CV 2. HEART AS A PUMP

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LEARNING OBJECTIVES

1. Describe the structure and function of the heart chambers and associated valves.
2. Explain systole and diastole.
3. Explain pressure-volume loops, stroke volume and cardiac output.
4. Explain the cardiac cycle and associated heart sounds.
5. Discuss the Frank-Starling relationship in terms of venous return and cardiac output.

HEART STRUCTURE

The human heart is a four-chambered organ consisting of two **atria** and two **ventricles** (Fig 1). Blood flows from the atria to the ventricles in a unidirectional manner. Valves interposed between these two chambers prevent backwards flow of blood.

The right side of the heart has a thin muscular wall and works at low pressures. Contraction of the **right ventricle** pumps blood into the pulmonary circulation (lungs) where oxygen is taken up and carbon dioxide is eliminated. The **left side of the heart** has a thicker muscular wall and works at higher pressures. Contraction of the left ventricle pumps blood into the systemic circulation for delivery to the limbs and to all of the organs (except lungs). The right atrium receives blood returning from the systemic circulation; the left atrium receives blood from the lungs (Fig 1).

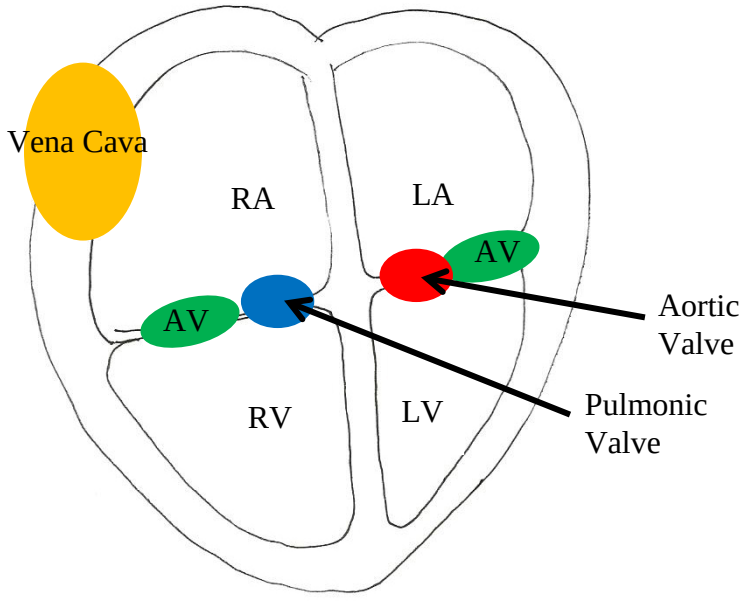


Figure 1. Blood flows from the atria to the ventricles in a unidirectional manner. Valves interposed between these two chambers prevent backwards flow of blood.

Because the circulation is a closed system, in a steady state, the flow of blood (**cardiac output**) from the left side of the heart equals the cardiac output from the right side of the heart. Total amount of blood circulating is ~5 liters/ minute.

Most of the heart is cardiac muscle (**myocardium**) which is covered on the outside surface by a thin epithelial sac called the **pericardium**. The inner surface facing the blood is lined by a thin epithelium called endothelium. The cardiac muscle of the myocardium is attached to a thick fibrous connective tissue **skeleton** which divides the upper two chambers (atria) from the lower two chambers (ventricles). The major blood vessels (aorta and pulmonic artery) which conduct blood away from the heart emerge from the base of the heart at the A-V junction (Fig 1). The pulmonary veins and vena cava which return blood to the heart from the lung and systemic tissues, respectively, connect to the left and right atria, respectively. The coronary arteries and coronary veins run across the surface of the ventricles to supply blood to the heart muscle.

Note that blood enters and leaves the ventricles at the base (A-V junction). That means that the ventricles must contract from the bottom (apex) up to expel the blood from the base.

Four valves are located within the cardiac skeleton between the atria and ventricles (Fig 2).

