Can J Anesth/J Can Anesth (2018) 65:822–836
https://doi.org/10.1007/s12630-018-1121-3

REVIEW ARTICLE/BRIEF REVIEW

Anesthesia for interventional pulmonology procedures: a review of advanced diagnostic and therapeutic bronchoscopy

Anesthésie pour procédures interventionnelles en pneumologie : revue des implications de la bronchoscopie avancée à buts diagnostique et thérapeutique

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Received: 12 October 2017 / Revised: 17 January 2018 / Accepted: 17 January 2018 / Published online: 5 April 2018

Abstract

Purpose *Interventional pulmonology is a growing subspecialty of pulmonary medicine with flexible and rigid bronchoscopies increasingly used by interventional pulmonologists for advanced diagnostic and therapeutic purposes. This review discusses different technical aspects of anesthesia for interventional pulmonary procedures with an emphasis placed on pharmacologic combinations, airway management, ventilation techniques, and common complications.*

Source *Relevant medical literature was identified by searching the PubMed and Google Scholar databases for publications on different anesthesia topics applicable to interventional pulmonary procedures. Cited literature included case reports, original research articles, review articles, meta-analyses, guidelines, and official society statements.*

Principal findings *Interventional pulmonology is a rapidly growing area of medicine. Anesthesiologists need to be familiar with different considerations required for every procedure, particularly as airway access is a shared responsibility with pulmonologists. Depending on the individual case characteristics, a different selection of airway method, ventilation mode, and pharmacologic combination may be required. Most commonly, airways are managed with supraglottic devices or endotracheal tubes. Nevertheless, patients with central airway obstruction or tracheal stenosis may require rigid bronchoscopy and jet ventilation. Although anesthetic approaches may vary depending on factors such as the length, complexity, and acuity of the procedure, the majority of patients are anesthetized using a total intravenous anesthetic technique.*

Conclusions *It is fundamental for the anesthesia provider to be updated on interventional pulmonology procedures in this rapidly growing area of medicine.*

Résumé

Objectif *La pneumologie interventionnelle est une sous-spécialité de la pneumologie en progression grâce à l'utilisation croissante des bronchoscopes souples et rigides par les pneumologues interventionnels à des fins diagnostiques et thérapeutiques avancées. Cette analyse aborde les différents aspects techniques de l'anesthésie pour les procédures interventionnelles en pneumologie en insistant sur les combinaisons pharmacologiques, la gestion des voies respiratoires, les techniques de ventilation et les complications fréquentes.*

Source *La littérature médicale pertinente a été identifiée par une recherche des publications sur différents sujets d'anesthésie applicables aux procédures interventionnelles en pneumologie dans les bases de données PubMed et Google Scholar. Les publications citées ont inclus des rapports de cas, des articles de recherche originale, des articles de synthèse, des méta-analyses, des lignes directrices et les déclarations officielles de sociétés savantes.*

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Constatations principales *La pneumologie interventionnelle est une branche de la médecine qui se développe rapidement. Les anesthésiologistes ont besoin de se familiariser avec les différents problèmes soulevés par chaque procédure, en particulier dans la mesure où la responsabilité de l'accès aux voies respiratoires est partagée avec les pneumologues. La méthode de gestion des voies aériennes, le mode de ventilation et la combinaison pharmacologique pourront être choisis en fonction des caractéristiques de chaque cas particulier. Le plus souvent, les voies respiratoires sont gérées avec des dispositifs supraglottiques ou des tubes endotrachéaux. Néanmoins, les patients présentant une obstruction centrale des voies respiratoires ou une sténose de la trachée peuvent nécessiter le recours à un bronchoscope rigide et à une jet-ventilation. Bien que la démarche anesthésique puisse varier en fonction de facteurs tels que la durée, la complexité et la gravité de la procédure, la majorité des patients sont anesthésiés en employant une technique intraveineuse totale.*

Conclusions *Il est essentiel que le professionnel assurant l'anesthésie connaisse les plus récentes procédures interventionnelles en pneumologie dans ce domaine rapidement croissant de la médecine.*

Interventional pulmonology is a growing subspecialty in pulmonary medicine with remarkable advancements in recent years having been made in diagnostic and therapeutic innovations.[1,2] A growing number of procedures are performed by interventional pulmonologists. Different procedures require different anesthetic considerations based on the complexity of the procedure performed and underlying patient conditions; these range from conscious sedation to general anesthesia, including the use of either conventional or jet ventilation.[3,4] Hence, it is fundamental for anesthesiologists to be familiar with the nuances of the different techniques commonly performed by interventional pulmonologists.

This narrative review addresses the various methods used for securing the airway as well as the pharmacologic considerations, ventilation modes, and potential complications relevant to the different interventional bronchoscopic procedures.

Pre-procedure assessment

Over 500,000 bronchoscopies are performed annually in the United States[5] to address many conditions including malignancy (i.e., for diagnostic, staging, and palliative purposes), interstitial lung disease, asthma, and central airway obstruction.[6] Current American Thoracic Society recommendations state that, based on the patient's underlying condition and physician's criteria, a full preoperative evaluation (including a full physical examination, laboratory tests, and relevant imaging) should be done prior to bronchoscopy.[7] Emphasis should be placed on airway assessment and identification of challenging airway predictors.[3,8] Interventional pulmonologists and anesthesiologists should plan each case collaboratively to minimize complications.

Generally, bronchoscopic procedures may be classified as basic diagnostic, advanced diagnostic, and/or therapeutic procedures. These are summarized in Table 1.

