

Extracorporeal support in airway surgery

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Abstract: Extracorporeal life support (ECLS) is increasingly used for major airway surgery. It facilitates complex reconstructions and maintains gas exchange during endoscopic procedures in patients with critical airway obstruction. ECLS offers the advantage of an uncluttered surgical field and eliminates the need for crossing ventilation tubes, thus, making precise surgical dissection easier. ECLS is currently used for hemodynamic and respiratory support in lung transplantation as well as extended tumor resections with an acceptable risk profile. This work reviews the published experience of ECLS in airway surgery both in adults and in pediatric patients. It highlights currently available devices and their indications.

Keywords: Extracorporeal support; airway surgery; extracorporeal membrane oxygenation (ECMO)

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Introduction

Surgery involving the main airways requires optimal exposure and maintenance of adequate oxygenation and ventilation. For the vast majority of airway surgical cases, conventional cross-table ventilation with periodic apneic phases, is sufficient to provide excellent technical surgery with minimal morbidity. Jet ventilation is a reasonable alternative that is used predominately for high resections involving the larynx. For complex surgical cases and in patients with near total occlusion of the airways, extracorporeal life support (ECLS) is a good and safe option to support the patient's respiratory functions during a complex resection. Today, a variety of ECLS devices and modes are available. The purpose of this review is to give an overview of the current application of ECLS in airway surgery. In addition, a practical guide on when and how ECLS should be implemented is also provided.

History

Cardiopulmonary bypass (CPB) was the first clinical

application of extracorporeal support. It dates back to 1953 when John Gibbon was able to repair an atrial septal defect in an 18-year-old woman. During this case, the patient's cardiopulmonary function was completely replaced for a short period of time. It was not until the early 1960s when the first reports on CPB in airway surgery were published. In 1961, Woods *et al.* successfully resected a recurrent adenoid cystic carcinoma (ACC) of the distal trachea (1). Two similar cases were consecutively published by Adkins *et al.* (2) and Nissen *et al.* (3). Interestingly, all those early cases were advanced stage ACC patients requiring a complete replacement of their cardiopulmonary function for a repair. A major problem during the early phase of CPB was the direct damage to blood cells caused by bubble oxygenators, which subsequently led to multi-organ dysfunction when used for more than a few hours. This problem was mitigated when small gas exchange membranes were interposed between the blood and the oxygen tank. The technology significantly evolved as new membranes were developed and evolved from silicone to polypropylene (PP) and eventually to new generation

polymethylpentene (PMP). This development became known as extracorporeal membrane oxygenation (ECMO) and was slowly implemented in the 70s and 80s to treat acute respiratory failure in infants (4). The first described use of ECMO in airway surgery was published by Walker *et al.* in 1992 (5). They reported a case of a 2.5 kg infant suffering from a congenital distal airway stenosis. The child was successfully treated by a segmental resection and end-to-end anastomosis. Peripheral ECMO support was chosen over a traditional CPB because it did not require median sternotomy, required less heparin, and facilitated the anticipated postoperative ECLS prolongation. Shortly thereafter, the first series of cases using ECMO for intraoperative ventilatory support in pediatric airway patients was published by Connolly *et al.* (6). Since that time, ECMO has gradually found its way into the everyday clinical practice of large thoracic centers and is currently routinely applied in lung transplant and ARDS patients. In addition, it has also proven to be a powerful tool in the armamentarium of extended airway surgery (*Table 1*).

Available ECLS configurations

Venous-venous (v-v) ECMO

Veno-venous (v-v) ECMO can be considered the gold standard if ECLS is needed during airway surgery. It can provide complete support of pulmonary function with effective CO₂ removal and oxygenation. The main advantage of v-v support over veno-arterial (v-a) ECMO is the lower risk of vascular complications that may be associated with arterial cannulation such as bleeding, arterial (pseudo-)aneurysms, limb ischemia and embolic events (41,42). The typical and simplest cannulation configuration is a femoral-jugular approach with two cannulas.

