

Measurement of gas flow and volume

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Abstract

The ability to accurately and precisely measure gas volume and gas flow is a fundamental component in the safe provision of modern anaesthesia. This is vital for the delivery of gasses and monitoring of respiration. A range of techniques are used to measure gas volume and flow, both by direct and indirect measurement. Direct methods of gas volume measurement tend to be large and impractical. By using physical properties of gases indirect measurements can be made. Understanding the principles of these techniques allows interpretation of the data they produce. Descriptions of devices used in anaesthetic practice are given. These devices include the variable orifice flowmeter, differential pressure flowmeter, hot wire anemometer, mechanical flow transducer, ultrasonic flowmeter, Wright respirometer, Vitalograph and peak flowmeter.

Keywords Flow; flowmeter; gas; Hagen–Poiseuille equation; laminar; measurement devices; Reynolds number; turbulent; volume

Royal College of Anaesthetists CPD Skills Framework: Scientific principles

Introduction

The ability to accurately and precisely measure volume and flow of gases is a fundamental component in the safe practice of anaesthesia. To measure the volume of a gas in the simplest form, a chamber can be used, but due to size this is often impractical and other physical properties of the gas are used to derive measurements of volume and flow. To be able accurately to measure gas flow knowledge of the flow regime and the gas composition are required. With this knowledge the appropriate and correct choice of device for measurement of gas volume and flow can be made.

Gases are a type of fluid. A fluid is a substance that flows or deforms when a shear stress is applied to it, with the resistance to deformation being known as the viscosity. Liquids and plasmas are other fundamental states of matter that are fluids. Fluids can be further categorized into Newtonian and non-Newtonian fluids. A Newtonian fluid is one in which the viscosity of the fluid is constant when a varying amount of shear stress is applied. Gases in anaesthesia are considered as Newtonian fluids, as are many liquids including water. Non-Newtonian fluids demonstrate a change in viscosity when shear stress is applied. An example of a non-Newtonian fluid is blood, in which up to a point, viscosity decreases as shear stress increases. This phenomenon is known as shear-thinning.

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Learning objectives

After reading this article, you should be able to:

- calculate flow of fluid through a system
- explain the principles of and differences between laminar and turbulent flow
- describe how commonly used devices in anaesthesia measure gas volume and flow

Principles of gas flow

Relationship between flow and volume

Flow is the movement of a gas or liquid through a tube or system. The flow is defined as the volume of liquid passing a point per unit time in the following relationship:

$$\dot{Q} = \Delta V / \Delta t$$

where flow is represented by \dot{Q} , change in volume by ΔV and change in time by Δt . The symbol \dot{Q} with a dot above it represents the rate of change of quantity Q .

In a gas delivery system flow is generally constant. In physiological systems flow can vary and so volume is calculated by integrating flow rate with respect to time.

Types of flow

Laminar flow: is that which is smooth and without eddies. Flow occurs in many parallel layers, or laminae. The greatest velocity is in the centre and the lowest velocity at the edges where there is friction between the fluid and the wall. The velocity profile has a distinctive parabolic shape and is maintained as long as laminar flow exists (Figure 1).

Laminar flow is calculated from the Hagen–Poiseuille equation:

$$\dot{Q} = \Delta P \pi r^4 / 8 \eta l$$

where ΔP is change in pressure, π is the mathematical constant pi, r is the radius of the tube, l is length of the tube and η is viscosity of the fluid.

Laminar flow has a number of important features. These features include flow being proportional to the pressure difference, proportional to the fourth power of the radius and inversely proportional to the viscosity of the gas. Of note is that in a perfect laminar flow system a doubling of the internal diameter of a tube increases flow rate by 16 times.

Turbulent flow: is chaotic, irregular flow with multiple eddy currents. The velocity profile of turbulent flow is flat (Figure 2). It is more likely to occur when a tube has uneven walls, bends or if the fluid flows through an orifice. Turbulent flow can occur in laminar flow when the flow velocity is fast and exceeds the critical velocity. The critical velocity is the velocity when flow of a fluid changes from laminar to turbulent.

