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LARYNGOLOGY

Refashioned lamb tissue as an animal model for training complex techniques of laryngotracheal stenosis surgery

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Abstract Open reconstructive upper airway surgery for laryngotracheal stenosis (LTS), whether for subglottic or tracheal stenosis, constitutes a group of complex approaches. LTS requiring open reconstruction is overall rare and primarily performed at tertiary centres. This poses an obvious challenge for the acquisition and maintenance of surgical skills for this group of complex approaches. In this context, animal models provide a unique opportunity for open reconstructive airway surgery training. Such models ought to take into consideration ethical aspects, be easily available and easy to maintain, and have similar macroscopic anatomical features to the human laryngotracheal frame. Here, we provide a brief surgical guide for the use of refashioned lamb tissue as a training model for surgery of adult and pediatric reconstructive airway surgery. The techniques of laryngotracheal reconstruction, partial cricotracheal resection, tracheal resection with end-to-end anastomosis, and slide tracheoplasty are presented. Proper training in open LTS surgery is challenging, time consuming and its complexity further lengthens the learning curve. The lamb larynx and trachea model is an effective model for practising various airway reclaiming surgeries.

Keywords Animal model · Subglottic stenosis · Tracheal stenosis · Airway surgery

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Introduction

Endotracheal intubation (ETI) is the mainstay technique for management of critically ill children and adults requiring invasive respiratory support. With time, ETI became the leading cause for laryngotracheal stenosis (LTS). Other etiologies include congenital causes, external neck trauma, infections (e.g. epiglottitis, diphtheria, tuberculosis, and syphilis), thermal injury, and caustic/foreign body ingestion [1, 2]. Historically, management options for the compromised airway were very much limited to tracheostomy, a technique already reported in an ancient Indian manuscript dating to 2000 BCE (the *Rig Veda*) [3].

The introduction of inhalation anesthesia during the nineteenth century allowed the development of more sophisticated therapeutic approaches such as airway dilatation with the use of rubber bougies and resection with end-to-end anastomosis for short-segment stenosis. Nevertheless, it was only with the introduction of ETI in the 1950s that complex reconstructive procedures were gradually developed [4].

Currently, approaches for LTS encompass a wide range of endoscopic and open techniques. Severe cases of congenital or acquired LTS, however, most often require open modalities, including laryngotracheal reconstruction (LTR), partial

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cricotracheal resection (PCTR) and its technical variants, as well as slide tracheoplasty (ST), depending on the original pathology and its extent [5, 6].

Due to the low incidence of severe LTS and the complexity of surgical approaches for its correction, successful management of patients with LTS requires a multidisciplinary approach by a trained team in a tertiary center, as the best chances of success lie in the first repair attempt. Moreover, all reconstructive airway procedures carry potential complications such as recurrent laryngeal nerve (RLN) palsy, anastomotic dehiscence, restenosis, aberrant scar tissue, with substantial morbidity and difficult further management [7].

Parallel to these clinical considerations, there is an obvious need for suitable models to train surgical skills for open laryngotracheal surgery. While a number of models have been previously described for training in endoscopic approaches [8–10], the use of models suitable for open reconstructive laryngotracheal surgery is seldom.

The object of this work is to provide a concise surgical guide for the use of refashioned laryngotracheal lamb tissue as a training tool for LTR, PCTR and extended-PCTR (ePCTR), tracheal resection and anastomosis (TRA), and ST.

Animal model and mounting procedure

Elaboration of this manual is based on the experience gathered within the context of airway surgery courses organized by the Department of Otorhinolaryngology, Head and Neck Surgery of the Lausanne University Hospital, CHUV, Switzerland. Permission was granted from our Institutional Review Board. Lamb specimens for the course were obtained at a local slaughter house (with proper government authorizations). According to Swiss law, after an initial electroshock animals are slaughtered by a single bold cut on the lateral aspect of their neck, resulting in section of the trachea and the carotid arteries. Upon completion of this procedure, the neck of 22 animals were fully dissected by trained head and neck surgeons to remove the entire laryngotracheal frame (from the base of tongue down to 20 tracheal rings) with the esophagus and the hypopharynx. Extracted specimens were thoroughly washed to remove all blood clots, kept in individual plastic bags and preserved at −25 °C at the anatomy laboratory of the Lausanne University Hospital. Specimens were slowly thawed during 24 h prior to their use in the airway course. The macroscopic features were consistent in all the larynges and a step-by-step surgical training was performed.

