Last lecture we talked about venous return and cardiac output.

Our Last objective was to relate cardiac output curve with venous return curve.

We drew cardiac output curve then we drew venous return curve separately. Then we put them together, and the working cardiac output was the intersection of both curves at any states what so ever ex. Sympathetic stimulation or inhibition etc… Whatever the state is; the intersection point is the working cardiac output.

We also talked about the idea of mean systemic filling pressure. It is mainly affected by blood volume, venous tone or venous compliance. This is because our veins contain about 2/3 of our blood volume.

Measurement of Cardiac Output

Note: I advise you to look at the slides while reading this sheet.

We can measure the cardiac output directly with experimental animals. We will need to collect the blood coming from the aorta per minute and this is cardiac output.

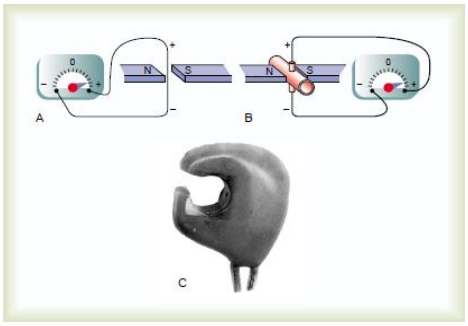
Cardiac Output: It is the flow of blood from the aorta or pulmonary artery per minute.

In humans we measure it indirectly, although sometimes directly during cardiac surgery.

Measurements are by:

1. **Electromagnetic flowmeter**. (Direct Method)
2. **Indicator dilution** (dye such as cardiogreen). You use an indicator something you can measure such as a dye. This substance has to be nontoxic; it should give us indication, and has to be non-degradable so it doesn't change in concentration so you can measure it.
3. **Thermal dilution**. An Indicator such as a dye as said earlier in point 2 are nontoxic but the problem is that you can be allergic to that particular substance and once it is Injected IV an anaphylactic shock may occur! So this is dangerous. This is why we use something natural; thermal. Here we inject cold saline, and we measure how much is the drop in temperature.
4. **Oxygen Fick Method**. Also natural

First Method: Electromagnetic Flowmeter



This is a **direct method**. There are 2 poles, south and north which are used to generate current that is read by a device. When fluid moves between these two poles of the magnet, it will give rise to a current. The amount of current is proportional to the flow rate of the fluid, and especially if the solution has electrolytes like the blood which has positive and negative ions. So if you move this solution in between these 2 poles of the magnet, it will generate a current. Now we place this flowmeter around the Aorta, and as blood is passing by, current will be generated and then measured. The reading that is measured is calibrated, and the cardiac output is measured right away.

This is easy, but not applicable because you need to put the electromagnet around the aorta so you need to do a surgery just to measure cardiac output.

This is a direct method, and as we said before, direct methods are used on experimental animals only. Unless the patient is already under cardiac surgery then this method can become applicable.

Second Method: Oxygen Fick Method

In this method, you will need to measure the oxygen concentration in the arterial blood and in the venous blood. The measurement of oxygen concentration in the arterial blood is easy because any artery in the body has the same concentration of oxygen like the pulmonary veins which carry oxygenated blood coming from the lungs to the heart. This is because there is no exchange in substances except at the level of the capillaries. So before the capillaries everything is the same starting from the aorta till the arteriole such as oxygen, glucose, other gases etc… Once you go beyond the capillary the concentrations become different.

The principal is that the amount of blood ejected from the pulmonary artery per minute is Cardiac Output. The amount of blood coming to the pulmonary veins per minute equals Cardiac Output as well. It is the same amount of blood coming from the pulmonary artery to the lungs and then to the pulmonary veins. The amount of blood ejected from the aorta per minute equals Cardiac Output too.

Now before you continue please refer to slide no.24 in slides 8 according to the website

The amount of oxygen that passes to the pulmonary artery per minute (Q1) EQUALS cardiac output MULTIPLIED by oxygen concentration in the mixed systemic venous blood (pulmonary artery blood). [q1= CO * C_{VO2}]

The amount of oxygen found in the pulmonary veins per minute (Q3) EQUALS the cardiac output MULTIPLIED by oxygen concentration in the systemic arterial blood.

Also **The amount of oxygen in the pulmonary venous blood** = the amount of oxygen in the pulmonary artery blood (which is mixed venous blood) PLUS how much oxygen is being up taken from the lung (Q2).