Unlike laminar flow, there is no single equation to calculate turbulent flow. Turbulent flow is proportional to:

- square of the radius of the tube
- square root of the change in pressure

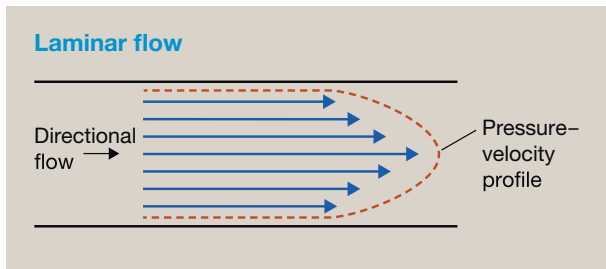


Figure 1

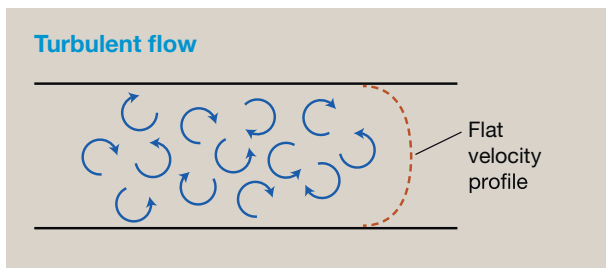


Figure 2

- inversely proportional to the length of the tube
- inversely proportional to the density of fluid.

Predicting laminar or turbulent flow: turbulent flow tends to occur in fluids that are dense, flow at high velocity, have low viscosity and flow through large diameter tubes. To predict whether fluid flow will be laminar or turbulent the Reynolds number, named after Professor Osborne Reynolds of the University of Manchester, can be calculated. The Reynolds number is a dimensionless value that gives the ratio of internal forces to viscous forces.

The Reynolds number (Re) is calculated from:

$$Re = v\rho d/\eta$$

where v is the linear velocity of the fluid, ρ is the density of the fluid, d is the diameter of the tube and η is the viscosity of the fluid.

When the Reynolds number is less than 2000, flow is predominately laminar, and when greater than 4000 is predominantly turbulent. When the Reynolds number is between 2000 and 4000 the flow is called transitional. In transitional flow laminar flow occurs with some eddies in it.

From the equation for Reynolds number it can be shown that for a fluid of known density and viscosity that once the critical velocity is reached flow becomes turbulent. In addition, as the diameter of the tube increases the Reynolds number, and therefore tendency to turbulent flow increases. If the diameter of a tube increases so that it exceeds the length of a tube, then it is known as an orifice. In general terms flow through a tube is, laminar if the velocity is below critical velocity and flow through an orifice is density dependent and turbulent.

Measurement of gas volume and gas flow

Principles of measurement

When measuring gas volume and flow measurement can be either direct or indirect. In direct measurement gas volume and

flow is measured using an enclosed space of a known volume. The major limitation of these devices is their size as they tend to be large and bulky. Due to their large size they are limited in where they can be used.

The alternative to direct measurement of gas volume and flow is indirect measurement. With indirect measurement a physical property of the gas is measured which changes with flow. This changing property is then measured and from its values for gas volume and flow can be calculated.

The ideal device for measuring gas volume and flow would have the following features:

- accurate across a wide range of flow rates
- unaffected by gas composition
- unaffected by temperature
- unaffected by condensation
- low resistance
- no affect to performance over time
- portable.

Devices for measuring gas volume and flow

Benedict–Roth spirometer – water-displacement spirometer:

The Benedict–Roth spirometer directly measures gas volume and has been in use since the nineteenth century. It consists of an expandable compartment, a movable, statically counterbalanced, rigid chamber, a base and a dynamic seal between them. The chamber moves up and down freely, and the movement of the chamber is proportional to changes in internal volume. The movement of the chamber is then recorded on a calibrated rotating drum. Measurements recorded include tidal volume expiratory reserve volume and inspiratory reserve volume. The Benedict–Roth spirometer can underestimate expired volumes due to expired air cooling and condensation of water vapour inside the spirometer (Figure 3).

The Vitalograph: was developed in the 1960s and initially used to screen coal miners for pneumoconiosis. It contains a set of bellows attached to a top plate. As the bellows fill the top plate pivots and the motion is recorded on a chart. When the patient exhales the motor on the scribe starts and an expired time–volume plot is created. From the plot values including forced vital capacity and forced expiratory volume in 1 second can be derived.

