Macroscopic Barotrauma Caused by Stiff and Soft-Tipped Airway Exchange Catheters: An In Vitro Case Series

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BACKGROUND: Many airway management guidelines include the use of airway exchange catheters (AECs). There are reports, however, of harm from their use, from both malpositioning and in particular from the administration of oxygen via an AEC leading to barotrauma.
METHODS: We used an in vitro pig lung model to investigate the safety of administering oxygen at 4 different flow rates from a high-pressure source via 2 different AECs: a standard catheter and a soft-tipped catheter. Experiments were performed with the catheters positioned either above the carina or below it at the first point of resistance to advancement (hold-up). The experiments were then repeated to produce a series of 32 cases.
RESULTS: With an AEC positioned above the carina, we did not observe macroscopic lung damage after the administration of oxygen. The administration of oxygen through an AEC positioned below the carina resulted in macroscopic barotrauma regardless of the rate of oxygen delivery. Increasing speed of oxygen flow led to faster and more extensive damage. Use of an "injector" at 2.5 or 4 bar led to instantaneous macroscopic lung damage and advancement of the AEC through the lung tissue. Our observations were the same when both types of AECs were used.
CONCLUSIONS: Our results are consistent with reports of harm during the use of AECs and demonstrate the risk of administering oxygen through these devices when they are positioned below the carina. An indicator, ideally made on an AEC at the time of manufacture and designed to lie at the same level as the teeth, may be useful in preventing the insertion of that AEC beyond the level of the carina and improve the safety of using such devices. (Anesth Analg 2015;120:00–00)

An airway exchange catheter (AEC) is a long, small-diameter, semirigid tube that can be inserted through an in situ airway device. AECs are used in 2 situations: first to assist tracheal tube (TT) exchange, including changing from a smaller to larger TT, a single to double-lumen TT, or replacing a TT with a malfunctioning cuff; second, they are used as an aid to extubation, particularly when reintubation may be required at a later stage and may be difficult. In both circumstances, it may be considered desirable to administer oxygen through the AEC. The use of AECs is positively advocated, including "strong recommendation" in several recent national airway management guidelines,[1–3] and as a result their use may become more widespread.

An AEC can cause harm by directly injuring the airway, by causing barotrauma during oxygen delivery, or a combination of both mechanisms. Because it is a semirigid device, simple malpositioning of the catheter can cause direct injury to a patient's airway.[4–6] Barotrauma after oxygen delivery through an AEC is widely reported, in many cases associated with malpositioning[7,a] and is not limited to the airway.[8] A recently published large case series reported a 7.8% airway injury rate when TT exchange was performed using an AEC, including a 1.5% rate of pneumothorax.[9]

Several publications advocate limiting the depth of AEC insertion to 25 or 26 cm from the patient's mouth, both to avoid injury to the lungs and bronchial tree and to increase the safety of oxygen administration.[1,10,11] One AEC manufacturer (Cook Medical, Bloomington, IN) includes this warning in its instructions[12] and recently has introduced an AEC for double-lumen tube exchange: this tube has extra firm rigidity up to the distal 7 cm and a distal tip, which is notably softer.

We performed an in vitro case series to observe the effect of AEC position and oxygen delivery methods on the risk of macroscopic barotrauma. The study compared the standard and soft-tipped AECs and their risk of causing macroscopic barotrauma.

METHODS

We performed an in vitro case series with a convenience sample. The study used "waste products" from a butcher and did not involve patients or examination of clinician performance. The study took place in a nonclinical area. The study was approved by our local Research and Development committee. After discussion with the Research and Development committee, it was agreed that there was no requirement to seek ethical review.

Experiments were performed in an airway laboratory. Pig trachea and lung specimens less than 48 hours' postmortem and stored in refrigerated conditions (<4°C) were

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[a]Scottish Courts Fatal Accident Enquiry into the death of Gordon Ewing, Glasgow April 2010. Available at: www.scotcourts.gov.uk/opinions/2010FAI15.html. Accessed March 20, 2013.

used. Specimens that showed signs of gross macroscopic damage on inspection were excluded.

AECs manufactured by Cook Medical were used: a standard 83-cm AEC (part number C-CAE-14.0–83) shown in Figure 1 and a 100-cm, soft-tipped Cook Airway Exchange Catheter, designed for double-lumen tube exchange (C-CAE-14.0-100-DLT-EF-ST), shown in Figure 2. Both devices have a 3.0-mm (14 F) diameter.

