Measurement of gas volume and gas flow

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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

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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Introduction

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

Scientific principles of gas flow

Gas flow ($\dot{Q}$) refers to the 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:

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

(t = time).

In the less controlled physiological setting (e.g. tidal volume), flow is rarely constant; here 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

Laminar flow is efficient. The molecules move forwards in smooth, concentric layers and produce a parabolic 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 in smooth-walled, parallel-sided channels of greater length than diameter (e.g. tubes) and at low flow rates (see Figure 1).

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

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

where $\dot{Q}$ is flow, ΔP is the pressure difference, 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 the pressure difference between the two ends
- proportional to the fourth power of the radius.
- inversely proportional to the viscosity of the fluid.

Turbulent flow

Turbulent flow is more likely to occur at high flow rates, and characterized by the irregular and chaotic movement of particles in a fluid. It is less efficient and has multiple eddy currents, which occur in the overall direction of flow resulting in a flat velocity profile. It is likely to occur in channels with sharp bends, uneven walls, constrictions, junctions and where channel diameter is greater than channel length (e.g. orifices) (see Figure 2).

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.

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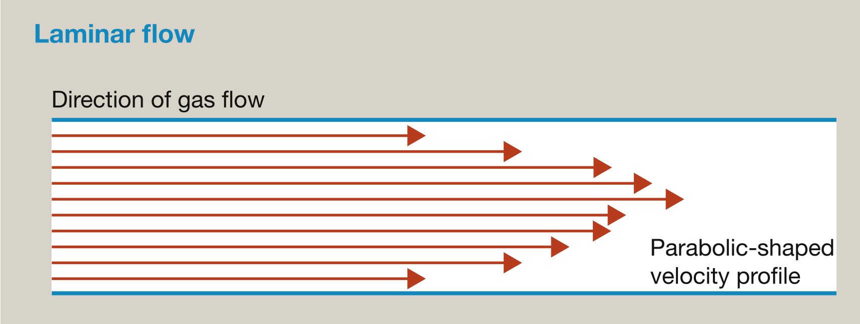

Figure 1

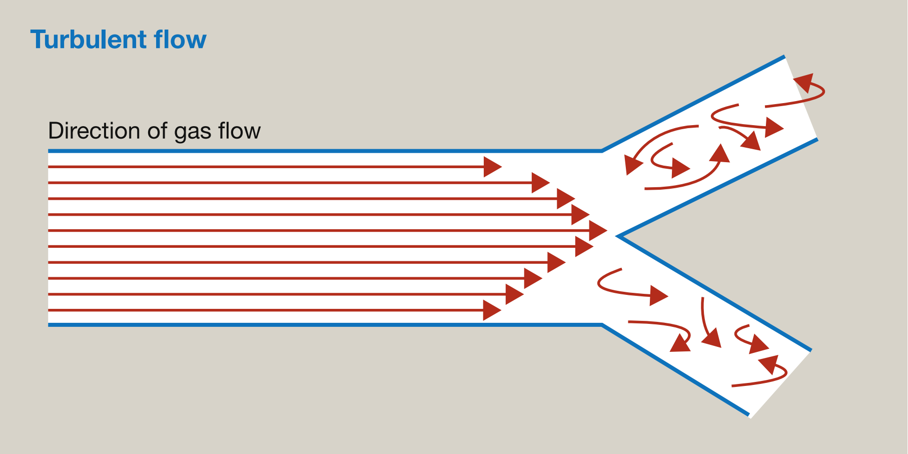

Figure 2

The Reynolds number

The Reynolds number (dimensionless) is the ratio of inertial forces to viscous forces, and is a predictor of whether a fluid flow condition will be laminar or turbulent. A variety of factors determine the type of flow that predominates. These are combined to give the Reynolds number (Re).

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

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.

- $\mathrm{Re} < 2000$ indicates flow will probably be laminar.
- $\mathrm{Re} > 3000$ indicates turbulent flow.
- $2000 < \mathrm{Re} < 3000$, laminar or turbulent flow may occur (‘transitional flow’).

Measurement of gas volume and flow

Methods of gas volume and flow measurement can be broadly separated into two groups, direct and indirect. Filling of a chamber of known volume allows direct measurement. Using other physical properties of a gas which alter with flow enables indirect measurement of volume (and hence flow).

Mechanical devices

Direct measurement of gas volume: Gas volume, and hence the associated gas flow, can be measured directly through filling of an enclosed space of known volume. These devices present various logistical problems and hence their use in clinical practice is limited.

Benedict Roth spirometer (water displacement spirometer) — Prior to the advent of more advanced techniques, this was widely used for physiological and clinical studies. The patient’s respiratory cycle moves a light bell suspended over a water seal. The motion of the bell is transmitted via a wire over pulleys to a pen which records the movement and hence the volumes on a calibrated rotating drum (see Figure 3).

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 from their empty position. This produces an expired volume—time graph. Parameters including the forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1) can be derived from the 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 pointer 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