Measurement of Volume and Flow in Gases

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The ability to measure gas flows and volumes accurately is essential to the anaesthetist, both for precise delivery of gas mixtures and for monitoring respiratory volumes in the ventilated or spontaneously breathing patient. Gases are fluid, compressible and usually invisible, which makes them difficult to measure. Gas volumes (and associated flows) can be measured directly using a system with a calibrated chamber, but in clinical practice, measurement is usually made indirectly, using a property of the gas that changes in parallel to flow or volume and which can be more easily determined.

Scientific principles

To understand the working principles of the various devices used for measurement, a few aspects of the relevant basic science must be considered. Gas flow conventionally refers to volume flow per unit time (Q) rather than linear velocity (v) of the flowing gas.

Relationship between flow and volume: for gas delivery systems (e.g. oxygen flowmeters), flow is generally constant and the relationship between flow and volume is expressed by \( V = Q \times t \), where \( V \) is volume, \( Q \) is flow and \( t \) is time.

In a physiological setting (e.g. tidal volume) flow is seldom constant and thus volume must be calculated by integrating the measured flow rate with respect to time. In a graph plotting flow against time, this represents the area under the curve; if the data are recorded electronically it is usually computed.

Types of flow: the influence of many of the variables that determine flow depends on whether flow is laminar or turbulent. Several factors determine which type of flow predominates, and these are amalgamated into Reynolds’ number (Re), a dimensionless value that can be calculated for a smooth parallel-sided tube by:

\[
Re = \frac{v \cdot \rho \cdot d}{\eta}
\]

where \( v \) is linear velocity, \( \rho \) is density, \( d \) is diameter and \( \eta \) is viscosity. At an Re less than 2000 flow will probably be laminar; an Re over 2000 indicates flow is likely to be turbulent.

Laminar flow is efficient, with layers passing smoothly over each other producing a parabolic (bullet-shaped) flow profile, with the greatest velocity centrally. It is determined by the Poiseuille–Hagen formula:

\[
Q = \frac{P \cdot \pi \cdot r^4}{8 \cdot \eta \cdot l}
\]

where: \( P \) is pressure drop, \( r \) is the radius of the tube and \( l \) is the length of the tube. Important features are that flow is:

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

Turbulent flow is less efficient, with multiple eddy currents occurring in the overall direction of flow. Because of the variable nature of turbulence, there is no precise and comprehensive equation to calculate flow, but turbulent flow is related to the:

- square root of the pressure drop
- density of the gas rather than its viscosity.

If flow is being calculated by measuring one of the above variables, unforeseen changes in any of the others will compromise accuracy. Changes could occur directly, such as by alteration in gas composition, or indirectly, such as temperature variation causing a change in viscosity.

Working principles

Direct measurement: gas volumes (and associated flows) can be measured directly using bulk filling of an enclosed space of known volume. Instruments using direct measurement include the gas meter, vitalograph and water-displacement spirometer. Because of the logistical problems of such devices, their use in clinical practice is limited.

Indirect measurement: for clinical use, measurement is usually made indirectly, using a property of the gas that changes in parallel to flow or volume and which can be more easily determined.

Pressure drop across a resistance – as flow occurs through a resistance, a pressure drop occurs. This effect can be used to calculate flow by:

- keeping the resistance constant and measuring the pressure change as the flow varies, as in a pneumotachograph
- having a constant pressure drop and varying the resistance in a measurable way (e.g. bobbin rotameter).

Mechanical movement – flowing gas has kinetic energy related to its velocity, which can be converted into a measurable value by:

- rotation of a vane (e.g. a spirometer)
- bending a flexible obstruction, transducing this to produce an electrical signal.

Heat transfer – gas flowing past a heated element acts to cool it, as in a hot-wire anemometer.

Ultrasound interference – the velocity of an ultrasound signal is increased by a gas flowing alongside it in the same direction, and decreased if the gas is flowing against it.

Ideal features of a device used for gas flow or volume measurement in clinical practice include:
• accurate across a wide range of flows
• unaffected by changes in gas temperature or composition
• low resistance so that it can be used in a spontaneously breathing patient
• minimal impairment of performance with prolonged use.

Measurement site: for measuring tidal volume, it is important that the characteristics of the breathing system are taken into consideration when deciding where to measure. For a semi-closed rebreathing system (any of the Mapleson A–F classification – see Anaesthesia and Intensive Care Medicine 2:1: 70), measurement must be made at the distal end of the system, adjacent to the mask or tracheal tube, or the fresh gas flow may produce an addition to the tidal volume.

With some older designs of circle system, circulating fresh gas flow could erroneously increase the tidal volume when measured within the circle and the only reliable site was distal to the Y-piece. With improved circle design, appropriate placement of flow sensors adjacent to the unidirectional valves enables the tidal volume to be measured accurately within the circle in the inspiratory or expiratory limb.

Intensive care ventilators are non-rebreathing systems, and measurements can be made accurately in the inspiratory or expiratory parts of the system. In practice, both inspiratory and expiratory tidal volumes are usually measured, because clinically important discrepancies between them can occur, for example a leak caused by lung pathology or the use of an uncuffed tube.

Specific devices

Most devices for measuring gas flow and volume measure the whole gas flow, though some incorporate a mechanism for splitting the flow and then measure only a part of it, extrapolating from this sample to calculate the whole flow. Devices may be designed to measure primarily flow or volume, though the two are closely related and information about both may be readily obtained. Some devices also give other clinical data, such as inspiratory pressure and information about the pattern of flow.

