Physics of Flow

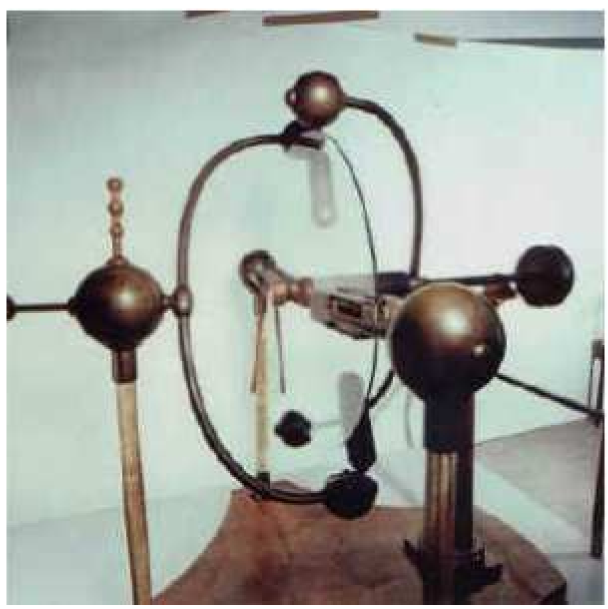
In respiration, the ultimate problem is simply one of producing sufficient airflow, defined as volume per unit time, from the atmosphere to the alveolus, to meet the metabolic needs of the organism.

This problem brings together fundamental principles in physics.

We will discuss:
- Ohm's Law
- Poiseuille's equation
- Reynolds number
- Turbulence

Ohm's Law

• Airway resistance is used in respiratory physiology to describe mechanical factors which limit the access of inspired air to the pulmonary alveoli, and thus determine airflow.
• It is determined by the diameter of the airways and by the density of the inspired gas and can be calculated using Ohm's law.
• Ohm's`Law, a fundamental law of physics, states that:-
current (I) equals the voltage difference (DV) divided by resistance (R).
$V = IR$
• In relating Ohm's Law to air flow, the voltage difference is the pressure gradient between mouth and alveolus, the resistance is the resistance to flow (R) offered by the airways and their interactions with the flowing air, and the current is the air flow (F).
$F = \Delta P/R$



Flow within a vessel

There are three primary factors determining the resistance to blood flow within a vessel (or air within an airway):

- vessel diameter (or radius),
- vessel length, and
- viscosity of the blood or gas.

Of these three, the most important quantitatively and physiologically is diameter because of changes due to contraction and relaxation of the smooth muscle in the wall. Furthermore, very small changes in diameter lead to large changes in resistance. On the other hand, vessel length does not change significantly and blood and gas viscosity normally stays within a small range so that these two can generally be considered as a constant.

- Vessel resistance (R) is directly proportional to vessel length (L) and blood viscosity (h), and inversely proportional to the radius to the fourth power (r4). Because changes in diameter and radius are directly proportional to each other (D = 2r; therefore D µ r), diameter can be substituted for radius.
- Therefore, a vessel having twice the length of another vessel of same radius will have twice the resistance to flow. Similarly, if the viscosity of the blood increases 2-fold, the resistance to flow will increase 2-fold. In contrast, an increase in radius will reduce resistance. Furthermore, the change in radius alters resistance to the fourth power of the change in radius and a 2-fold increase in radius decreases resistance by 16-fold! Therefore, vessel resistance is exquisitely sensitive to changes in radius.
- If the expression for resistance is combined with the equation describing the relationship between flow, pressure and resistance (F=DP/R), then Poiseuille's equation is described.

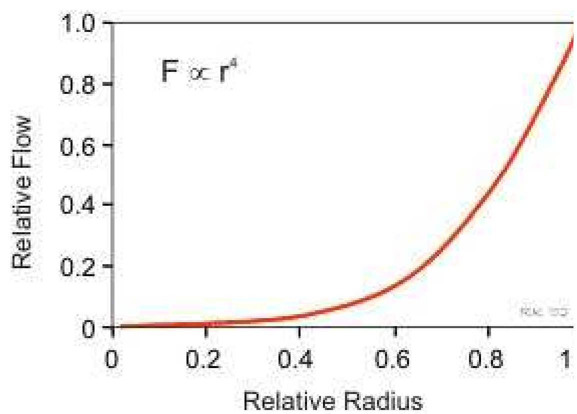
$$F \propto \frac{\Delta P \cdot r^4}{\eta \cdot L}$$

Poiseuille's Equation

$$F \propto \frac{\Delta P \cdot r^4}{\eta \cdot L}$$

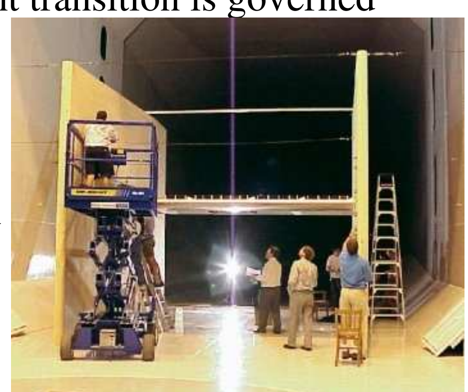
This equation was first stated by the 19th century French physician Poiseuille ("pwa-zoo-yuh") and describes how flow is related to perfusion pressure, radius, length, and viscosity.

- This relationship assumes long, straight tubes (blood vessels), a Newtonian fluid and steady, laminar flow conditions, which don't exactly apply to the body.
- Nevertheless, the relationship clearly shows the dominant influence of vessel radius on resistance and flow.
- The same principles apply when the 'fluid' is air.
- [Newtonian fluid is an incompressible uniform viscous liquid].



Reynold's Number

- Poiseuille's findings on blood circulation in the body are dependent on laminar flow, but in turbulent flow, the flow rate is proportional to the square root of the pressure gradient, as opposed to its direct proportionality to pressure gradient in laminar flow.
- Enter Osborne Reynolds of the University of Manchester. He discovered the ratio in 1883 that has since been called the Reynolds number, when examining fluid flow characteristics - how a liquid flows in a pipe. He demonstrated that the motion of a fluid may be either laminar (in smooth layers) or turbulent, and that the change from a laminar flow to a turbulent flow can happen suddenly. The transition from a smooth laminar flow to a turbulent flow always occurred when the ratio ?VD/µ was the same, where ? = density of the fluid, V = velocity, D = pipe diameter, and µ = fluid viscosity. This ratio is now known as the Reynolds number.
- Using the Reynold's equation we can see that a large diameter, with rapid flow, where the density of the blood is high tends towards turbulence.
- Rapid changes in vessel diameter may lead to turbulent flow, for instance when a narrower vessel widens to a larger one.
- Furthermore, an atheroma may be the cause of turbulent flow, and as such detecting turbulence with a stethoscope may be an indication of such a condition.
- Because laminar-turbulent transition is governed by Reynolds number, the same transition occurs if the size of the object is gradually increased, or the viscosity of the fluid is decreased, or if the density of the fluid is increased.



Turbulence

• Consider the flow of water over a simple smooth object, such as a sphere. At very low speeds the flow is laminar, i.e., the flow is smooth (though it may involve vortices on a large scale).

• As the speed increases, at some point the transition is made to turbulent flow in which unsteady vortices appear and interact with each other.

• Drag due to boundary layer skin friction increases.