Flexible bronchoscopy

Procedure description

The flexible bronchoscope has become an increasingly popular tool over the past years following its introduction in 1968 by Ikeda *et al.*[9] It involves an endoscopic minimally invasive approach to the tracheobronchial tree allowing airway visualization from the nares to the subsegmental bronchi.[5] The development of various devices, including brushes, forceps, needles, laser probes, cryoprobes, argon plasma coagulation, electrocautery devices, ultrasound probes (linear and radial), inflatable balloons, and others compatible with the flexible bronchoscope, has increased the diagnostic and therapeutic applications for this technique (Table 2).[10,11]

Tissue biopsies can be adequately obtained from mediastinal and hilar lymph nodes using transbronchial needle aspiration (TBNA) and from airway or parenchymal lesions with endobronchial and transbronchial forceps biopsies.[12-15] Endobronchial lesions such as tumours and strictures can be debrided, resected/excised, cauterized, dilated, and/or ablated using flexible bronchoscopy.[16] Other procedures performed using flexible bronchoscopy include foreign body removal, bronchioalveolar lavage (BAL), airway stenting (self-expanding metallic airways stents, both covered and uncovered), bronchial thermoplasty, intrabronchial valve placement, and photodynamic therapy.[17-22] Anesthesiologists should be familiar with these and their potential complications.[23]

Endobronchial ultrasound (EBUS)-TBNA is the preferred method for mediastinal and hilar lymph node sampling. Using real-time ultrasound imaging, this technique achieves a sensitivity and negative predictive value close to 90% with a very low complication rate ($< 0.5\%$).[11,24,25] Radial probe EBUS uses a 360°-view small-sized ultrasound probe that fits through the working channel of a flexible bronchoscope. It is typically used in

Table 1 Bronchoscopic procedures and their common clinical indications

Procedure	Common clinical indication
Basic diagnostic procedures	
Dynamic flexible bronchoscopy	Diagnostic assessment of dynamic central airway collapse
Endobronchial biopsy	Diagnostic evaluation of endobronchial lesion
Bronchoalveolar lavage	Analysis of alveolar contents ➢ Diagnosis of alveolar proteinosis, opportunistic infections, eosinophilic pneumonia, etc.
Transbronchial biopsy	Parenchymal tissue sampling
Brushings	Obtaining cytologic samples of endobronchial lesions and parenchymal tumuors
Conventional TBNA	Diagnostic evaluation of mediastinal and/or hilar lymphadenopathy
Advanced diagnostic procedures	
Linear EBUS – TBNA	Diagnostic evaluation of mediastinal and/or hilar lymphadenopathy
Radial EBUS	Assessment of solitary pulmonary nodule or peripheral lung lesion
Electromagnetic navigation/Virtual bronchoscopy	
Cryobiopsy	Airway or parenchymal tissue sampling
Bronchoscopic transparenchymal nodule access	Peripheral solitary pulmonary nodule sampling (without a leading airway)
Advanced therapeutic procedures	
Rigid bronchoscopy	Management of central airway obstruction Management of massive hemoptysis Foreign body removal Stent deployment
Stent placement (metallic and silicone)	Airway obstruction secondary to malignancy or benign disease
Ablation techniques · Laser · Electrocautery · Argon plasma coagulation · Cryotherapy · Spray cryotherapy · Micro-debridement · Photodynamic therapy	Endobronchial/mixed lesion
Bronchial thermoplasty	Severe asthma
Intrabronchial valves	Persistent airway leak (alveolopleural fistula)
Intrabronchial valve/coil placement or steam	Endoscopic lung volume reduction for severe emphysema (experimental)

EBUS = endobronchial ultrasound, TBNA = transbronchial needle aspiration

Table 2 General recommendations and common complications in bronchoscopic procedures

Bronchoscopy type		Anesthesia		Frequent airway	Common complications
Basic diagnostic		Generous topical anesthetic irrigation over larynx (Lidocaine 1%: 3-5 mg·kg^{-1})	MAC – moderate sedation	None	Hypoxemia Desaturation Laryngospasm Bronchospasm Pneumothorax Hemorrhage Postoperative cough
			General anesthesia	ETT	
				SGA	
Advanced diagnostic			MAC – moderate sedation	None	
			General anesthesia	ETT	
				SGA	
Advanced therapeutic	Flexible		General anesthesia	ETT	
				SGA	
	Rigid			Rigid bronchoscope	

ETT = endotracheal tube, MAC = monitored anesthesia care, SGA = supraglottic airway conjunction with standard bronchoscopy using a guide sheath or navigational techniques, such as electromagnetic navigation bronchoscopy (ENB) or virtual bronchoscopy (VB). Radial EBUS provides a real-time confirmation of the location of a peripheral lung lesion reached by a navigation method.[26-28]

Electromagnetic navigation bronchoscopy is a minimally invasive approach to reach peripheral lesions. A locator guide is tracked in the electromagnetic field and blended with the existing chest computed tomography data. The locator guide and a sheath, which are steerable, are advanced together in real time based on the virtual imaging and system guidance of direction and distance. Once the lesion is reached, the locatable guide is removed and the working sheath is left in place at the target through which instruments such as a radial EBUS, brush, and forceps can be passed.[29]

Bronchoscopy-guided technologies such as ENB,[26,29] VB,[30] radial probe endobronchial ultrasound,[27,28] and ultrathin bronchoscopes with guided sheaths have been developed to improve the diagnostic yield of transbronchial biopsy for solitary pulmonary nodule diagnosis.[31] A recent meta-analysis showed that the pooled diagnostic yield of guided bronchoscopy using one or a combination of the above modalities was 70%.[30]

Anesthetic depth and pharmacologic considerations

Pharmacologic approaches vary depending on the indication for bronchoscopy and complexity of the case being undertaken. Basic bronchoscopy procedures are performed under minimal to moderate procedural sedation (i.e., monitored anesthesia care). On the contrary, advanced diagnostic and therapeutic bronchoscopy procedures often require more complex techniques with deep sedation (or even general anesthesia) as defined by the American Society of Anesthesiologists.[32]

According to American College of Chest Physicians (ACCP) recommendations, all patients undergoing bronchoscopy should receive some degree of sedation (unless contraindicated), as this improves patient satisfaction and procedure tolerability. For this, the ACCP supports the use of propofol alone as a safe and efficient method for bronchoscopy sedation. Nevertheless, it acknowledges the possibility of using regimens of short-acting benzodiazepines, such as midazolam, in combination with an opioid (which itself may be beneficial for its antitussive properties).[33]

A recently published survey conducted in Switzerland evaluated the practice of 299 pulmonologists and included 27,149 bronchoscopies. It revealed that most basic bronchoscopy cases are performed using propofol, with or without midazolam and/or fentanyl. Interestingly, in this cohort, propofol was administered by the proceduralist in 84% of cases without the presence of an anesthesiologist, with extremely low (0.02%) complication rates (mainly apnea and hypotension).[34] A recent retrospective study conducted in Germany assessed nearly 1,600 basic diagnostic bronchoscopy procedures to compare different moderate sedation combinations. Its results support the administration of moderate sedation with triple-sedative combinations (propofol, midazolam, and fentanyl) because it reduces the total dosage of each medication administered without increasing the incidence of adverse events.[35] Nevertheless, the addition of short-acting opioid infusions to propofol infusions during bronchoscopy must be closely monitored as they have been associated with lower oxygen saturation levels (SaO_2) compared with propofol infusions alone.[36] Patient premedication with hydrocodone (4-5 mg *iv*) prior to propofol-based sedation for bronchoscopy effectively reduces cough during the procedure, increases patient and proceduralist satisfaction, and decreases the total propofol dose required to achieve adequate sedation levels. This measure is most effective for complex procedures such as BAL or TBNA.[37]

