Anaesthesia
Journal of the Association of Anaesthetists of Great Britain and Ireland

Anaesthesia, 2011, **66** (Suppl. 2), pages 65–80 doi:10.1111/j.1365-2044.2011.06936.x

Equipment and strategies for emergency tracheal access in the adult patient

A. E. Hamaekers[1] and J. J. Henderson[2]

1 Consultant, Department of Anaesthesia, Maastricht University Medical Centre, Maastricht, The Netherlands
2 Consultant (Retired), Department of Anaesthesia, Gartnavel General Hospital, Glasgow, UK

Summary

The inability to maintain oxygenation by non-invasive means is one of the most pressing emergencies in anaesthesia and emergency care. To prevent hypoxic brain damage and death in a 'cannot intubate, cannot oxygenate' situation, emergency percutaneous airway access must be performed immediately. Even though this emergency is rare, every anaesthetist should be capable of performing an emergency percutaneous airway as the situation may arise unexpectedly. Clear knowledge of the anatomy and the insertion technique, and repeated skill training are essential to ensure completion of this procedure rapidly and successfully. Various techniques have been described for emergency oxygenation and several commercial emergency cricothyroidotomy sets are available. There is, however, no consensus on the best technique or device. As each has its limitations, it is recommended that all anaesthetists are skilled in more than one technique of emergency percutaneous airway. Avoiding delay in initiating rescue techniques is at least as important as choice of device in determining outcome.

Correspondence to: A. E. Hamaekers
Email: a.hamaekers@mumc.nl
Accepted: 12 Sept 2011

The 'cannot intubate, cannot oxygenate' (CICO) scenario describes the clinical situation where attempted tracheal intubation has failed and oxygenation cannot be maintained by non-invasive means. The phrase 'cannot intubate, cannot ventilate' is also used, but is arguably less accurate: for the purposes of this review, they are, however, considered synonymous. If not corrected rapidly, CICO will inevitably lead to brain hypoxia and death. As emphasised in the Difficult Airway Society guidelines, a percutaneous airway must be established without delay [1]. The terminology can be confusing as, although these airways are often referred to as 'emergency surgical airways', many techniques are not 'surgical' and therefore we use the term 'emergency percutaneous airway' (EPA).

Incidence and causation of CICO

The incidence of CICO in general anaesthetic practice is low. Kheterpal et al. reported four cases of impossible mask ventilation and intubation in 53 041 anaesthetics in a tertiary university hospital; only in one was an EPA performed [2]. The Fourth National Audit Project of the Royal College of Anaesthetists and Difficult Airway Society (NAP4) reported a calculated incidence of EPA of 1 in 12 500–50 000 general anaesthetics [3]. The incidence of EPA is strongly influenced by clinical setting and case mix. In the emergency department, incidences of 0.3% [4] and 0.8% [5], and in the pre-hospital setting as high as 11% [6], have been reported.

Risk factors for CICO include known risk factors for difficult mask ventilation [7] and difficult direct laryngoscopy [8]. Patients whose lungs are difficult to ventilate by mask are more likely to present a difficult or impossible intubation compared with patients with easy mask ventilation [9]. Furthermore, multiple attempts at tracheal intubation can cause airway oedema and may change a 'cannot intubate, can oxygenate' situation into a CICO situation [10–12].

Cricoid pressure, especially when performed poorly, can hinder laryngoscopy [13] and may itself cause airway obstruction and hence CICO [14–16]. Laryngospasm in the non-paralysed patient can be an important factor in failure of mask ventilation. Use of narcotic anaesthesia without paralysis may cause ventilation difficulty with the likely mechanism being vocal cord closure [17, 18].

Diagnosed and undiagnosed laryngeal disease is a more frequent contributor to CICO than generally realised [19, 20]. Out of the 58 cases of EPA in 133 anaesthetic patients reported to NAP4, 43 (74%) were head/neck cases [12], suggesting a significantly increased risk in this patient population.

Anaesthetic management of CICO

Anticipation of risk and preparing an optimum strategy

Reducing the risk of CICO starts with assessment of the airway and use of awake fibreoptic intubation in patients in whom difficulty with mask ventilation, direct laryngoscopy or cricothyroidotomy is anticipated. A clear airway strategy including back-up plans in case of failure and availability of an anaesthetist skilled in alternative techniques of laryngoscopy (e.g. flexible laryngoscopy with or without a conduit and straight blade or rigid indirect laryngoscopy) may all reduce the risk of CICO [21]. Effective pre-oxygenation increases the time available to secure the airway before profound hypoxia occurs [22, 23]. Strictly limiting the number of intubation attempts makes better use of the available time and decreases the likelihood of airway trauma [10, 11].

Initial, non-invasive techniques for managing CICO

Standard airway clearing manoeuvres (head extension, jaw thrust, two-person mask ventilation, an oropharyngeal airway and a gently inserted nasopharyngeal airway) are the first steps in management of the obstructed airway [1]. Early insertion of a supraglottic airway device (SAD) – as long as mouth opening is sufficient – is now standard practice. The SAD chosen should be familiar and easy to insert, but should also be reliable in achieving ventilation, and ideally offer some protection against aspiration. While SADs have been effective in many cases of difficult or impossible mask ventilation [24], success is not guaranteed [24–27]. Cricoid pressure, if applied, should be reduced or withdrawn completely [28]. The Larson manoeuvre [29] (strong medial digital pressure between the angle of the mandible and the mastoid process) should be tried and is easily added to conventional jaw thrust. If all these fail and the airway is still obstructed, the option of waking the patient should be strongly considered at this point. In the NAP4 report, the probable value of neuromuscular blockade, when CICO arises in a patient who is not paralysed, has been emphasised [12].

Decision to proceed to emergency surgical airway

Immediate EPA is indicated when maximal efforts at non-invasive techniques fail to relieve severe hypoxaemia [1]. Unfortunately, decision-making in CICO is often delayed. Retrospective studies of pre-hospital airway management show that most patients were already in cardiac arrest before EPA [30, 31]. In two thirds of the claims included in a closed claims analysis where an airway emergency occurred, EPA was performed too late to prevent poor outcome [11]. A reluctance to perform EPA (i.e. human factors reasons) is likely to be the most common cause of delay. Of note, most studies examining EPA techniques fail to include 'the time taken to act' and 'time taken to prepare' when studying speed of EPA, perhaps leading to an underestimation of the real time taken from onset of hypoxia to completion of EPA. It is not possible to define the oxygen saturation at which cricothyroid otomy should be performed. However, it should certainly have been started (rather than just considered) by the time bradycardia supervenes. In a life-threatening airway emergency, there are no contra-indications to EPA. However, the presence of a large laryngeal tumour, neck pathology, obesity or coagulopathy will make the procedure more hazardous.

Cricothyroid membrane anatomy and its advantages over other sites

Percutaneous (or transcutaneous) access to the trachea can be achieved by tracheostomy through the upper tracheal cartilages (usually the second and third) or by cricothyroidotomy. Tracheostomy involves incision through the skin and subcutaneous tissues, separation of the strap muscles, division of the isthmus of the thyroid gland, control of haemorrhage and incision through two tracheal cartilages. Access to the trachea can be difficult because of its depth in the neck and the vascularity of the thyroid gland. Good lighting, competent assistance and a range of surgical instruments are needed. Although elective tracheostomy has a high success rate and a low risk of complications, emergency tracheostomy is associated with a higher complication rate [32].

Cricothyroidotomy achieves percutaneous tracheal access through the cricothyroid membrane, a dense fibro-elastic membrane between the thyroid and cricoid cartilages with an average height of 10 mm and a width of 11 mm [33] (Fig. 1). Transverse incision in the lower half of the cricothyroid membrane is recommended to avoid the cricothyroid arteries and the vocal cords. The circumferential cricoid cartilage is partially resistant to compression [34] and its posterior lamina lies behind the cricothyroid membrane, providing some protection against posterior wall and oesophageal injury during cricothyroidotomy. Failure to identify the cricothyroid membrane occurs frequently [35] and is the principal cause of failed cricothyroidotomy. We recommend that its position should be confirmed before induction of anaesthesia in all patients using palpation of the hyoid bone and the thyroid and cricoid cartilages. The hyoid can be located by balloting the bone laterally between the thumb and index finger. The thyroid cartilage's superior notch is then identified in males as the greatest laryngeal prominence. In females, the greatest prominence is usually the cricoid cartilage, which is best identified by moving the palpating finger upwards from the sternal notch. Identification of the thyroid and cricoid cartilages leads to the cricothyroid membrane over which there is a slight depression.

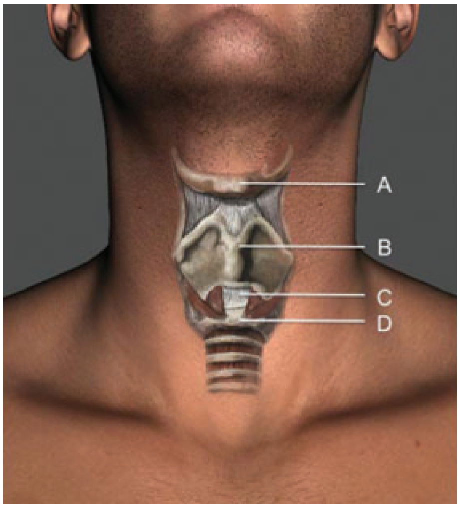

Figure 1 Relevant anatomical structures for cricothyroidotomy: A: hyoid bone, B: thyroid cartilage, C: cricothyroid membrane, and D: cricoid cartilage. Copyright D&L Graphics, Kerkrade, The Netherlands; printed with permission.