The Wright respirometer: was developed by Dr Basil Wright in the 1950s. The device contains angled slits which direct exhaled gas to a central vane that rotates (Figure 4). This vane is connected through a series of gears to a pointer which displays volume of gas measured. The vane only rotates on exhalation and is only calibrated to measure tidal volume. It cannot be used to measure continuous flow.

Electronic rotating vane flowmeter: this device is based on the principles of the Wright respirometer. There is a small turbine in the gas flow path. The rotation of the turbine is related to the volume flow of gas. As the turbine moves a light beam is interrupted, which is converted to a voltage proportional to the flow and continuous read out. It can be used to measure tidal volume and minute ventilation.

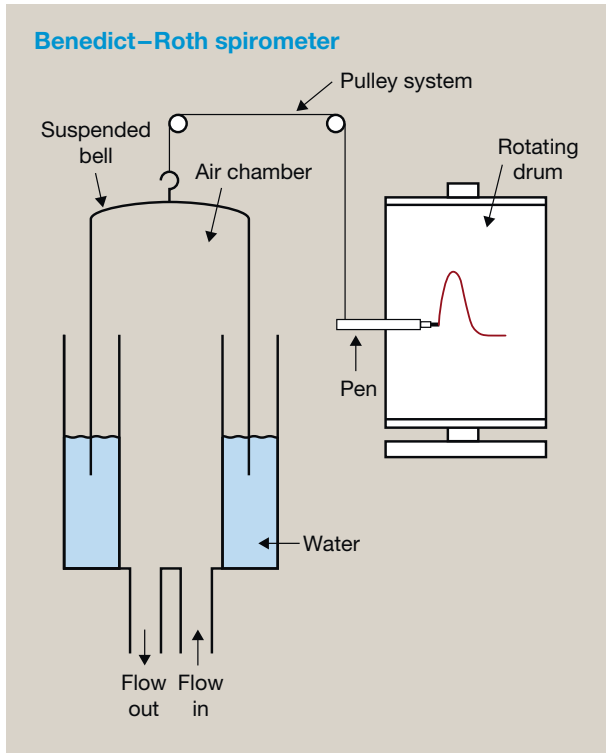


Figure 3

The variable orifice flowmeter: also commonly known by the tradename Rotameter, is a commonly used measurement device in gas delivery systems requiring a continuous flow measurement. This type of flowmeter comprises a simple design without the need for a power supply. It most commonly has a vertical tapered tube within which a float is contained. Below this glass

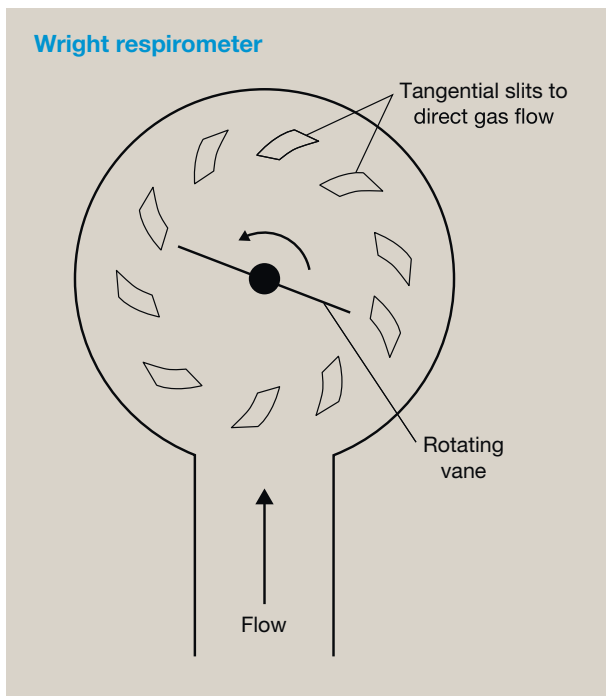


Figure 4

tube is a control knob with a needle valve that allows precise adjustment of gas flow. The float is then supported by the upward flow of gas within the tube. When gas flow starts the float rises until the downward force of gravity is balanced by the upward force of the gas (Figure 5).

In the lower, narrower part of the tube the annulus is long compared to its cross-sectional area and resembles a tube. In this part of the flowmeter the gas flow is predominantly laminar and viscosity dependent. In the higher, wider part of the flowmeter the annulus is short compared to its cross-sectional area and resembles an orifice. In the higher part of the tube density dependent, turbulent flow tends to predominate.