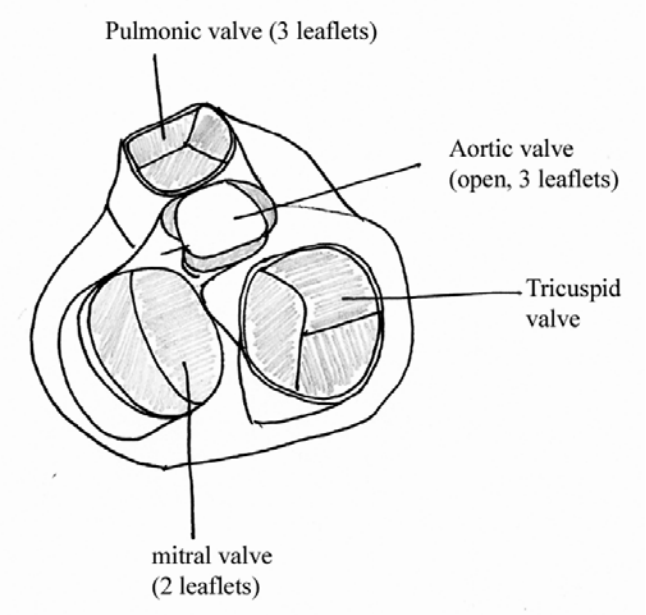


Figure 2. Cardiac valves viewed from the base of the heart.

These valves respond passively to pressure gradients. The **pulmonic and aortic valves** open when the ventricles contract and close with relaxation. The pulmonic and aortic valves prevent back flow from the arteries into the relaxing ventricles. The AV valves (**mitral and tricuspid)** close once the ventricles fill. These two valves are closed during contraction of the ventricles and ejection of blood and therefore experience high pressures. To prevent the **mitral and tricuspid** valves from prolapse (being pushed into the atria) they are tethered to the ventricle wall via tendon like cords and the papillary muscles. One way to remember the location of the different valves is that the mitral valve (two leaflets) is most often replaced because it is subjected to the high pressures of the left ventricle. The pulmonic and aortic valves do not have tendons to resist prolapse, instead they are semilunar valves (cup like in shape) which fill with blood when closed. These two valves are closed during relaxation and passive filling of the ventricles.

One other point regarding the connective tissue skeleton of the heart is that it isolates the electrical activity of the atria from the ventricles. Thus the ONLY passage for the electrical signal is via the AV node. With a complete AV block, the bundle of His will take over as pacemaker.

CARDIAC CYCLE

Recall that each action potential in muscle is followed by a contraction. In the heart, the period of contraction is called **systole**. The period of relaxation is called **diastole**. The **cardiac cycle** is the period of time from the beginning of one heart beat (depolarization) to the beginning of the next.

Because the atria and ventricles do not contract and relax at the same time, we will discuss the events in the atria and ventricles separately. We start the cardiac cycle in the ventricles at the beginning of diastole (See Fig 3). At this time, the ventricles are relaxed and filling passively with blood. The AV valves are open. A P wave occurs, the atria depolarize and contract. Blood is ejected into the ventricles, ventricular pressure exceeds atrial pressure and the AV valves close. Note that the last 20% of ventricular filling is due to the active contraction of the atria. The QRS complex occurs, the two ventricles depolarize and start to contract. Note that all four valves are closed so that contraction increases pressure within the ventricles. This is called **isovolumic contraction** because the amount of blood within the ventricles is not changing only the pressure. Eventually the pressure within the ventricle exceeds that in the pulmonic artery and aortic artery and these two valves open. Blood is **ejected**.

Following ejection of the blood, the myocardium of the two ventricles relaxes (diastole) and the pressure within the ventricles falls. When the ventricular pressures are less than that in the pulmonic artery and aorta, the pulmonic and aortic valves close. Again all four valves are closed. The two ventricles relax further (isovolumic relaxation). When the pressure within the ventricles is less than that within the atria, the AV valves open and blood flows from the atria passively into the ventricles. The cycle repeats.