Experiment 1: Oxygen Delivery Above the Carina

The AEC was inserted into the pig trachea-lung specimen to lie with the 26 cm marking on the AEC level in line with the tip of the tongue as illustrated in Figure 3. The position of the tip of the AEC above the carina was confirmed by palpation of the trachea. The position of the AEC was maintained carefully by the operator.

Oxygen was delivered from a high-pressure source CD cylinder (BOC Industrial Gases, Guildford, UK) at a pressure of 4 bar, either through standard oxygen tubing (low flow) or a Manujet III (VBM Medizintechnik GmbH, Sulz, Germany) (high flow). Oxygen was administered via the

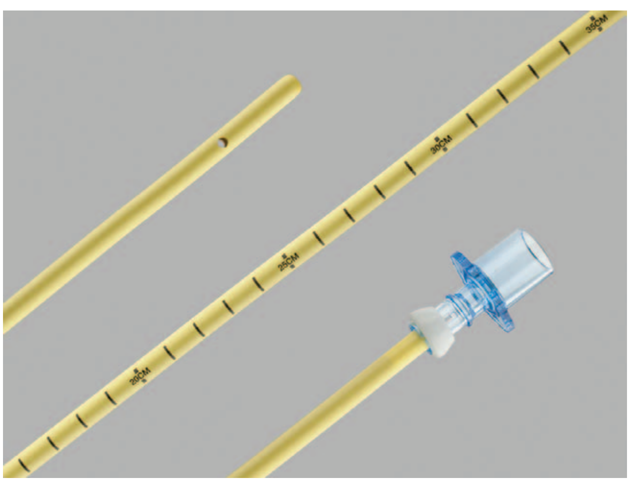

Figure 1. Standard Cook Airway Exchange Catheter. Images from Cook Medical; reproduced with permission.

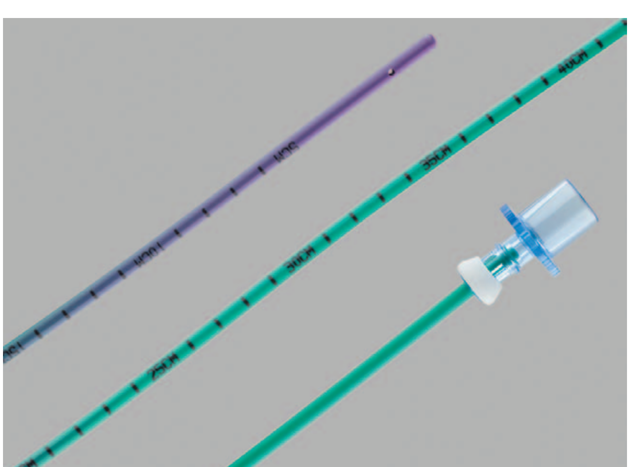

Figure 2. Soft-tipped Cook Airway Exchange Catheter. Images from Cook Medical; reproduced with permission.

Figure 3. Inserting a soft-tipped airway catheter into the pig trachea-lung specimen.

catheter at 2 L·min^{-1} and 15 L·min^{-1} and then with the Manujet III at 2.5 and 4 bar driving pressure.

The lungs were observed for external signs of changes and damage. The experiments were videoed. Each experiment was repeated twice.

Experiment 2: Oxygen Delivery Below the Carina

The AEC was gently inserted until resistance was first encountered (hold-up point). No attempt was made to advance the AEC further, but the position of the catheter was carefully maintained by the operator. Oxygen administration was then repeated as described previously.

When significant damage occurred during 1 experiment, the lungs were either discarded or the catheter was reinserted to lie in an undamaged part of the specimen. Each experiment was performed with both a standard and soft-tipped AEC.

The recorded video footage was edited to blind the observer to the type and position of the AEC, the oxygen administration method, and the flow rate. The video clips were then reviewed, in a random order, by a senior thoracic surgeon, who rated any visible barotrauma according to the scales in Table 1. This was a pragmatic experiment with no formal hypothesis and the results are presented simply as observations, akin to a case series. No power analysis or statistical analysis was performed.