Variable orifice flowmeters are calibrated for a particular gas as density and viscosity affect the position of the float. The float is usually either a bobbin or ball. If a bobbin is used then flow rate is taken from the top of the bobbin and if a ball is used flow rate is taken from the middle of the ball. Most variable orifice flowmeters can read over a wide range of flow rates by using a variable taper or having low and high flow devices in series. They are designed to be read in the upright position. The variable orifice flowmeter is often found on the auxiliary oxygen supply of anaesthetic machines, as they do not require external power if electricity supply fails.

Static electricity and dirt may cause the float to become stuck. To prevent static electricity the internal walls of the flowmeter are coated with a conductor and earthed. The float, when a bobbin, rotates due to flutes along its length to indicate that it is not stuck. Downstream pressure can cause the flowmeter to read low, when flow rate has not changed.

Peak flowmeter: the Wright peak flowmeter is a device for measuring peak expiratory flow rate. It is a constant pressure variable orifice device and is able to measure flows of up to 1000 litres per minute. Exhaled air is directed by a fixed baffle into a movable vane, which moves against a spring and a slot in the base allows gas escape. The vane moves and in doing so opens up the slot, increasing the orifice size. Peak expiratory flow rate is then read from a dial.

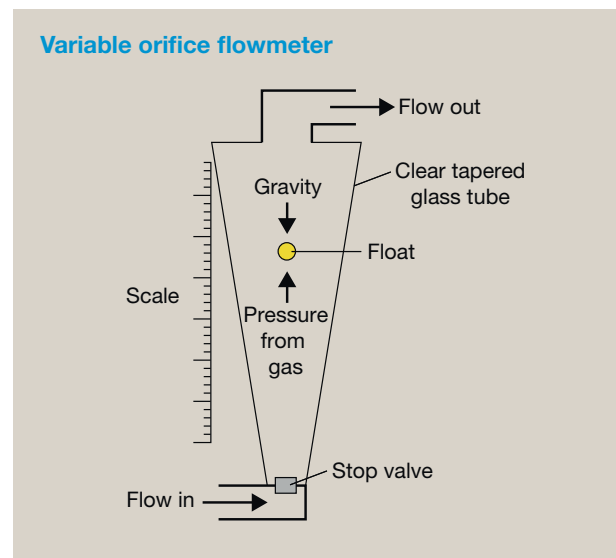


Figure 5

An alternative version known as the Mini-Wright peak flowmeter is available. This has a cylindrical shape and a piston to blow along the length. As the piston is blown along the linear slot along the tube opens and a value is read from the scale. It also works on the variable orifice principle.

Differential pressure flowmeter – pneumotachograph: the pneumotachograph, also known as the pneumotachometer, is a circular tube containing a fine metal mesh. The fine metal mesh provides a small resistance and allows laminar flow. During breathing gas flow causes a small pressure difference across the mesh. A small tube on each side of the mesh connects to a pressure sensor. The drop in pressure across the sensor is directly proportional to the volumetric flow rate of the gas.

There are two main types of pneumotachograph. The Lilly pneumotachograph measures the pressure difference across a membrane of known resistance (Figure 6). The Fleisch pneumotachograph measures pressure difference across a series of parallel tubes. Fleisch pneumotachographs are considered to be more reliable than Lilly pneumotachographs.

The pneumotachograph has no moving parts which helps make it a reliable device. Condensation of water vapour can potentially lead to increased resistance in the device. To prevent water vapour condensation a heating element is incorporated.

Differential pressure flowmeter – Pitot tube flowmeter: the Pitot tube flowmeter is similar to the pneumotachograph but does not contain a flow resistor. In the Pitot tube flowmeter two pressure sensors are connected to a pair of tubes. One tube faces into and parallel with the fluid flow and the other tube faces backwards and away from the fluid flow. With this symmetrical design flow measurements can be made in either direction. Gas in the tube facing the flow is compressed and the pressure rises, which is called dynamic or total pressure. The tube facing away from the pressure measures static pressure. The difference in pressure between the two tubes is dependent on the kinetic energy of the gas. The kinetic energy is converted into potential energy and the pressure difference is equal to the square of the velocity. From this flow can then be calculated (Figure 7).

