier 6th edition 2020.

Sjaastad OV, Sand O & Hove K, *Physiology of Domestic Animals*, 2nd Edition, 2010.