RESULTS

Experiment 1

With the standard AEC above the carina and administration of low flow oxygen, no lung inflation or barotrauma was seen. When high-flow oxygen from the Manujet III was used, still with the standard AEC above the carina, lung inflation was seen but no external signs of barotrauma (Table 2).

Table 1. Empirical Rating Scale for Assessing Macroscopic Barotrauma: Degree of Lung Damage and Speed of Onset

Lung damage	Onset time
No inflation	Nil
No visible inflation of lung tissue, no barotrauma	>20 s or no effect seen
Partial inflation	Very slow
Partial inflation of lung segment(s), no barotrauma	10–20 s
Full inflation	Slow
Full inflation of lung segment(s), no barotrauma	5–10 s
Mild barotrauma	Fast
Lung tissue damage visible but limited or minor	3–5 s
Moderate barotrauma	Very fast
Lung tissue damage of increased severity without rupture of overlying pleura	1–3 s (approximately "2 breaths")
Severe barotrauma	Instantaneous
Gross lung tissue damage and rupture of overlying pleura	Immediate effect on first breath

the AEC to a depth of 26 cm and confirm the position of the catheter tip above the carina. This simple in vitro case series implies that oxygen administration through an AEC above the carina is unlikely to lead to barotrauma, regardless of the method of oxygen delivery. In contrast, high-pressure oxygen source administration with an AEC below the carina, and positioned at the first point of resistance, seems to have the potential to cause barotrauma within a few seconds. This appears to be true whatever the oxygen flow rate and whatever the design of the AEC tip. The speed of barotrauma we witnessed was increased by greater oxygen flow rates and occurred instantaneously with use of a Manujet III even at pressures below 4 bar. Observed effects included segmental hyperinflation, bullae formation, perforation of lung tissue, and visceral pleura. During oxygen administration, the AEC catheter also was seen to advance through the lung tissue on several occasions and emerge through the visceral pleura. This phenomenon did not occur without oxygen being supplied. Although these observations may not be surprising to those already informed, we believe

Table 2. Experiment 1: Airway Exchange Catheter (AEC) Above Carina

		Oxygen administration			
		2 L·min^{-1}	15 L·min^{-1}	Manujet III 2.5 bar	Manujet III 4 bar
Standard AEC	Effect	No inflation	No inflation	Partial inflation	Partial inflation
	Speed	Nil	Nil	Instantaneous	Instantaneous
Soft tipped AEC	Effect	No inflation	No inflation	Partial inflation	Partial inflation
	Speed	Nil	Nil	Very fast	Instantaneous

Table 3. Experiment 2: Airway Exchange Catheter (AEC) Inserted to First Resistance Below Carina

		Oxygen administration			
		2 L·min^{-1}	15 L·min^{-1}	Manujet III 2.5 bar	Manujet III 4 bar
Standard AEC	Effect	Mild barotrauma	Moderate barotrauma	Severe barotrauma	Severe barotrauma
	Speed	Very slow	Fast	Instantaneous	Instantaneous
Soft tipped AEC	Effect	Mild barotrauma	Severe barotrauma	Severe barotrauma	Severe barotrauma
	Speed	Fast	Very fast	Instantaneous	Instantaneous

When the experiment was repeated with the soft-tipped AEC above the carina, the observers recorded the same categories of outcome as with the standard AEC (Table 2).

Experiment 2

With the standard AEC below the carina, lung inflation and barotrauma were seen with all modes of oxygen administration in <1 minute (Table 3). The speed and extent of visible barotrauma appeared to increase with increasing oxygen flow rate and were dramatic and instantaneous with use of high flow oxygen from the Manujet III. When the experiment was repeated with the soft-tipped AEC placed below the carina, the observers recorded the same categories of outcome as with the standard AEC (Table 3). Typical barotrauma is illustrated in Figures 4–7 and Videos 1–4. (Supplemental Digital Content 1–4, Video 1, http://links.lww.com/AA/B45; Video 2, http://links.lww.com/AA/B46; Video 3, http://links.lww.com/AA/B47; Video 4, http://links.lww.com/AA/B48).

DISCUSSION

The porcine postmortem trachea-lung preparation has a similar gross anatomy to human lungs, enabling us to insert they illustrate the importance of safe use of the AEC and the dangers of their misuse.

