The heart and circulation

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Physiologist Holly Shiels describes how the heart rates of humans and fish are regulated. She explains what happens when this regulation fails in humans as a result of disease, and in fish due to climate change

Key words
Heart
Cardiac cycle
ECG
Single circulation
Double circulation
Climate change

The heart is a propulsive organ that pumps blood around the body. In mammals and birds the heart has four chambers. Two thick-walled muscular ventricles contract to propel blood into the circulation; two thinner-walled atria act as reservoirs to receive blood returning to the heart (see Figure 1).

Each heartbeat has three phases (see Figure 2). In the first phase the atria contract and blood is forced from the atria into the ventricles. In the second phase the ventricles contract and blood is ejected into the circulation. When the cardiac chambers are contracted it is called systole. The right ventricle sends deoxygenated blood to the lungs through the pulmonary arteries; the left ventricle sends oxygenated blood to the rest of the body via the aorta (see Figure 3). The left ventricle is the more powerful of the two, enabling it to pump blood at high pressures to overcome the resistance of all the capillary beds in the body. The right ventricle pumps blood at lower pressures thus avoiding damage to the delicate respiratory surfaces of the lungs. The final phase of the cardiac cycle is called diastole when the chambers relax. The time between heartbeats represents the length of the cardiac cycle (see Figure 2).

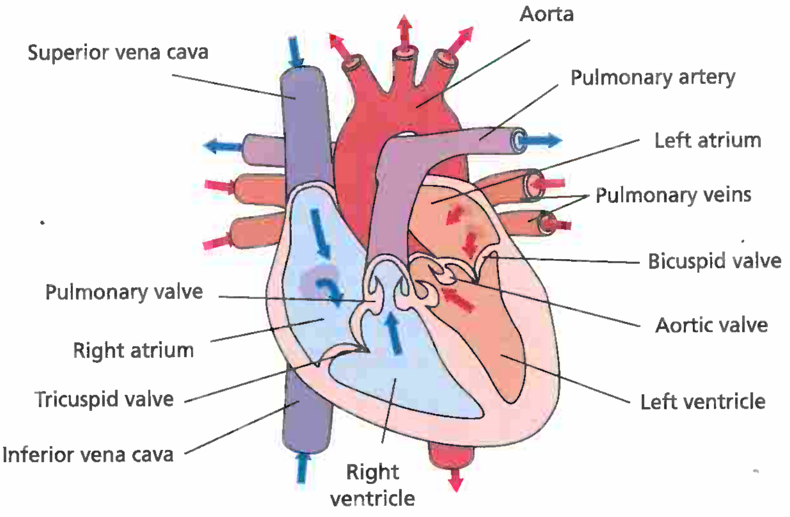


Figure 1 An adult human heart, showing its internal structure and the direction of blood flow

