Physiology of the normal heart

David EL Wilcken

Abstract

The mechanical events of the cardiac cycle provide the circulation with normal cardiac output and blood pressure. This requires an appropriate venous return, regulation of outflow resistance, a normal myocardial contractile state and heart rate control, together with an adequate supply of oxygenated blood via the coronary circulation. Other neural influences contribute to cardiac regulation, including natriuretic peptides and the renin–angiotensin system. The atria and ventricles are richly supplied with adrenergic nerves that may augment cardiac function, particularly with increased cardiac output during exercise. Inhibitory vagal fibres are largely confined to the sinus and atrioventricular nodes. Exercise causes increased sympathetic outflow, with a decrease in peripheral vascular resistance, and increased cardiac output, heart rate, systolic blood pressure and venous return. Regular rhythmic exercise has a training effect, which enhances cardiac performance. This is important for the maintenance of many aspects of cardiovascular health.

Keywords Asymmetric dimethylarginine; cardiac cycle; cardiac output; Frank–Starling; inotropic effect; nitric oxide synthase; outflow resistance; renin–angiotensin; venous return

The normally functioning heart provides sufficient oxygenated blood containing nutrients, metabolites and hormones to meet moment-by-moment metabolic needs and preserve a constant internal milieu. Its two essential characteristics are contractility and rhythmicity. In the regulation of these, the nervous system and neurohumoral effects modulate relationships between venous return, outflow resistance, frequency of contraction and inotropic state. There are also intrinsic cardiac autoregulatory mechanisms.

The cardiac cycle

Electrical events

Figure 1 shows the impulse-generating and impulse-conducting system of the normal heart. The cardiac cycle begins with depolarization of the sinoatrial node in the upper right atrium and spread of the action potential through the atria, resulting in atrial systole. Conduction of the electrical impulse from atrium to ventricle is permitted only through the specialized cells of the atrioventricular (AV) node. This slow conductance delays activation of the bundle of His, allowing completion of ventricular filling, and passes on via the right and left bundle branches, producing an orderly sequence of ventricular contraction. The ECG records the summation of the spread of these electrical potentials.

The specialized cells of the sinoatrial node, the AV node and Purkinje tissue have an inherent rhythmicity and depolarize spontaneously. The sinoatrial node, with the fastest inherent depolarization rate, normally determines heart rate. Without this, the AV node, bundle of His or Purkinje system assumes this role, but the resulting heart rate is considerably slower.

Mechanical events

After the P wave of the ECG (and coinciding with atrial systole), 'a' waves appear in pressure tracings. Atrial contraction increases ventricular filling by about 10%. The onset of ventricular contraction coincides with the R wave, and the rapid increase in intraventricular pressure closes the mitral and tricuspid valves, producing the first heart sound. When ventricular pressures exceed those in the pulmonary artery and aorta, the outflow valves open and ventricular ejection follows. As ventricular contraction declines, the aortic and pulmonary valves close, coinciding with the end of the T wave of the ECG and the dicrotic notch seen in both pressure tracings. Aortic closure slightly precedes pulmonary closure, resulting in the two components of the second heart sound. A third heart sound, coinciding with early rapid diastolic filling, is usually audible in children and young adults.

Normal volumes, pressures and flows

The blood volume in adults is about 5 litres (haematocrit 45%), of which 1.5 litres are in the heart and lungs (the central blood volume), 0.9 litres in the pulmonary arteries, capillaries and veins, and 75 ml in the pulmonary capillaries. About 0.6 litres of blood are in the heart; the left ventricular (LV) end-diastolic volume (EDV) constitutes about 140 ml, the stroke volume (SV) about 90 ml and the ejection fraction (SV/EDV) about 70% for each ventricle. The normal resting values for pressures in the heart and great vessels (measured with reference to the zero pressure, arbitrarily set at 5 cm below the sternal angle with the patient recumbent) are shown in Table 1. Cardiac output (stroke volume × heart rate) is related to body size and is expressed in litres/minute/m^2 body surface area (the 'cardiac index'). The mean cardiac index under relaxed resting conditions is 3.5 litres/minute/m^2 (values below 2 and above 5 are abnormal). In normal subjects, the arteriovenous difference for oxygen at rest is maintained within narrow limits (35–45 ml/litre, values of 55 ml/litre or more are always abnormal). Estimated pulmonary or systemic vascular resistance is the difference between the mean inflow and outflow pressures in mmHg, divided by flow in litres/minute. In normal subjects, this flow is the cardiac output. Stroke work is usually estimated as the product of stroke volume and mean ejection pressure. Normal LV work at rest is about 6 kg/m^2/minute.