Although oxygen administration with the AEC above the carina appeared safe, the cadaveric nature of our pig lung model with abducted vocal cords meant we were unable to recreate dynamic upper airway conditions. Previous authors have described the safety of oxygen administration as being dependent on adequate space around the AEC for gas to escape.[1,10] In 1 case report, high-pressure source ventilation through an AEC in an awake patient proceeded uneventfully until the patient phonated (adducting his vocal cords), which led to significant hypotension.[13] In addition, lack of gas egress may have contributed to a recent death in Canada.[b]

We observed no difference between the standard and soft-tipped AEC in the speed or degree of lung inflation or barotrauma. A standard catheter may cause more tissue

[b]McCallum A. Airway exchange catheters (AEC)/Endotracheal Ventilation Catheter September 16, 2010. Available at: www.cas.ca/English/Page/Files/109_coroner_letter.pdf. Accessed March 20, 2013.

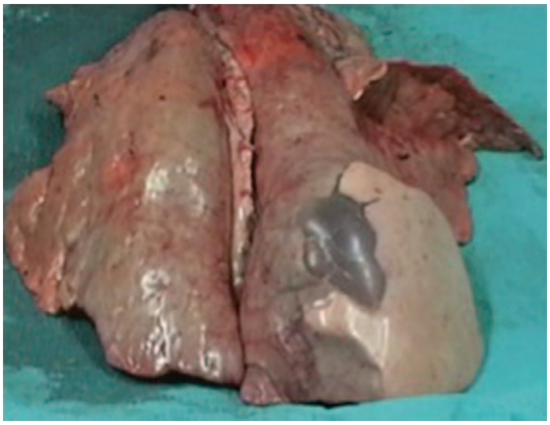

Figure 4. Moderate barotrauma showing segmental inflation and minor bulla formation without pleural rupture. Standard airway exchange catheter (AEC) inserted to first resistance, 15 L·min^{-1} oxygen.

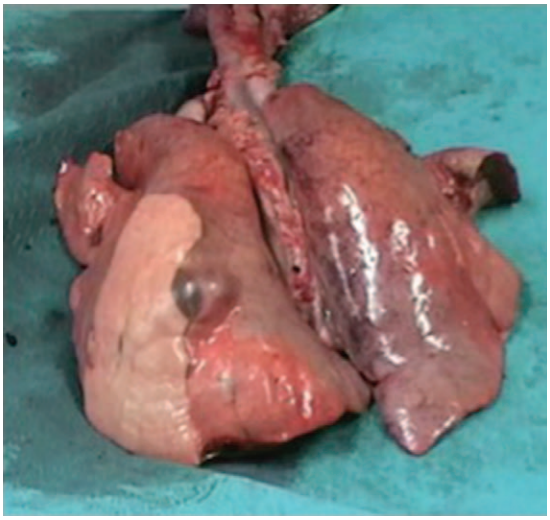

Figure 5. Early severe barotrauma showing segmental inflation and bulla formation (moderate at this point). As time passed, this developed into severe barotrauma with pleural rupture. Soft-tipped airway exchange catheter (AEC) inserted to first resistance, 15 L·min^{-1} oxygen.

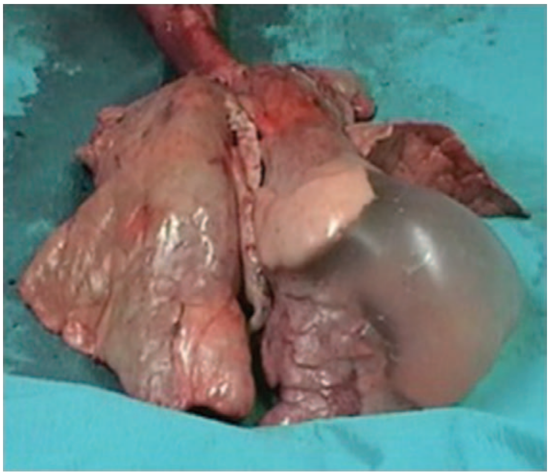

Figure 6. Development of severe barotrauma, with lung inflation, lung tissue disruption, massive bullae formation, and (subsequent) rupture of overlying pleura. Soft-tipped airway exchange catheter (AEC) inserted to first resistance, oxygen delivered via Manujet III at 2.5 bar.