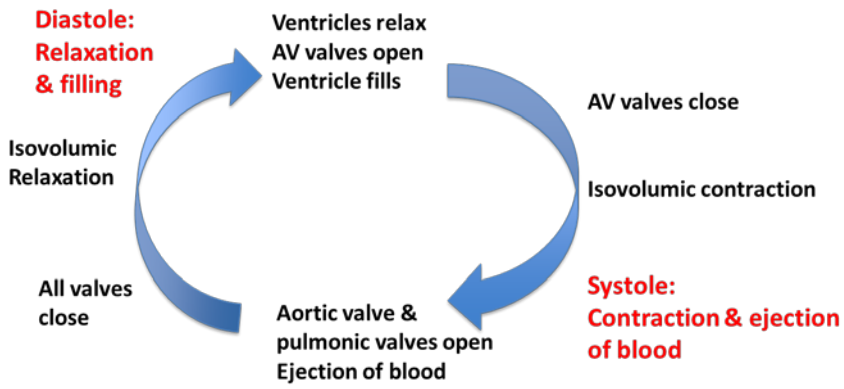


Figure 3. One cardiac cycle includes one systole and one diastole. This occurs with every heart beat.

The events of the cardiac cycle are summarized in the Wigger's Diagram (Fig 4). The Wigger's diagram (Fig 4) shows the relationship between the ECG, the pressure, and volume changes in the left ventricle and aorta. Note that there are two heart sounds (lub-dub). The first is associated with the onset of systole and the second with the start of diastole (Fig 4).

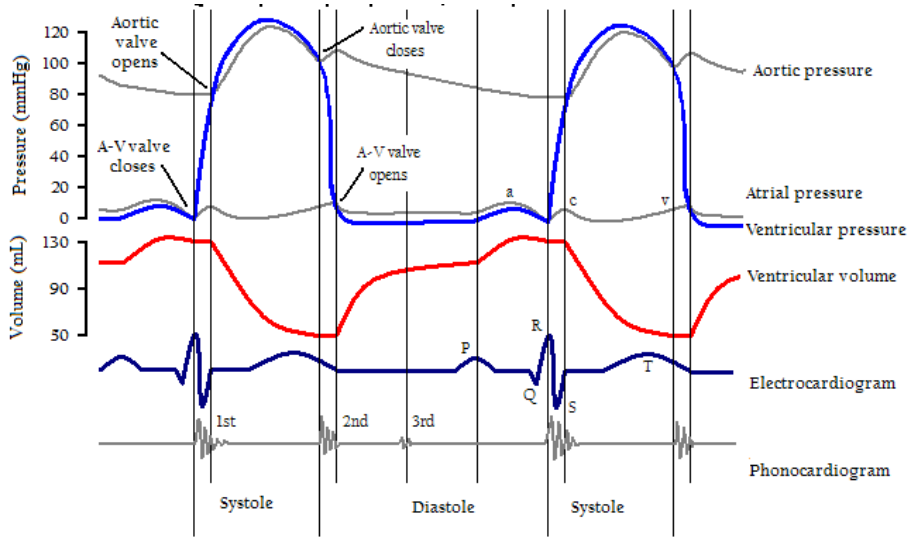


Figure 4. Wigger's diagram integrates left ventricular pressure, volume, electrical activity (electrocardiogram) and heart sounds (phonogram). By DanielChangMD revised original work of DestinyQx [CC-BY-SA-2.5 (http://creativecommons.org/licenses/by-sa/2.5)], via Wikimedia Commons.

The volume of blood in the ventricles at the end of ventricular relaxation (filling) is the **end diastolic volume (EDV)**. EDV in the left ventricle is usually about 125 ml. The volume of blood ejected with each beat during contraction of the ventricles is the **stroke volume (SV)** (~70 ml). Not all of the blood in the ventricles is ejected. The volume of blood remaining at the end of ventricular contraction is the **end systolic volume (ESV)**. ESV in the left ventricle usually averages 55 ml but the EDV, ESV, and SV can vary with different physiologic states. (See discussion below).

