Measurement of gas volume and gas flow

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Abstract

Accurate measurement of gas flow and volume is vital for the safe conduct of anaesthesia. Gas volume, and hence gas flow, may be measured directly with devices such as the vitalograph; however these devices have limited use in clinical practice, as they are bulky and unsuitable for measurement of continuous flow.

This has led to the development of techniques that measure gas flow indirectly by using physical properties of the gas. Methods include mechanical devices such as the variable orifice flow meter (Rotameter™) or the peak flow meter. Various electrical techniques have also evolved such as the pitot tube flow meter and the pneumotachograph, which rely on differential pressure transducers.

There is also the Wheatstone bridge circuit based on a hot wire anemometer, and a mechanical flow transducer that is reliant on an electrical strain gauge.

More recently ultrasonic flow meters have been developed, which are advantageous as they have no moving parts and can be situated outside pipes; and hence do not cause an increase in resistance to gas flow.

Keywords Flow; flow meter; gas; Hagen–Poiseuille equation; laminar; measurement; Reynolds number; turbulent; volume

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Learning objectives

After reading this article, you should be able to:

- discuss the scientific principles of gas flow and the differences between laminar and turbulent flow
- describe the various physical principles underlying direct and indirect measurement of gas flow and volume
- explain the functions of a Benedict Roth spirometer, a variable orifice flow meter (Rotameter™), a pneumotachograph and an ultrasonic flow meter

Introduction

Accurate measurement of gas flow and volume enables precise delivery of gas mixtures and accurate monitoring of respiratory volumes in ventilated and spontaneously breathing patients. As gases are fluid, compressible and often invisible, they are difficult to measure. Gas volumes can be measured directly with a calibrated chamber. However, in clinical practice measurement is usually made using various properties of the gas that change in relation to flow or volume and which can be more easily measured.

Scientific principles of gas flow

Gas flow ($\dot{Q}$) refers to volume flow per unit time as opposed to the linear velocity (v) of the flowing gas.

Under conditions of constant flow the relationship between flow and volume (V) is given by the equation:

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

where t = time.

In the physiological setting, flow is rarely constant, therefore volume (e.g. tidal volume) must be calculated by integrating measured flow rate with respect to time. Alternatively a graphical plot of flow against time may be used as the area under the curve represents volume.

Laminar flow (Figure 1)

Laminar flow is efficient. The layers of fluid pass smoothly over each other to produce a parabolic (bullet shaped) flow profile within which the greatest velocity lies centrally and the velocity of those molecules in contact with the walls of the tube is zero. It is most likely to occur at low flow rates in smooth-walled, parallel-sided channels of greater length than diameter (i.e. tubes).

The laminar flow rate is predicted by the Hagen–Poiseuille equation:

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

where $\dot{Q}$ is flow, P is pressure drop, r is the radius of the tube, η is viscosity and l is the length of the tube.

Therefore laminar flow is:

- directly proportional to pressure drop
- proportional to the fourth power of the radius
- related to the viscosity but not the density of the gas.

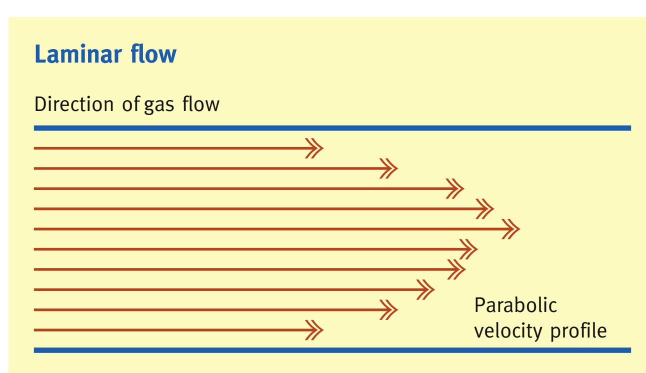

Figure 1

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Turbulent flow (Figure 2)

Turbulent flow is less efficient. It has multiple eddy currents, which occur in the overall direction of flow resulting in a flat velocity profile. It is likely to occur at high flow rates in channels with sharp bends, uneven walls, constrictions, junctions and channels where diameter is greater than length (i.e. orifices).

Turbulent flow is:
- directly related to the square root of the pressure drop
- inversely related to the density of the gas
- inversely related to the length of the tube
- approximately related to slightly greater than the fourth power of the diameter of the tube.

The Reynolds number

A variety of factors determine the type of flow that predominates and these are combined to give the dimensionless Reynolds number (Re):

$$Re = \frac{v\rho d}{\eta}$$

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

$Re < 2000$ indicates that flow will probably be laminar, whereas $Re > 3000$ predicts turbulent flow. If $2000 < Re < 3000$, laminar or turbulent flow may occur ('transitional flow').