The differences between the lamb and human laryngotracheal frame could be summarized as follows (Fig. 1a–d):

1. Lambs have a large, two-level hyoid bone, created by large minor cornu extending laterally and superiorly
2. Regarding the endolarynx, the anterior commissure is situated at the inferior edge of the thyroid cartilage, the arytenoids are comma shaped and there is a reduced interarytenoid space due to a thin interarytenoid muscle. The ventriculus Morgagni is lacking due to the caudally oriented glottis, but true vocal cords are clearly recognizable
3. The tracheal rings in the lamb are near-complete, with a very small membranous trachea

The extracted laryngotracheal frames were mounted on a rubber platform mat and fixed with pins for stability throughout the entire dissection. We used regular office erasers in place of autologous cartilage to practice sculpting and shaping of the interposition grafts.

Basic dissection procedure for open reconstructive airway surgery

Following classical midline dissection (Fig. 2a), the strap muscles are laterally retracted along with the thyroid gland after isthmotomy to obtain full exposure of the trachea (Fig. 2b). Dissection of the trachea is carried out staying in close contact with the outer perichondrium and only anteriorly and slightly laterally without formal identification of the RLNs (Fig. 2c). Safe dissection in this manner can be performed up to the caudal edge of the cricoid ring (Fig. 2d). Since the RLNs run posteriorly to the cricothyroid joints, to avoid their injury lateral and posterior dissection of the cricoid cartilage must be avoided.

For adequate airway mobilization, a laryngeal drop is sometimes required for PCTR, ePCTR and TRA. This laryngeal mobilization is obtained after incising the thyrohyoid membrane (Fig. 2e, f) while staying close to the upper border of the thyroid cartilage and sectioning the thyrohyoid muscles at the level of their insertion on the oblique line. Additional careful sectioning of both the superior horns of the thyroid cartilage gives an optimal infrahyoid laryngeal drop and avoids damage to the superior laryngeal nerves. The cricothyroid muscles are dissected off the cricoid arch bilaterally from the midline and reflected over the cricothyroid joint, protecting both the RLNs, which as mentioned above run posterior to the joints.

Laryngotracheal reconstruction with partial or complete laryngofissure, with anterior and posterior grafting

LTR and expansion with anterior cartilage grafting is indicated for grade I (that is symptomatic) and grade II subglottic stenosis (SGS) according to the Myer-Cotton classification