Now we said that:

The amount of oxygen that passes in the pulmonary veins per minute = Cardiac Output X Oxygen concentration in the systemic arterial blood
→ [$q3 = CO * C_{AO2}$]

Also,The amount of oxygen that passes in the pulmonary veins per minute = Cardiac Output X oxygen concentration in the pulmonary artery + oxygen concentration coming from the lungs
→ [$q3 = q1 + O_2$ uptake]

This means that:

Cardiac Output X Oxygen concentration in the systemic arterial blood = **Cardiac Output X oxygen concentration in the pulmonary artery + oxygen concentration coming from the lungs**

$CO * C_{AO2} = q1 + O_2$ uptake
$CO * C_{AO2} = CO * C_{VO2} + O_2$ uptake
O_2 uptake $= CO * C_{AO2} - CO * C_{VO2}$
Now take Cardiac Output as a common factor, and then rearrange the equation.
Finally you will end up with:
O_2 uptake $= CO (C_{AO2} - C_{VO2})$
$CO = O_2$ uptake $/ (C_{AO2} - C_{VO2})$

Cardiac Output= Oxygen uptake / (Concentration of oxygen systemic arterial blood – concentration of oxygen in systemic venous blood)

The Values needed to calculate cardiac output:

Arterial concentration of oxygen is done by taking blood from any artery (as said previously all arteries have same concentrations of substance; there might be very little difference but it is negligible) such as Radial artery, we take blood from the radial artery and measure the oxygen concentration.

For the veins it is different since not all veins have the same concentrations of oxygen for example, if we take blood from the vein of an exercising muscle, the oxygen concentration will be different from that in blood from veins of the metabolizing thyroid gland (Remember exchange occurs at the level of capillaries and that is why all arteries have the same concentration of oxygen and in veins there is a difference, it depends on the tissue how much it is consuming oxygen from the capillaries). So what is done?

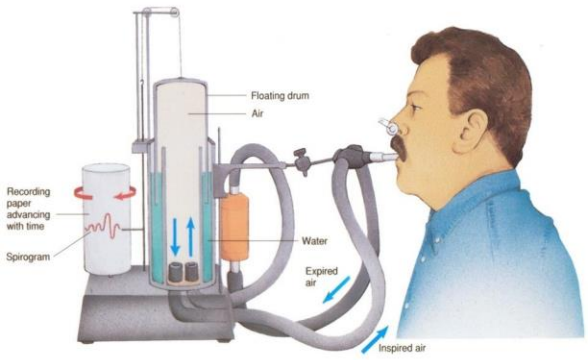
We put a catheter in the Median Cubital vein (antecubital vein) which is going to lead us the right ventricle through the axillary vein → subclavian vein → superior vena cava → right atrium and finally right ventricle where we take a sample from the right ventricular blood which collects all the venous blood from the body (Mixed Venous Blood).

** One of the students asked why we didn't take blood from the right atrium. The doctor said because blood is not mixed just as well as in the right ventricle. Sometimes we even reach the pulmonary artery and take blood from there (Blood is mixed even better there).

So now we have the concentration of oxygen in the arterial and venous blood, and all we need to know now is the oxygen taken up from the lungs per minute

This is measured by a device called the **Spirometer** which is connected to the person. This Spirometer has fixed amount of oxygen. We measure how much the patient has inhaled oxygen from the Spirometer in one minute then we switch the Spirometer off. We then measure the difference in oxygen concentration in the Spirometer. For a better accuracy we let the patient inhale oxygen for 5 to 10 minutes then we divide the difference in oxygen concentration by the time to get it per minute.

A spirometer



Cardiac Output can then be calculated.

Now the Catheter we talked about previously used is called the **Swan-Ganz Catheter** (it is important to refer to the picture in slide no.26)

This catheter contains a lot of tubes inside it. As we said previously this catheter placed into the Median Cubital vein and directed towards the right ventricle.