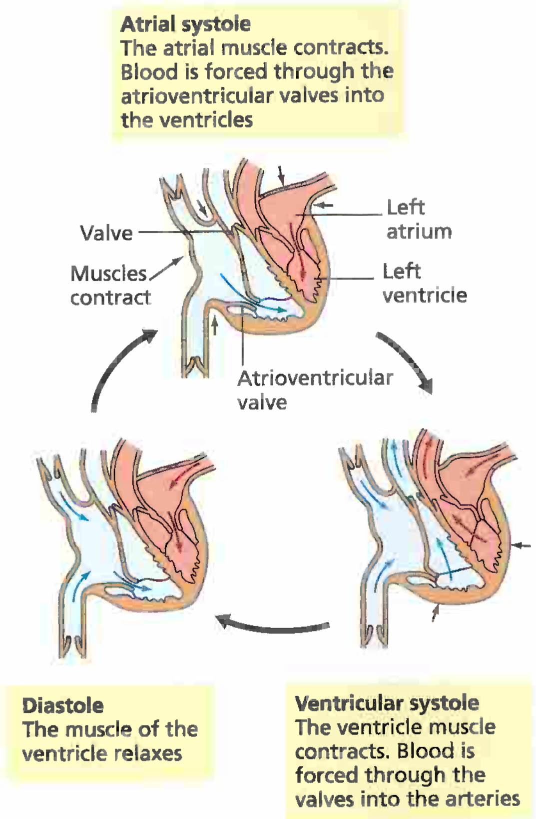


Figure 2 The mammalian cardiac cycle

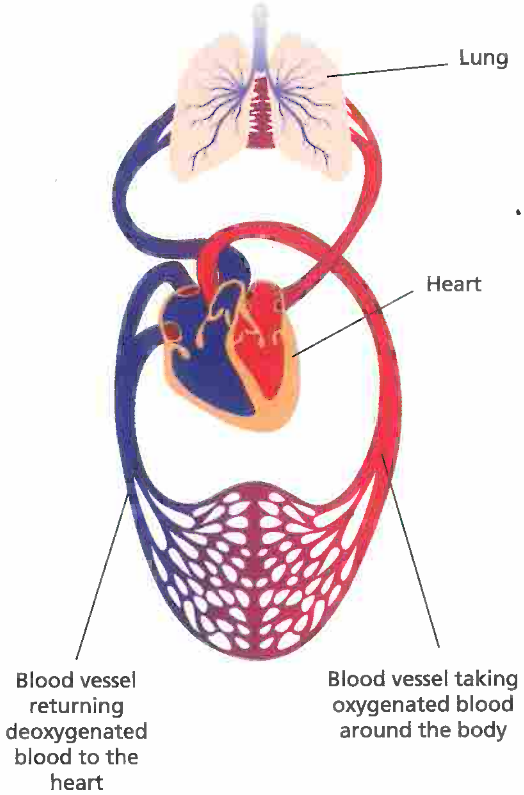


Figure 3 The double circulation in a mammal

Something fishy about fish hearts

The hearts and circulation of fish differ from those of mammals. Fish hearts have only one atrium and one ventricle. Blood from the body flows into the atrium and then on to the ventricle. From there it is propelled to the gills for oxygenation. Blood leaves the gills and flows to the rest of the body, before returning to the heart (see Figure 4). There are important consequences of this single circulation for fish. The first is that blood pressure leaving the fish heart is low. This protects the delicate respiratory surfaces of the gills but it means that blood pressure throughout the entire circulation is low.

Fish manage life with low blood pressure in two main ways. First, their **metabolic rate** is approximately ten times lower than that of birds or mammals. This is why blood does not need to flow around their bodies quickly for nutrient delivery and gas exchange. Second, water provides buoyancy, which, together with the fact that the majority of the major blood vessels in fish are horizontal (see Figure 4), means that gravity can be easily overcome even at low blood pressures.

Another consequence of the single circulation of fish is that the heart is the last organ to receive blood. The heart's oxygen supply is, therefore, provided by the oxygen remaining in the venous blood after other tissues have extracted the oxygen they need. Under resting conditions in most fish there is enough oxygen in the venous blood to satisfy the demands of the heart. However, when fish swim faster, the locomotory tissues take up more oxygen, leaving less oxygen in the blood for the heart. This can become problematic because the heart is required to work harder to deliver blood to exercising tissues while, at the same time, its own oxygen supply is reduced.

Some species of fish, such as tuna and swordfish, compensate for the reduction in venous oxygen supply by increasing **coronary** blood flow (see red colour surrounding the ventricle of the fish heart in Figure 4). These coronary vessels supply oxygenated blood directly to the surface layers of the fish heart from the gills. However, many fish, such as sea bass and tilapia, do not have a coronary blood supply, and in this era of climate change (see Biological Sciences Review, Vol. 28, No. 1, pp. 2–7), even those that do may struggle to get enough oxygen.

Climate change and the fish heart

Climate change is affecting rivers, lakes and oceans in ways that impact on the cardiovascular system of fish. Increasing water temperatures increases fish metabolic rates, which increases the demand on the heart to supply oxygen to metabolising body tissues (see Box 1). Warming also reduces the solubility

Terms explained

Acetylcholine A neurotransmitter that slows heart rate.

Autonomic nervous system The branch of the central nervous system that supplies muscles and glands that are not under conscious control, including the heart.

Coronary Relating to or denoting the arteries that surround and supply the heart with blood.

Hypoxia Oxygen deficiency in either the environment or in body tissues.

Metabolic rate The rate at which living organisms expend energy. Metabolic rate is often estimated by measuring the oxygen consumption of an organism because the rate at which oxygen is used is proportional to energy expenditure.

Neurotransmitter A chemical messenger that sends signals between neurones and other cells in the body.

Noradrenaline Neurotransmitter of the sympathetic nervous system that accelerates heart rate.