Infusion regimens using total intravenous anesthesia (TIVA) for either moderate to deep sedation or general anesthesia have been described for certain bronchoscopic procedures. Propofol infusions are seen in everyday practice with different pharmacologic combinations depending on each patient and the procedure performed. Effective dosing schemes have been described with an initial bolus of 0.5-1.0 mg·kg^{-}1 followed by an infusion that can be titrated from 75 g·kg^{-1}·min^{-1} to 250 g·kg^{-1}·min^{-1}, depending on the anesthetic depth desired.[17,23,38] The administration of propofol can be guided safely based on electroencephalographic methods and its routine use has been be encouraged by some.[39] For short-duration bronchoscopic procedures that require moderate sedation, propofol boluses should be preferred over midazolam boluses as these are associated with shorter recovery times and lower levels of reported pain, nausea, and breathlessness postoperatively.[39] Depending on local regulations, propofol should only be administered in the presence of a certified anesthesia provider because it has a narrow therapeutic window that can quickly result in general anesthesia and respiratory depression.[17] Other studies have validated the addition of other sedative agents to propofol infusions, such as ketamine, that also favor hemodynamic stability.[40] Recently published literature shows that the addition of ketamine to midazolam and propofol infusions is as effective (to achieve sedation and analgesia) and as safe (in terms of hemodynamic and respiratory stability) as the addition of fentanyl to midazolam and propofol combinations.[41] Hypotension induced by propofol infusion can almost always be adequately managed with boluses of phenylephrine or ephedrine.[23]

The use of topical anesthetics is recommended by the ACCP for both basic and advanced bronchoscopy as it reduces the dose of sedative agents needed and effectively decreases cough.[42] Successful suppression of the gag reflex can be achieved by spraying lidocaine 1% directly over the oropharynx, vocal cords, and aryepiglottic folds.[43] Lidocaine 1% is generally a preferred concentration (over 2%) for topical anesthesia during bronchoscopy, as it has been shown to achieve equal patient and operator satisfaction levels while delivering a significantly lower total drug dose.[44]

Lastly, volatile agents are highly discouraged because bronchoscopic procedures require constant suctioning of the airways, making it impossible to determine the concentration of the agent delivered to the patient (risking inadequate depth of anesthesia in the patient and significant contamination of the procedural room).[23,38]

Specific advanced bronchoscopic procedures such as EBUS-TBNA may be performed with moderate to deep sedation or general anesthesia as shown by recently published literature. Nevertheless, conflicting evidence exists regarding the impact that sedation level has on the diagnostic yield, complication rate, and procedure tolerability.[45,46] Hence, the sedation method selection for EBUS-TBNA should be made individually, considering the operator's experience, patient preference, local resources (i.e., access to an anesthesiologist), and procedure duration.[47] A common practice for this purpose includes an infusion using propofol (75-250 $g \cdot kg^{-1} \cdot min^{-1}$) along with small boluses of opioids (fentanyl or remifentanil).[38]

Dynamic flexible bronchoscopy, a protocol used to diagnose tracheobronchomalacia, requires dynamic airway maneuvers. This procedure is often performed under minimal sedation and abundant topical anesthesia that allows forced inspiratory and expiratory maneuvers while diminishing cough and patient anxiety. Minimal sedation for this situation can be adequately achieved using fentanyl and midazolam boluses as needed during the procedure [mean (standard deviation) total dose per procedure has been reported as fentanyl 37.5 (12.5) g, midazolam 1.5 (0.5) mg].[43]

Patients undergoing bronchial thermoplasty (for severe asthma) or Chartis assessment (of collateral ventilation in patients who are candidates for endoscopic lung volume reduction with endobronchial valves) may benefit from small doses of anticholinergics (i.e., 10 $g \cdot kg^{-1}$ atropine *iv* or *im* or glycopyrrolate 5 $g \cdot kg^{-1}$ *iv*) as premedication to reduce bronchial secretions.[48] Nevertheless, the ACCP discourages the routine use of anticholinergics as current evidence fails to show a general clinical benefit.[42]

Airway and ventilation modes

Depending on the procedure performed, as well as patient medical comorbidities, different modalities of airway-securing devices can be used. Selected short-duration procedures can be safely performed under minimal to moderate sedation with spontaneous ventilation and no airway-securing device. A bite block should be placed to protect the bronchoscope and the patient's teeth. In patients able to maintain spontaneous ventilation while undergoing endoscopic airway surgery, the use of humidified high-flow nasal oxygen (HFNO) (40-60 $L \cdot min^{-1}$) is an effective option to prevent hypoxia or hypercapnia.[49,50] For patients with respiratory failure who are undergoing bronchoscopy, the application of non-invasive positive pressure ventilation via resuscitation face mask has been proven superior to HFNO in maintaining adequate oxygenation.[51] The Janus mask (Biomedical Srl, Florence, Italy) is another option for these cases as it allows delivery of continuous positive airway pressure while bronchoscopy is performed.[52]

When deep sedation or general anesthesia is desired and an airway-securing device is required, patients should be pre-oxygenated with a non-rebreathe face mask at 10-12 $L \cdot min^{-1}$.[38] Once sedation or anesthesia has been induced, the airway can be supported using a supraglottic airway (SGA) over a regular endotracheal tube (ETT). A laryngeal mask airway (LMA®; Teleflex Medical Inc; Wayne, PA, USA) is a common option as it allows adequate examination of the larynx and facilitates sampling of high-level (e.g., station 2) mediastinal lymph nodes. Other SGAs have similarly been used.[53] Because they produce less stimulation at placement, SGAs require lower doses of sedating agents compared with an ETT and are a relatively non-traumatic method when a tracheal lesion (i.e., mass or stenosis) is present.[17,54] An SGA also allows proper evaluation and treatment of subglottic/high-tracheal lesions[54,55] and provides airway support, improving oxygen saturation and facilitating insertion of the bronchoscope into the larynx.[56,57]