Cricothyroidotomy is the preferred route for EPA on account of the shorter duration required for its completion and its greater safety [36, 37].

Overview of types of cricothyroidotomy

Cricothyroidotomy can be performed by surgical incision or puncture of the cricothyroid membrane. Puncture may be achieved using a narrow-bore (usually an internal diameter (ID) of ≤ 2 mm) cannula-over-needle, a wide-bore (usually ID ≥ 4 mm) cannula-over-trocar or a wire-guided (Seldinger) technique, with dilation after cricothyroid membrane puncture.

Narrow-bore cricothyroidotomy

Surveys have shown that for most anaesthetists, the first-choice device for EPA is a narrow-bore cannula [38, 39], which is suggested to be simple, safe and relatively atraumatic [40].

Once inserted, a high-pressure ventilation/oxygen source is necessary to achieve normal tidal volume via the narrow-bore cannula [41–43]. Egress of gas must take place via the upper airway. In 1967, Sanders introduced a hand-triggered oxygen injector using hospital oxygen pipeline pressure (4 bar) for ventilation through a narrow-bore cannula placed down the side arm of a rigid bronchoscope [44]. The modern oxygen injector, e.g. Manujet (VBM Medizintechnik GmbH, Sulz, Germany; http://www.vbm-medical.de/cms/files/p329_2.0_05.08_gb.pdf), allows adjustment of the driving pressure between 0.5 and 4 bar and is designed for emergency use. In a sheep model of CICO, rescue with a narrow-bore cricothyroidotomy and a manual injector was as efficient as with a surgical wide-bore cricothyroidotomy [45]. Various simple, self-assembled devices, consisting of a three-way stopcock or hole in the oxygen tubing, have also been proposed for emergency ventilation through a narrow-bore cannula [46–48]. Connected to an appropriate high-pressure source (e.g. a wall flow meter or oxygen cylinder set at 15 $l.min^{-1}$ or higher), such self-assembled devices create an adequate inspiratory flow [49] and are capable of maintaining adequate oxygenation in a 36-kg pig model [47]. Many self-assembled devices, however, have been advocated without validation of their ability to achieve sufficient ventilation to restore oxygenation in the hypoxaemic patient. Such techniques are dangerous as they may be ineffective [50]. In addition, self-assembled devices are an 'off-licence' use of equipment and often carry inherent risks [51]. Therefore, we believe, they should not be used. The Oxygen Flow Modulator (OFM; Cook Medical, Bloomington, IN, USA; http://www.cookmedical.com/cc/content/mmedia/C-EMB1004.pdf) is a single-use emergency device for use with a narrow-bore cannula. Connected to a flow meter set at 15 $l.min^{-1}$, the OFM was as effective as the Manujet (at 1.5 bar) in restoring oxygenation in a 30-kg hypoxic pig model [52].

It is mandatory to maintain a patent upper airway for the egress of gas when ventilating through a narrow-bore cannula. Obstruction of the outflow tract and/or insufficient expiratory time result(s) in air trapping [53] with subsequent barotrauma and haemodynamic instability. In a CICO situation, partial obstruction of the upper airway (resulting from oedema, laryngospasm or distorted anatomy) occurs frequently, so chest movements should be observed carefully and subsequent inspirations should not be initiated before complete fall of the chest wall. Administering a neuromuscular blocking agent during high-pressure source ventilation, to prevent laryngospasm, should be considered. If the upper airway is completely obstructed and cannot be relieved from above (e.g. airway clearing manoeuvres, SAD) the injector, which has a one-way valve, must be detached from the cannula to allow slow egress of gas via the cannula. The OFM has no valve and can function as a bidirectional airway (allowing expiration through the cannula), although the rate of egress of gas through a narrow-bore cannula is limited [54]. Eger and Dunlap have suggested that expiration could be facilitated by applying suction to increase the achievable minute volume through a narrow-bore cannula and lower the risk of air trapping [55, 56]. An ejector applying expiratory ventilation assistance achieved a minute volume of 6.1–7.5 $l.min^{-1}$ through a 2-mm ID transtracheal cannula when used in vitro at a driving flow of 15 $l.min^{-1}$ [57]: a portable, emergency ventilator applying this technique is now commercially available (Ventrain; Dolphys Medical BV, Eindhoven, The Netherlands; http://www.ventrain.eu/public/files/ventrain%20brochure%20EN.pdf). Clinical studies need to be conducted to determine its efficacy in a CICO situation.

In one case series, emergency narrow-bore cannula cricothyroidotomies achieved a success rate of 79%. Several cases of subcutaneous emphysema and pneumomediastinum (but no fatalities) were described. The Fourth National Audit Project reported a much lower success rate and described several complications of attempted re-oxygenation via a narrow-bore cricothyroidotomy [12]. In addition, numerous case reports have described failures, severe complications and deaths as a consequence of the emergency use of high-pressure source ventilation [58–61]. It is not clear whether the reason for these complications was poor technique, lack of training and practice or an inherently greater risk involved in use of manual high-pressure source ventilation. Experience with high-pressure source ventilation and meticulous technique should reduce the risk of complications. The steps included in the technique are shown in Table 1. It is strongly recommended to use a kink-resistant cannula such as the Ravussin cannula (VBM) or the emergency transtracheal airway catheter (Cook Medical). Where there is no kink-resistant cannula or suitable high-pressure source ventilation device readily available, it is probably safer to perform a wide-bore cannula puncture or surgical cricothyroidotomy.

Wide-bore cannula-over-trocar cricothyroidotomy

Insertion of a wide-bore cannula/tube (ID of ≥ 4 mm) offers advantages regarding ventilation. Adequate

Table 1 The steps to achieve narrow-bore cannula cricothyroidotomy and high-pressure source ventilation.

1. Position the patient (head and neck extended) and identify the landmarks
2. Immobilise the cricoid cartilage between the thumb and middle finger of the non-dominant hand
3. Puncture the cricothyroid membrane in the midline with a kink-resistant narrow-bore cannula attached to a 5- or 10-ml syringe
4. Confirm needle placement in the trachea by aspiration of air; if time permits partially filling the syringe with saline makes the end-point of tracheal entry much easier to identify
5. Hold the needle in one hand and use the other to advance the cannula in a 45° caudad direction over the needle; remove needle only when cannula is fully inserted
6. Aspirate air or saline through cannula to confirm correct placement; capnography may also be used to confirm tracheal entry
7. Delegate one person to hold the cannula in position
8. Connect high-pressure source ventilation and insufflate oxygen for 1 second; start at a driving pressure of 1 bar
9. Watch (and palpate) the chest rise *and fall*
10. Do not insufflate until the chest has fallen: adjust frequency to ensure there is sufficient time for expiration to prevent air trapping
11. If there is inadequate egress of gas through the upper airway (as seen by the chest wall not falling and hemodynamic instability) place oral airway or supraglottic airway, performing jaw thrust if necessary. Consider administering neuromuscular blocking agent if not already done, detach injector from cannula and manually compress chest to augment exhalation
12. Discuss plan: wake the patient, intubate or convert to cuffed tracheostomy or cricothyroidotomy

minute volumes can be achieved using a conventional breathing system with expiration via the cannula. However, reliable ventilation can only be guaranteed with a cuffed tube, as use of an uncuffed tube may lead to gas leakage to the upper airway [62]. Some advocate the use of uncuffed tubes with simultaneous attempts to create upper airway obstruction [53, 63]. However, we believe that during a CICO situation, only techniques that guarantee rapid re-oxygenation should be used and that there is no place for use of uncuffed tubes. The Quicktrach II (VBM; http://www.hospitecnica.com.mx/productos/VBM/cricotomia.pdf) and Portex® cricothyroidotomy kit (PCK; Smiths Medical Ltd, Hythe, UK; http://www.smiths-medical.com/catalog/cricothyroidotomy-kits/) have cuffed cannulae and are designed and marketed for emergency cricothyroidotomy. When wide-bore cannula-over trocar devices are used, there is a risk of compression of the airway as considerable force is sometimes required to push the device through the cricothyroid membrane with the consequence that the trocar enters the trachea with a high velocity and lack of control, increasing the risk or damage or perforation of the posterior tracheal wall [64]. An initial scalpel incision (not recommended by VBM) to reduce the force required [65] and insertion of the Quicktrach in a caudal direction minimise risks. The Quicktrach includes a red detachable stopper designed to limit initial insertion depth and thereby prevent posterior airway trauma. This mechanism does limit the utility in obese patients (patients with a thick neck) as the cannula might fail to reach the trachea: such failure was reported in NAP4. The PCK incorporates a Veres needle and signalling system that indicates tracheal entry and any subsequent contact with the posterior tracheal wall. Although designed to limit posterior wall damage, a 70% incidence of such damage was reported in a pig larynx model [66].