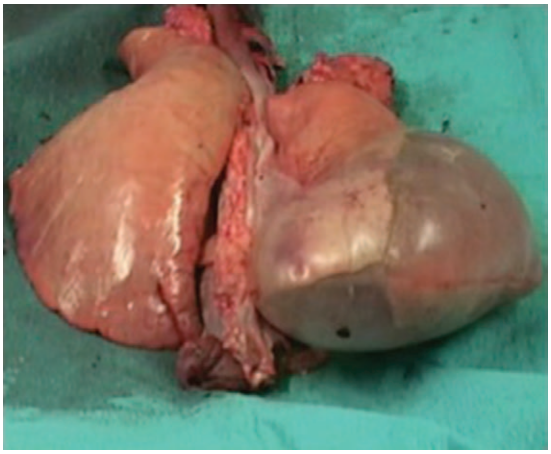

Figure 7. Established severe barotrauma with large bulla formation and rupture of overlying pleura. Standard airway exchange catheter (AEC) inserted to first resistance, oxygen delivered via Manujet III at 4 bar.

Video 1. Soft-tipped airway exchange catheter (AEC) inserted to first resistance. 2 L·min^{-1} oxygen.

Video 2. Standard airway exchange catheter (AEC) inserted to first resistance. 15 L·min^{-1} oxygen.

Video 3. Soft-tipped airway exchange catheter (AEC) inserted to first resistance. Oxygen delivered by Manujet III 2.5 bar.

Video 4. Standard soft-tipped airway exchange catheter (AEC) inserted to first resistance. Oxygen delivered by Manujet III 4 bar.

damage on insertion than a soft-tipped catheter and thereby increase the risk of barotrauma with subsequent oxygen administration. We were not able, however, to test this theory in our study.

Our findings should be treated with caution because our experimental design involved only 2 repetitions of each experiment and the classification of observations into pragmatic nonvalidated categories. We performed no statistical test because this would be meaningless in such a sample. A larger series might usefully examine our findings further.

We have used a high-pressure oxygen source for these experiments.[14] This is the type of oxygen source likely to be applied to an AEC on the wards for oxygen supplementation (wall or cylinder oxygen) or during emergency ventilation in the operating room (Manujet III or similar). Low-pressure oxygen sources (e.g., a self-inflating bag or anesthetic circuit) may have a different propensity to cause barotrauma.

There are clearly limitations of the model used. The lungs were up to 48 hours postmortem and subjected to refrigeration. The dissected lungs were fully collapsed, which may have had effects on the investigators ability to advance the AEC, the depth at which resistance was encountered, the ability to inflate the lungs, and their susceptibility to barotrauma. In a live specimen, it may be possible to insert an AEC further before encountering resistance, perhaps increasing the risk of barotrauma. The collapsed state of the lungs means that our observations on (lack of) lung inflation with the AEC above the carina should not be interpreted as meaning oxygenation will be ineffective by this method. The collapsed lungs also might protect against barotrauma because significant pressures will be needed to inflate the tissues before hyperinflation, barotrauma, and rupture can occur. This finding suggests to us that it is unlikely that our model dramatically overrepresents the risk of barotrauma in vivo and, if anything, might overestimate the safety of administration of oxygen through an AEC positioned above the carina. Each experiment was repeated only twice, but results were notably similar on each "run." Therefore, when we report that results were observed in "no cases" (Table 2) or "all cases" (Table 3), these are none or all of 2 cases, and hence no statistical inference can be made. It is possible larger series might find quite different results.

These in vitro observations are consistent with the published data of harm from oxygen administration via an AEC, especially high-pressure oxygen source delivered at a high flow rate. In a case series of the use of jet ventilation through an AEC using the endotracheal ventilation catheter (Cardiomed Supplies, Lindsay ON, Canada), 11% of patients suffered barotrauma.[15] Numerous case reports have documented jet ventilation through an AEC leading to pneumothorax, pneumomediastinum, pneumoperitoneum, cardiovascular collapse, and death as well as extrapulmonary injuries.[7,13] In contrast, high-pressure source ventilation through devices confirmed to be within the trachea appears less likely to result in complications. In a review of 10 years of endoscopic laryngeal surgery in 469 patients ventilated via a transglottal polyurethane jet cannula or metallic cannula, there was only 1 case of pneumothorax.[16] Similarly, 15 years experience with the Hunsaker Mon-Jet tube (Medtronic Xomed Inc., Jacksonville, FL) and automatic jet ventilation in 839 patients reported 2 cases of barotrauma.[17]