Single-cannula v-v ECMO

The development of double-lumen cannulas enabled single vessel access instead of a femoro-femoral or a femoro-jugular insertion. It is a good alternative to the standard two-cannula approach. With the growing experience of using these cannulas in ARDS and lung transplant patients, they have also been adopted in airway surgery (43,44). The placement of the cannula in the right atrium requires fluoroscopic (preferably) or TEE guidance (45). Its first successful use in airway surgery was published by the Toronto group in 2015. In their reported case, the cannula

supplied stable respiratory support and facilitated tumor debridement of a near occluding tracheal squamous cell cancer (25).

Veno-arterial (v-a) ECMO

The main advantage of a v-a over a v-v ECMO is the hemodynamic support that can be provided. This is especially important during emergency settings, when an airway occlusion has already led to severe hemodynamic compromise. In addition, it results in a more stable support during complex airway reconstructions, most notably when the heart needs to be retracted to improve visualization. It is considered more invasive than v-v ECMO and is associated with a higher incidence of neurologic events (infarction, microemboli, hemorrhage) as well as peripheral vascular complications (dissection, limb ischemia, aneurysm). Moreover, femoro-femoral v-a ECMO sometimes fails to provide adequate central oxygenation, especially in patients with a high cardiac output (46).

Cardiopulmonary bypass

Although some centers still use conventional CPB for support during airway surgery, several disadvantages limit its use. In contrast to v-a ECMO, which also provides hemodynamic stability, CPB requires higher levels of anticoagulation and uses a venous reservoir with an air-blood interface. This is thought to contribute to the higher incidence of coagulopathy and systemic inflammatory reactions, especially during longer pump runs (47). However, CPB has the advantage of using a cardiotomy suction, which enables the rescue of large blood volumes during major bleeding, although this is a rare situation in airway surgery.

Novalung assist

Pumpless lung assistance devices like the Novalung are based on the development of low transmembrane pressure gradient oxygenators. These devices are interposed between the femoral artery and vein and can effectively remove CO₂. However, they have a lower capacity to oxygenate compared to ECMO devices. Novalung membranes alone cannot provide hemodynamic support without a pump, and their gas exchange capacity is dependent on a stable cardiac output (9). To the best of our knowledge, there is only one published case on the use of a Novalung during airway

Table 1 Published experience of ECLS support in adult airway surgery and in pediatric airway surgery

Author	Journal	Year	Pt #	Indication	Intervention	Support mode	Cannulation site	Induction type
Published experience of ECLS support in adult airway surgery								
Ishikawa et al. (7)	<i>Surg Today</i>	1995	2	ADC tracheal, post TBC stenosis	Rigid bronchoscopy debridement and stent	v/v ECMO	Femoro-femoral	
Horita et al. (8)	<i>Thorac Cardiovasc Surg</i>	1996	2	SCC lung	Carinal resection	v/v ECMO	Femoro-femoral	
Wallis et al. (9)	<i>J Thorac Cardiovasc Surg</i>	2008	1	TEF	Repair with bioartificial patch	Novalung	Femoro-femoral	
Chen (10)	<i>J Bronchology Interv Pulmonol</i>	2009	1	Stent-in-stent	Removal of stent—rigid bronchoscopy	v/a ECMO	ND	
Lei et al. (11)	<i>J Cardiothorac Surg</i>	2010	1	ADC lung	Left pneumonectomy	v/a ECMO	Femoro-femoral	Awake induction
Holliday et al. (12)	<i>Crit Care Resusc</i>	2010	1	Foreign body—food bolus	Rigid bronchoscopy and removal	v/v ECMO	Femoro-femoral	
Gourdin et al. (13)	<i>J Cardiothorac Vasc Anesth</i>	2012	1	Previous stents for stenosis	Removal of stent—rigid bronchoscopy	v/v ECMO	Femoral + IJV	
Thung et al. (14)	<i>Middle East J Anaesthesiol</i>	2012	1	Granulation left main bronch—post LuTx	Rigid bronchoscopy and removal	v/v ECMO	ND	
George et al. (15)	<i>Ann Thorac Surg</i>	2012	1	Tracheobronchomalacia	Rigid bronchoscopy and stent	v/v ECMO	Femoro-femoral	Awake induction
Willms et al. (16)	<i>Respir Care</i>	2012	1	Sarcoma tracheal	Rigid bronchoscopy and removal	v/a ECMO	Femoro-femoral	
Keeyapaj et al. (17)	<i>Can J Anaesth</i>	2012	1	SCC tracheal	Carinal resection	v/v ECMO	Femoral + IJV	
Hong et al. (18)	<i>J Crit Care</i>	2013	18	Various tumors	Stent removal, stent insertion, debridement	v/v ECMO	Femoro-femoral	
Metcalf et al. (19)	<i>J Emerg Med</i>	2013	1	Foreign body—sand	Rigid bronchoscopy and removal	v/a ECMO	Femoro-femoral	
Liou et al. (20)	<i>J Chin Med Assoc</i>	2014	1	Thyroid carcinoma	Segmental resection	v/v ECMO	Femoro-femoral	
Chang et al. (21)	<i>Perfusion</i>	2014	7	Different tracheal carcinoma	Resection (5 tracheal segmental, 2 carinal)	v/a ECMO	Femoro-femoral	Awake induction
Park et al. (22)	<i>J Thorac Dis</i>	2014	1	Trauma	Airway occlusion for tamponade	v/v ECMO	ND	
Wang et al. (23)	<i>Ann Thorac Cardiovasc Surg</i>	2014	1	TEF	Exclusion of esophagus + saliver fistula + gastrostomy	v/a ECMO	Femoro-femoral	
Park et al. (24)	<i>Am J Respir Crit Care Med</i>	2014	1	Foreign body—cement aspiration	Rigid bronchoscopy and removal	v/v ECMO	ND	
Ko et al. (25)	<i>Ann Thorac Surg</i>	2015	1	SCC tracheal	Debridement by rigid bronchoscopy	v/v ECMO (double-lumen cannula)	IJV	