Seldinger cricothyroidotomy

A guidewire is placed in the trachea through a narrow-bore needle and the tract is then dilated for the passage of a larger cannula (Fig. 2), a sequence familiar to anaesthetists. The separation of the puncture and dilatation steps minimises the risk of trauma [67]. Although several anaesthetists have attempted to use the Portex® Mini-Trach II device (Smiths Medical; http://www.smiths-medical.com/catalog/cricothyrotomy-kits/), which is widely available, during CICO, this is not recommended by the manufacturer. It was designed for sputum aspiration, is uncuffed and several failures to restore oxygenation have been reported [68, 69]. The Melker emergency cricothyroidotomy set (Cook Medical; http://www.cookmedical.com/cc/content/mmedia/C-EMB1004.pdf) is Seldinger-based and sizes 3.0–6.0 mm ID are available. Only the 5.0-mm ID cannula has a cuff. In general, anaesthetists prefer the wire-guided cricothyroidotomy technique over the surgical and wide-bore cannula-over-trocar techniques [66]. In a manikin study, the Seldinger technique was considered more intuitive and 75% of anaesthetists felt confident with the Melker wire-guided technique [70]. While good results have been achieved with the Seldinger technique in human cadavers and manikin studies by those well trained, inexperienced operators have low success rates and a long performance time [71]. The most frequent technical problems are kinking of the guidewire [70] and attempts to place the cannula without using the dilator [72, 73]. Guidewire kinking prevents passage of a dilator and increases risk of misplacement by creation of a false passage. If identified, it is safer to convert immediately to a surgical cricothyroidotomy.

Surgical cricothyroidotomy

Although many anaesthetists are reluctant to use this technique, the skills are basic and all should be capable of this procedure. A horizontal scalpel incision through the lower part of the cricothyroid membrane is common to all variations of surgical cricothyroidotomy. In the Advance Trauma Life Support (ATLS®) technique, the steps are initial skin incision, horizontal incision through the cricothyroid membrane with a no. 11 blade, blunt dilation with the handle of the scalpel or surgical forceps and tube insertion [74]. In the rapid four-step cricothyroidotomy technique, the steps are palpation, horizontal incision through both skin and cricothyroid membrane, insertion of a tracheal hook while the blade is within the larynx, retraction of the cricoid cartilage anteriorly and caudally with the hook, and passage of the tube (Fig. 3) [75]. A no. 20 blade is used to minimise extension required for passage of a 6-mm ID tube and to lower the risk of damage to the posterior wall of the larynx. Holding a blade between thumb and index finger to limit insertion depth also reduces this risk. Many techniques use an initial vertical midline skin incision: although the standard rapid four-step technique does not, this is an essential first step in patients (e.g. obesity) in whom cricothyroid membrane identification is difficult. In many techniques, the incision is kept maximally patent during tube insertion by a dilator, speculum or tracheal hook. If there is difficulty advancing the tube through the incision, the

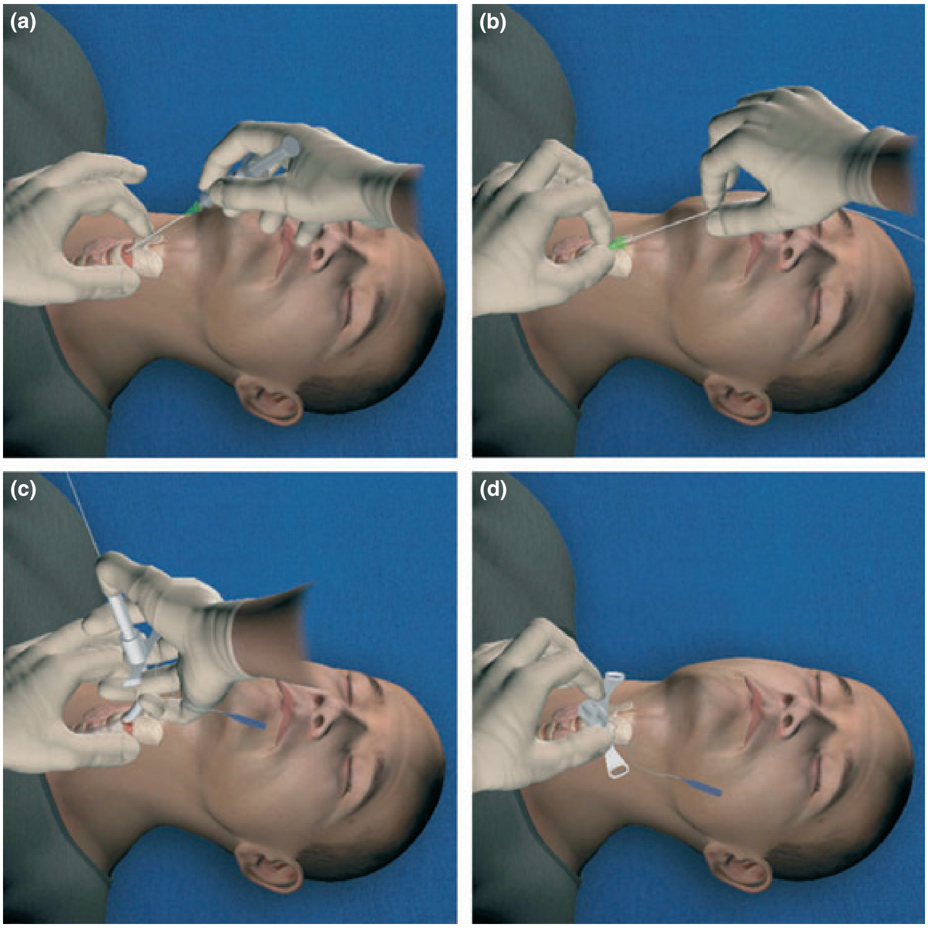

Figure 2 Illustrated procedure for Seldinger cricothyroidotomy: (1) Position the patient (head and neck extended) and identify the landmarks. (2) Immobilise the cricoid cartilage between the thumb and middle finger of the non-dominant hand and puncture the cricothyroid membrane in the midline with the puncture needle attached to a 5- or 10-ml syringe while aspirating (a). (3) Confirm needle placement in the trachea by aspiration of air. If time permits partial filling the syringe with saline makes the end-point of tracheal entry much easier to identify. Disconnect the syringe and insert guidewire through the needle in a caudad direction; to confirm the wire is not kinked, check if it can be withdrawn and advanced 1–2 cm without resistance (b). (4) Incise the skin and membrane close to the guidewire and remove the needle. (5) Insert the dilator and cannula over the guidewire into the trachea in the same direction as the needle was inserted; a single advancement is ideal and lessens the risk of kinking the wire (c). (6) Remove the guidewire and dilator, leaving the cannula in place (d). (7) Inflate the cuff, ventilate the lungs, check correct placement (capnography and auscultation) and secure the cannula. Copyright D&L Graphics, Kerkrade, The Netherlands; printed with permission.

incision should be extended with a blunt rather than sharp instrument (surgical forceps, an appropriate dilator or a digit) and initial passage of an introducer (e.g. bougie or exchange catheter) should be used to facilitate tube placement [76]. Whatever procedure is used, gentle technique should minimise the risk of complications. Where no tracheostomy tube is immediately available, a tracheal tube should be inserted. Its cuff should be placed just beyond the incision to reduce the risk of endobronchial intubation. Although some bleeding is normal, life-threatening haemorrhage is exceptionally rare and can normally be controlled by pressure after passage of the tube.

Complications of EPA

Reported complication rates of cricothyroidotomy vary from 0% to 52%, depending on the technique, the experience level of the operator, the patient population and the clinical situation [30, 36, 77–79]. The main complication is initial misplacement (e.g. paratracheal, superior or inferior to the cricothyroid membrane or through the posterior tracheal wall) and