One cardiac cycle can be represented by a pressure-volume (P-V) loop. Consider the P-V loop ABCD shown in Figure 5. B is the EDV and D is the ESV. What is the stroke volume? What valve opens at C? What valve closes at D?

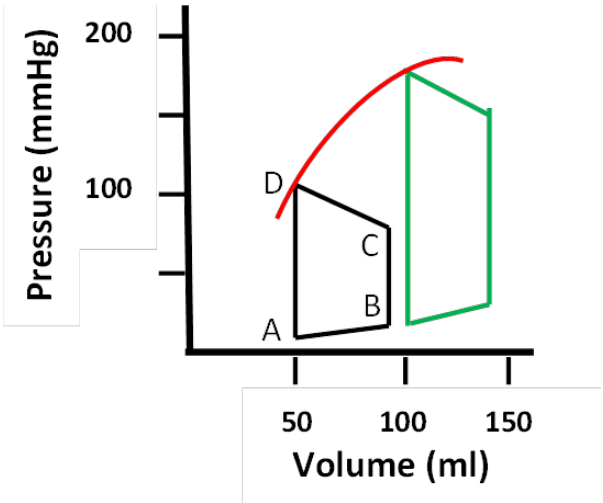


Figure 5. Pressure-volume loop ABCD depicts changes in left ventricle in one beat. The ventricle

fills between A-B. B-C depicts isovolumic contraction. C-D depicts ejection. D-A depicts isovolumic relaxation.

CARDIAC PERFORMANCE

Cardiac output (CO) is the volume of blood ejected by one ventricle in a period of time. Cardiac output is one measure of the effectiveness of the heart as a pump. It dynamically adjusts by changing either the heart rate or stroke volume or both.

Cardiac output = stroke volume x heart rate
CO= SV x HR

For an average resting heart rate of 72 beats per min (bpm) and a stroke volume of 70 mL per beat, the

CO = ~ 5L/min.

The average **total volume of blood circulating in the body is ~ 5L**. Therefore, each ventricle pumps all of the blood of the body through it in only one minute.

The **ejection fraction** (EF) describes the efficiency of the heart. It is SV divided by end diastolic volume (EDV) times 100.

EF (%) = SV/ EDV x 100

During strenuous exercise, CO can increase to 30-35 L/min. What parameter (stroke volume or heart rate) limits this increase in CO? [Answer: heart rate.] As heart rate increases, the time for contraction and relaxation of the cardiac muscle will shorten; the filling time limits CO.

CONTROL OF STROKE VOLUME

Normally as the force of contraction increases, the stroke volume increases. Because the contractile cells of the heart act as an electrical syncytium with all of the cells contracting during a single beat, it is not possible to increase the force of contraction by fiber recruitment. Instead, the force of contraction is increased by changing: (1) **length of the cardiac muscle fibers** at the beginning of the contraction and (2) the **contractility** of the muscle fiber itself.

The length of the fiber is dependent on the volume of blood in the ventricle. In the intact heart, as the ventricle wall stretches with the filling of blood, the overlap of the actin and myosin increases in the sarcomere up to an optimal length and contractile force increases. This is called the Frank-Starling relationship. It means that within physiological limits, the heart pumps all of the blood returned to it.

The degree of stretch of the myocardium before contraction is called **preload**. An increase in venous return (filling) will increase preload and thus increase the force of contraction. Consider the P-V loop depicted in Figure 5. An increase in preload (filling) will move the EDV to the right along the X axis and increase the pressure generated (Y axis). The heart (depicted as ABCD) when filled to an EDV of 140 ml, generates a systolic pressure of 180 mmHg. The “red curved” line in Figure 5 depicts the force generated for each increase in EDV for this particular heart.

