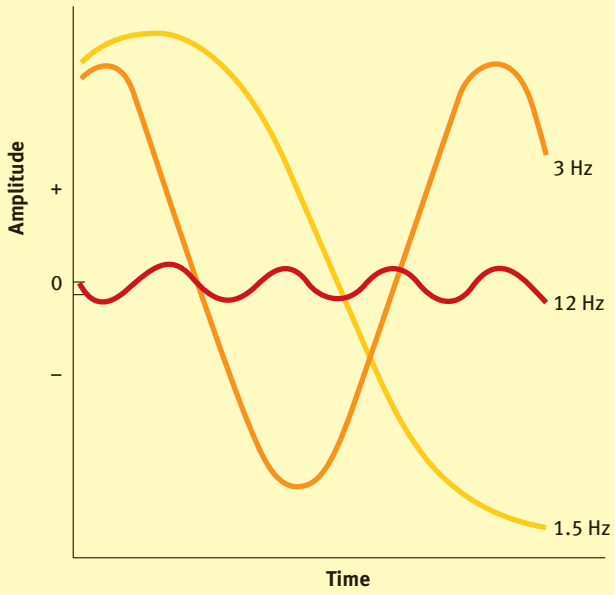
Fourier analysis of the arterial pressure waveform



The first or fundamental harmonic (1.5 Hz) together with the second (3 Hz) and eighth (12 Hz) harmonics of a single blood pressure beat waveform are shown, for a heart rate of 90 beats/minute. Progressively higher harmonics display decreasing amplitude. As a consequence, only the first 8–10 harmonics need to be summed to reproduce the shape of the arterial pressure waveform accurately

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sensors are the closest available systems to this ideal. For the more commonly used manometric systems, the total measuring chain, consisting of catheter or cannula, tubing, stopcocks and transducer, has a much lower resonant frequency, and damping is therefore vital for increasing accuracy. Optimally damped systems can accurately reproduce frequencies up to 67% of the resonant frequency. An optimally damped manometric transducer system with a resonant frequency of 36 Hz or more should therefore be able to reproduce the shape of the arterial pressure waveform accurately up to a heart rate of 180 beats/min.

All manometric pressure monitoring systems introduce a degree of dynamic distortion into the pressure waveform. Some manufacturers produce complete pressure measurement systems where the performance of the entire measurement pathway has been measured dynamically using the Gabarith™ test. The accuracy of these systems is guaranteed to lie within tightly defined limits. ◆

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The role of tracheostomy in ICU

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Indications for tracheostomy in the ICU

Tracheostomy is usually performed in critically ill patients to provide prolonged airway care during slow weaning from assisted ventilation. Several factors (which may coexist in an individual patient) indicate the need for tracheostomy (Figure 1). For example, survivors of severe sepsis may have persistent weakness from critical illness neuropathy or myopathy and be unable to clear pulmonary secretions unaided.

Tracheostomy in the critically ill patient offers significant advantages over prolonged translaryngeal intubation. Less discomfort may allow a reduction in analgesic, sedative and muscle relaxant drugs; clearance of airway secretions, mouth care and enteral nutrition are all facilitated. Airway resistance and anatomical dead space are reduced, reducing the work of breathing and improving the speed and overall success in weaning from assisted ventilation. Tracheostomy allows a seamless transition between different modes of assisted ventilation and weaning modes without trials of extubation and reintubation. However, improved outcome has not been proven in large controlled trials. There is a reduced frequency of accidental extubation and endobronchial intubation. As the patient recovers, a fenestrated tracheostomy tube may be inserted

Indications for tracheostomy in ICU

- Prolonged weaning from assisted ventilation
- Acute or chronic neuromuscular conditions
- Poor cardiorespiratory reserve
- Bulbar dysfunction
- Brain injury
- Upper airway obstruction

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or the cuff deflated to allow phonation and better communication. Tracheostomy may allow earlier discharge from the ICU to a high-dependency unit or ward. Follow-up by an outreach team may improve safety and acceptance of patients with a tracheostomy outside a critical-care area.