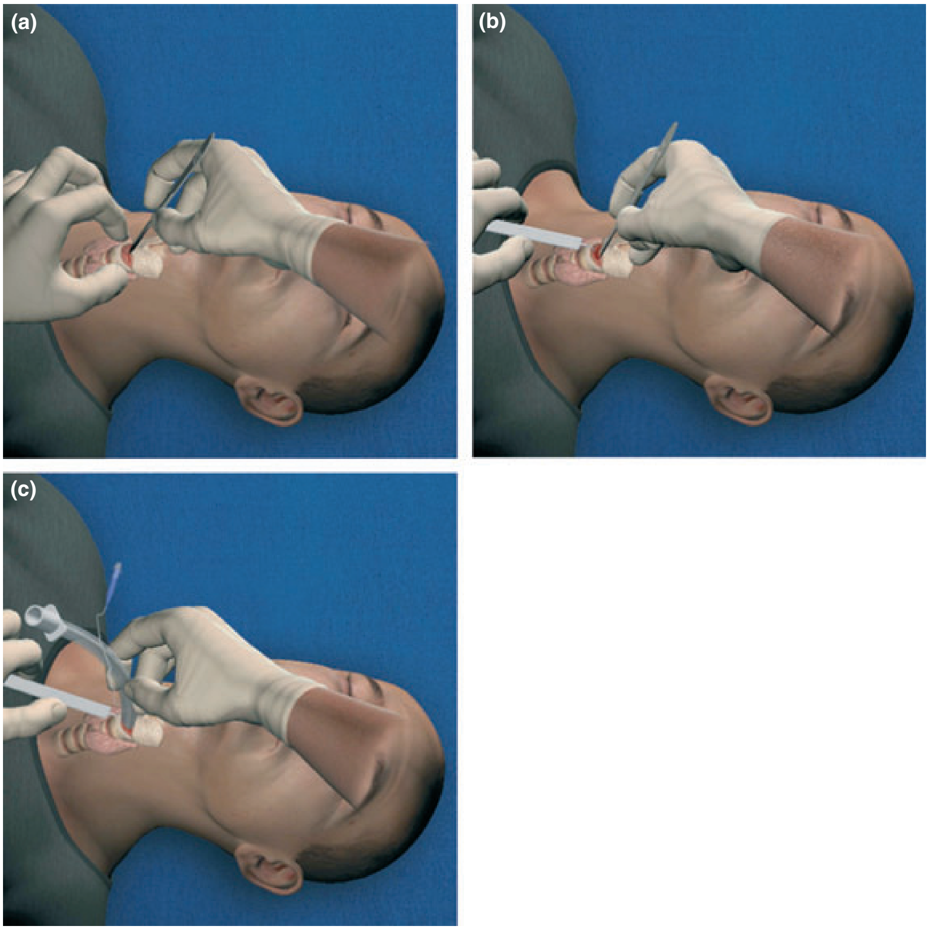

Figure 3 Illustrated procedure for surgical cricothyroidotomy (rapid four-step cricothyroidotomy): (1) Position the patient (head and neck extended) and identify the landmarks. (2) Immobilise the trachea with non-dominant hand and make a horizontal 25-mm stab incision through the skin and cricothyroid membrane with a no. 20 scalpel blade; keep the scalpel blade in place (a). (3) Place the tracheal hook in the incision before removing the blade and apply caudal and ventral traction on the cricoid cartilage (b). (4) Remove scalpel blade and insert 6.0-mm tracheal tube gently (c). (5) Inflate the cuff, ventilate the lungs, check correct placement (capnography and auscultation) and secure the tube. Copyright D&L Graphics, Kerkrade, The Netherlands; printed with permission.

is the principal cause of failure. This underlines the importance of taking care to identify the cricothyroid membrane. Inferior placement through the crico-tracheal space increases the risk of airway injury [34] and bleeding, but can still result in effective re-oxygenation.

Some complications are technique-related. Narrow-bore cannula techniques are associated with ventilation-related complications such as barotrauma [40, 41] (e.g. subcutaneous emphysema, pneumothorax, pneumomediastinum and circulatory arrest due to impaired venous return), and cannula obstruction due to kinking. Kinking of the guidewire is a common problem peculiar to the Seldinger technique and increases the risk of tube misplacement [70, 80]. The surgical method is associated with complications of tube insertion (e.g. bleeding, laryngeal fracture). Damage to the larynx is normally a consequence of excessive pressure during device insertion and is reduced by use of small tubes and gentle technique [64]. Long-term complications are subglottic stenosis, scarring and voice changes [36].

Management of the patient and staff after re-oxygenation

Once re-oxygenation has been achieved, a new airway strategy is needed. If a narrow-cannula technique has been used and it is not possible to awaken the patient, it is desirable to convert to tracheal intubation, a cuffed cricothyroidotomy cannula or a formal tracheostomy. High-pressure source ventilation may aid subsequent intubation by direct laryngoscopy as bubbles may be seen emerging from the glottis [40, 81, 82]. The Seldinger technique has been recommended to convert a narrow-bore cannula into a cuffed wide-bore cricothyroidotomy [83, 84]. While conversion of cricothyroidotomy to tracheostomy within 72 h has been advocated because of the increased risk of developing subglottic stenosis with prolonged intubation through the cricothyroid membrane, this risk may be much lower than previously believed [79, 85]. The risk of conversion, although less well examined, may also be appreciable [86, 87].

The airway difficulty must be documented and the patient and carers fully informed so that appropriate management can be planned for future care.

A CICO situation can be very stressful for the healthcare team [88]. An adverse event can result in significant emotional sequelae, such as depression, post-traumatic stress symptoms and burn-out [89]. The Association of Anaesthetists of Great Britain and Ireland has proposed debriefing as a means to foster open communication, reviewing the medical aspects of a critical event and providing emotional support after an incident [90]. Detailed analysis of an airway event, as recommended in NAP4, can contribute to the understanding of what happened and help reduce the risk of similar events harming this or other patients in the future.

Which cricothyroidotomy technique should we use?

The ideal EPA technique is readily available, can be completed rapidly, has few steps and is easy to master and retain, has a high success and low complication rate, allows adequate ventilation independent of upper airway resistance and provides protection against aspiration [91]. While recent technical developments probably make EPA simpler, faster and more precise, the ideal technique does not yet exist. Although several studies have compared EPA techniques for management of CICO, the findings are inconclusive.

Recently, NAP4 reported a success rate of only 37% for narrow-bore cannula-over-needle cricothyroidotomy, 57% for wide-bore cannula techniques and 100% for surgical cricothyroidotomy [12]. In a recent meta-analysis, the pooled success rates of pre-hospital puncture cricothyroidotomy (27 patients included) and surgical cricothyroidotomy (485 patients included) were 66% and 91%, respectively [92]. Retrospective cohorts from emergency departments confirm the high success rate of surgical cricothyroidotomy [6, 93]. While these studies provide valuable data, they cannot be used to directly compare the effectiveness and safety of different EPA techniques. Randomised control trials (RCTs) are normally required to find the best management. For obvious reasons, which have been recently discussed by Cook and Bogod [94], no RCT exists or is likely to be completed in the CICO setting. Although several RCTs, the majority comparing insertion time rather than time to re-oxygenation, have been performed on manikins, isolated pig larynxes, animals or human cadavers, these studies vary in anatomic validity, outcome measures used and in the qualifications, prior experience and training of those performing EPA (Tables 2–4). Consequently, conflicting results have been published.

For example, in a pig trachea model, paramedics were faster and more successful with the surgical technique than the Seldinger technique [95]. Other studies in larynx models or manikins also reported a greater speed with the surgical technique [66, 72, 96]. However, in three out of four human cadaver studies, the performance time of the Seldinger technique was as fast as [80, 97] or faster than [98] the surgical technique. Reported success rates of the different techniques vary widely and range for surgical cricothyroidotomy from 55% to 100%, for wide-bore cannula-over-trocar from 30% to 100%, and for Seldinger technique from 60% to 100% [34, 65–67, 70–72, 80, 95–106]. The differences in success rates may reflect varying definition of success (e.g. only one attempt allowed, or a certain time limit) and operator experience, but the study model probably has also an important influence on the outcome [107]. Due to lack of fidelity, the results obtained from plastic models are probably positively biased towards wide-bore cannula-over-trocar and surgical techniques [83].

Although there is no consensus on the use of a narrow-bore or wide-bore technique for rescue during CICO, or on the best insertion technique, there is, however, one area of some consensus. It is clear that conventional (low-pressure source) ventilation should not be used with a narrow-bore cannula [42, 43, 108]; a high-pressure oxygen source and a secure pathway for the egress of gas are both mandatory to achieve adequate ventilation. If a wide-bore cannula is used, a cuffed cannula is preferable because it provides a more reliable conduit for ventilation and protects against aspiration [62].

Table 2 An overview of the randomised control trials on cricothyroidotomy insertion in human cadavers.

Authors [ref]	Techniques studied	Number of cadavers	Operator	Outcome measures	Results
Benkhadra et al. [105]	Melker, Portex	n = 40	Anaesthetists (n = 2)	Insertion time: from incision/puncture of the skin to inflation of the cuff	Melker 71 s vs Portex 54 s (p = 0.01)
				Success rate: device in the correct position in < 300 s	Melker 95% vs Portex 80% (NS)
				Incidence of major tracheal and laryngeal injury	Melker 0% vs Portex 20% (p = 0.003)
Chan et al. [97]	Melker, surgical	n = 15	EM attendings/ residents (n = 15)	Insertion time: initial incision to final placement of cannula	Melker 75 s vs surgical 73 s (p = 0.86)
				Accuracy of placement	Melker 93% vs surgical 87% (p = 0.05)
				Complication rate	Melker 7% vs surgical 15%
				Operator preference	93% preferred the Melker
Davis et al. [99]	RFSC, standard surgical	n = 30	EM residents (n = 2)	Incidence of tissue damage or balloon rupture	RFSC 16.7% vs standard surgical 0% (< 0.05)
				Size of largest tube able to pass	Both 7.0 mm ID
Davis et al. [100]	RFSC (Bair Claw), standard surgical	n = 33	Emergency physicians (n = 5)	Time to definitive airway: not defined	RFSC 33 s vs standard surgical 52 s (p = 0.037)
				Size of largest tube able to pass	RFSC 7.7 mm ID vs standard surgical 7.8 mm ID (NS)
				Complication rate	Both 0%
Eisenburger et al. [80]	Arndt Seldinger, surgical	n = 40	ICU physicians (n = 20)	Procedure time: from start to first ventilation	Arndt 100 s vs surgical 102 s (NS)
				Rate of tracheal placement	Arndt 60% vs surgical 70% (NS)
				Incidence of laryngotracheal injury	Arndt 10% vs surgical 15% (NS)
				Ease of use: from 1 (easiest) to 5 (worst)	Melker 2.4 vs surgical 2.2 (NS)
Holmes et al. [102]	RFSC, standard surgical	n = 64	EM interns, residents, students (n = 32)	Insertion time: from incision to removal trocar from the Shiley tube	RFSC 43 s vs standard 134 s (p < 0.001)
				Success rate: within first attempt	RFSC 88% vs standard 94% (p = 0.16)
				Incidence of major complications	RFSC 9% vs standard 3% (p = 0.32)
Johnson et al. [103]	Pertrach, surgical	n = 44	Students (n = 44)	Insertion time: from palpation to first ventilation	Pertrach 148 s vs surgical 55 s (p < 0.01)
				Tracheal placement in the first attempt	Pertrach 78% vs surgical 86% (p = 0.186)
				Ease of insertion: 0 (very easy) to 10 (impossible)	Pertrach 5.1 vs surgical 3.0 (p < 0.01)
Schaumann et al. [98]	Arndt Seldinger, surgical	n = 200	Emergency physicians (n = 20)	Time from start of procedure to first ventilation	Arndt 109 s vs surgical 137 s (p < 0.001)
				Success rate: through cricothyroid membrane within one attempt	Arndt 88% vs surgical 84% (NS)
				Incidence of injury	Arndt 0% vs surgical 6% (p < 0.05)
Schober et al. [71]	Crico-scissor, Melker, Quicktrach, surgical	n = 63	Students (n = 63)	Insertion time: from beginning of inspection until complete termination of procedure	Crico-scissor 60 s vs Melker 135 s vs Quicktrach 74 s vs surgical 78 s (Melker vs surgical p < 0.05)
				Success rate	Crico-scissor 100% vs Melker 71% vs Quicktrach 82% vs surgical 94% (Melker vs surgical p < 0.05)
				Complication rate	Crico-scissor 36% vs Melker 64% vs Quicktrach 71% vs surgical 0% (Melker vs surgical p < 0.05)