Direct measurement of gas volume

Gas volume and associated gas flow can be measured directly through bulk filling of an enclosed space of known volume. These devices present logistical problems and their use in clinical practice is therefore limited.

Mechanical devices

Benedict Roth spirometer (water displacement spirometer) (Figure 3)**:** previously this was widely used for physiological and clinical studies. The patient's tidal volume moves a light bell suspended over a water seal. The motion of the bell is transmitted via a wire over pulleys to a pen. The pen records the movement and hence the volumes on a rotating drum.

The vitalograph: a set of bellows is used to measure gas volume. As the top plate pivots it transfers the motion to a scriber, which records volume changes on a chart. The chart is driven by a motor and automatically starts when the patient exhales and the bellows start to move. This produces an expired volume–time graph.

Wright respirometer: angled slits direct exhaled breath to a central vane which rotates with gas flow. The vane is connected via a series of gears to a gauge, which displays the volume measured. The vane does not rotate on reversal of flow and is only calibrated to measure tidal volume. It is inaccurate if used to measure continuous flow.

Drager volumeter: based on Wright's respirometer, this device contains two interlocking, lightweight dumbbell-shaped rotors. It is therefore bidirectional and records volume more accurately.

Electronic volume monitor: also based on the Wright's respirometer, this device depends on the rotation of a vane mounted on jewelled bearings within the flow of gas. The gas is passed through a set of six fixed, angled blades on either side of the moving vane which create spiral movement of the gas. The vane moves clockwise with inspiration, and anticlockwise with expiration. Two paired infrared beams and photo detectors monitor movement of the vane, which breaks the beams during rotation. A computer processor analyses the signal to produce a reading for tidal volume and minute ventilation.

Indirect measurement of flow and volume

Mechanical devices

Variable orifice flow meter (e.g. Rotameter™) (Figure 4)**:** Rotameters™ are commonly found in gas delivery systems

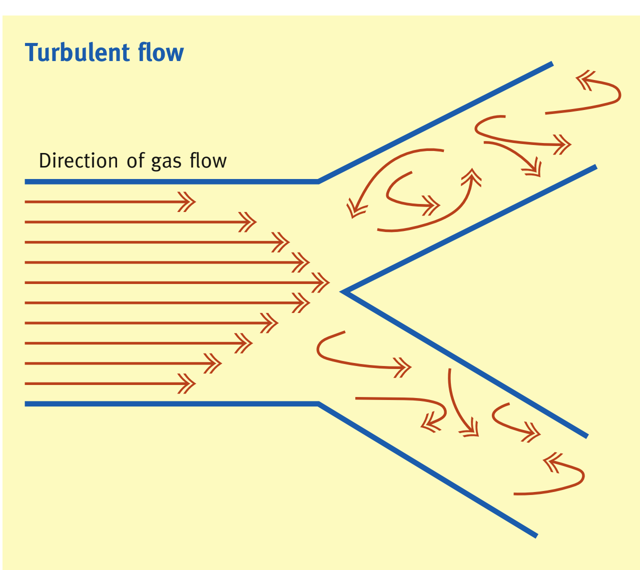

Figure 2

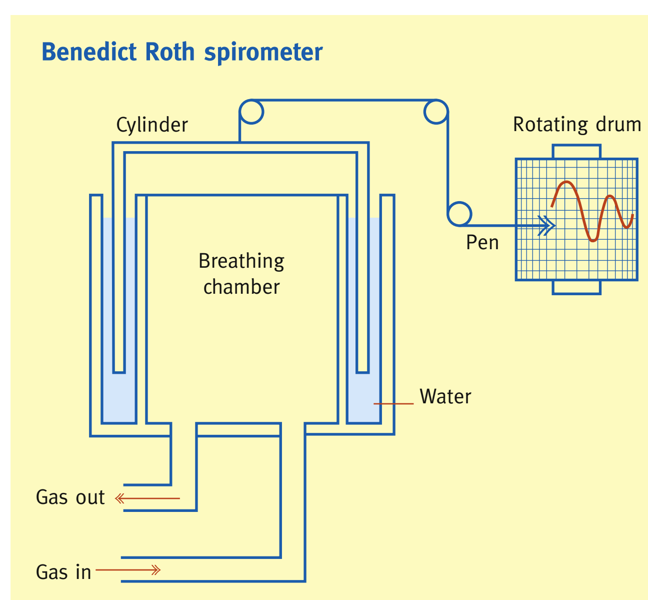

Figure 3