Gas meter

A gas meter acts as a volumetric turnstile, with sequential filling of internal chambers of known volume and recording the number of times each has been filled. They are classified as dry or wet, depending on whether an underwater seal is used in the mechanism. They have a substantial resistance and are cumbersome, thus largely restricting use to industrial applications.

Vitalograph

The vitalograph is used specifically to record a single vital capacity breath. Its design uses an expanding bellows with a recording pen attached and a motor to move the paper at constant speed. Volume is displayed on the y-axis and time on the x-axis, so that the pattern of expiration is shown as well as the volume.

Water-displacement spirometer

A water-displacement spirometer involves directing gas (usually respiratory gas) into an inverted bell chamber that is immersed in water but free to move up and down via a pulley as the volume of gas in the chamber varies. This movement is linked to a record-
the flow increases its position in the tube rises, lowering the resistance as a larger pathway is created alongside the bobbin.

Amalgamation of the space for gas flow around the bobbin to equate to a simple pathway reveals that at the bottom of the flowmeter the resulting dimensions lead to laminar flow but at the top of the tube produce turbulent flow. The physical characteristics of the gas that determine the resulting flow are therefore viscosity at the bottom and density at the top of the tube. The main implication of this is that calibration of rotameters is gas-specific and for accuracy its use must be restricted to that gas. Calibration is usually done to read the flow rate from the top of a bobbin but the centre of a ball.

The range of gas flow measurements can be increased by using two tubes (one for low and one for high flow rates), or by varying the taper so that a greatly increased diameter results at the top of the tube.

Inaccuracy results from anything that causes the bobbin to stick in the tube, including dirt or static electricity. To prevent build-up of static, the inside walls of a rotameter and its mounting points are made of conductive material. To demonstrate that the bobbin is not stuck, it has angled flutes to produce rotation, which is made easier to see by appropriate colouring.

Back pressure caused by downstream resistance also leads to an inaccurately low reading on a rotameter, though the actual flow is the same as that shown before the resistance was applied.

Vane meters
The most common vane meter is the Wright’s spirometer, in which the gas flow is directed tangentially to strike a rotating vane in the gas pathway (Figure 3). Originally this rotation was linked mechanically to a needle and the volume read from the adjacent dial, but modern versions use a light source and photodetector positioned across the vane to count its rotation. The Wright’s spirometer tends to under-read at low flows (because of friction) and to over-read at high flows (because of momentum).

The peak flow meter is a specialized vane meter that measures the maximum flow rate only, without calculation of the associated volume. It is modified so that movement of the vane by expiratory gas results in a steadily enlarging pathway for gas escape. The final position to which the bar has moved corresponds to the peak expiratory flow rate.

Its clinical use is to assess conditions such as asthma, where the problem is largely confined to airway resistance, which limits the expiratory flow rate. Although its use is limited in this respect, it is a very simple and reliable bedside test.

Mechanical flow transducers
Another device using mechanical movement is the flow transducer used in the Siemens Servo™ 300 and 900 series intensive care ventilators. The gas flow is split so that measurement is made in a small side channel using a thin metal disc supported on a flexible pin, resembling a lollipop (Figure 4). The disc is placed in the measuring channel at right angles to the direction of gas flow, which results in it being bent backwards by the flow. A strain gauge situated immediately behind the pin is compressed as it is bent, with a force dependent on the flow. The resulting electrical signal is processed to calculate the flow rate with a high degree of accuracy.

Hot wire anemometer
In this device an electrically heated wire is placed in the gas pathway, which is cooled by the gas flow (Figure 5). The degree of cooling depends on the gas flow rate, which can thus be calculated. A modification of this device uses a heated screen or film instead of a wire.

The hot wire (usually platinum) has an operating temperature as high as 400°C, and is incorporated into a balanced Wheatstone bridge circuit. Cooling the wire changes its resistance and unbalances the bridge. Most designs work on the constant-temperature system, whereby a correcting current is applied
through the hot wire to compensate for the cooling effect of the
gas, maintaining a constant wire temperature and thus restoring
the balance in the Wheatstone bridge. This current is measured
and from it the gas flow rate is determined. To compensate
for changes in the gas temperature, a second wire is usually incor-
porated, which is maintained at ambient temperature. Minor
corrections are also made according to the gas composition, to
accommodate the variation in specific heat capacity, but hot wire
anemometry is generally extremely accurate.

This cooling effect occurs with flow in either direction, and
so to measure exhaled tidal volume the hot wire anemometer is
placed in the expiratory limb of the circuit. It can be modified
to provide information about the direction of flow by using an
additional heated wire placed just downstream from a small bar,
as shown in Figure 5b. This bar shelters the wire from the full
cooling effects of flow in one direction but not the other, and
thus inspiratory and expiratory flows can be calculated
separately. For this purpose the sensor must be placed in the
Y-piece of the circuit. This technique is particularly useful for
neonatal ventilation.

**Ultrasonic flowmeters**

Ultrasonic flowmeters work on the principle that when an ultra-
sound signal is being transmitted within a flowing gas, its vel-
cocity changes in proportion to that of the gas flow. When the gas
flow and ultrasound signal are in the same direction, an increase
in signal velocity occurs. Conversely, when the signal is against
the direction of gas flow, its velocity decreases. The usual design
is to incorporate a pair of ultrasound beams aimed in opposite
directions, each with a sensor. The beams can be situated either
directly along the line of flow (within the lumen of the tubing) or
tangentially across it (Figure 6). When no flow is present the
velocity of the two beams is equal, and pulses of ultrasound arrive
at the sensors simultaneously. When flow occurs there is a time
difference between signal detection at the sensors, from which
the gas velocity and flow rate can be calculated.

**CROSS REFERENCE**

**FURTHER READING**

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