Table 1 (continued)

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Author	Journal	Year	Pt #	Indication	Intervention	Support mode	Cannulation site	Induction type
Kim et al. (26)	<i>Ann Thorac Cardiovasc Surg</i>	2015	15	Lacerations, tumors, stenosis	Resection and repair	v/a and v/v ECMO	Femoro-femoral and femoral + IJV	
Kim et al. (27)	<i>J Thorac Dis</i>	2015	1	Malignant teratoma	Flexible bronchoscopy and debridement	v/v ECMO	Femoro-femoral	Awake induction
Lang et al. (28)	<i>Eur J Cardiothorac Surg</i>	2015	10	Various tumors	Carinal resections and bronchovascular sleeves	v/a ECMO	7 central, 3 femoro-femoral	
Published experience of ECLS support in pediatric airway surgery								
Walker et al. (5)	<i>Anesth Analg</i>	1992	1	Tracheal stenosis	Segmental resection	v/a ECMO	Carotid + IJV	
Goldman et al. (29)	<i>J Pediatr</i>	1996	4	Various indications (laceration, failed previous surgery, etc.)	Repair, replacement and conservative	ECMO (mode ND)	ND	
Shiraishi et al. (30)	<i>Thorac Cardiovasc Surg</i>	1997	1	Fibrosarcoma tracheal	Segmental resection	v/a ECMO	Femoro-femoral	Awake induction
Angel et al. (31)	<i>Pediatr Surg Int</i>	2000	2	Congenital stenosis	Rib cartilage interposition; segmental resection	v/a ECMO	Carotid + IJV	
Connolly et al. (6)	<i>Ann Otol Rhinol Laryngol</i>	2001	6	4 long-segment, 1 posttraumatic stenosis, 1 cyst	Segmental resection; slide tracheoplasty	ECMO (mode ND)	ND	
Brown et al. (32)	<i>Pediatr Crit Care Med</i>	2003	1	Foreign body—grape	Rigid bronchoscopy and removal	v/a ECMO	ND	
Hines et al. (33)	<i>Ann Thorac Surg</i>	2003	4	Congenital stenosis	Slide tracheoplasty	v/a ECMO and prolonged v/v ECMO	Aorta and IJV	
Ignacio et al. (34)	<i>J Pediatr Surg</i>	2006	1	Foreign body—bean	Rigid bronchoscopy and removal	v/a ECMO	Carotid + IJV	
Kunisaki et al. (35)	<i>J Pediatr Surg</i>	2008	3	2 complete rings, 1 bronchogenic cyst	Resection, slide tracheoplasty, carinal resection	2 v/v ECMO; 1 v/a ECMO	IJV +/- carotid	
Smith et al. (36)	<i>Anesthesiology</i>	2009	2	Papillomatosis	Debridement	v/v ECMO	Femoral + IJV	
Collar et al. (37)	<i>Otolaryngol Head Neck Surg</i>	2010	1	Papillomatosis	Debridement	v/v ECMO	Femoral + IJV	Awake induction
Fuzaylov et al. (38)	<i>Paediatr Anaesth</i>	2012	1	Long-segment stenosis	Slide tracheoplasty	v/v ECMO (double-lumen cannula)	IJV	
Park et al. (39)	<i>Int J Pediatr Otorhinolaryngol</i>	2014	3	Foreign body (bean, almond, peanut)	Rigid bronchoscopy and removal	2 v/v ECMO; 1 v/a ECMO	v/v ND, v/a carotid + IJV	
Liston et al. (40)	<i>J Cardiothorac Vasc Anesth</i>	2014	1	TEF and congenital bronchomalacia	Pneumectomy and segmental esophagus resection	v/a ECMO	IJV and carotid	