RFSC, rapid four-step cricothyrotomy

 Anaesthesia, 2011, 66 (Suppl. 2), pages 65–80

Table 3 An overview of the randomised control trials comparing cricothyroidotomy insertion techniques in non-human material (i.e. manikins or animal models).

Authors	Techniques studied	Study model	Operator	Outcome measures	Results
Assmann et al. [70]	Melker, Portex	Manikin	Anaesthetists (n = 64)	Insertion time: from palpation of skin to ventilation	Melker 42 s vs 33 s (p < 0.001)
				Success rate: insertion of the device in the correct position	Melker 95% vs Portex 93% (NS)
				Operator preference	59% preferred the Melker
Dimitriadis and Paoloni [72]	Melker, Mini-Trach, Quicktrach, surgical	Manikin	EM physicians/ trainees (n = 23)	Time to first ventilation	Melker 126 s, Mini-Trach 48 s, Quicktrach 48 s, surgical 34 s (p < 0.0001)
				Success rate: correct placement within 210	Melker 74%, Mini-Trach, Quicktrach and surgical 100%
				Operator preference: numeric scale 1–4	Melker least preferred by 78%
Fikkers et al. [65]	Mini-Trach, Quicktrach	Pig-larynx model	Anaesthesia and ENT residents (n = 20)	Insertion time: from inspection of instruments to first ventilation	Mini-Trach 149.7 s vs Quicktrach 47.9 s (p < 0.001)
				Success rate: correct position within 240 s	Mini-Trach 85% vs Quicktrach 95% (NS)
				Ease of procedure: VAS 0–10	Mini-Trach 5.5 vs Quicktrach 2.1 (p < 0.001)
Hill et al. [101]	RFSC RFSC with bougie	Sheep (n = 21)	Residents and students (n = 21)	Insertion time: from palpation to cuff inflation	RFSC 149 s vs with bougie 67 s (p = 0.002)
				Success rate: one attempt, within 180 s in correct position	RFSC 73% vs with bougie 90%
				Ease of use: 1 (very easy) to 5 (very hard)	RFSC 3 vs with bougie 2 (p = 0.04)
Keane et al. [95]	Melker, surgical	Pig-larynx model	Paramedics (n = 22)	Procedure time: puncture/incision of the skin to completion of procedure	Melker 123 s vs surgical 29 s (p < 0.001)
				Success rate	Melker 91% vs surgical 100% (p = 0.1)
Mariappa et al. [104]	Melker, Portex, surgical	Pig-larynx model	Intensivist (n = 3)	Time to achieve patent airway: from location of cricothyroid membrane to first ventilation	Melker 47 s vs Portex 63 s vs surgical 50 s (NS)
				Success rate: intraluminal placement with resistance-free ventilation	Melker 100% vs Portex 30% vs surgical 55% (p ≤ 0.001)
				Incidence of posterior wall injury	Melker 0% vs Portex 55% vs surgical 20% (p < 0.001)
Metterlein et al. [67]	Melker, Quicktrach	Sheep cadaver (n = 16)	Anaesthetists (n = 2)	Time from incision/puncture to first successful ventilation	Melker 53 s vs Quicktrach 32 s (p < 0.05)
				Success rate: within 180 s	Melker 100% vs Quicktrach 63% (p < 0.05)
				Incidence injury posterior wall	Melker 13% vs Quicktrach 63%
Salah et al. [34]	Mini-Trach Quicktrach Ravussin, surgical	Pig-larynx model	Anaesthetic trainees (n = 10)	Incidence and severity of tissue damage tracheal site or CTM	Tissue injury more frequent when procedure is performed at tracheal site compared with CTM with Quicktrach and surgical rank order: surgical = Quicktrach > Mini-Trach = Ravussin
				Maximum tracheal compression	Compression more common at tracheal site compared with cricothyroid membrane rank order: Quicktrach > surgical > Mini-Trach > Ravussin

RFSC, rapid four-step cricothyrotomy

Table 4 An overview of the randomised control trials concerning cricothyroidotomy insertion and ventilation.

Authors	Techniques studied	Study model	Operator	Outcome measures	Results
Manoach et al. [45]	narrow-bore cannula, surgical	Sheep (n = 12)	Researchers (n = 2)	Procedure time: start procedure (at oxygen saturation of 80%) to initiation of ventilation	Narrow-bore cannula 20 s vs surgical 24 s (p = 0.69)
				Respiratory and haemodynamic parameters	No significant differences
Murphy et al. [66]	Melker Portex Quicktrach, surgical	Pig-larynx model	Anaesthetists (n = 20)	Insertion time: from opening the cricothyroidotomy kit until placement of device in the trachea	Melker 94 s vs Portex 182 s vs Quicktrach 52 s vs surgical 59 s
				Success rate: placement in the trachea within 300 s	Melker 100% vs Portex 60% vs Quicktrach 95% vs surgical 95%
				Ease of use: 0 (very easy) to 10 (very difficult)	Melker 2.8 vs Portex 5.7 vs Quicktrach 4.8 vs surgical 3.1
				Operator preference: ranking 1–4	Melker the most preferred technique
				Incidence of posterior wall damage	Melker 40% vs Portex 70% vs Quicktrach 15%, vs surgical 45%
				Tidal volumes	No significant difference
Sulaiman et al. [62]	Melker (cuffed and uncuffed), surgical	Manikin	Anaesthetists (27)	Time to achieve ventilation Failure rate on first attempt Operator preference Difficulty score: 0 (very easy) to 5 (very difficult) Operator preference: ranking 1 to 4 Minute volume	Melker cuffed 87 s vs uncuffed Melker 88 s vs surgical 44 s (p<0.001) Melker cuffed 2/27, Melker uncuffed 1/27, surgical 4/27 (p=0.25) Melker cuffed 52% vs surgical 48% Melker cuffed 3 vs uncuffed Melker 3 vs surgical 2 (NS) Melker cuffed 6.6 $l.min^{-1}$ vs Melker uncuffed 0.3 $l.min^{-1}$ vs surgical 6.5 $l.min^{-1}$
Vadodaria et al. [106]	Melker Quicktrach Patil, narrow-bore cannula	Human patient simulator	Anaesthetists (10)	Time required to achieve a patent airway	Melker 38 s vs Quicktrach 51 s vs Patil 123 s vs narrow-bore cannula 102 s
				Time required to achieve a $P^{a}o2$ exceeding 13.3 kPa	Melker 130 s vs Quicktrach 58 s vs Patil 140 s vs narrow-bore cannula 185 s
				Success rate: correct tracheal placement within 300 s and achieving $P^{a}o2$ > 13.3 kPa	Melker 100% vs Quicktrach 100% vs Patil 60% vs narrow-bore cannula 40%
				Incidence of posterior wall injury	20% for each technique
				Operator preference	60% preferred Quicktrach and 40% Melker

Overall, the strength of current evidence does not justify recommending one technique over others. Successful EPA perhaps relies more on the operator's experience, practice and skill than on the devices themselves [109]. However, as each technique can fail, it is desirable to be skilled in more than one EPA technique [12, 84].

Training

In NAP4, the success rate of EPA performed by anaesthetists was only 36% [3]. This low success rate may be inherent to the technique used, but seems also to be a consequence of lack of training and inadequate equipment. Various studies and surveys indicate that most anaesthetists are poorly prepared for EPA. Confidence in performing surgical cricothyroidotomy is particularly low [38], and knowledge and availability of the equipment necessary to oxygenate through a narrow-bore cannula are often inadequate [110, 111]. Thorough knowledge of anatomy, clear understanding of insertion and ventilation techniques and good practical skills are essential for performing EPA rapidly and successfully. The best training methods for EPA have still to be determined [112], but in general, hands-on teaching of manual skills is necessary in addition to conventional didactic instructions [113]. Such systematic teaching in a workshop setting improves both confidence [114] and practical skills [114–116]. The minimum number of attempts at Seldinger cricothyroidotomy to obtain basic proficiency is suggested to be five [115, 116]. Various models have been used for training in EPA. Simple manikins enable learning of basic techniques [117]. An isolated pig trachea is a relatively inexpensive model for more realistic training [118].