The tubes inside the catheter have different functions. As there is:

1. **Thermistor** To measure temperature
2. **Infusion Port.** To inject substances
3. **Balloon Port**. To measure pressure. When we inject the catheter to the pulmonary artery, we blow up the balloon there, and the

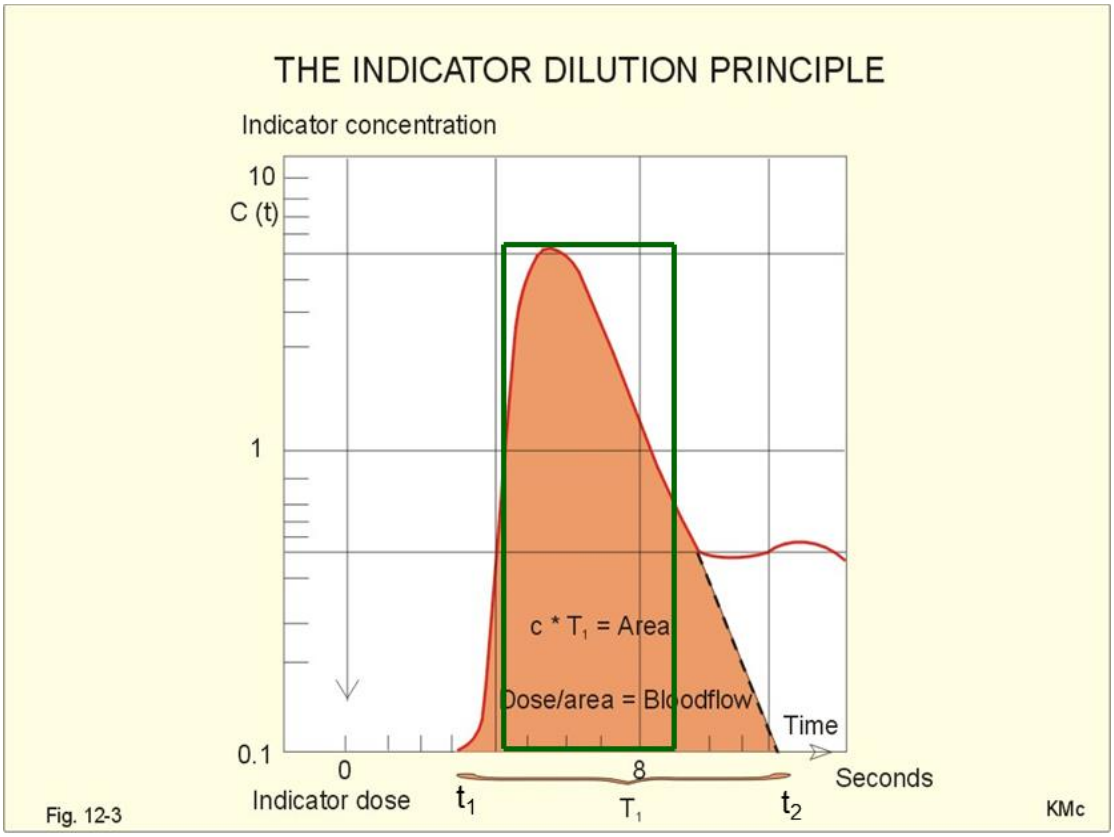
back pressure is measured. This is called *Pulmonary Wedge Pressure*

4. **Distal PA** . To measure the pulmonary artery pressure and Others (look at the slide)… the doctor didn't mention

Ex : If pulmonary vein O2 content = 200 ml O2/L blood, Pulmonary artery content = 160 ml O2/L blood, lungs add 400 ml O2/ min, then what is the cardiac output?
answer : CO = O_2 uptake / (C_{AO2} - C_{VO2})
= 400 / (200-160)
= 10 L/min

Note: Remember that you have to unify the units. The doctor said he could give us different units in the exam.

Third Method: The Indicator Dilution Method



In this method we inject a dye at 0 point as in the graph. Note: We use the same catheter we talked about previously (Swan-Ganz catheter), but this time we use the infusion port tube which reaches the right ventricle for the injection of the dye. You know the amount of dye injected which is **(q)** in mg. Now we measure how much the concentration of the dye in the arterial blood which doesn't appear straight after injection as it appears after a while until circulation occurs. As in the graph, when the concentration of the dye starts to appear its starts increasing rapidly, and at one point it reaches its peak, and then it starts to decrease because blood is continuously moving, but it never reaches down to zero, and this is because of recirculation. So as the dye is decreasing in the concentration it will increase again

due to recirculation (look at the rigid line on the graph). Now because this dye's concentration never decreases to zero, we extrapolate the line on the graph to zero (look at the dashed line in the graph), the dye is collected under this area. We calculate the mean concentration of the dye by calculating first the area of the rectangle we drew on the graph by integration:

$$\textbf{Area} = \int_{t2}^{t1} dc.dt$$

Then we divide this area by the time (T1) which is equal to t2 – t1 as in the graph to get the mean concentration of the dye.