Timing of tracheostomy

Deciding when to convert translaryngeal intubation to tracheostomy remains controversial. A daily assessment of the risks and benefits of performing a tracheostomy should be carried out. Tracheostomy has an appreciable incidence of serious complications but the incidence of laryngeal injury and subglottic stenosis increases significantly over time with prolonged translaryngeal intubation. The aim is to minimize the risks of both methods of airway maintenance.

Translaryngeal intubation is commonly converted to tracheostomy at 7–14 days, unless rapid improvement is likely to make tracheostomy unnecessary. There is increasing evidence for better outcomes associated with tracheostomy within the first few days of intensive care in patients who will require prolonged respiratory support. This includes patients with severe respiratory failure, severe traumatic brain injury and older patients with chronic chest disease or neurological disease (e.g. Guillain–Barré syndrome).

If there is uncertainty about the patient's ability to maintain their own airway and respiratory function unaided, a trial of extubation may be performed, though this may risk deterioration due to failure to clear secretions. There is little evidence to suggest that any factors are reliable predictors of successful extubation.

Tracheostomy techniques

Open tracheostomy

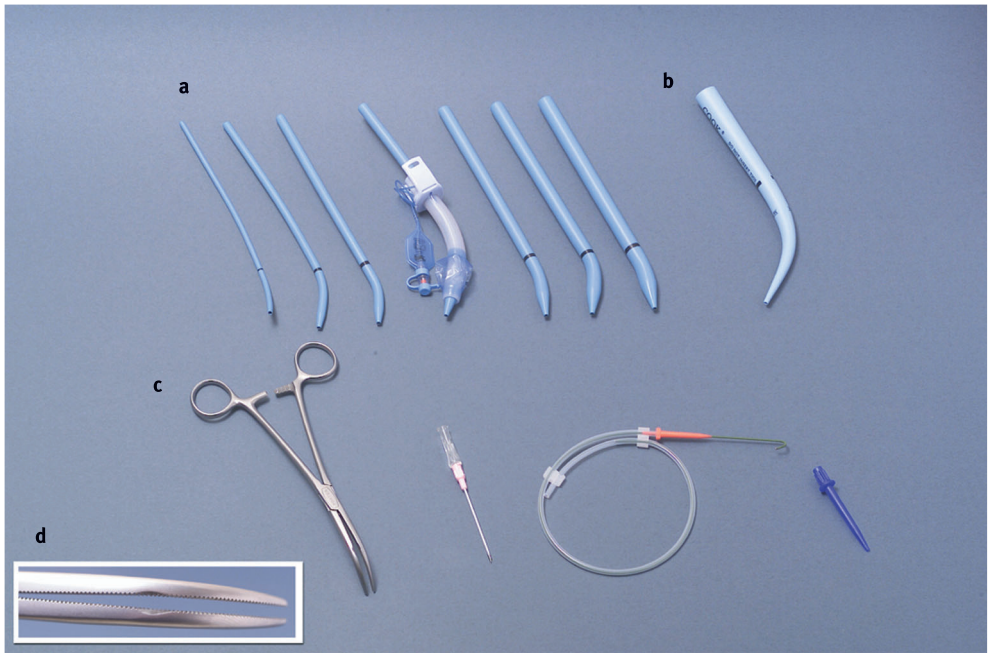
The neck is extended and a skin incision is made over the trachea. The strap muscles are separated and the thyroid isthmus is retracted or divided to expose the trachea. An incision is made into the trachea to accommodate the tube. There is scant evidence to assist in choosing between different tracheal incisions and pressure necrosis from the tube ultimately makes all incisions circular and of a size dependent on the tube used. Adequate haemostasis is crucial to minimize bleeding into the trachea with the potential for airway obstruction by blood clot.