Training should be repeated at intervals of 6 months or less to maintain an adequate skill level [119]. Other opportunities for training can be gained during narrow-bore cricothyroidotomy for local anaesthetic administration during awake intubation [120], during use of prophylactic non-emergency cricothyroidotomy in patients with difficult airways and during percutaneous dilational tracheostomy.

Technical aspects of EPA procedures, however, are only one half of the training needed [112, 121]. During CICO, the situation must be recognised and the decision made to proceed to EPA [122]. Errant or delayed decision-making may have catastrophic consequences. A physician without the necessary skills may hesitate when EPA is needed. High-fidelity simulation teaching has been shown to influence decision-making in a CICO scenario: times to initiate EPA and times to achieve ventilation improved significantly [123]. Good and repeated training can ensure best results. Some hospitals have shown that such good training can be achieved [84, 124, 125] and all should emulate this example.

Conclusion

Whatever EPA technique is chosen, it is essential that the equipment is readily available at all sites where anaesthesia is administered. However, it is not only appropriate equipment that will save a patient's life, but having a trained professional who is able to make the decision to perform an EPA and then performs this procedure promptly and successfully before the patient suffers irreversible brain damage or death [112]. Anaesthetists are naturally reluctant to perform EPA, but it is the only means of saving the life of a patient in the CICO situation. Being responsible for the entire safety of our patients mandates that we have the skills for handling any difficult situation. Cricothyroidotomy must be a core skill [126].

Competing interests

AEH is one of the investigators of a research project that is generously supported by a European grant (OP-Zuid 31R104). She is a member of the medical advisory board of Ambu and has received free samples of airway equipment for teaching and clinical evaluation from several companies. She has no financial interest in any company. JJH has received royalties for the sale of the Henderson blade. He has received free samples of airway equipment from several companies for evaluation and training. He has had no other commercial relationship with any airway products.

References

1 Henderson JJ, Popat MT, Latto IP, Pearce AC. Difficult Airway Society guidelines for management of the unanticipated difficult intubation. *Anaesthesia* 2004; **59**: 675–94.

2 Kheterpal S, Martin L, Shanks AM, Tremper KK. Prediction and outcomes of impossible mask ventilation: a review of 50,000 anesthetics. *Anesthesiology* 2009; **110**: 891–7.

3 Cook TM, Woodall N, Frerk C. Major complications of airway management in the UK: results of the 4th National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Part 1: anaesthesia. *British Journal of Anaesthesia* 2011; **106**: 617–31.

4 Stephens CT, Kahntroff S, Dutton RP. The success of emergency endotracheal intubation in trauma patients: a 10-year experience at a major adult trauma referral center. *Anesthesia and Analgesia* 2009; **109**: 866–72.

5 Walls RM, Brown CA, Bair AE, Pallin DJ. Emergency airway management: a multi-center report of 8937 emergency department intubations. *Journal of Emergency Medicine* 2010; Nov 8; doi: 10.1016/j.jemermed.2010.02.024.

6 Bair AE, Panacek EA, Wisner DH, Bales R, Sakles JC. Cricothyrotomy: a 5-year experience at one institution. *Journal of Emergency Medicine* 2003; **24**: 151–6.

7 Kheterpal S, Han R, Tremper KK, et al. Incidence and predictors of difficult and impossible mask ventilation. *Anesthesiology* 2006; **105**: 885–91.

8 el-Ganzouri AR, McCarthy RJ, Tuman KJ, Tanck EN, Ivankovich AD. Preoperative airway assessment: predictive value of a multivariate risk index. *Anesthesia and Analgesia* 1996; **82**: 1197–204.

9 Langeron O, Masso E, Huraux C, et al. Prediction of difficult mask ventilation. *Anesthesiology* 2000; **92**: 1229–36.

10 Benumof JL. Management of the difficult adult airway: with special emphasis on awake tracheal intubation. *Anesthesiology* 1991; **75**: 1087–110.

11 Peterson GN, Domino KB, Caplan RA, Posner KL, Lee LA, Cheney FW. Management of the difficult airway: a closed claims analysis. *Anesthesiology* 2005; **103**: 33–9.

12 Frerk C, Cook T. Management of the 'can't intubate can't ventilate' situation and the emergency surgical airway. In: Cook TM, Woodall N, Frerk C, eds. *Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Major Complications of Airway Management in the United Kingdom. Report and Findings*. London: Royal College of Anaesthetists. March 2011, ISBN 978-1-9000936-03-3. http://www.rcoa.ac.uk/index.asp?PageID=1089 (accessed 06/05/2011).

13 Levitan RM, Kinkle WC, Levin WJ, Everett WW. Laryngeal view during laryngoscopy: a randomized trial comparing cricoid pressure, backward-upward-right-ward pressure, and bimanual laryngoscopy. *Annals of Emergency Medicine* 2006; **47**: 548–55.

14 Shorten GD, Alfille PH, Gliklich RE. Airway obstruction following application of cricoid pressure. *Journal of Clinical Anesthesia* 1991; **3**: 403–5.

15 Allman KG. The effect of cricoid pressure application on airway patency. *Journal of Clinical Anesthesia* 1995; **7**: 197–9.

16 Hartsilver EL, Vanner RG. Airway obstruction with cricoid pressure. *Anaesthesia* 2000; **55**: 208–11.

17 Arandia HY, Patil VU. Glottic closure following large doses of fentanyl. *Anesthesiology* 1987; **66**: 574–5.

18 Abrams JT, Horrow JC, Bennett JA, Van Riper DF, Storella RJ. Upper airway closure: a primary source of difficult ventilation with sufentanil induction of anesthesia. *Anesthesia and Analgesia* 1996; **83**: 629–32.

19 Jones DH, Cohle SD. Unanticipated difficult airway secondary to lingual tonsillar hyperplasia. *Anesthesia and Analgesia* 1993; **77**: 1285–8.

20 Ovassapian A, Glassenberg R, Randel GI, Klock A, Mesnick PS, Klafta JM. The unexpected difficult airway and lingual tonsil hyperplasia: a case series and a review of the literature. *Anesthesiology* 2002; **97**: 124–32.

21 Henderson J. Airway management in the adult. In: Miller RD, ed. *Miller's Anesthesia*, 7th edn. Philadelphia, PA: Churchill Livingstone/Elsevier, 2009: 1573–610.

22 Farmery AD. Simularing hypoxia and modelling the airway. *Anaesthesia* 2011; **66** (Suppl 2): 11–18.

23 Pandit JJ, Duncan T, Robbins PA. Total oxygen uptake with two maximal breathing techniques and the tidal volume breathing technique: a physiologic study of preoxygenation. *Anaesthesiology* 2003; **99**: 841–6.

24 Parmet JL, Colonna-Romano P, Horrow JC, Miller F, Gonzales J, Rosenberg H. The laryngeal mask airway reliably provides rescue ventilation in cases of unanticipated difficult tracheal intubation along with difficult mask ventilation. *Anesthesia and Analgesia* 1998; **87**: 661–5.

25 Fundingsland BW, Benumof JL. Difficulty using a laryngeal mask airway in a patient with lingual tonsil hyperplasia. *Anesthesiology* 1996; **84**: 1265–6.

26 Bromiley M. The case of Elaine Bromiley. http://www chfgorg/wp-content/uploads/ElaineBromileyAnonymousReportpdf (accessed 21/04/2011).

27 Metzner J, Posner KL, Lam MS, Domino KB. Closed claims' analysis. *Best Practice & Research Clinical Anaesthesiology* 2011; **25**: 263–76.

28 Vanner RG, Asai T. Safe use of cricoid pressure. *Anaesthesia* 1999; **54**: 1–3.

29 Larson CP Jr. Laryngospasm: the best treatment. *Anesthesiology* 1998; **89**: 1293–4.

30 Spaite DW, Joseph M. Pre-hospital cricothyrotomy: an investigation of indications, technique, complications, and patient outcome. *Annals of Emergency Medicine* 1990; **19**: 279–85.

31 Boyle MF, Hatton D, Sheets C. Surgical cricothyrotomy performed by air ambulance flight nurses: a 5-year experience. *Journal of Emergency Medicine* 1993; **11**: 41–5.

32 McClelland RM. Complications of tracheostomy. *British Medical Journal* 1965; **2**: 567–9.

33 Dover K, Howdieshell TR, Colborn GL. The dimensions and vascular anatomy of the cricothyroid membrane: relevance to emergent surgical airway access. *Clinical Anatomy* 1996; **9**: 291–5.

34 Salah N, El Saigh I, Hayes N, McCaul C. Airway injury during emergency transcutaneous airway access: a comparison at crico-thyroid and tracheal sites. *Anesthesia and Analgesia* 2009; **109**: 1901–7.

35 Elliott DS, Baker PA, Scott MR, Birch CW, Thompson JM. Accuracy of surface landmark identification for cannula cricothyroidotomy. *Anaesthesia* 2010; **65**: 889–94.