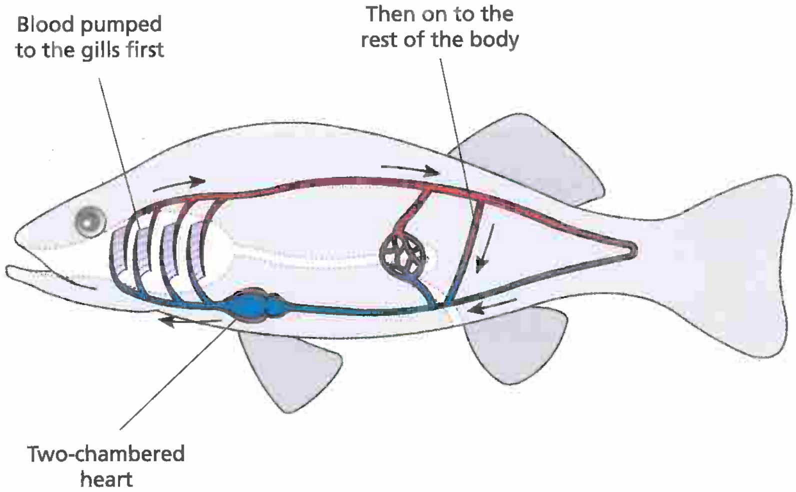


Figure 4 In the single circulation of a fish, deoxygenated blood from the body (blue) enters the heart before being pumped to the gills for oxygenation (red). In some fish a coronary blood supply leaves the gills and brings oxygenated blood directly to the heart (the orange colour surrounding the periphery of the heart)

of oxygen in water. As a consequence, the oxygen content in water decreases (this is called **hypoxia**).

Together this is bad news for fish — their oxygen demand increases due to increased metabolic rate at a time when oxygen levels in water decrease. In addition, severe weather events associated with climate change can increase water flow in rivers, which can also impact on the fish cardiovascular system. Fast flowing rivers force fish to swim faster, which can exacerbate the mismatch of oxygen supply from the venous blood and oxygen demand of the working heart.

Regulation of heart rhythm

Our hearts pump blood in an orderly fashion nearly 100 000 times per day. Atrial and ventricular systole is coordinated by electrical impulses that arise spontaneously from a region of the heart called the sinoatrial node (SA node) (see Box 2). These impulses are myogenic — they originate from the muscle cells that make up the SA node rather than being triggered by the nervous system. The electrical activity occurring during each heartbeat can be measured using an electrocardiogram (ECG) (see Box 2).

The rate at which the SA node fires an electrical impulse sets the rate at which the heart beats. The heart rate of a healthy adult man or woman is between 60 and 100 beats per minute. The heart rate of human babies is usually faster — around 150 beats per minute. The resting heart rate of trained endurance athletes is slower, around 50 beats per minute. The six-time Olympic gold medallist Sir Chris Hoy famously has a resting heart rate of 30 beats per minute. But what accounts for these differences in human heart rates?

The answer lies in the fact that the myogenic firing rate of the SA node is influenced by the **autonomic nervous system** (ANS). The ANS has two branches: the sympathetic branch, which uses the **neurotransmitter noradrenaline** to accelerate heart rate, and the parasympathetic branch, which uses the neurotransmitter **acetylcholine** to slow heart rate.

When the body's oxygen requirements increase — for example during exercise — the heart increases the rate at which it delivers blood to the lungs and the body. This increase in heart rate is called tachycardia. It happens in response to the release of noradrenaline via the sympathetic branch of the ANS. Bradycardia is a decrease in heart rate and occurs with release of acetylcholine. As mentioned above, bradycardia and tachycardia can occur in healthy individuals, such as elite athletes. However,

Box 1 Measuring metabolic rate in brown trout

Using an environmentally controlled swim flume can help us to understand the effect of temperature and water speed on metabolic rate in brown trout. These studies help scientists to predict the vulnerability of different fish species to climate change.

Figure 1.1 shows a brown trout in the swim flume (which acts like a treadmill for fish). The temperature and the water speed in the flume can be adjusted while the oxygen consumed by the fish is measured. We can also track how fast and how far the tail moves during swimming, which tells us about the effect of environment on fish locomotion. The movement of the tail is recorded by digitally tracking body movements using the coloured dots shown along the fish's body. Figure 1.2 shows that warming and increasing water speed both increase oxygen consumption and thus metabolic rate of swimming fish (data courtesy of Karlina Ozolina).