Four factors can increase **venous return (EDV)**: (1) contraction of the veins returning blood to the heart due in part to contraction of leg muscles surrounding these veins (**skeletal muscle pump**); (2) deeper breathing which expands the chest and decreases the intra-thoracic cavity

pressure (**respiratory pump)**; and (3) **sympathetic innervation of veins** which causes constriction of the vessel wall and (4) an **increase in blood volume**.

In contrast, **contractility** of the myocytes is affected by specific chemicals. Any agent that affects contractility is called an **inotropic agent**. For example, catecholamines, epinephrine and norepinephrine, and drugs such as digitalis enhance contractility and are said to have positive inotropic effects (Fig 6). The myocardium uses preload and contractility to regulate the pressure generated.

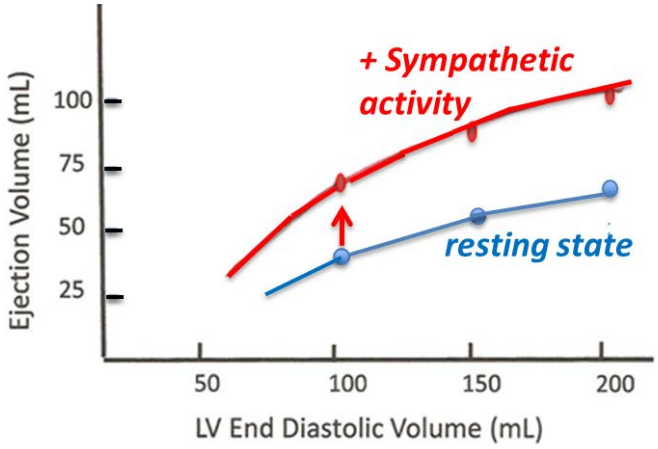


Figure 6. Sympathetic nervous stimulation of the heart increases the ejection volume (stroke volume) at any given end diastolic volume.

KEY CONCEPTS

- The heart consists of two separate pumps that move blood in a unidirectional manner through the pulmonary circulation for gas exchange and then to the systemic circulation for the delivery of O2 and nutrients and removal of waste products.

- Each beat of the heart (cardiac cycle) involves the electrical activation of the atria and ventricles, contraction and relaxation of those chambers, closing and opening of the cardiac valves and filling and emptying of the atria and ventricles. The sequence is the same for the right and left chambers.

- Ventricular contraction and ejection occur during systole. The beginning of the systole coincides with the first heart sound and ends with the 2nd heart sound.

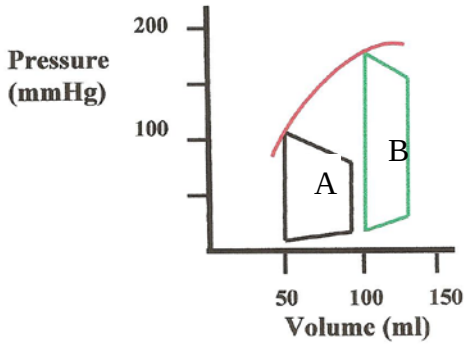
- Ventricle relaxation and filling occur during diastole. Diastole begins with second heart sound and ends with the first heart sound.

- The volume of blood ejected with each beat is the *stroke volume*.

- The sum of the stroke volumes ejected in one minute is the *cardiac output*.

QUESTIONS

1. What are the stroke volumes of the two loops (A and B) shown below?



2. What is the ejection fraction of loops A and B?
3. What is the electrical event on the ECG that precedes contraction of the atria?
4. What is the electrical event on the ECG that precedes ventricular diastole?

ANSWERS

1. Stoke volume of loop A = 40 ml; loop B = 40 ml
2. Ejection fraction for loop A = 40 / 90 x 100 = 44%
   Ejection fraction for loop B = 40 / 130 x 100 = 30%
3. P wave
4. T wave