surgery. Walles *et al.* used the system during a repair of a TEF with a bioartificial patch (48).

Awake induction

In the 1970s, the risk of fatal airway obstruction and cardiopulmonary arrest during induction of anesthesia was first recognized in patients with large anterior mediastinal masses (49). Initiation of ECLS under local anesthesia prior to induction of general anesthesia can be performed safely and may prevent this grave complication in such patients. Awake induction and initiation of ECLS has been described for different ECLS configurations [v-v ECMO (27), v-a ECMO (50), CPB (51)] predominately in patients with a near occlusion of the cervical trachea from primary tracheal neoplasms or with tumorous infiltrations of the trachea from thyroid carcinomas (25,27,52). Once ECLS is initiated, general anesthesia can be fully administered and airway tumor debridement or resection can be performed under more safe and controlled conditions.

Extracorporeal support in adult airway surgery

ECLS in oncological surgery

The first reported use of ECLS for airway surgery was published in 1961 in a patient with ACC. While CPB was used in these earlier reported cases, ECMO technology has considerably evolved over the past few decades and has become the preferred support option for ECLS in most institutions that perform airway surgery today. Complex tracheobronchial resections require optimal surgical exposure and adequate control of the patient's ventilation. The traditional approach of cross-table ventilation with intermittent apnea phases or jet ventilation is sufficient for most oncological airway surgery cases, but presents challenges in extended resections and complex reconstructions.

The use of ECMO poses several advantages in these cases. Firstly, it provides a clear, un-obstructed (tubeless) operative field (especially if peripheral cannulation is used), facilitating precise dissection and reconstruction. If veno-arterial support is used, this additionally provides hemodynamic stability during the surgery if required. The risk of bleeding can be minimized by only partial heparinization with activated clotting times (ACTs) targets between 160–180 seconds. The theoretical spread of tumor cells is neglectable, since ECMO is a closed system and

suctioned blood can be discarded (53). There are several institutional reports on the use of ECLS for extended, oncological airway procedures including carinal resections/reconstructions (8,17,28) and extended (crico-)tracheal resections (20,26,54,55).

ECLS during airway surgery in non-malignant cases

There are only few case reports on the use of ECLS in patients with benign airway stenosis. V-v ECMO support has been advocated for endoscopic removal of extensive tracheal papillomata (36). ECLS was also successfully used during the repair of a complex TEF (23,48) and catastrophic airway trauma (transection of the trachea and life-threatening hemoptysis) (22,56).