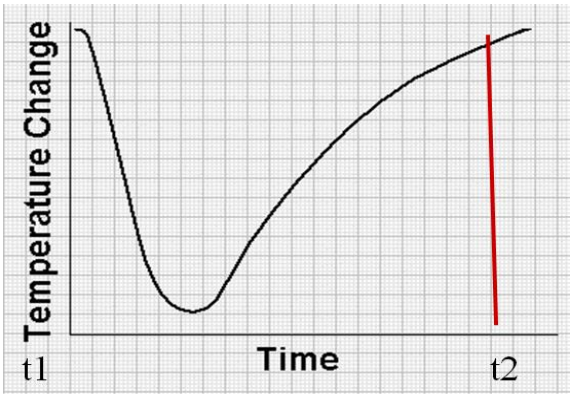
$$\text{Area} = C^* (t_2\text{-}t_1)$$
$$\text{(Rectangular)}$$
$$C = \text{Area}/(t_2\text{-}t_1)$$

The amount of dye we injected (q) which is known, *equals* the Volume *multiplied* by the mean concentration [q = v * C] → so **the volume** *equals* the amount of dye (q) *divided* by the mean concentration (C) [v = q/c]

Now **Cardiac Output** = $\frac{q}{C} X \frac{60}{\text{duration in seconds}}$

Note: We divide 60 by the duration in seconds (T1) to measure the cardiac output per minute.

Forth Method: Thermodilution



This method is very similar to the previous, and we also use the same Catheter (Swan-Ganz Catheter) which has an injection port**.** We inject a certain amount of cold saline for example 10ml. The temperature of the blood is measured by the catheter which is connected to a computer. Remember: We said previously that the catheter has many tubes with different functions, and one of the tubes is responsible for measuring temperature. So you insert the quantity (in ml) and the temperature of the saline on the computer. So right away you inject the saline and turn on the instrument, and after a while the instrument will give you the reading. When you inject at time zero, the temperature of the right ventricle increases, but as

blood is flowing to the right ventricle and pushes blood toward the pulmonary vein the temperature will decrease, and then increases after a while.

Now we calculate the integration of the area, drop in temperature over time which is done by the computer. Then Cardiac Output is measured by the computer.

Area = $\int_{t1}^{t2} dT.dt$

T :Temperature t: time

Now the advantages of this method:

- You can repeat it many times. You measure many Cardiac Outputs and then take the average.
- You use something natural.
- Very Fast.

New Topic: Hemodynamics

Now look at slides no. 9 according to the website

Objectives: slide no. 2

1. Point out the physical characteristics of the circulation:
   - Distribution of blood volume
   - Total cross sectional area
   - Velocity
   - Blood Pressure
2. List the determinants of blood flow
3. Define and calculate blood flow, resistance, and pressure
4. Define and calculate conductance
5. Apply Poiseulle's law

Blood flow through body tissues is involved in: slide no. 3

- Delivery of O2 and removal of CO2 from tissue cells
- Gas exchange in lungs
- Absorption of nutrients from GIT
- Urine formation in the kidneys

Circulation: slide no. 4

You start circulation from the aorta (flow of blood through this Aorta per minute equals Cardiac Output). This Aorta bifurcates and gives you 3 large arteries (Left Subclavian, Left Common Carotid, Brachiocephalic Trunck). The flow through these arteries together (as one unit) per minute is equal to Cardiac Output as well. After that comes medium sized arteries, and the flow through medium sized arteries (as one unit) per minute is equal to Cardiac Output. Then come small arteries, and the flow through small arteries (as one unit) per minute is equal to Cardiac Output

too. The flow through the whole capillaries per minute is equal to the Cardiac Output as well.

Capillaries: slide no. 5

We have the arterial side of the capillaries then venous side of the capillaries and after that there are the beginning venules.

Capillaries lack smooth muscles, so there is nothing called vasoconstriction or vasodilation of the capillaries because they are one cell layer. Arteries and Veins they have smooth muscles, but the difference between arteries and veins is the thickness in the smooth muscles. (Arteries have a thicker smooth muscle layer)

Blood Volume Distribution: slide no. 6

Veins contain more than 2/3 of our blood volume and that's why we call them **Capacitance vessels** (Capacitance of blood vessels describes the capability of blood vessels to distend; stretch and expand. It is directly related to elasticity).

