Gas, tubes and flow

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Abstract

Gases behave as 'fluids' under flow conditions. There are two main flow patterns: laminar and turbulent. Here, we review the flow characteristics of gases and how they relate to the airway and endotracheal tubes. An understanding of these characteristics can be manipulated to improve flow in clinical situations; for example, using a gas with a lower density than air such as heliox reduces turbulent flow and may be helpful in patients with airway obstruction. The Bernoulli principle and Venturi effect have been used to develop fixed-performance masks, jet ventilators and suction devices.

Keywords Bernoulli principle; Coanda effect; fluid flow; heliox; laminar flow; turbulent flow; Venturi effect; viscosity

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Learning objectives

After reading this article, you should be able to:

- understand flow characteristics of gas through tubes
- understand the characteristics of laminar and turbulent flow and how they relate to the respiratory system
- understand the Bernoulli principle and Venturi effect and how they can be incorporated into medical devices

Gases and liquids have different physical properties but behave similarly under flow conditions and are both 'fluids'. An understanding of the principles of fluid mechanics is helpful when looking at flow of gas within the respiratory system. The behaviour of gases is described in terms of pressure, volume and temperature and is governed by the gas laws (Box 1). The general physical principles governing the behaviour of gases are described in *Anaesthesia and Intensive Care Medicine* 2012; **13(3):** 102–105.

Fluid flow

Flow is defined as the *volume of gas or liquid passing a cross-sectional area per unit of time*; its dimension is litres per second.

It is produced by application of a pressure gradient. The two main patterns of flow are: laminar and turbulent flow.

Laminar flow

During laminar flow, the molecules of the fluid move in smooth parallel concentric streams without eddies. Molecules at the edge of the tube move more slowly than those in the middle due to the frictional forces between the fluid and the side of the tube; this produces the classical parabolic flow profile (Figure 1). Laminar flow in Newtonian fluids (fluids with constant viscosities) is governed by Poiseuille's law and the Hagen–Poiseuille equation:

$$\text{Flow}(Q) = \frac{\pi \text{Pr}^4}{8\eta l}$$

where Q is the flow rate, P is the pressure gradient along the tube, r is the radius of the tube, η is the viscosity of the fluid, and l is the length of the tube.

Important features of laminar flow are:

- the pressure drop down the tube is directly proportional to the flow rate and *inversely proportional to the viscosity* (not the density) of the fluid
- resistance is inversely proportional to the 4th power of the radius.

Viscosity (pascal seconds, Pa s) is the property of a fluid that causes it to resist flow, it refers to the 'stickiness' of a fluid. When comparing the flow of water through a tube with a more viscous substance such as honey, water flows faster. The velocities of the adjacent layers of the fluid differ, and a 'slip' occurs between parallel layers as a result of the shear force acting between them. It is dependent on the intermolecular forces. At higher temperatures the molecules have more kinetic energy and, therefore, it is easier to break the bonds and viscosity decreases and hence the flow increases. The viscosity of Newtonian fluids decreases with increase in temperature and, hence, flow increases. Blood is non-Newtonian and its viscosity is largely dependent on haematocrit, red cell characteristics and blood protein levels. Its viscosity increases in diseases such as leukaemia and flow decreases, which can result in 'sludging' in the pulmonary and cerebral vasculature. Treatment often involves fluid 'hyper-hydration' to 'dilute' the blood and reduce viscosity, thereby increasing flow. In truth, the viscosity of gases increases with increased temperatures as the gas molecules collide more, but this is not significant at clinically experienced temperatures.

Changing from laminar to turbulent flow (Reynolds number): several factors determine which type of flow predominates, and these are amalgamated into the Reynolds number (Re), a

Gas laws

Boyle's law	$PV = k$ (at constant temperature)
Charles's law	$V/T = k$ (at constant pressure)
Gay-Lussac's law	$P/T = k$ (at constant volume)
Ideal gas law	$PV = nRT$

k, constant; n, number of moles of gas; P, pressure; R, gas constant (8.3143 J/mol/K, where K is the absolute temperature); T, temperature (in Kelvin); V, volume.