As no studies have compared the use of different SGA designs in the context of flexible bronchoscopy, the size and type of the SGA chosen will depend on each patient's size and product availability. Different alternatives, such as the ProSeal™ (Teleflex Medical Inc; Wayne, PA, USA) or i-gel® SGA (Intersurgical, Wokingham, UK), may be used. An SGA with its own bite block, such as the i-gel, can be used to prevent injury to the patient as well as damage to the bronchoscope. Sizes 4 and 5 are the main options described in the literature for use in the adult population.[58] The size 4 i-gel has a 12.3-mm internal diameter and fits a therapeutic bronchoscope (5.9-mm external diameter) or EBUS scope (6.9-mm external diameter) without significantly compromising ventilation.[38] This device will also allow the introduction of a 7.0-mm external diameter ETT in case intubation is needed.[59] Recent literature suggests that the i-gel SGA is a reliable and safe alternative in patients with severe chronic obstructive pulmonary disease undergoing bronchoscopy procedures in whom excessive tracheal stimulation from laryngoscopy and ETT insertion should be avoided.[60]

Because the bronchoscope is constantly inserted and withdrawn, the SGA can be dislodged, leading to an air leak.[23] Proper ventilation should be assessed with end-tidal capnography, auscultation, and inspection of the mask position using the bronchoscope. In cases of difficult SGA placement, obesity, or severe gastroesophageal reflux, an ETT is a reasonable option. Typically, a larger sized ETT (i.e., 8-9 mm) is recommended, particularly if a wide-diameter therapeutic bronchoscope (5.7-mm external diameter) or an EBUS scope (6.9-mm external diameter) is being used.[38]

Ventilator settings should be adjusted according to a patient's physiologic parameters. Pressure-controlled ventilation with a standard continuous positive end-expiratory pressure (PEEP) between 5 and 10 cmH_2O as well as positive pressure support ventilation between 15 and 20 cmH_2O is a reasonable approach.[51,61] Other parameters suggested include a tidal volume close to 10 $mL \cdot kg^{-1}$ body weight, F_IO_2 of 100%, a 1:2 inspiratory to expiratory ratio, and a respiratory rate of 12 $cycles \cdot min^{-1}$. When performing electrosurgical procedures, different settings (including low F_IO_2) are recommended to prevent airway fire (see *common complications and special considerations* as discussed further it the text). For endoscopic lung volume reduction procedures (valves or coils), a 1:3 to 1:4 inspiration-to-expiration ratio is recommended to avoid auto-PEEP.[62]

When using an SGA, a maximum peak pressure of 20-30 cmH_2O is preferred to minimize air leaks and gastric distention.[63] Patients who despite these measures have unreasonably high end-tidal carbon dioxide (CO_2) or persistent low SaO_2 should undergo endotracheal intubation with volume-controlled ventilation. When performing balloon dilation, mechanical ventilation is recommended since apnea during the balloon inflation is needed.[64]

Common complications and special considerations

Flexible bronchoscopy is generally a very safe procedure. In 2003, the ACCP reported a major complication rate of $< 1\%$ with a mortality rate of $< 0.04\%$ after evaluating nearly 68,000 cases.[5] A retrospective study that evaluated over 23,000 procedures in China reported a major complication rate of 0.64% with a mortality rate of 0.013%.[65] The most common complications included airway (larynx, trachea, or bronchi) spasm (0.28%), bleeding (0.16%), arrhythmias (0.10%), and pneumothorax/airway perforation (0.03%).[5,65,66]

Most cases of endobronchial bleeding that occur during bronchoscopy are minimal (estimated < 20 mL) and do not represent a major threat to the patient´s clinical condition.[67,68] Massive endobronchial hemorrhage occurs in $< 0.1\%$ of cases but may have a fatality rate as high as 10%.[69] For these events, conversion to rigid bronchoscopy may be required to protect and selectively ventilate the non-bleeding lung.

Procedures such as EBUS-TBNA carry an extremely low risk of endobronchial bleeding (0.2%), as shown in the over 1,300 cases evaluated by the ACCP Quality Improvement Registry, Evaluation, and Education (AQuIRE) registry.[70] Nevertheless, it is important to highlight the close anatomical relation that exists between major vascular structures and mediastinal lymph nodes—i.e., stations in the left lower paratracheal region (4 L, 5, and 6) with the aortic arch and the pulmonary artery; stations in the right lower paratracheal region (4R) with the superior vena cava; and upper paratracheal stations (2R and 2L) with the innominate artery, left common carotid artery, and bilateral innominate veins.[71] The use of colour Doppler ultrasound during EBUS procedures allows for proper identification of vascular structures.[72]

Aspirin use does not increase the bleeding risk during biopsies and should not preclude bronchoscopy from taking place.[73] Nevertheless, clopidogrel does significantly increase the risk of hemorrhage and has an additive effect when combined with aspirin. Current recommendations state that clopidogrel should be discontinued seven days prior to bronchoscopic biopsies.[66,74]

Anticoagulant agents increase the risk of hemorrhage and should not be taken prior to endobronchial biopsies. Low-molecular-weight heparin should be discontinued 12-24 hr before procedure (depending on therapeutic doses), while intravenous heparin should be discontinued four to six hours prior to procedure.[16,75] Warfarin also increases bleeding risk and should be discontinued five days ahead of procedure.[66] Oral anticoagulants are highly dependent on patient renal function; apixaban and rivaroxaban should be discontinued at least 24-48 hr before procedure, whereas dabigatran should be stopped for 36-72 hr in advance. In patients with impaired renal function (i.e., creatinine clearance 30-50 $mL \cdot min^{-1}$) apixaban and rivaroxaban should be discontinued 36-72 hr prior to procedure. Because dabigatran has a significantly higher renal elimination, it should be withdrawn 48-96 hr ahead of the procedure in patients with renal impairment.[76] Despite recommendations, antiplatelet/anticoagulation regimes should be managed considering each patient's condition, carefully evaluating the risk-benefit relation for each case.