Figure 1.1 Brown trout swimming in a swim flume

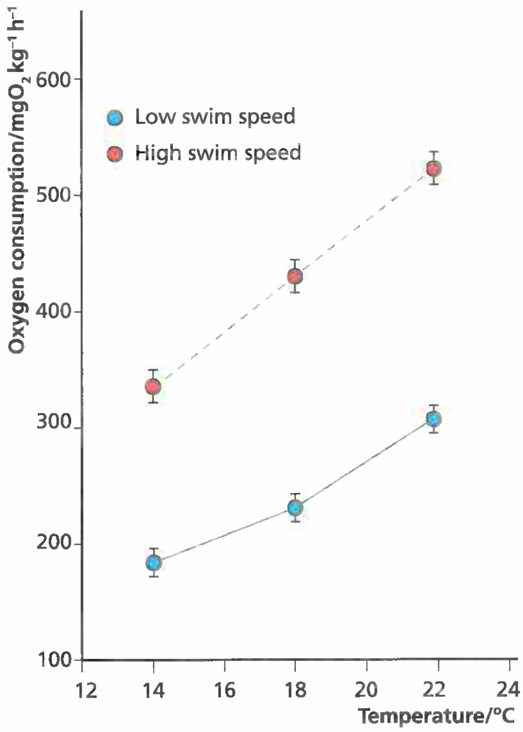


Figure 1.2 The effects of temperature and swim speed on the metabolic rate, measured as oxygen consumption in brown trout

Box 2 The electrical conduction system of the mammalian heart

Electrical impulses arise spontaneously from a group of specialised cells in the wall of the right atrium called the sinoatrial node (SA node) (see Figure 2.1). From the SA node the electrical activity spreads quickly through the right and left atria, initiating their contraction. It is slowed momentarily at the atrioventricular node (AV node), which is a group of cells at the junction between the atria and ventricles of the heart. This slowing is important because it allows time for the atria to contract and fill the ventricles before the ventricles start to contract.

The electrical impulse then leaves the AV node and rapidly spreads to the tip (apex) of the ventricles via the bundle of His. It then spreads across the ventricles via fast conducting fibres called the Purkyne system, which carries the electrical signal to the heart muscle cells — myocytes — and initiates ventricular contraction and ejection of blood into the circulation.

An electrocardiogram (ECG) can be used to measure the electrical activity of the heart. Each of the waves represents the electrical activity associated with the cardiac cycle (see Figure 2.2). The P wave is atrial systole, the QRS wave is ventricular systole, and the T wave is ventricular diastole. An electrical signal occurs with atrial diastole but it is small and is masked by the signals coming from the ventricles.