36 Sise MJ, Shackford SR, Cruickshank JC, Murphy G, Fridlund PH. Cricothyroidotomy for long-term tracheal access. A prospective analysis of morbidity and mortality in 76 patients. *Annals of Surgery* 1984; **200**: 13–7.

37 Mace SE. Cricothyrotomy. *Journal of Emergency Medicine* 1988; **6**: 309–19.

38 Wong DT, Lai K, Chung FF, Ho RY. Cannot intubate-cannot ventilate and difficult intubation strategies: results of a Canadian national survey. *Anesthesia and Analgesia* 2005; **100**: 1439–46.

39 Ezri T, Szmuk P, Warters RD, Katz J, Hagberg CA. Difficult airway management practice patterns among anesthesiologists practicing in the United States: have we made any progress? *Journal of Clinical Anesthesia* 2003; **15**: 418–22.

40 Patel RG. Percutaneous transtracheal jet ventilation: a safe, quick, and temporary way to provide oxygenation and ventilation when conventional methods are unsuccessful. *Chest* 1999; **116**: 1689–94.

41 Benumof JL, Scheller MS. The importance of transtracheal jet ventilation in the management of the difficult airway. *Anesthesiology* 1989; **71**: 769–78.

42 Cook TM, Nolan JP, Cranshaw J, Magee P. Needle cricothyroidotomy. *Anaesthesia* 2007; **62**: 289–90.
43 Flint NJ, Russell WC, Thompson JP. Comparison of different methods of ventilation via cannula cricothyroidotomy in a trachea-lung model. *British Journal of Anaesthesia* 2009; **103**: 891–5.
44 Sanders RD. Two ventilating attachments for bronchoscopes. *Delaware Medical Journal* 1967; **39**: 170–5.
45 Manoach S, Corinaldi C, Paladino L, et al. Percutaneous transcricoid jet ventilation compared with surgical cricothyroidotomy in a sheep airway salvage model. *Resuscitation* 2004; **62**: 79–87.
46 Gal T. Airway management. In: Miller RD, ed. *Miller's Anesthesia*, 6th edn. Philadelphia, PA: Elsevier, 2005: 1637–9.
47 Schaefer R, Hueter L, Preussler NP, Schreiber T, Schwarzkopf K. Percutaneous transtracheal emergency ventilation with a self-made device in an animal model. *Pediatric Anesthesia* 2007; **17**: 972–6.
48 Mace SE. Needle cricothyrotomy. *Emergency Medicine Clinics of North America* 2008; **26**: 1085–101.
49 Bould MD, Bearfield P. Techniques for emergency ventilation through a needle cricothyroidotomy. *Anaesthesia* 2008; **63**: 535–9.
50 Tighe SQ, Staber M, Hardman JG, Henderson JJ. Emergency airway access equipment. *Anaesthesia* 2004; **59**: 505–6.
51 Hamaekers A, Borg P, Enk D. The importance of flow and pressure release in emergency jet ventilation devices. *Pediatric Anesthesia* 2009; **19**: 452–7.
52 Yildiz Y, Preussler NP, Schreiber T, et al. Percutaneous transtracheal emergency ventilation during respiratory arrest: comparison of the oxygen flow modulator with a hand-triggered emergency jet injector in an animal model. *American Journal of Emergency Medicine* 2006; **24**: 455–9.
53 Craven RM, Vanner RG. Ventilation of a model lung using various cricothyrotomy devices. *Anaesthesia* 2004; **59**: 595–9.
54 Hamaekers A, Borg P, Enk D. A bench study of ventilation via two self-assembled devices and the Oxygen Flow Modulator in simulated upper airway obstruction. *Anaesthesia* 2009; **64**: 1353–8.
55 Eger EI, Hamilton WK. Positive-negative pressure ventilation with a modified Ayre's T-piece. *Anesthesiology* 1958; **19**: 611–8.
56 Dunlap LB, Oregon E. A modified, simple device for the emergency administration of percutaneous transtracheal ventilation. *Journal of the American College of Emergency Physicians* 1978; **7**: 42–6.
57 Hamaekers AE, Borg PA, Gotz T, Enk D. Ventilation through a small-bore catheter: optimizing expiratory ventilation assistance. *British Journal of Anaesthesia* 2011; **106**: 403–9.
58 Kiyama S, Koyama K, Takahashi J, Fukushima K. Tension pneumothorax resulting in cardiac arrest during emergency tracheotomy under transtracheal jet ventilation. *Journal of Anesthesia* 1991; **5**: 427–30.
59 Metz S, Parmet JL, Levitt JD. Failed emergency transtracheal ventilation through a 14-gauge intravenous catheter. *Journal of Clinical Anesthesia* 1996; **8**: 58–62.
60 Nunn C, Uffman J, Bhananker SM. Bilateral tension pneumothorax following jet ventilation via an airway exchange catheter. *Journal of Anesthesia* 2007; **21**: 76–9.
61 Cook TM, Alexander R. Major complications during anaesthesia for elective laryngeal surgery in the UK: a national survey of the use of high-pressure source ventilation. *British Journal of Anaesthesia* 2008; **101**: 266–72.
62 Sulaiman L, Tighe SQ, Nelson RA. Surgical vs wire-guided cricothyroidotomy: a randomised crossover study of cuffed and uncuffed tracheal tube insertion. *Anaesthesia* 2006; **61**: 565–70.
63 Wong DT, Kumar A, Prabhu A. The laryngeal mask airway prevents supraglottic leak during ventilation through an uncuffed cricothyroidotomy. *Canadian Journal of Anesthesia* 2007; **54**: 151–4.
64 Abbrecht PH, Kyle RR, Reams WH, Brunette J. Insertion forces and risk of complications during cricothyroid cannulation. *Journal of Emergency Medicine* 1992; **10**: 417–26.
65 Fikkers BG, van Vugt S, van der Hoeven JG, van den Hoogen FJ, Marres HA. Emergency cricothyrotomy: a randomised crossover trial comparing the wire-guided and catheter-over-needle techniques. *Anaesthesia* 2004; **59**: 1008–11.
66 Murphy C, Rooney SJ, Maharaj CH, Laffey JG, Harte BH. Comparison of three cuffed emergency percutaneous cricothyroidotomy devices to conventional surgical cricothyroidotomy in a porcine model. *British Journal of Anaesthesia* 2011; **106**: 57–64.
67 Metterlein T, Frommer M, Ginzkey C, et al. A randomized trial comparing two cuffed emergency cricothyrotomy devices using a wire-guided and a catheter-over-needle technique. *Journal of Emergency Medicine* 2011; **41**: 326–32.
68 Department of Health. *Report on Confidential Enquiries Into Maternal Deaths in the United Kingdom 1991 – 1993*. London: Her Majesty's Stationery Office, 1996.
69 Clancy MJ. A study of the performance of cricothyroidotomy on cadavers using the Minitrach II. *Archives of Emergency Medicine* 1989; **6**: 143–5.
70 Assmann NM, Wong DT, Morales E. A comparison of a new indicator-guided with a conventional wire-guided percutaneous cricothyroidotomy device in mannequins. *Anesthesia and Analgesia* 2007; **105**: 148–54.
71 Schober P, Hegemann MC, Schwarte LA, Loer SA, Noetges P. Emergency cricothyrotomy-a comparative