Pre-procedure coagulation tests (activated partial thromboplastin time, prothrombin time, and international normalized ratio) are poor predictors of bleeding risk and should not be routinely performed.[77,78] These should be reserved for cases with known bleeding risk factors, including immunosuppression (HIV), thrombocytopenia, uremia, mechanical ventilation, and history of coagulopathy.[79] Platelet counts as low as 20,000-30,000 mm^{-3} may be sufficient to avoid endobronchial bleeding when doing airway inspection or BAL, but platelet counts above 50,000 mm^{-3} are recommended for advanced diagnostic or therapeutic bronchoscopy.[67,80]

Even though most procedures done via flexible bronchoscopy are relatively safe, there is always a risk of airway perforation when dilating a narrowed airway or performing a transbronchial biopsy, for example. This can present as subcutaneous emphysema, pneumothorax, pneumomediastinum, or even air embolism.[23] On the other hand, the pneumothorax risk associated with transbronchial biopsies is $< 3\%$.[81,82] with a recent meta-analysis reporting a pneumothorax rate of only 1.5% during guided transbronchial biopsies.[30] This risk is increased up to 14% in mechanically ventilated patients. Because the risk depends on a variety of factors such as the anatomical location of the biopsies and the technique used, some authors suggest doing a routine chest *x-ray* 30-60 min after high-risk procedures, particularly if the patient exhibits signs of respiratory distress.[83]

Cardiovascular comorbidities may represent a challenge when performing bronchoscopy. Invasive airway procedures increase myocardial work load by increasing the heart rate and systolic and diastolic blood pressure as well as decreasing SaO_2.[84,85] High-risk patients should be fully monitored and receive adequate O_2 supplementation. Some authors suggest that patients with an acute coronary event or recent heart failure exacerbation should have their procedure deferred for four to six weeks.[16] Nevertheless, if there is an strong need for bronchoscopy, this may be performed safely as long as the patient is not having an active ischemic episode.[86] Although the magnetic field generated over the patient during ENB is a potential source of interference over implantable pacemakers and cardioverter defibrillators,[87] current evidence suggests that ENB can be safely performed in patients with such devices.[88]

Lung edema secondary to negative airway pressure is an uncommon complication, but can occur if the patient coughs or inhales against a closed glottis or an obstructed airway (by balloon or bronchoscope). This situation is best prevented by maintaining an adequate anesthetic depth and proper muscle relaxation and generously irrigating the glottis with topical lidocaine.[38]

Rigid bronchoscopy

Procedure description

Rigid bronchoscopy is an invasive procedure that allows simultaneous ventilation, oxygenation, and airway inspection/intervention. It was first described in the late 1800s by the German physician Gustav Killian as a tool to remove foreign bodies from the tracheobronchial tree.[10] Rigid bronchoscopy procedures represent a challenge for the anesthesiologist because it requires allowing the interventionist easy access to the airway, with an adequate degree of muscle paralysis, all the while maintaining proper ventilation and oxygenation.[17]

The rigid bronchoscope is composed of a hollow metal tube with a beveled distal end. On the proximal end, the scope's "head" has three ports: one for an optical device (fibrescope or eyepiece), one for a working instrument, and one for ventilation (lateral port). Lengths usually range from 33 cm (tracheoscope) to 43 cm (bronchoscope), while diameters may be as small as 3 mm and as large as 14 mm. The rigid bronchoscopes have fenestrations on the distal segment that allow lateral ventilation when selective intubation is performed (see Figure).[8,89]

It is typically used to perform airway procedures that involve bypassing an obstruction or those that require a large working channel. In contrast to the flexible bronchoscope, the rigid bronchoscope offers fewer limitations in terms of the working channel size and field exploration. Endobronchial tumour destruction and removal are commonly performed using rigid bronchoscopy. Other frequently used indications include mechanical dilation (for central airway obstruction) and endobronchial ablation (laser, argon plasma coagulation, electrocautery, and cryodebridement).[24,90-92]

Rigid bronchoscopy is particularly suitable for foreign object removal because it allows securing the airway while facilitating its inspection. This helps prevent accidental object dislodgement into the distal airways.[93] Rigid bronchoscopy is also useful for airway stent placement (silicone and metallic) or treating both benign and malignant obstructions, tracheoesophageal fistulae, and tracheobronchomalacia.[91] Flexible bronchoscopy through the rigid scope that is used as a conduit frequently complements rigid bronchoscopy because it reaches more distal airways (i.e., the rigid bronchoscope only reaches the mainstem bronchi) facilitating suction and tool guidance.[5,8]

Anesthetic depth and pharmacologic considerations

Because rigid bronchoscopy is a much more stimulating procedure than flexible bronchoscopy, it almost always