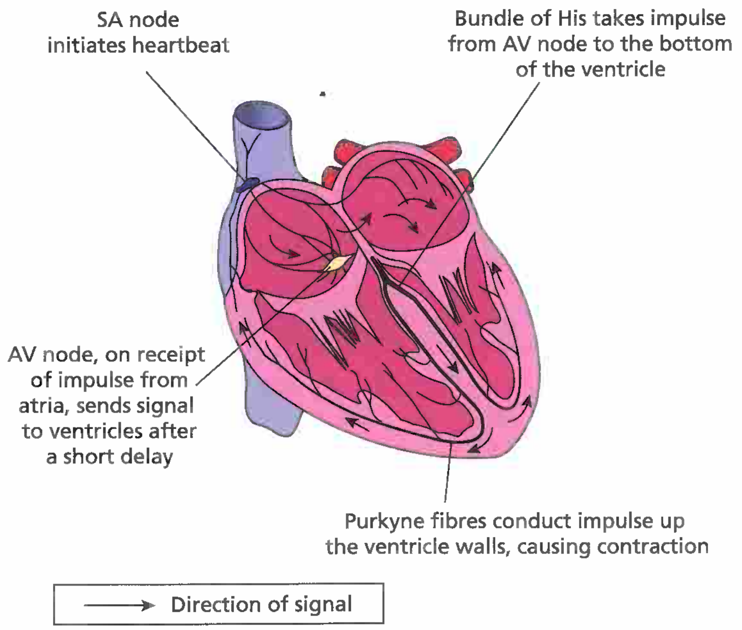


Figure 2.1. Coordination of the heartbeat

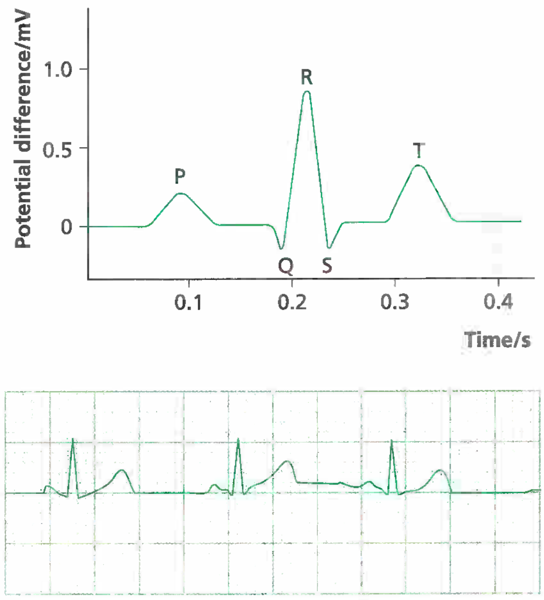


Figure 2.2. A trace from an electrocardiogram

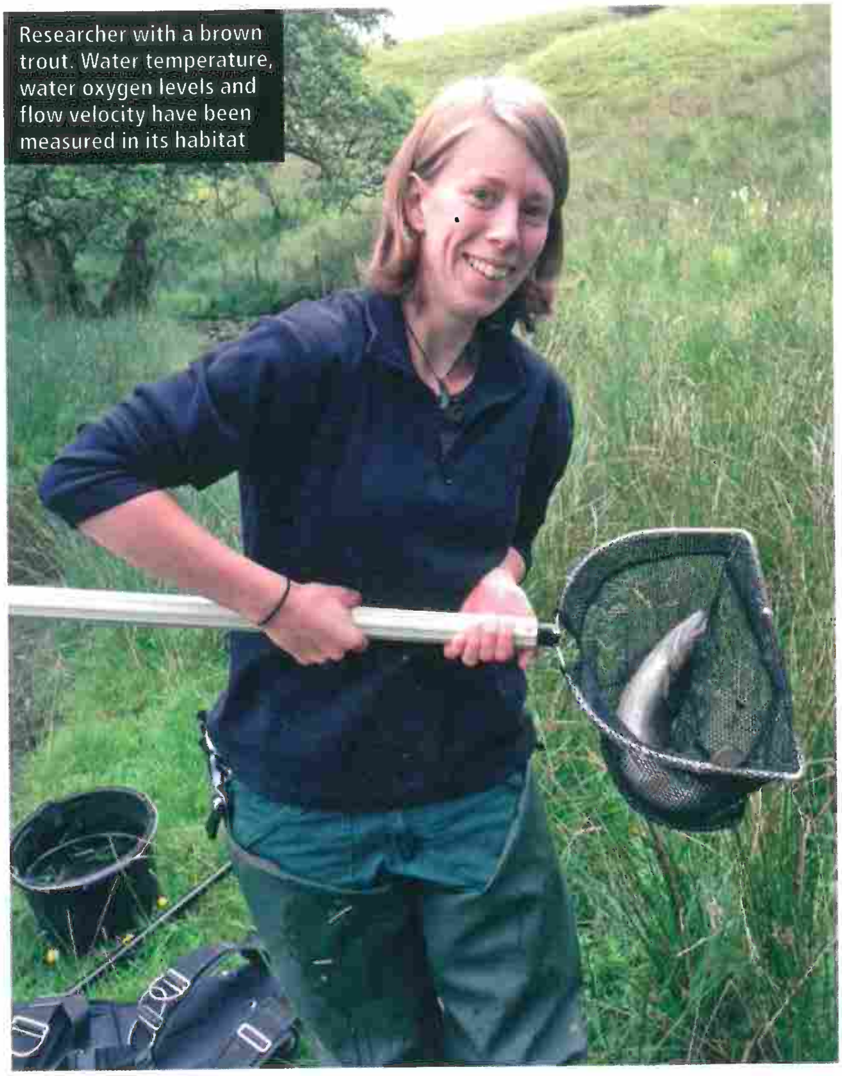
it may also indicate a problem with some part of the electrical system of the heart, as described in the next section.

Heart rate in fish is also influenced by the ANS. However, the largest factor influencing fish heart rate is ambient water temperature. As a fish moves into warmer water, its body temperature (and thus its heart temperature) warms up and this causes the firing rate of the SA node to increase, thereby accelerating heart rate. The opposite occurs with cold temperature. The fish ANS counters the direct effect of temperature on heart rate by releasing noradrenaline or acetylcholine. However, at extremes of temperature, which can arise from climate change, ANS control of heart rate becomes less effective.