Percutaneous tracheostomy techniques

Modern descriptions of percutaneous tracheostomy techniques date from the 1960s and are based on the Seldinger needle-guidewire method. Common to all dilatational techniques are: a skin incision, localization of the trachea by needle with free aspiration of air, insertion of a guidewire, formation of a tract with some form of blunt dilator and the subsequent insertion of a tracheostomy tube. The technique of dilatation varies between different kits, using one or more dilators, specially designed forceps or a screw device (Figure 2).

The procedure is usually performed at the bedside in ICU by, or directly supervised by, senior staff in daytime hours. Anaesthesia is provided as for conventional surgical tracheostomy by a separate anaesthetist. The use of a muscle relaxant makes the procedure safer and easier. The tracheal tube is withdrawn under direct laryngoscopy until the cuff is seen to lie within the larynx to avoid the risk of transfixion of the tube or cuff with the needle and guidewire. Alternatively, the tracheal tube may be replaced by a laryngeal mask airway.

After carefully positioning the patient with their neck extended, the site for incision is chosen at a point midway between the cricoid cartilage and the suprasternal notch, corresponding to the space between the 2nd and 3rd or 3rd and 4th tracheal rings. Large anterior jugular veins are checked visually or by ultrasound; these may require ligation during the procedure. The skin is prepared with sterilizing solution and the application of drapes to maintain a sterile field. The area of incision is infiltrated with 10–20 ml of local anaesthetic (e.g. lidocaine 1% with epinephrine 1:200,000). A superficial 1.5–2.5 cm horizontal skin incision is made over the injection site. The subcutaneous and pretracheal fascial layers are



2 Percutaneous tracheostomy kits. **a** Cook Ciaglia serial dilators, 12 FG to 36 FG (Portex tube mounted on 24 FG dilator); **b** Cook Blue Rhino single dilator; **c** Portex kit – dilating forceps, cannula over needle, guidewire and dilator; **d** indentations on Portex dilating forceps marking top of groove through which guidewire runs to allow insertion of forceps in closed position.

opened by blunt dissection with forceps. The trachea is palpated through the incision to improve orientation and confirm anatomy. The thyroid isthmus need not be identified or specifically avoided. The trachea is entered with a cannula over needle, confirmed by the free aspiration of air into a fluid-filled syringe. A guidewire is passed into the trachea and the tract dilated to accept a tracheostomy tube of 8 or 9 mm internal diameter.

Bronchoscopy using a fibre-optic scope passed through the tracheal tube may be used to guide correct placement of needle, guidewire and tube and to reduce the risk of posterior tracheal wall injury. It may be done routinely or reserved for teaching or for difficult cases only. The presence of a fibre-optic scope may hinder ventilation, with consequent risk of hypoxia or an increase in the partial pressure of carbon dioxide in arterial blood ($PaCO_2$) and intracranial pressure. It is also easy to cause expensive damage to the bronchoscope by needle puncture.

Open versus percutaneous techniques

The complications of tracheostomy are common to all techniques (Figure 3). Studies comparing open and percutaneous techniques in ICU patients have tended to favour the latter, but operator experience and local after-care are likely to be as important as choice of insertion technique. In many units, dilatational techniques have almost completely replaced conventional techniques in adult patients. The potential advantages of percutaneous techniques are:

- quicker and easier to perform at the bedside
- less risk of early bleeding
- less risk of tracheal stenosis
- reduced risk of stomal infection
- better cosmetic result because of the smaller incision.

However, there is a higher risk of tracheal damage and other complications related to insertion. With experience, percutaneous techniques can be performed successfully in more difficult patients including those with coagulopathy, chronic lung disease, morbid obesity, previous tracheostomy or thyroidectomy, halo-traction or critical oxygen dependency. Relative contraindications to dilatational techniques include a large goitre, malignant infiltration or other anatomical abnormalities.