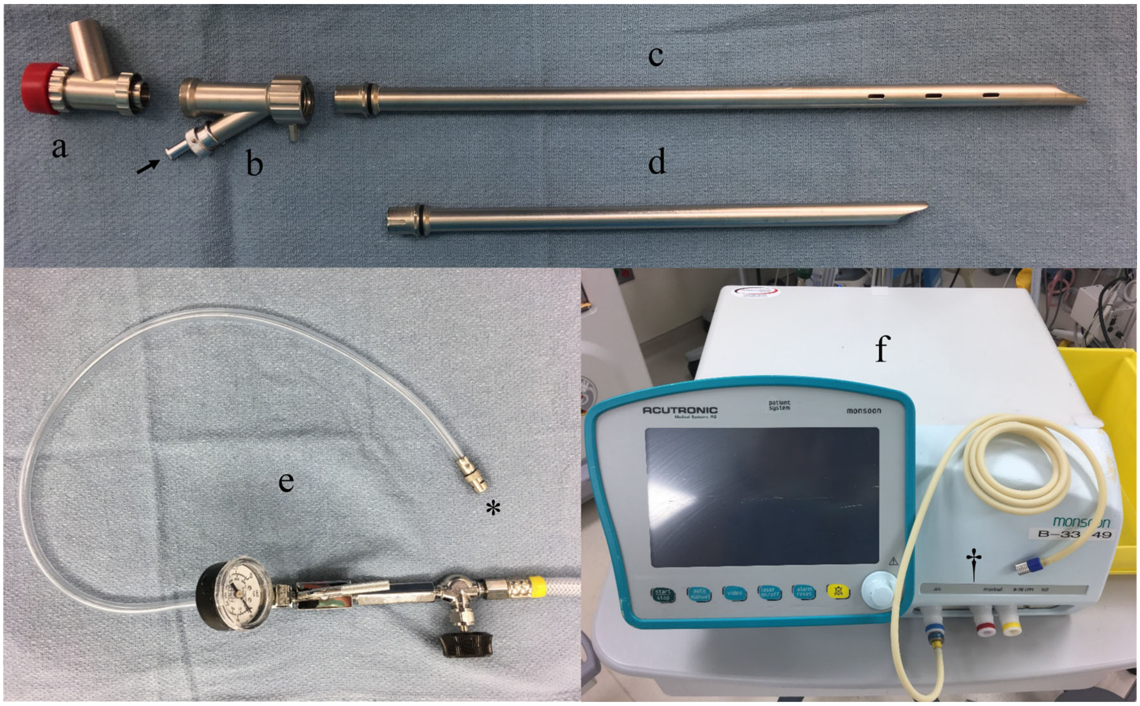

Figure Rigid bronchoscope, manual jet ventilator, and automatic jet ventilator. a. Volume ventilation adaptor. b. Jet ventilation adaptor (arrow points at ventilator port). c. Rigid bronchoscope with lateral fenestrations and beveled tip. d. Rigid tracheoscope. e. Manual jet ventilator with barometer (Sanders jet ventilator). f. Automatic mechanical jet ventilator (Monsoon®, Acutronic medical systems). Note the * and the † at the end of the jet ventilators are connected to the port (arrow) on the adaptor (b)

requires general anesthesia.[94] As with flexible bronchoscopy, the use of volatile anesthetics for induction and maintenance of anesthesia is discouraged. The ventilation methods used and constant airway leaks during rigid bronchoscopy make inhaled anesthetics highly unreliable and can lead to considerable operating room contamination.[23,38,95]

Premedication with midazolam (2-4 mg *iv*) helps reduce anxiety and produces anterograde amnesia.[96,97] Although it is not a routine practice, some authors suggest premedication with oral clonidine (300 g) to blunt the cardiovascular response produced by rigid bronchoscope insertion. This protects against potential arrhythmias and myocardial ischemia.[98] Spraying topical lidocaine 1% (3-5 mg·kg^{-1}) over the supraglottic and glottic areas is another strategy proposed to blunt the cardiovascular response associated with bronchoscope insertion.[99] Anticholinergics, particularly glycopyrrolate, are options because of their antisialagogue properties and reduction in overall airway secretions.[48] Premedication with small intramuscular doses of glycopyrrolate (0.005 mg·kg^{-1}) 30 min prior to procedure is commonly seen in clinical practice.[100,101] Atropine use is discouraged as it has been associated with greater hemodynamic fluctuations and increased procedure time,[48] though available data on this subject are limited.

Anesthesia induction and maintenance are best performed with propofol-based TIVA infusions, titrating doses of 100-200 g·kg^{-1}·min^{-1}.[23,102] Additional 30-50-mg boluses may be used to suppress hemodynamic responses and laryngospasm when changing or re-introducing the rigid scope.[64] Propofol is also thought to attenuate some of the postoperative coughing that often occurs.[103] Because awareness during anesthesia is a major concern when performing rigid bronchoscopy, some authors suggest that propofol infusions should be guided by bispectral index (BIS) monitoring, with the target between 40 and 60.[104,105]

In addition to propofol, short-acting opioids (remifentanil) are a safe option and should be used particularly when low levels of postoperative pain are expected.[106] Remifentanil bolus (1 g·kg^{-1}) followed by infusion (0.3 g·kg^{-1}·min^{-1}) can effectively attenuate the cardiovascular response to bronchoscopy better than fentanyl (2 g·kg^{-1}).[107] Similarly, a remifentanil bolus of 2 g·kg^{-1} (in addition to a target-controlled infusion of propofol) attenuates the cardiovascular response during rigid bronchoscopy better than remifentanil at 1 g·kg^{-1}.[108] Recent literature supports the use of higher doses of remifentanil infusions (0.25-0.5 g·kg^{-1}·min^{-1}) over lower doses, as these are associated with lower risk of coughing and laryngospasm and increased proceduralist satisfaction.[109]

Other pharmacologic strategies for rigid bronchoscopy including dexmedetomidine and ketamine have been described.[64] Dexmedetomidine has been used for foreign object extraction in elderly patients receiving an initial bolus of 1-2 g·kg^{-1} followed by a 0.2-0.7 g·kg^{-1}·hr^{-1} maintenance infusion.[110] In children, dexmedetomidine (4 g·kg^{-1} bolus followed by 1-2 g·kg^{-1}·hr^{-1} infusion) plus propofol (200 g·kg^{-1}·min^{-1}) has been described for cases that require spontaneous ventilation.[111] The addition of ketamine to remifentanil-based TIVA does not provide an advantage in terms of hemodynamic stability compared with remifentanil and propofol-based TIVA.[94]

For pediatric patients, the use of volatile anesthetics during induction is accepted, especially in scenarios when spontaneous ventilation is desired (i.e., foreign object removal). For these situations, sevoflurane is used as the induction agent because of its less pungent nature as well as providing better hemodynamic stability, less respiratory depression, and faster induction and recovery times compared with other TIVA alternatives.[112] Nevertheless, propofol with remifentanil TIVA (under BIS guidance) is a safe induction alternative for children undergoing rigid bronchoscopy.[113] Infusions using propofol (200 g·kg^{-1}·min^{-1}) and remifentanil (0.05-0.15 g·kg^{-1}·min^{-1}) have been described for anesthesia maintenance in this population.[102]

Muscle relaxation is desired during most scenarios to facilitate proper intubation and minimize airway injury. Proposed pharmacologic schemes include depolarizing and non-depolarizing agents. Indeed, short-acting neuromuscular blocking agents (e.g., succinylcholine) are suitable for intubation in cases that require subsequent maintenance of spontaneous ventilation to evaluate dynamic airway obstruction.[17,106] Low-dose succinylcholine (0.5 mg·kg^{-1}) is associated with better intubating conditions and lower costs compared with low-dose rocuronium (0.25 mg·kg^{-1}) with sugammadex reversal (0.5 mg·kg^{-1}).[114] For cases requiring more prolonged paralysis, additional rocuronium boluses of 0.3 mg·kg^{-1} may be administered.[23] Postoperative myalgia associated with depolarizing agents may be reduced using low precurarization doses of rocuronium (5 mg) or vecuronium (0.5 mg).[17]

Complete reversal of the neuromuscular blockade at the end of the procedure is fundamental as most patients who undergo rigid bronchoscopy have a significantly decreased pulmonary reserve and do not tolerate residual paralysis.[115] An SGA can be placed as a transitory airway to provide partial ventilation support after rigid scope removal.[17] The SGA allows inspection of the larynx, which can be facilitated by spraying with lidocaine 1%. This common practice effectively decreases the incidence of laryngospasm.[116] In the post-anesthesia care unit, simple maneuvers such as raising the head of the bed and administering high F_IO_2 with humidified oxygen can reduce coughing and respiratory distress; nebulized lidocaine can also be beneficial.[96]