Oxygen insufflation through an AEC is likely to be safer in expert hands: in 3 case series, with 96 adult and pediatric patients, there were no reported complications.[18–20] Insufflation, however, is not without risk if the AEC is misplaced. In the high-profile United Kingdom case of Gordon Ewing's death, an AEC was likely advanced beyond the carina.[a] An oxygen cylinder delivering oxygen at high flow caused massive barotrauma, and this was the major cause of death. At postmortem, the AEC was found to lie outside the parietal pleura in the intercostal muscles.[a] In a second more recent case reported by the Chief Coroner of Ontario, an AEC had been inserted into a patient after dental surgery as part of an extubation strategy. Oxygen was insufflated at 5 L·min^{-1} through this AEC, but the patient rapidly deteriorated and suffered cardiorespiratory arrest, tension pneumothorax, and subsequently death.[b]

All the available evidence suggests that any administration of oxygen through an AEC that is inserted too deeply into the bronchial tree is dangerous, and this evidence is supported by our experimental findings. As discussed by other authors and included in the product information, the key to safely administering gas via an AEC is ensuring sufficient egress of administered gas.[1,10,21] The AEC tip must lie above the carina and be securely positioned: this will avoid risk of the AEC tip becoming "wedged" and transmitting the driving pressure of the delivered gas directly to the lung parenchyma. Ensuring a patent upper airway is a second key point, allowing escape of administered gas. The depth to which an AEC can be inserted to ensure it is above the carina has not been studied. Limiting insertion to 25 or 26 cm has been advocated as safe,[1,10,11,21] but a recent review of the published literature, performed as part of a study of a safety innovation of a bougie, suggests this may not ensure the tip lies above the carina.[22] The range of average distances to the carina measured from various points at the mouth was 23 to 26.9 cm in men and 21.1 to 24.1 cm in women. In a situation in which the position of the tip of the AEC cannot be confirmed visually, then the use of conservative limits for the depth of insertion would seem advisable; however, the effect of this approach on AEC positioning and migration has not been studied.

Our study has practical implications. When an AEC is left in place after extubation, as recommended in recent publications,[1–3] 2 concerns arise: (1) the patient's airway may be obstructed by dynamic changes in the upper airway, and (2) the device may migrate inwards. The latter is particularly likely because ensuring an AEC does not migrate inwards is challenging. Secure positioning and awareness of all those in attendance of the insertion depth are vital to safe use. The administration of oxygen through an AEC that has migrated inwards, at whatever flow, poses a risk of rapid patient harm. On the basis of our findings and reports of harm with the use of AECs, we suggest that AECs should be primarily considered to be a device for airway exchange or reintubation rather than for oxygen delivery. Oxygen should only be administered via an AEC in exceptional circumstances because in most cases there are safer alternatives. This is in line with recommendations from the United Kingdom Difficult Airway Society and other authors.[1,7] Any administration of oxygen through an AEC should be restricted to an area in which the position of the AEC can be confirmed and maintained and should be in the hands of an expert. Use of a high-pressure source ventilation via an AEC poses the highest risk of barotrauma and should be avoided if at all possible.

Finally, it would be beneficial for the manufacturers of AECs to further emphasize the importance of safe use: the addition of a clearly visible marker to indicate maximum insertion depth would be of considerable benefit. We have suggested this to the manufacturers in previous discussions. In a recent study, a color-coded "traffic light" bougie was intuitive to use and led to users reducing the depth of insertion: the authors speculate a similar system would be effective for other airway exchange devices.[22]

DISCLOSURES

Name: Robert Axe, FRCA.
Contribution: This author helped design the study, collect data, analyze data, and prepare the manuscript.
Attestation: Robert Axe approved the final manuscript. Robert Axe attests to the integrity of the original data and the analysis reported in this manuscript. Robert Axe is the archival author.
Conflicts of Interest: Soft-tipped AECs were provided by Cook Medical. The company had no other involvement in the study or in its write-up. The Department of Anaesthesia and Intensive Care Medicine at Royal United Hospital, Bath, has received free or at-cost airway devices for evaluation or for research.
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Contribution: This author helped design the study, collect data, analyze data, and prepare the manuscript.
Attestation: Alex Middleditch approved the final manuscript. Alex Middleditch attests to the integrity of the original data and the analysis reported in this manuscript.
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