Complications of tracheostomy

Early	Late
• Haemorrhage	• Stomal infection
• Obstruction due to blood clot or plugs of mucus	• Tracheal stenosis
• Misplacement of the tube	• Tracheo-oesophageal fistula
• Dislodgement of the tube	• Tracheo-innominate artery fistula
• Subcutaneous emphysema	• Tracheomalacia
• Pneumothorax	• Obstruction by plugs of mucus
• Injury to adjacent structures	

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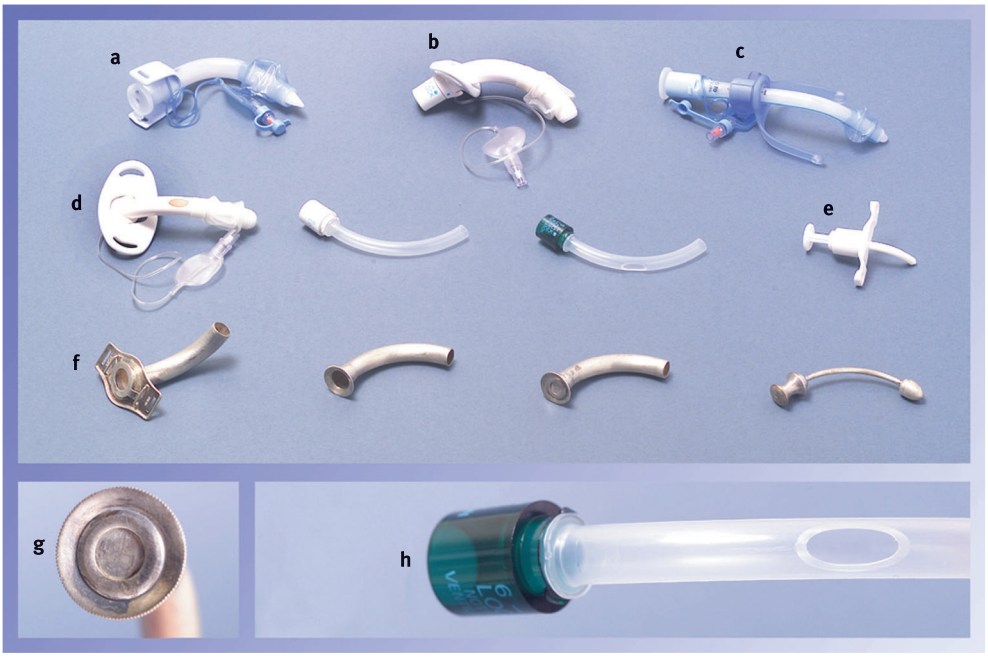
Choice of tracheostomy tube

A large number of different tubes and materials are commercially available (Figure 4). Some manufacturers provide custom-made tubes for anatomically challenging cases. In an adult, a tube with an internal diameter of 7–9 mm is typically used. In the patient with an increased distance between skin and trachea (e.g. obesity, tumour, haematoma) a long-stem tracheostomy tube with adjustable flange should be used. Fenestrated tubes are available to allow speech as the patient recovers. These, and some other models, have a removable inner tube for easier cleaning.

The role of the minitracheostomy

The trachea lies most superficially at the level of the cricothyroid membrane and therefore a cricothyrotomy may be performed rapidly in an emergency to relieve airway obstruction. Kits are available for rapid insertion of a 4–6 mm uncuffed tube by a modified Seldinger technique or by a traditional surgical cut-down. Elective



4 Tracheostomy tubes.
a Portex 9.0 mm profile cuff tube;
b Shiley size 8 low pressure cuff tube;
c Portex 7.0 mm adjustable flange tube;
d Shiley size 6 fenestrated tube with plain and fenestrated inner tubes;
e Shiley 3.0 neonatal tube;
f silver 34 FG tube with plain and speaking valve inner tubes and trocar;
g silver tube speaking valve;
h Shiley fenestrated inner tube.

cricothyroidotomy is used for patients with sputum retention. It does not give protection against pulmonary aspiration nor does it enable assisted ventilation or other advanced respiratory support such as continuous positive airway pressure (CPAP). The widespread use of percutaneous tracheostomy in ICU has reduced the use of minitracheostomy.