Regulation of cardiac function

Four essential factors determine the performance of the heart:

- venous return (preload)
- outflow resistance (afterload)
- inotropic state (or contractility)
- heart rate.

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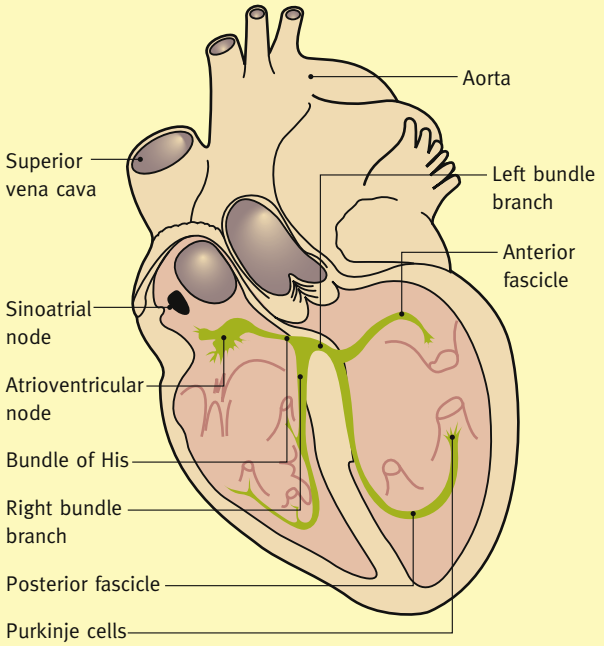
Impulse-generating and impulse-conducting systems of the heart



Source: Junqueira L C, Carneiro J, Kelley R O. *Basic Histology*. 9th ed. Stamford: Appleton and Lange, 1998 with permission.

Figure 1

Mechanisms altering these factors modulate cardiac performance.

Venous return, preload and the Frank–Starling relationship

The relationship between end-diastolic fibre length and force of contraction was described independently by Frank–Starling (Figure 2). When the ventricle contracts against a constant pressure, the degree of stretch of the muscle fibres in diastole (resulting from variations in venous return) determines contraction strength and work output. Within limits, force of contraction and stroke work are positively related to end-diastolic fibre length. For clinical purposes, venous return can be equated with preload – as this changes from beat to beat it adjusts the strength of the subsequent contraction by varying the force stretching the relaxed cardiac muscle and altering end-diastolic fibre length.

The contractile response of the heart at any particular time depends on:

- the intrinsic state of the muscle
- the prevailing neurohumoral state (increased sympathetic outflow produces a more forceful contraction at any end-diastolic fibre length and shifts the Frank–Starling curve upwards and to the left)
- extrinsic inotropic influences (drugs with a positive inotropic effect shift the Frank–Starling curve upwards and to the left, whereas myocardial depressants shift the curve downwards and to the right).

Outflow resistance (afterload)

The pressures needed to open the pulmonary and aortic valves are determined largely by pulmonary and systemic vascular resistance, respectively. These resistances (together with an inertial component) constitute the impedance to ventricular outflow – the afterload against which the ventricle contracts. Ventricular volume has a major effect on afterload. Because pressure represents force per unit area, the force acting radially on the inner surface of the whole ventricle at any time during systole is the product of intraventricular pressure and ventricular surface area at that time. An increase in LV diameter from 5 cm (normal) to, for example, 10 cm would result in an approximate fourfold increase in the force opposing ejection for the same intracavity systolic pressure. To overcome that force, the ventricle must develop greatly increased wall tension. Wall tension developed during systole is the major determinant of myocardial oxygen consumption, so contraction is much less efficient in the larger heart for the same stroke volume and ejection pressure (stroke work).

EDV is influenced by preload, afterload, circulating blood volume, the inotropic state of the ventricle, heart rate and neurohumoral influences. For example, it is smaller in the erect position than in the horizontal position because of reduced venous return. It is difficult to measure changes in cardiac

Normal resting values for pressures in the heart and great vessels

Site	Systolic pressure (mmHg)	Diastolic pressure (mmHg)	Mean pressure (mmHg)
• Right atrium	$a \leq 7$ $v \leq 5$	$x \leq 3$ $y \leq 3$	≤ 5
• Right ventricle	≤ 25	End-pressure before a ≤ 3 End-pressure on a ≤ 7	Not applicable
• Pulmonary artery	≤ 25	≤ 15	≤ 18
• Left atrium (direct or indirect pulmonary capillary wedge)	$a \leq 12$ $v \leq 10$	$x \leq 7$ $y \leq 7$	≤ 10
• Left ventricle	120	End-pressure ≤ 7 End-pressure on $a \leq 12$	Not applicable

Table 1