That is why also the veins are responsible for the **mean systemic filling pressure** (the mean systemic filling pressure is mean pressure that exists in the vascular system if the cardiac output stops and the pressure within the vascular system redistributes). The mean systemic filling pressure is due to the blood volume and since veins contain a large portion of the blood volume this means that they control the increase or decrease of it. So venoconstriction or venodilation affects the mean systemic filling pressure, but arteriolar dilation or constriction affect the resistance.

Arteries contain 15% of blood volume. When you constrict arteries you constrict 15% of our blood volume. So the mean systemic filling pressure did not get affected, but the resistance got affected (increased).

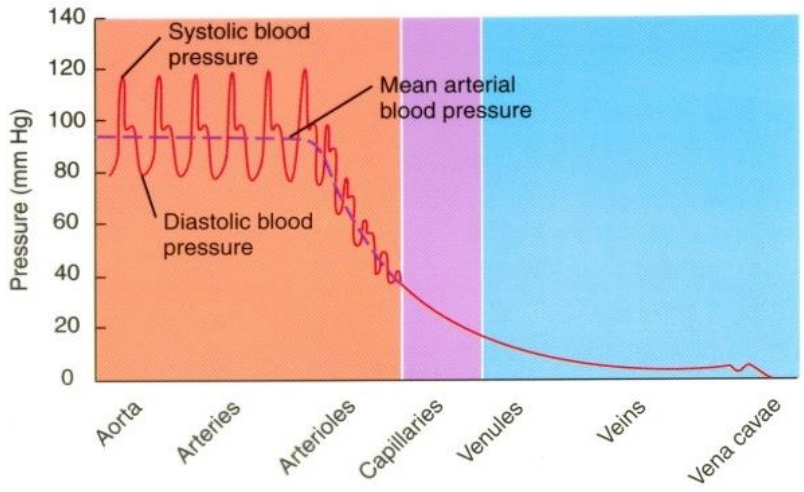
Capillaries at any one time contain 5% of our blood volume, but this 5% is flowing. The flow through the capillaries per minute equals Cardiac Output.

- Systemic circulation contains 84% of blood. Lungs contain 9% of blood volume and heart contains 7%.
- 60% of the blood is in the veins.
- Spleen and Liver contain a certain amount of blood called **Blood Reservoir**, and this is for conditions such as hemorrhage were spleen becomes constricted as it sends certain amounts of blood to the circulation.

Blood flow to the tissue is always controlled to the minimum (A tissue is never given a maximum blood supply, but only its minimum need because we don't have that much blood volume) and is always regulated (according to the tissue need).

Cardiac Output is mainly controlled by local tissue flow, and as we said, cardiac output is the sum of blood flow to the tissues.

Pressure changes through the circulation:



Here we took every segment of the blood vessels and grouped them in one unit, meaning that all the arteries are taken as one unit, all the arterioles are taken as one unit, capillaries as well etc… As we said previously the flow through each of these units is the Cardiac Output.

In the Aorta, the pressure is variable (80-120) mmHg. This is called **Pulsatile pressure** (there are pulses). The pressure that moves the blood in the circulation is not the systolic and it is not the diastolic, it is the **mean pressure**. The mean arterial pressure equals to 1/3 of systolic pressure plus 2/3 of diastolic pressure.

According to the graph:

Let us assume that the aortic pressure is 100 mmHg, and if we come to the large arteries its 95 mmHg so ΔP= 5 mmHg. The ΔP is small because the resistance is not large. The resistance of large arteries is small; hence the pressure difference is small, and the flow in both of them is equal. Now if we come to the arterioles, at the beginning of the arterioles the pressure was 85 mmHg and at the end of the arterioles the pressure is 30 mmHg so the pressure drop is 55 mmHg. This huge drop in pressure is because of the high resistance of the arteriole even though the flow is still the same. So the high drop in pressure in the arterioles is due to the high resistance of them. That's why arterioles are called **Resistance Vessels**. So the main resistance is in the arterioles.

If you look at the graph, notice that the pulsatile pressure drops significantly in the arterioles. So if you want to feel the pulse you don't do it on the arterioles, you feel the pulse in the arteries, because after the arteries there is no pulsation. This is called **damping of the pulsation.** The damping occurs because of the very high resistance in the arterioles.

After the arterioles, the blood pressure is going down without any pulsation. At the beginning of the capillary the pressure is 35 mmHg and at the end its 15

mmHg. In the venules, the pressure is 15 mmHg at the beginning and 5 mmHg at the end.

Remember: **Pressure gradient** is required for the movement of blood.

Good Luck ☺

Done by: Salem Karadsheh