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The Physics of Flow

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Introduction

Flow is defined as the quantity of fluid (gas, liquid or vapour) that passes a point per unit time. A simple equation to represent this is:

$$\text{Flow (F)} = \frac{\text{Quantity (Q)}}{\text{Time (t)}}$$

Flow is sometimes written as ΔQ (rate of change of a quantity, mass or volume).

Due to the a quantity of different fluids that are given to our patients during a routine anaesthetic, flow is an important area of physics to understand.

Consider the following questions - the answers are contained within the following text.

1. Why are the scales on rotameters (flow meters) non uniform as the flow increases? Why are there different rotameters for different gases? See Figure 1.

2. Under what circumstances is the gas in Figure 2 useful, and why?

3. Will there be much difference in ventilating through a size 4 endotracheal tube compared to a size 8 endotracheal tube?

4. How much more fluid can be administered through a 14G cannula than a 22G cannula?

In order to answer these questions we need to understand the physical principles that govern flow.
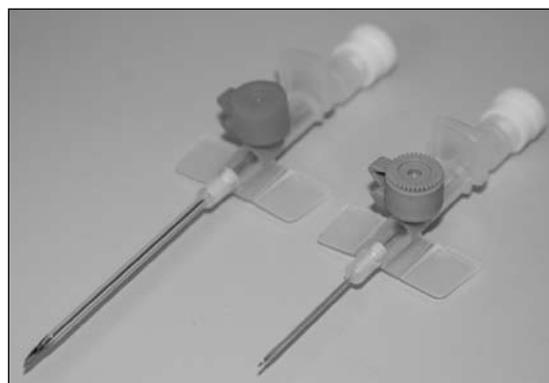

Figure 4. *22G and 14G cannulae*

THE PHYSICS OF FLOW

Flow can be divided into two different types, laminar and turbulent. A number of different physical characteristics determine whether a fluid obeys the principles of one or the other.

Summary

This article covers the definition of flow, the different types of flow are there and the physical principles govern them. The Hagan-Pouseille equation and its relevance to clinical anaesthetic practice are explained.

Figure 1. *Rotameters*

Figure 2. *Heliox*

Figure 3. *4mm and 8mm internal diameter endotracheal tubes*

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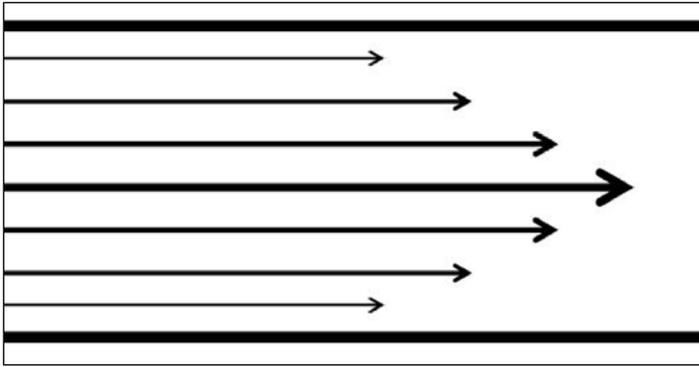Hope Hospital
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Figure 5. *Diagrammatic representation of laminar flow*

Laminar Flow

In laminar flow the molecules of the fluid can be imagined to be moving in numerous 'layers' or laminae as shown below.

Although all the molecules are moving in straight lines they are not all uniform in their velocity. If the mean velocity of the flow is v, then the molecules at the centre of the tube are moving at approximately 2v (twice the mean), while the molecules at the side of the tube are almost stationary. To help to understand this consider what happens when walking across a small river or stream; at the edge of the water by the river bank it does not feel like there is much movement of the water, whereas once you reach the middle the water is moving a lot faster. This is represented by the different lengths of the lines in the figure.

Flow is usually considered to be laminar when a fluid flows through a tube and the rate of flow is low. This is therefore the type of flow we would expect to see when a fluid flows through a cannula or a tracheal tube.

For flow to occur, there must be a pressure difference (ΔP) between the ends of a tube, and it can be demonstrated that ΔQ is directly proportional to ΔP, in other words the greater the pressure difference, the greater the flow. (We squeeze a bag of IV fluid, to increase the pressure difference between the bag and the vein, so that the fluid is given more quickly.)

As fluid flows through tubes there is resistance between the fluid and vessel wall that opposes the flow. For any given system, this resistance is constant and can be expressed as:

$$\text{Resistance, R (a constant)} = \frac{\Delta P}{\Delta Q}$$

(This can be compared with V=IR in electrical physics).

Flow is affected by a number of other physical characteristics:

Tube diameter
If the diameter (d) of the tube is halved the flow through it reduces to one sixteenth. This means that flow is directly proportional to d^4. Think about how much more rapidly fluid flows through a 16G than a 22G cannula.