Box 1

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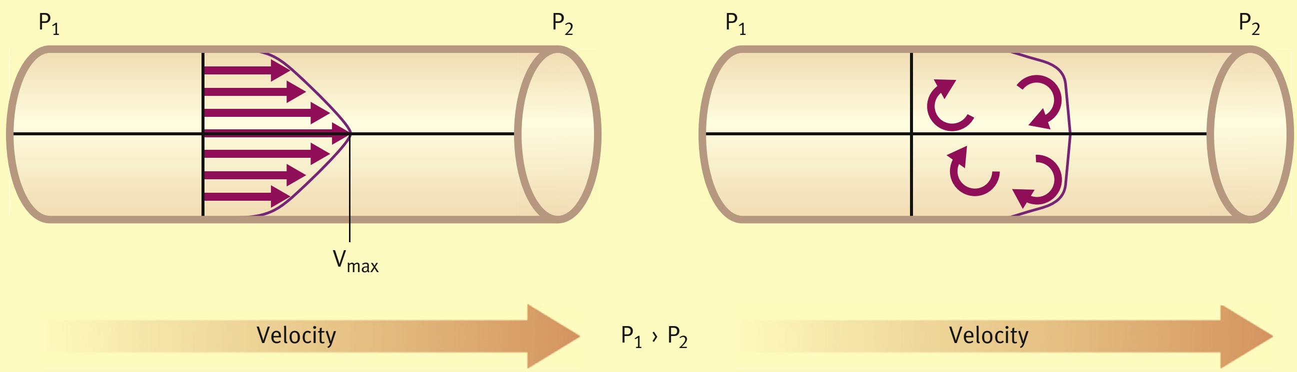
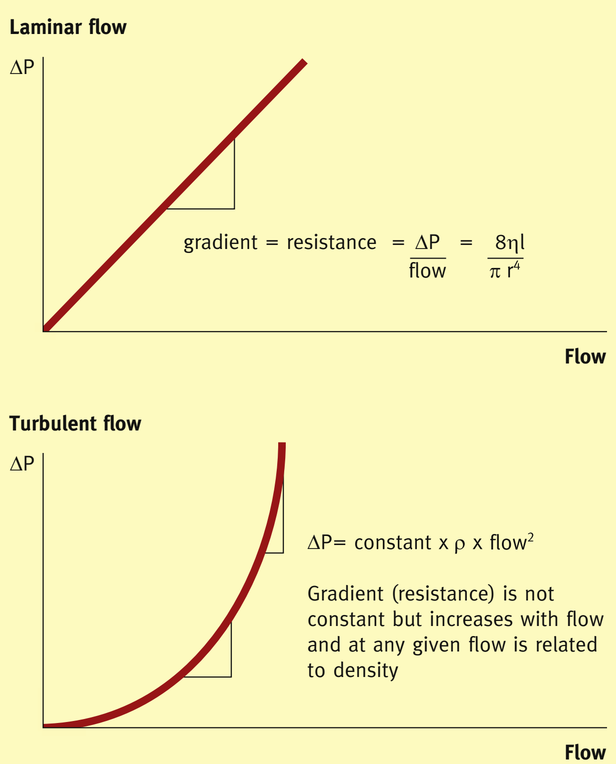
Laminar and turbulent flow



During laminar flow (smooth, steady flow) the flow profile is parabolic, with the fluid travelling most quickly at the centre of the tube and not moving at the edges of the tube. During turbulent flow (fluctuating and agitated flow) the flow profile is essentially flat, with all fluid travelling at the same velocity except at the tube edges where flow velocity is zero.

Figure 1

Pressure gradient and flow



ΔP, pressure gradient along the tube; η, viscosity of the fluid; l, length of the tube; r, radius of the tube; ρ, density

Figure 2

dimensionless value that is a measure of the ratio of inertial forces to viscous forces:

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

where Re is the Reynolds number, v is the linear velocity of the fluid, ρ is the density (mass per unit volume), η is the viscosity, and d is the diameter of the tube.

Laminar flow occurs at Re less than 2000, where viscous forces are dominant. There is a period of 'transitional flow' between Re 2000 and 4000, where pressure is related both directly to the flow rate (laminar) and to the square root of the flow rate (turbulent). At Re >4000, turbulent flow occurs.

Turbulent flow

During turbulent flow, the molecules swirl in eddies and vortices rather than in an orderly way, so that they have a rotational as well as a linear velocity (Figure 1). Irregularities and corners in the tube facilitate turbulence. Conversion from laminar flow to turbulent flow approximately halves the flow for a given pressure drop (Figure 2). The rate of turbulent flow is a *function of fluid density,* not viscosity like laminar flow. There is no precise equation to calculate turbulent flow.

Clinical application

These characteristics are important in the airways. Laminar flow requires less pressure change for the same flow rate, hence less energy expenditure. The smaller the airway, the greater the increase in resistance; for example, if the diameter of a trachea is reduced by half, the flow through it is reduced by a factor of 16. This explains why a paediatric airway is so dramatically affected by tracheal oedema or secretions inside the tracheal tube.

In the airways, laminar flow usually occurs only in the small conducting airways, where the Re is low. Flow tends to be turbulent in the trachea and larynx, where the velocity of airflow is