When regulation goes wrong

Animals have control systems to regulate heart rate. If heart rate regulation fails, not only will there be poor matching of oxygen requirements with oxygen demands, but it may also cause arrhythmias — irregular, faster or slower heart rhythms. Arrhythmias can indicate a disruption of the normal electrical activity of the heart, which affects the orderly contraction and relaxation of the muscular chambers during the cardiac cycle. As discussed above, some arrhythmias can occur in healthy individuals, and are barely noticeable. Others are associated with life-threatening diseases such as coronary artery disease, or with heart-valve disorders, or injury after a heart attack. Understanding how different arrhythmias are caused is one of the primary research focuses in cardiology today.

Arrhythmias can be problematic for all animals. Increasing water temperature alters the electrical activity of the heart of brown trout (see Figure 5). Electrical activity in these trout was measured using a surgically implanted heart-rate tag. At temperatures above 22°C the duration of the QRS complex of the ECG (see Box 2) became progressively prolonged, indicating



Researcher with a brown trout. Water temperature, water oxygen levels and flow velocity have been measured in its habitat

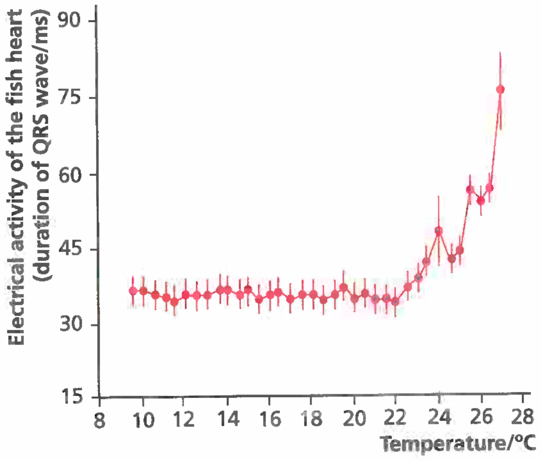


Figure 5 The effect of warming ambient water on the electrical activity of the heart of a brown trout. Data adapted with permission from Vornanen et al. (2014) *Journal of Experimental Biology*, Vol. 217, pp. 299–309

a disruption in the heart's electrical activity and stability (see Figure 5). The loss of cardiac electrical stability above 22°C may contribute to the deaths that happen during warming events. Sadly, warming river temperatures have already caused fish migrations to fail and some fish populations to decline. Collapse of the cardiovascular system at warm temperatures is implicated in fish fatalities.

The mechanisms behind cardiovascular collapse are not known but researchers are investigating the role of reduced oxygen supply to the heart and the role of arrhythmias during warming as possible contributors. Thus, understanding how the cardiovascular system is designed and how heart rate is regulated may help save human lives and may help us to understand what goes wrong for fish and other animals in an era of climate change.

Points for discussion

- Do changes in environmental temperature affect human hearts? What about hypothermia?
- What happens to heart rate in a hibernating animal during winter?
- What other changes in the circulatory system occur during exercise, stress or anxiety? How do they help to ensure blood flow matches tissue oxygen demand?
- Why do fish such as carp cope so well with environmental hypoxia?

Dr Holly Shiels is a senior lecturer in animal physiology in the Faculty of Life Sciences at The University of Manchester. She works on cardiac function in fish, reptiles and mammals and how heart rate and cardiac output is adjusted or maintained in a changing environment.

Further reading and viewing

For more information about the Ribble River Trust, see: **http://ribbletrust.org.uk** and **www.youtube.com/watch?v=4liOFH2AB7o**

Powell, K. (2013) 'Congenital heart disease', Biological Sciences Review, Vol. 26, No. 1, pp. 22–25.

Mamas, M. (2011) 'Heart attacks', Biological Sciences Review, Vol. 24, No. 1, pp. 34–37.

YouTube videos of fish swimming during oxygen consumption measurements:
www.youtube.com/watch?v=P-c-EXmTmQY
www.youtube.com/watch?v=n_QpPlNDb8A

Key points

- In both fish and mammals, the heartbeat originates in the sinoatrial node and the heart rate is regulated by the autonomic nervous system.
- Fish are ectotherms (cold-blooded) and so their heart must function across a range of temperatures. However, the temperature extremes that can occur with climate change may cause cardiac arrhythmias.
- Cardiac arrhythmias are unusually fast, slow or irregular heart rates. They can be indicative of poor health in mammals and can occur because of changes in the environment in fish.
- Arrhythmias can interrupt the contraction and relaxation cycle of the heart and thus affect the flow of blood in the body.
- Understanding how heart rate is regulated is important for health in mammals and environmental tolerances in fish.