Length
If the length (l) is doubled the flow is halved, therefore flow is inversely proportional to the length of the tube. A central line is much longer than a cannula, and for the same diameter fluid flows more slowly. This demonstrates why a cannula is far better for giving fluid rapidly, during resuscitation.

Viscosity
This is a measure of the frictional forces between the 'layers' of a fluid described above - almost how 'sticky' the fluid is. As the viscosity increases the flow decreases proportionally, therefore flow and viscosity are inversely proportional. Viscosity is represented as η (the Greek letter, eta).

The Hagan-Poiseuille equation brings together all of the variables that determine flow along with a constant ($\pi/128$, that is derived theoretically).

$$\Delta Q = \frac{\pi P d^4}{128 \eta l}$$

where,   P   =   pressure difference

ΔQ =   flow

d   =   diameter of tube

η =   viscosity

l   =   length of tube

Turbulent Flow

Not all fluid flow is laminar. Under certain physical conditions it becomes turbulent. When this happens, instead of the fluid moving in seemingly ordered layers, the molecules become more disorganised and begin to swirl with the formation of eddy currents, as shown in Figure 6.

Flow is less ordered and the eddy currents interfere with each other, increasing drag or resistance to flow. As a result, a greater energy input is required for a given flow rate, when flow is turbulent compared to when flow is laminar. This is best demonstrated by the fact that in turbulent flow, the flow rate is proportional to the square root of the pressure gradient, whereas in laminar flow, flow rate is directly proportional to the pressure gradient. This means that to double the flow, the pressure across the tube must be quadrupled.

When does turbulent flow occur?
Turbulent flow occurs when fluids flow at high velocity, in large diameter tubes and when the fluids are relatively dense. Also,
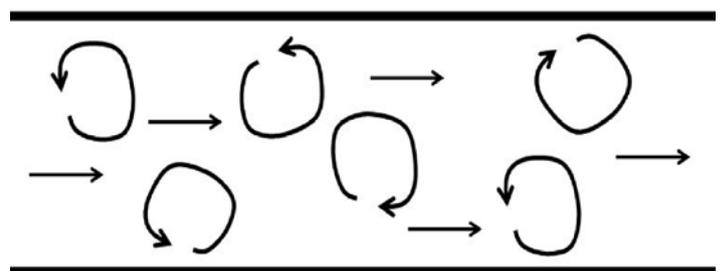

Figure 6. *Diagrammatic representation of turbulent flow*

decreasing the viscosity of a fluid leads to turbulent flow. The factors that determine when turbulent flow commences can be combined to form an equation which calculates the Reynolds number:

$$\text{Reynolds number} = \frac{v \, \rho \, d}{\eta}$$

where,   v = velocity

ρ = density

d = diameter

η = viscosity

Measurements in tubes have shown that:
- when the Reynolds number is less than 2000 there is laminar flow,

- when the Reynolds number is 2000-4000 there is transitional flow i.e. a mixture of laminar and turbulent flow,

- when the Reynolds number is greater than 4000 flow will be turbulent.

Note that Reynolds number does not have any units associated with it - it is called a dimensionless number.

This equation shows that for a given fluid (of a certain density and viscosity), in a given tube, once a critical velocity is reached flow will become turbulent. The relevance of this within the body is that whenever a tube divides (e.g. bronchi, blood vessels) or there is a sharp bend or narrowing, velocity of the fluid increases, making turbulent flow likely to occur. Blood flow in the carotid artery becomes turbulent as it flows past an atheromatous plaque, hence the bruit heard with a stethoscope.

As we have seen, as the diameter of a tube increases, the Reynolds number increases. Eventually if the diameter of the tube increases enough, it will exceed the length of the tube. We then call this an orifice (see Figure 7). Generally speaking, provided that the critical velocity is not exceeded, flow through a tube is laminar and hence dependent on viscosity, whereas if it is through an orifice it is turbulent and dependent on density.

CLINICAL APPLICATIONS

Flowmeters
The flowmeters that are commonly used on anaesthetic machines are constant pressure, variable orifice flowmeters (the tradename is 'rotameter').

These are cone shaped tubes that contain a bobbin and are specific for each gas. The gas enters the bottom of the tube applying a force to the bobbin. The bobbin then moves up the tube until the force from below pushing it up is cancelled out by the gravitational force pulling the bobbin down. At this point it remains at that level and there is a constant pressure across the bobbin (pressure is force divided by area, with the area being constant).