ECLS as a support for endoscopic interventions

Rigid bronchoscopic interventions (e.g., tumor debridement and stent placement) are well-established therapies for malignant obstructions of the airways (57). At times, such cases can be very challenging. In patients with high-grade stenosis, surgeons are sometimes reluctant to recanalize a patient, because of the considerable risk of peri-procedural asphyxia. The published experience is extensive for the use of ECLS support during complex endoscopic airway interventions. Although the use of CPB with full heparinization has been anecdotally reported, ECMO should be used as the device of choice (50,58). V-a ECMO is favored in the acute setting of a patient who is hemodynamically unstable (16), but for all other interventions v-v ECMO is preferred (7,25,27). The largest reported series of ECLS during endoscopic airway intervention comes from the Asian Medical Center in Korea reporting 18 patients with different primary and secondary tracheal malignancies (18). Their results were excellent with a successful weaning from ECMO in all but one case. Most of their patients were anticoagulated with a single heparin bolus dose and despite extensive endoscopic tumor debulking, significant bleeding was only observed in two cases.

In children as well as adults, massive foreign body aspiration might also require ECLS. Case reports of sand, cement or massive food aspiration requiring ECMO have been published (12,19,59).

ECLS in emergency settings

An important indication for ECLS in airway surgery

is acute situations when conventional ventilation strategies fail. In patients with traumatic airway injuries, conventional ventilation is sometimes impossible. In the situation of a ruptured airway, an orotracheal tube must be advanced across the site of injury. Failing to bridge the defect can result in severe pneumomediastinum, tension pneumothorax and death (60). For extensive distal-tracheal injuries, bridging usually leads to a unilateral intubation, often poorly tolerated by the patients. These situations are considered an acute indication for ECLS (61). Once oxygenation has been restored and maintained, the rupture can be safely repaired (56).

Extracorporeal support in pediatric airway surgery

ECLS plays an important role in pediatric airway surgery. There are several features of the pediatric airway, which make children more vulnerable to airway compromise than adults. Firstly, the pediatric airway is smaller, measuring only a few millimeters in diameter. This is especially important with regard to the subglottic airway. In infants, the maximal diameter of the subglottis is 5–6 mm with a cross-sectional area of 28 mm². Following Hagen-Pouisselle's law, only a millimeter of mucosal edema results in a 50% reduction of the cross-sectional area (62). Furthermore, children have less cartilaginous stability in their airways, increased chest wall compliance and increased metabolic requirements. For example, the typical oxygen consumption at rest is 6–8 mL/kg/min in a child but only 3–4 mL/kg/min in adults (63). All these factors contribute to the fact that children are more prone to airway compromise than adults.

ECLS for foreign body removal

Aspiration of a foreign body can be lethal in children. Although aspiration can be seen at any age, the majority of reported cases occur within the first 3 years of age (64). The reason for this is that young children often explore their environment by mouth. There are several factors making infants prone to aspiration such as their edentulous oral cavities, a potential for aspiration of food during crying or yelling and immaturity of the neuromuscular structures that control swallowing (65). ECMO is the mode of choice when an aspirated foreign body leads to respiratory failure and the child is too unstable to undergo bronchoscopy. Sometimes extraction of the foreign body can be challenging because of tight impaction and an intermittent complete occlusion

of the airway by the manipulating instruments within the small airway lumen. Usually a veno-venous mode is sufficient to provide temporary respiratory support and safe bronchoscopic extraction. However, if respiration is severely impaired and the child is persistently acidotic, a veno-arterial support mode should be chosen. Published evidence is limited to two case reports and a retrospective multi-institutional review of a case series (32,34,39). Aspirated foreign bodies requiring ECMO support were beans (n=2), an almond, a peanut, and a grape (n=1), respectively.

ECLS for endoluminal masses

As in adults, endotracheal masses and their management can easily result in a critical airway. There are few reports when ECLS was required to stabilize a child and alleviate obstruction from an endoluminal mass. Malignant endotracheal tumors are rare in the pediatric population and only two cases utilizing ECMO for tracheal tumors can be found in the literature. Shiraishi *et al.* reported a case of a tracheal fibrosarcoma in a child, which was successfully treated by segmental resection and end-to-end anastomosis with femoro-femoral v-a ECMO (30). Another interesting case published by otolaryngologists and thoracic surgeons from the University of Michigan, described the use of v-v ECMO during vaporization of tracheal papillomatosis (37). This approach has advantages since ECLS facilitates a meticulous and thorough surgical procedure and there is a decreased risk of airway fire when using the laser since supplemental oxygen is not flowing through the surgical field.