Airway and ventilation modes

Different ventilation methods have been historically employed with rigid bronchoscopy. The most common are apneic oxygenation, spontaneous-assisted ventilation, controlled mechanical ventilation, and jet ventilation (manual or automatic, high or low frequency).[3] Apneic ventilation was the first approach described for ventilation during rigid bronchoscopy. Patients are pre-oxygenated and ventilated initially with a 100% F_IO_2. Ventilation is then suspended while the pulmonologist works through the bronchoscope. When the SaO_2 threshold has been reached (e.g., 92%), the procedure is paused, bronchoscopy instruments are removed, and the patient is ventilated, usually with a self-inflating bag system and an F_IO_2 of 100%. Once oxygenation has improved, apnea is reinstituted allowing the procedure to continue.[3] In more modern-day practice, apneic ventilation is discouraged, as it can lead to significant acid-base disturbances, blood pressure instability, and a higher probability of awareness episodes during bronchoscopy.[103,104]

Spontaneous-assisted ventilation is another technique used to support rigid bronchoscopy. It is performed concomitantly with TIVA by titrating the anesthetic dose such that patients maintain spontaneous ventilation. The bronchoscope is connected to the anesthetic circuit and respiratory support is provided as needed. The anesthesiologist will attempt to maintain a respiratory rate between 10 and 20 breaths·min^{-1}, in synchronization with the patient and the bronchoscopist's maneuvers. Oxygen supplementation using high F_IO_2 is given constantly through the rigid bronchoscope.[117] Spontaneous assisted ventilation was the method performed traditionally for foreign object removal, particularly in children. Nevertheless, a recent meta-analysis concluded that it is associated with a higher incidence of laryngospasm and coughing compared with controlled ventilation.[118] Although this meta-analysis suggests that these ventilation modes do not differ in terms of desaturation events, other authors have reported a higher incidence associated with spontaneous ventilation.[118,119]

Ventilation support for rigid bronchoscopy may be delivered in the form of mechanical positive pressure controlled ventilation. As with spontaneous assisted ventilation, the bronchoscope is connected to the anesthesia circuit, thus serving as an endotracheal tube. Air leaks can be minimized by sealing the bronchoscope ports with caps and packing the nasal and oral pharynx with gauze. This ventilation modality is less often used for rigid bronchoscopy because constant airway leaks interfere with the ventilator's ability to deliver pre-set gas volumes.[3] Similarly, conventional ventilators deliver large tidal volumes that cause constant displacement of diaphragm and thoracic structures, which can complicate the interventional procedure.

Jet ventilation is commonly used during rigid bronchoscopy. Based on the Venturi principle and other physical properties, the system achieves a high F_IO_2 by administering high-pressure gas through an open system. Jet ventilation is convenient because it provides adequate ventilation and allows proper technical access during rigid bronchoscopy procedures.[120,121] It can be delivered manually (i.e., with a Sanders adapter)[122] or mechanically, as high frequency jet ventilation (HFJV) (120-600 respirations·min^{-1}) and/or low frequency jet ventilation (LFJV) (10-30 respirations·min^{-1}).[89,120] Several hybrid jet ventilation techniques are now available thanks to modern ventilators such as the TwinStream Respirator™ (Carl Reiner, Vienna, Austria). Superimposed high-frequency jet ventilation (SHFJV) is a modality that combines both HFJV and LFJV and is commonly used for patients with laryngotracheal stenosis as it helps avoid excessively high airway pressures.[123] Delivered tidal volumes usually range between 1 and 3 mL·kg^{-1} and may be less than the anatomical dead space, hence the need for very high frequency.[89] Technical settings (e.g., driving pressure and duration) of the jet ventilator can be adjusted according to intraoperative blood-gas analysis or based on the quantity of conventional ventilation periods required to achieve adequate SaO_2. The end-tidal CO_2 after brief periods of HFJV interruption can be used to estimate partial pressure of CO_2 along with transcutaneous CO_2 monitoring to guide ventilator parameters.[124] Although some patients will require an arterial cannula to monitor arterial gases, the adequate use of capnography may reduce unnecessary arterial blood gas sampling.[125]

Recommendations to prevent barotrauma include maintaining a driving pressure around 1.5 bar (approximately 20 PSI) and limiting inspiration duration to 30-40% of the respiratory cycle.[89] Pressure parameters may be adjusted by targeting a maximum PEEP of 10 cmH_2O, especially when treating patients with severe central airway obstruction, as high auto-PEEP might develop, causing barotrauma.[126] Different airway pressures are displayed in real time by modern mechanical ventilators (e.g., Monsoon High Frequency Jet Ventilator®; Acutronic Medical Systems AG, Hirzel, Switzerland). Importantly, to prevent barotrauma, the expiratory pathway on the rigid bronchoscope must remain unobstructed.[89]

Following the procedure, the rigid bronchoscope is withdrawn and respiratory support is provided until residual sedation resolves. An SGA, particularly an LMA, is preferred over a face mask for this purpose, as its use favours hemodynamic and respiratory stability.[127] In addition, an LMA allows spraying vocal cords with topical anesthetic and a prompt airway inspection with a flexible bronchoscope in case of an emergent situation.[91]

Common complications and special considerations

Complication rates associated with rigid bronchoscopy vary significantly depending on the patient health status and procedure performed. A recent retrospective study evaluated complication rates in over 3,000 children undergoing foreign body extraction and reported a 9% complication rate. Frequent complications include hypoxemia (3.2%), laryngospasm (1.3%), laryngeal edema (0.9%), atelectasis (0.3%), and pneumothorax (0.3%). The mortality rate was 0.3%[128] but other series have reported complication rates as high as 19.8% and a 30-day mortality of 7.8%, particularly when bronchoscopy is performed urgently in patients with severe underlying disease and high American Society of Anesthesiologists (ASA) physical status scores.[129]