study of different techniques in human cadavers. *Resuscitation* 2009; **80**: 204–9.
72 Dimitriadis JC, Paoloni R. Emergency cricothyroidotomy: a randomised crossover study of four methods. *Anaesthesia* 2008; **63**: 1204–8.
73 Bruppacher HR, Naik VN, Bould MD, Friedman Z. Design flaw of Melker kit may compromise patient safety. *Anaesthesia* 2009; **64**: 1147.
74 Airway and ventilatory management. *Advance Trauma Life Support®* for Doctors. Student Course Manual, 6th edn. Chicago, IL: American College of Surgeons Committee on trauma, 1997: 83–5.
75 Brofeldt BT, Panacek EA, Richards JR. An easy cricothyrotomy approach: the rapid four-step technique. *Academic Emergency Medicine* 1996; **3**: 1060–3.
76 Morris A, Lockey D, Coats T. Fat necks: modification of a standard surgical airway protocol in the pre-hospital environmental. *Resuscitation* 1997; **35**: 253–4.
77 Morain WD. Cricothyroidotomy in head and neck surgery. *Plastic and Reconstructive Surgery* 1980; **65**: 424–8.
78 Kuriloff DB, Setzen M, Portnoy W, Gadaleta D. Laryngotracheal injury following cricothyroidotomy. *Laryngoscope* 1989; **99**: 125–30.
79 Schroeder AA. Cricothyroidotomy: when, why, and why not? *American Journal of Otolaryngology* 2000; **21**: 195–201.
80 Eisenburger P, Laczika K, List M, et al. Comparison of conventional surgical versus Seldinger technique emergency cricothyrotomy performed by inexperienced clinicians. *Anesthesiology* 2000; **92**: 687–90.
81 Boucek CD, Gunnerson HB, Tullock WC. Percutaneous transtracheal high-frequency jet ventilation as an aid to fiberoptic intubation. *Anesthesiology* 1987; **67**: 247–9.
82 Chandradeva K, Palin C, Ghosh SM, Pinches SC. Percutaneous transtracheal jet ventilation as a guide to tracheal intubation in severe upper airway obstruction from supraglottic oedema. *British Journal of Anaesthesia* 2005; **94**: 683–6.
83 Lacquiere A, Heard AM. Emergency cricothyroidotomy: training is paramount and oxygenation is the aim. *Anaesthesia* 2009; **64**: 447–8.
84 Heard AMB, Green RJ, Eakins P. The formulation and introduction of a ''can't intubate, can't ventilate'' algorithm into clinical practice. *Anaesthesia* 2009; **64**: 601–8.
85 Talving P, DuBose J, Inaba K, Demetriades D. Conversion of emergent cricothyrotomy to tracheotomy in trauma patients. *Archives of Surgery* 2010; **145**: 87–91.
86 Wright MJ, Greenberg DE, Hunt JP, Madan AK, McSwain NE Jr. Surgical cricothyroidotomy in trauma patients. *Southern Medical Journal* 2003; **96**: 465–7.
87 Altman KW, Waltonen JD, Kern RC. Urgent surgical airway intervention: a 3-year county hospital experience. *Laryngoscope* 2005; **115**: 2101–4.
88 Aitkenhead AR. Anaesthetic disasters: handling the aftermath. *Anaesthesia* 1997; **52**: 477–82.
89 Halpern J, Maunder RG, Schwartz B, Gurevich M. Identifying risk of emotional sequelae after critical incidents. *Emergency Medicine Journal* 2010; **28**: 51–6.
90 Association of Anaesthetists of Great Britain and Ireland. *Catastrophes in Anaesthetic practice; dealing with the aftermath*. 2005. http://www.aagbi.org/sites/default/files/catastrophes05.pdf (accessed 04/09/2011).
91 Smith CE, Dejoy SJ. New equipment and techniques for airway management in trauma. *Current Opinion in Anaesthesiology* 2001; **14**: 197–209.
92 Hubble MW, Wilfong DA, Brown LH, Hertelendy A, Benner RW. A meta-analysis of pre-hospital airway control techniques part II: alternative airway devices and cricothyrotomy success rates. *Pre-hospital Emergency Care* 2010; **14**: 515–30.
93 Gillespie MB, Eisele DW. Outcomes of emergency surgical airway procedures in a hospital-wide setting. *Laryngoscope* 1999; **109**: 1766–9.
94 Cook T, Bogod D. Evidence-based medicine and airway management: are they compatible? In: Cook TM, Woodall N, Frerk C, eds. *Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Major Complications of Airway Management in the United Kingdom. Report and Findings*. London: Royal College of Anaesthetists. March 2011, ISBN 978-1-9000936-03-3. http://www.rcoa.ac.uk/index.asp?PageID=1089. (accessed 01/06/2011).
95 Keane MF, Brinsfield KH, Dyer KS, Roy S, White D. A laboratory comparison of emergency percutaneous and surgical cricothyrotomy by pre-hospital personnel. *Pre-hospital Emergency Care* 2004; **8**: 424–6.
96 Salah N, Mhuircheartaigh RN, Hayes N, McCaul C. A comparison of four techniques of emergency transcricoid oxygenation in a manikin. *Anesthesia and Analgesia* 2010; **110**: 1083–5.
97 Chan TC, Vilke GM, Bramwell KJ, Davis DP, Hamilton RS, Rosen P. Comparison of wire-guided cricothyrotomy versus standard surgical cricothyrotomy technique. *Journal of Emergency Medicine* 1999; **17**: 957–62.
98 Schaumann N, Lorenz V, Schellongowski P, et al. Evaluation of Seldinger technique emergency cricothyroidotomy versus standard surgical cricothyroidotomy in 200 cadavers. *Anesthesiology* 2005; **102**: 7–11.
99 Davis DP, Bramwell KJ, Vilke GM, Cardall TY, Yoshida E, Rosen P. Cricothyrotomy technique: standard versus the Rapid Four-Step Technique. *Journal of Emergency Medicine* 1999; **17**: 17–21.
100 Davis DP, Bramwell KJ, Hamilton RS, Chan TC, Vilke GM. Safety and efficacy of the Rapid Four-Step Technique for cricothyrotomy using a Bair Claw. *Journal of Emergency Medicine* 2000; **19**: 125–9.
101 Hill C, Reardon R, Joing S, Falvey D, Miner J. Cricothyrotomy technique using gum elastic bougie is faster

than standard technique: a study of emergency medicine residents and medical students in an animal lab. *Academic Emergency Medicine* 2010; **17**: 666–9.

102 Holmes JF, Panacek EA, Sakles JC, Brofeldt BT. Comparison of 2 cricothyrotomy techniques: standard method versus rapid 4-step technique. *Annals of Emergency Medicine* 1998; **32**: 442–6.

103 Johnson DR, Dunlap A, McFeeley P, Gaffney J, Busick B. Cricothyrotomy performed by prehospital personnel: a comparison of two techniques in a human cadaver model. *American Journal of Emergency Medicine* 1993; **11**: 207–9.

104 Mariappa V, Stachowski E, Balik M, Clark P, Nayyar V. Cricothyroidotomy: comparison of three different techniques on a porcine airway. *Anaesthesia and Intensive Care* 2009; **37**: 961–7.

105 Benkhadra M, Lenfant F, Nemetz W, Anderhuber F, Feigl G, Fasel J. A comparison of two emergency cricothyroidotomy kits in human cadavers. *Anesthesia and Analgesia* 2008; **106**: 182–5.

106 Vadodaria BS, Gandhi SD, McIndoe AK. Comparison of four different emergency airway access equipment sets on a human patient simulator. *Anaesthesia* 2004; **59**: 73–9.

107 Hodgson R. A response to 'Emergency cricothyrotomy: a randomised crossover trial comparing the wire-guided and catheter-over-needle techniques'. *Anaesthesia* 2005; **60**: 105.

108 Scrase I, Woollard M. Needle vs surgical cricothyroidotomy: a short cut to effective ventilation. *Anaesthesia* 2006; **61**: 962–74.

109 Crosby ET, Cooper RM, Douglas MJ, et al. The unanticipated difficult airway with recommendations for management. *Canadian Journal of Anesthesia* 1998; **45**: 757–76.

110 Davies P. A stab in the dark! Are you ready to perform needle cricothyroidotomy? *Injury* 1999; **30**: 659–62.

111 Green L. Can't intubate, can't ventilate! A survey of knowledge and skills in a large teaching hospital. *European Journal of Anaesthesiology* 2009; **26**: 480–3.

112 Frerk C, Frampton C. Cricothyroidotomy; time for change. *Anaesthesia* 2006; **61**: 921–3.

113 Naik VN, Matsumoto ED, Houston PL, et al. Fiberoptic orotracheal intubation on anesthetized patients: do manipulation skills learned on a simple model transfer into the operating room? *Anesthesiology* 2001; **95**: 343–8.

114 Latif R, Chhabra N, Ziegler C, Turan A, Carter MB. Teaching the surgical airway using fresh cadavers and confirming placement nonsurgically. *Journal of Clinical Anesthesia* 2010; **22**: 598–602.

115 Wong DT, Prabhu AJ, Coloma M, Imasogie N, Chung FF. What is the minimum training required for successful cricothyroidotomy?: a study in mannequins. *Anesthesiology* 2003; **98**: 349–53.

116 Greif R, Egger L, Basciani RM, Lockey A, Vogt A. Emergency skill training – a randomized controlled study on the effectiveness of the 4-stage approach compared to traditional clinical teaching. *Resuscitation* 2010; **81**: 1692–7.

117 Friedman Z, You-Ten KE, Bould MD, Naik V. Teaching life saving procedures: the impact of model fidelity on acquisition and transfer of cricothyrotomy skills to performance on cadavers. *Anesthesia and Analgesia* 2008; **107**: 1663–9.

118 Cho J, Kang GH, Kim EC, et al. Comparison of manikin versus porcine models in cricothyrotomy procedure training. *Emergency Medicine Journal* 2008; **25**: 732–4.

119 Kuduvalli PM, Jervis A, Tighe SQ, Robin NM. Unanticipated difficult airway management in anaesthetised patients: a prospective study of the effect of mannequin training on management strategies and skill retention. *Anaesthesia* 2008; **63**: 364–9.

120 McNarry AF, Dovell T, Dancey FM, Pead ME. Perception of training needs and opportunities in advanced airway skills: a survey of British and Irish trainees. *European Journal of Anaesthesiology* 2007; **24**: 498–504.

121 Helm M, Gries A, Mutzbauer T. Surgical approach in difficult airway management. *Best Practice and Research, Clinical Anaesthesiology* 2005; **19**: 623–40.

122 Crosby ET. Complete airway obstruction. *Canadian Journal of Anesthesia* 1999; **46**: 99–104.

123 Borges BC, Boet S, Siu LW, et al. Incomplete adherence to the ASA difficult airway algorithm is unchanged after a high-fidelity simulation session. *Canadian Journal of Anesthesia* **57**: 644–9.

124 Heidegger T, Gerig HJ, Ulrich B, Kreienbuhl G. Validation of a simple algorithm for tracheal intubation: daily practice is the key to success in emergencies: an analysis of 13,248 intubations. *Anesthesia and Analgesia* 2001; **92**: 517–22.

125 Standley TD, Spears FD. Teaching cannula cricothyroidotomy. *Anaesthesia* 2004; **59**: 1138–9.

126 Tighe SQ. Failed tracheal intubation. *Anaesthesia* 1992; **47**: 356.