At low flows, the bobbin is near the bottom of the tube and the gap between the bobbin and wall of the flowmeter acts like a tube (the diameter is small compared to the length). Gas flow is laminar and
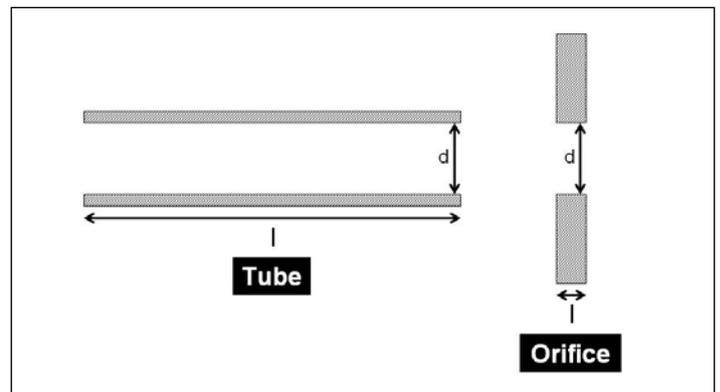
Figure 7. *Difference between a tube and an orifice*

hence the viscosity of the gas is important.

As flow rate increases, the bobbin rises up the flowmeter and the gap increases until it eventually acts like an orifice (the diameter becomes greater than the length). At this point the density of the gas affects its flow.

As flow changes from laminar to turbulent within the flowmeter:
- Individual gases have different densities and viscosities and therefore the flow past the bobbin will vary for each individual gas.

- The flow changes from being directly proportional to pressure to proportional to the square root of pressure and hence the graduations on the flowmeters are not uniform.

Heliox
Heliox is a mixture of 21% oxygen and 79% helium. Helium is an inert gas that is much less dense than nitrogen (which makes up 79% of air), therefore making heliox much less dense than air. In patients with upper airway obstruction, flow is through an orifice and hence more likely to be turbulent and dependent on the density of the gas passing through it. Therefore for a given pressure gradient (patient effort), there will be a greater flow of a low density gas (heliox) than a higher density gas (air). Although flow in the lower (smaller diameter) airways is considered to be laminar there may still be small areas of turbulence, giving some benefit, but not as much as that in the upper airways.
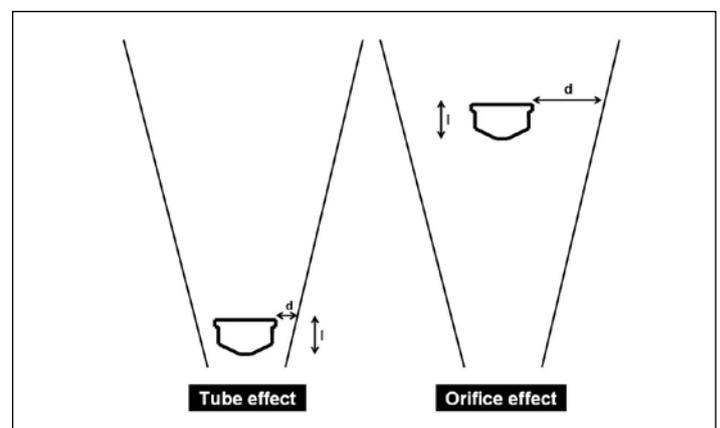
Figure 8. *Diagrammatic representation of a rotameter , showing low flow on the left and high flow on the right*

It must be noted that although flow with heliox increases in upper airway obstruction, it only contains 21% oxygen it may not be of benefit in the hypoxic patient.

Intravenous fluids

Intravenous fluids flow in a laminar fashion, therefore the rate of flow is determined by the Hagan-Pouseuille formula. This means that for a given fluid, with the same pressure applied to it, flow is greater through a shorter, wider cannula. This is why they are preferred in resuscitation to central cannulas that are long and small diameter.

To re-iterate, if the diameter of the tube is doubled the flow through it is increased by sixteen times.

Ventilation

The principles here are similar to those with the intravenous cannulae. Flow through a tracheal tube is laminar so the Hagan-Pouseuille formula applies. If a smaller diameter tracheal tube is used, then flow will be significantly reduced as it is proportional to the fourth power of the diameter, unless the pressure gradient is increased (changing the tube from an 8mm to a 4mm may reduce flow by up to sixteen-fold!). This may be relatively easy to achieve with a mechanical ventilator, but if the patient is breathing spontaneously they will need to generate a much greater negative intrathoracic pressure. This will require the patient to work a lot harder and over time they will become exhausted, tidal and minute volume will be reduced and they will become hypercapnic. This is the reason why we don't allow patients to breathe spontaneously for any length of time through narrow tubes, such as those used for laryngeal surgery.

Also, look at the rest of the breathing circuit, acute angles at connections cause turbulent flow, thereby reducing flow for a given driving pressure, and unnecessary long circuits will reduce flow making the work of breathing greater.