ECLS for congenital stenosis

Congenital stenosis is the main indication for ECLS utilization in pediatric airway surgery. One of the challenges in treating these often long-segment stenoses is the maintenance of adequate intraoperative and postoperative ventilation. Cross-table ventilation after opening the airway distal to the stenosis can obscure the operative site, especially in children, where the operative field and airway lumen are small. In distal airway stenosis requiring a resection at the level of the carina, cross-table intubation and ventilation of both lungs might be technically impossible. In order to avoid mechanical ventilation, CPB or ECMO can be utilized. Traditionally, surgical corrections of the airways (e.g., slide tracheoplasties) have been performed using a heart-lung machine and full heparinization (66,67). The reason for this might be

explained by the high percentage of concomitant defects of the heart and great vessels, which are often corrected in the same operation as the slide tracheoplasty (68). The drawback to CPB is that it generally requires a median sternotomy in children and therefore limits the surgical approaches to the trachea. Furthermore, the need for full heparinization also increases the risk for hemorrhagic complications. V-a ECMO cannulation can be performed using the internal jugular vein and the carotid artery creating an ideal surgical field free of cannulas. If needed, ECMO support can be continued postoperatively to avoid aggressive mechanical ventilation. This may be beneficial for the healing of a newly reconstructed airway (35). The use of ECMO during repair of congenital airway stenosis has been highlighted by several case series (6,31,33,35).

Practical considerations on ECLS in airway surgery

ECLS should be considered pre-emptively in all patients with critical intrathoracic airway stenosis, in patients requiring a complex lower tracheal/carinal reconstruction and in cases where a temporary complete airway occlusion is anticipated. In patients with a near-occlusion of the intrathoracic airways by a significant mediastinal mass, ECMO should be initiated under local anesthesia and light sedation, since the risk of total airway collapse after paralysis is not insignificant.

We consider v-v ECMO as the configuration of choice since it can fully support the patients' respiratory function. Traditionally, v-v ECMO is achieved via a two-cannula configuration, however, with the growing experience of single dual-lumen cannulas in other clinical settings (ARDS, lung transplantation), these cannulas present an interesting less-invasive alternative (25) when the accompanying resources are available (TEE or fluoroscopy). For complex carinal reconstructions, a central v-a approach is preferred if extensive manipulation of the heart and great vessels is anticipated (28).

Peripheral v-v ECLS configurations are usually inserted using a percutaneous Seldinger technique. For v-a ECMO, Seldinger or cut-down are acceptable approaches. Heparin coated tubing should be used in order to reduce systemic heparin doses. For adults, v-v ECMO cannula sizes of 21–25 Fr (drainage) and 17–21 Fr (inflow) are sufficient to provide adequate oxygenation and CO₂ removal. Single dual-lumen cannulas of 27 or 31 Fr are usually used depending on patient size. For v-a ECMO, a

17–21Fr arterial cannula and a 21–25 Fr venous cannula are recommended. Central v-a cannulations can be performed when the type of airway surgery requires a sternotomy or a right sided thoracotomy. This has the advantage of sparing the peripheral vessels.

Before inserting the cannulas, a single administration of intravenous unfractionated heparin (60 units/kg) is administered. Target ACTs should be between 160 and 180 seconds. ACT is measured every 15 to 30 minutes during the procedure. At the end of the operation, ECMO flow should be gradually reduced while oxygen saturation and hemodynamic parameters are closely monitored. If the patient is stable, cannulas may be clamped and the patient may be disconnected from the ECMO circuit.

Conclusions

In the vast majority of cases, airway surgery can be safely performed by experienced teams without the need for ECLS. However, there are instances where airway control is predictably very difficult or near impossible, or where loss of airway control can suddenly occur. ECLS is an important tool in the armamentarium of the thoracic surgeon to facilitate extended airway surgery or endoscopic airway manipulation in critical obstructions.

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Footnote

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