The ACCP recently published complication rates for malignant central airway obstruction based on results from the AQuIRE Registry. Over 1,000 procedures conducted in 947 patients revealed a complication rate of 3.9% with a 14.8% 30-day mortality rate. Variables identified as increased complication rate predictors for therapeutic bronchoscopy (including both rigid and flexible) included: emergent procedures, ASA physical status scores $>$ III, redo therapeutic bronchoscopy, and the need for moderate sedation.[128] Hence, careful patient selection and weighting the risk-benefit relation of the procedure contribute to its success. In patients with a high risk of central airway obstruction, availability of extracorporeal circulation devices or ability to perform emergency tracheotomy is advisable.[24]

Appropriate ventilation method selection is fundamental, as this may be the source for complications. Spontaneous ventilation is associated with an 18% risk of hypoxemia and a 1% risk of bronchospasm and laryngospasm. These events can be reversed with simple pharmacologic measures without severe consequences.[89] Jet ventilation is an option to maintain normocapnic oxygenation, but may cause barotrauma; cases of pneumothorax, pneumomediastinum, subcutaneous emphysema, and even tension pneumothorax have been described.[121,130] Since this is a high-pressure open system with no expiration valve, the air outlet should not be obstructed to prevent excessive airway pressure buildup. For this purpose, some automated jet ventilators have built-in alarm systems.[17,55]

Other devices, such as the Ventrain® system (Ventinova Medical B.V., Eindhovven, Netherlands), have an active expiration mechanism that facilitates ventilation through a small-bore cricothyroidotomy cannula and may be useful in acute upper airway obstruction scenarios.[131,132] Although this technique is not currently used to support interventional pulmonary procedures, it may be considered as an alternative to ventilate patients under cannot-ventilate-cannot-oxygenate scenarios. Two recently published case reports describe its elective use in patients with severe upper airway obstruction undergoing endoscopic debridement of supraglottic lesions.[132,133]

Jet ventilation in proximity to stenotic lesions may significantly increase the pressure in airways distal to the lesion.[134] Excessive pressure buildup can be prevented by placing the jet injector as far as possible from the lesion or by placing a jet ventilation catheter either on the mainstem bronchus contralateral to the lesion (while selectively intubated with a rigid bronchoscope) or distal to the lesion treated.[134] Other complications involving jet ventilation include injury to the mucociliary epithelium (due to extremely high respiratory frequency) and are best prevented by ventilators that allow air humidification and warming.[17,55] Patients with pneumonia, an acute asthma attack, severe obesity, or poor baseline oxygenation are poor candidates for jet ventilation because this may lead to severe heterogeneity in ventilation.[90]

Different risks are associated with specific surgical techniques. Airway fire is a rare but catastrophic event, caused by the combination of an ignitor (a heat-based surgical device such as a laser or electrocautery), an oxidizer (oxygen or nitrous oxide), and fuel (tissue, mesh, or plastic devices).[135] Hence, the main approach to prevent these events is to reduce the use of each of the three elements described previously. In that sense, it is recommended that F_IO_2 and end-tidal O_2 be below 40% prior to activation of the laser, electrocautery, or argon plasma coagulation (APC) systems.[136] Patients who cannot tolerate $F_IO_2 < 40\%$ should not undergo these procedures and a different therapeutic alternative should be considered.

Other safety measures that have been described include correcting air leaks, avoiding nitrous oxide, and using a shorter circuit with high fresh gas flow (i.e., $> 5\ L\cdot min^{-1}$) that allows for the more rapid achievement of low F_IO_2 concentrations.[136,137] To decrease exposure to potential fuels, a distance > 1 cm between the tip of the probe (laser, electrocautery, or APC) and the tip of the bronchoscope and a distance > 4 cm between the tip of the probe and the tip of the distal end of the ETT should be maintained. Similarly, gauzes sponges, mesh, drapes, or any other products used to pack the oropharynx should not be used as these may act as combustible material.[135]

Spray cryotherapy, used to recanalize the airway in benign and malignant conditions, may lead to tension pneumothorax, pneumothorax, or severe hypoxia due to rapid conversion of nitrous oxide from the liquid to gaseous form. Complications in this scenario are best prevented by generous preoxygenation, holding ventilation, and allowing free airway outflow.[138] The use of APC has a low yet life-threatening risk of argon gas embolism. Unfortunately, other than using a low flow of argon gas and avoiding direct contact with vessels, there are no other effective measures to prevent these events.[139] Although the risk of airway fire with APC is low (at least in theory) because argon gas displaces oxygen and thus reduces the combustion risk, the F_IO_2 should nonetheless still be kept < 40%.[93] Rigid bronchoscope insertion may cause a rise in intracranial pressure secondary to laryngeal stimulation; however, this effect is not clinically significant.[140]

Lastly, in patients who present with critical airway stenosis, positive pressure ventilation above the stenosis might not achieve adequate ventilation once the patient is under general anesthesia.[141] Balloon dilation using topical anesthesia and minimal sedation can be achieved in spontaneously breathing awake patients.[142] Such a technique can allow a safer tracheal luminal diameter to proceed with more conventional anesthesia and therapeutic intervention. Furthermore, in patients requiring stent placement, silicone (but not metallic) stents require the use of the rigid bronchoscope. In patients requiring further ventilatory support following tracheal stent placement, proper placement of an appropriately sized ETT directed visually under bronchoscopic guidance is necessary to avoid airway stent dislodgement.[143] Thus, coordination between the anesthesia team and interventional pulmonologist is required.

Conclusions

Interventional pulmonology is a rapidly growing area of medicine. Advanced diagnostic and therapeutic bronchoscopy is widely applied in different pathologies of the airways, lungs, and mediastinum. Therefore, it is fundamental for the anesthesia provider to be updated on this area.

Evidence-based recommendations regarding airway management, pharmacologic strategies, and complications should help guide anesthesiologists when approaching common bronchoscopic procedures. In daily practice, each case should be approached individually. A thorough evaluation of individual comorbidities, risk factors, and technical aspects associated with each procedure is necessary. Given that interventional pulmonologists and the anesthesia team share the working field, constant communication between specialists is fundamental.

Conflicts of interest Adnan Majid: Paid consultant for PneumRx, Inc., paid consultant for Olympus Corporations of the Americas, paid

consultant for Broncus Medical Inc., and paid consultant for Boston Scientific Corp.

Editorial responsibility This submission was handled by Dr. Hilary P. Grocott, Editor-in-Chief, *Canadian Journal of Anesthesia.*

Author contributions *Andrés de Lima, Fayez Kheir*, *Adnan Majid*, and *John Pawlowski* contributed substantially to all aspects of this manuscript, including conception and design; acquisition, analysis, and interpretation of data; and drafting the article.

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