Aftercare and decannulation

Obstruction is a recurrent problem with all types of tracheostomy tube. Humidification, frequent tracheal suction and removal of the inner tube for cleaning and physiotherapy are all essential to avoid accumulation of respiratory secretions with crusting and subsequent tube blockage.

In general, it is safer to remove a tracheostomy tube if there is doubt regarding its patency and the adequacy of the airway. In the short term, a spontaneously breathing patient will usually manage to breathe through their own airway. If the tracheostomy is more than 1 week old, the stoma is likely to be well established, allowing early replacement of the tube if necessary. Alternatively one may elect initially to re-intubate the patient by the oral route.

Once the patient is able to cough to clear secretions and protect the airway, consideration should be given to removing the tube, because its presence limits generation of an effective cough and may promote tracheitis. There is no ideal way to assess when the patient is ready for decannulation, though a multidisciplinary approach is helpful. The risks associated with a failed decannulation are likely to be minimized if it is done early in the day: the patient requires a period of close observation and possible tube re-insertion. After successful decannulation, stomas are usually left to granulate and close spontaneously. Recently-closed wounds may be re-opened by blunt dissection if decannulation fails. A few patients require late surgery to release a tethered wound or excise a persistent sinus. Others may have persistent voice change or exertional dyspnoea caused by granulation over the scar or a fractured tracheal cartilage leading to a degree of tracheal stenosis. Others will have laryngeal damage from translaryngeal intubation or established tracheal stenosis. These patients are likely to show extra-thoracic airway obstruction on spirometry; they require referral to an ENT/thoracic surgeon for evaluation and intervention. ◆

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Respiratory failure and ventilatory support

Peter Macnaughton

Respiratory failure is divided into hypoxaemic (type 1), defined as a PaO_2 of less than 6.7 kPa (50 mm Hg), and hypercapnic (type 2), defined as a $PaCO_2$ greater than 6.7 kPa. In practice, hypoxaemia and hypercapnia often occur together.

Hypoxaemia characterizes conditions such as pneumonia, aspiration, pulmonary oedema and atelectasis. It occurs because of ventilation/perfusion (V/Q) mismatch and shunt. Shunt responds poorly to increasing inspired oxygen tension and treatment is directed to removing any obstruction to ventilation within the lungs, re-opening atelectatic zones (recruitment) and preventing airway closure (derecruitment). Less common causes of hypoxaemia include hypoventilation, high altitude and alveolar–capillary diffusion impairment from interstitial oedema or fibrosis.

Hypercapnia arises because of inadequate minute ventilation from low tidal volume and/or respiratory frequency. High physiological dead space (hypovolaemia, pulmonary embolus or low cardiac output) and excessive CO_2 production (sepsis) may also contribute. An elevated $PaCO_2$ is a potent stimulus to increase respiratory drive. Hypercapnia implies that one or more of the following is present:

- lack of central respiratory drive (sedative or opioid drugs, brainstem pathology)
- impaired neural pathway between brainstem and respiratory muscles (spinal cord injury, neuromuscular blockers, Guillain–Barré syndrome, myasthenia gravis)
- weakness of respiratory muscles (fatigue, dystrophy)
- loss of chest-wall elasticity (kyphoscoliosis, morbid obesity)
- loss of chest-wall integrity (flail chest, pneumothorax)
- increased airway resistance (asthma, COPD).

Treatment should be directed at the underlying cause if possible, otherwise ventilatory support is required.

The clinical manifestations of respiratory distress reflect the effects of hypoxaemia and/or hypercapnia and include:

- altered conscious level (from agitation to coma)
- increased work of breathing indicated by tachypnoea, use of accessory muscles and nasal flaring
- paradoxical breathing reflecting diaphragmatic fatigue (the flaccid diaphragm paradoxically moves cephalad during inspiration causing inward movement of the abdominal wall)
- central cyanosis
- signs of excessive catecholamine release, including diaphoresis (sweating), tachycardia, arrhythmias and hypertension.

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