The Pitot tube is simple, inexpensive, reliable and can work across a range of temperatures and pressures. The Pitot tube only

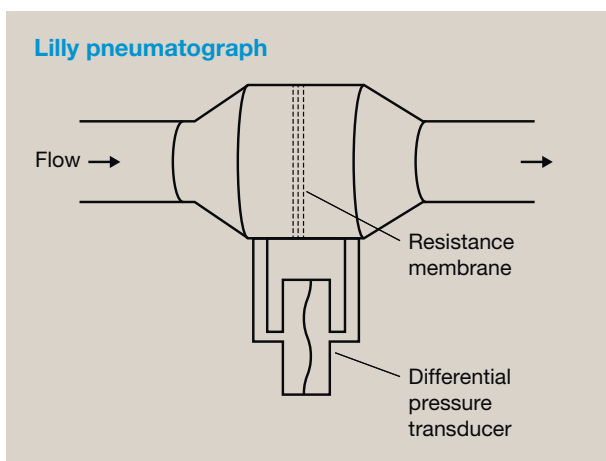


Figure 6

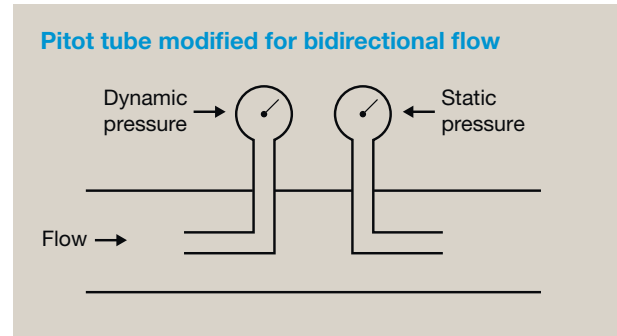


Figure 7

takes measurement in one part of a system. The tube can become occluded by foreign matter in the system and lead to inaccuracies.

The hot wire anemometer: is based on the principle of thermal energy transfer. Within the flow of gas are placed resistance wires. The wires are then heated and cooled as gas flows over them. As the wires cool their resistance reduces. Originally the wire was part of a Wheatstone Bridge circuit. Now the change in resistance is measured directly and converted from an analogue to digital signal. At this point a microprocessor can make corrections related to gas composition and to improve accuracy (Figure 8). This a common type of flowmeter found on many anaesthetic machines.

Mechanical flow transducers: use the principle of mechanical movement generated by gas flow. Gas flow is split down a side channel. In the side channel is a metal disc supported by a flexible pin. The gas flow exerts a pressure on the and causes the pin to bend. This then leads to compression of a strain gauge behind the pin. Following this an electrical signal is generated and from this a flow rate calculated.

Ultrasonic flowmeters are of two main types: time-of-flight flowmeters and vortex shedding flowmeters. In a time-of-flight system two ultrasound transmitter/receivers are placed on either side of a gas flow at an oblique angle. Ultrasound pulses are emitted and received by each device. The upstream time-of-flight is increased with increased flow and the downstream time-of-flight is decreased with increased flow. From knowing the distance between the ultrasound units and the time-of-flight

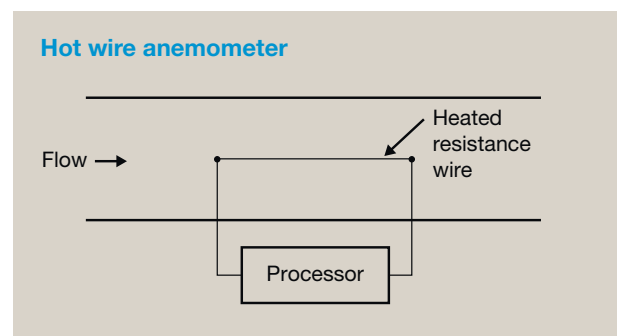


Figure 8

the flow of gas can be calculated. The absolute time-of-flight is dependent on the speed of sound in the gas and is affected by gas composition.

The vortex shedding flowmeter consists of a tube in the middle of which is a bluff body. The bluff body is designed to create vortices downstream from it. The number of vortices produced is proportional to the flow rate. An ultrasound beam is placed downstream and at 90° to the direction of flow. This can then detect the number of vortices. A second bluff body can be added to make the system bidirectional. Changes in gas composition can change the amount of vortex shedding. ◆

FURTHER READING

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