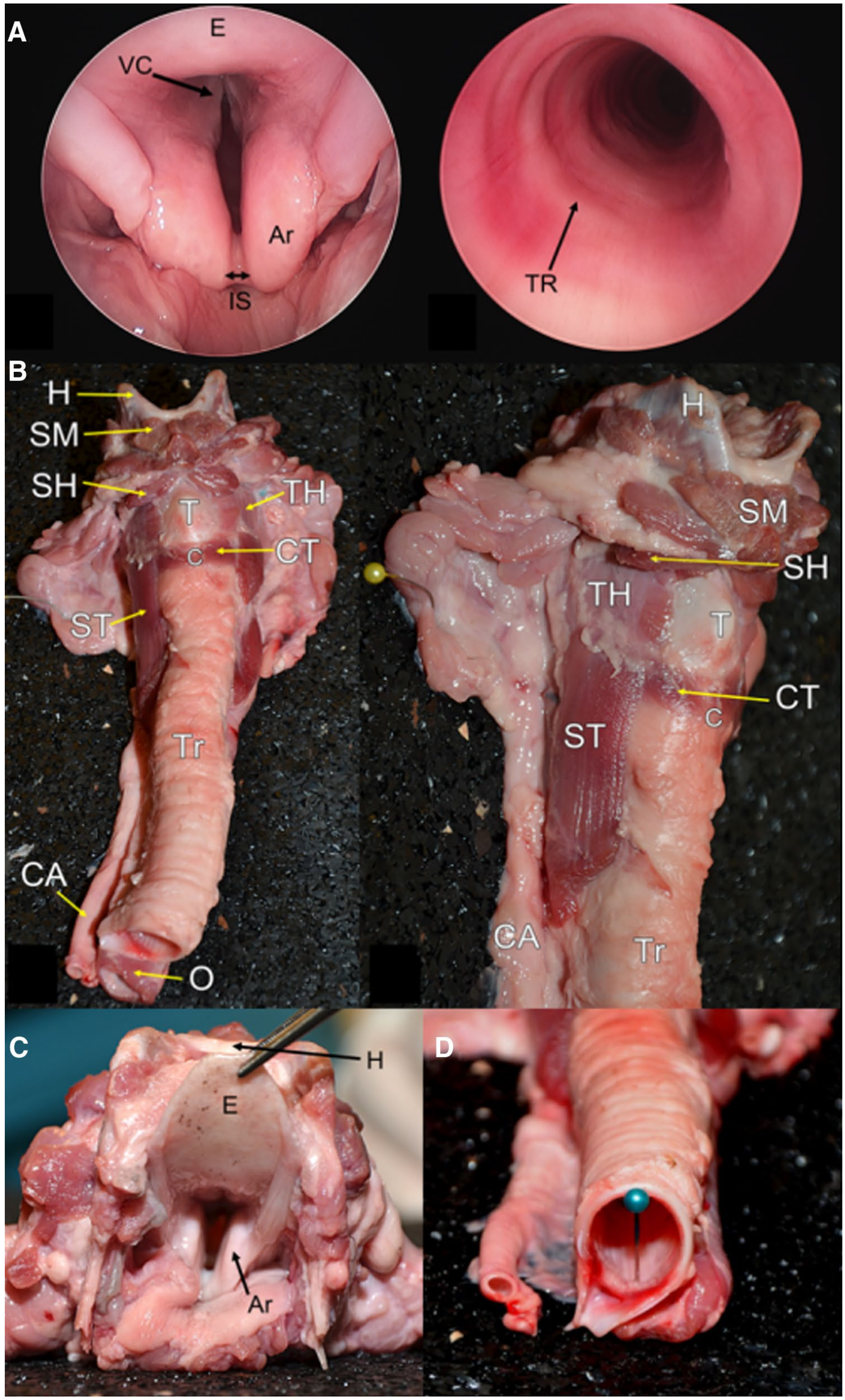

Fig. 1 Anatomical characteristics of the lamb larynx. **a** Endolaryngeal (left) and endotracheal (right) view in the lamb, with comma shaped arytenoids (Ar), small interarytenoid space (IS), and caudally-oriented vocal cords (VC). *E* epiglottis, *TR* tracheal rings. **b** Anterior (left) and lateral right (right) fixation of the laryngotracheal frame. *H* hyoid bone, *SM* suprahyoid muscles (here sectioned), *SH* sternohyoid muscle (sectioned), *T* thyroid cartilage, *C* cricoid cartilage, *CT* cricothyroid muscle, *TH* thyrohyoid muscle-removed in the figure on the right, *ST* sternohyoid muscle, *CA* carotid artery, *Tr* trachea, *O* oesophagus. **c–d** Proximal (**c**) and distal views (**d**)

system, as well as some selected cases of minor grade III SGS. Posterior grafting is performed in cases of posterior glottic stenosis—when expansion of the interarytenoid space is required. Combined anterior and posterior grafting is performed in severe cases of glotto-subglottic stenosis. However, in such scenarios some institutions, like the authors',

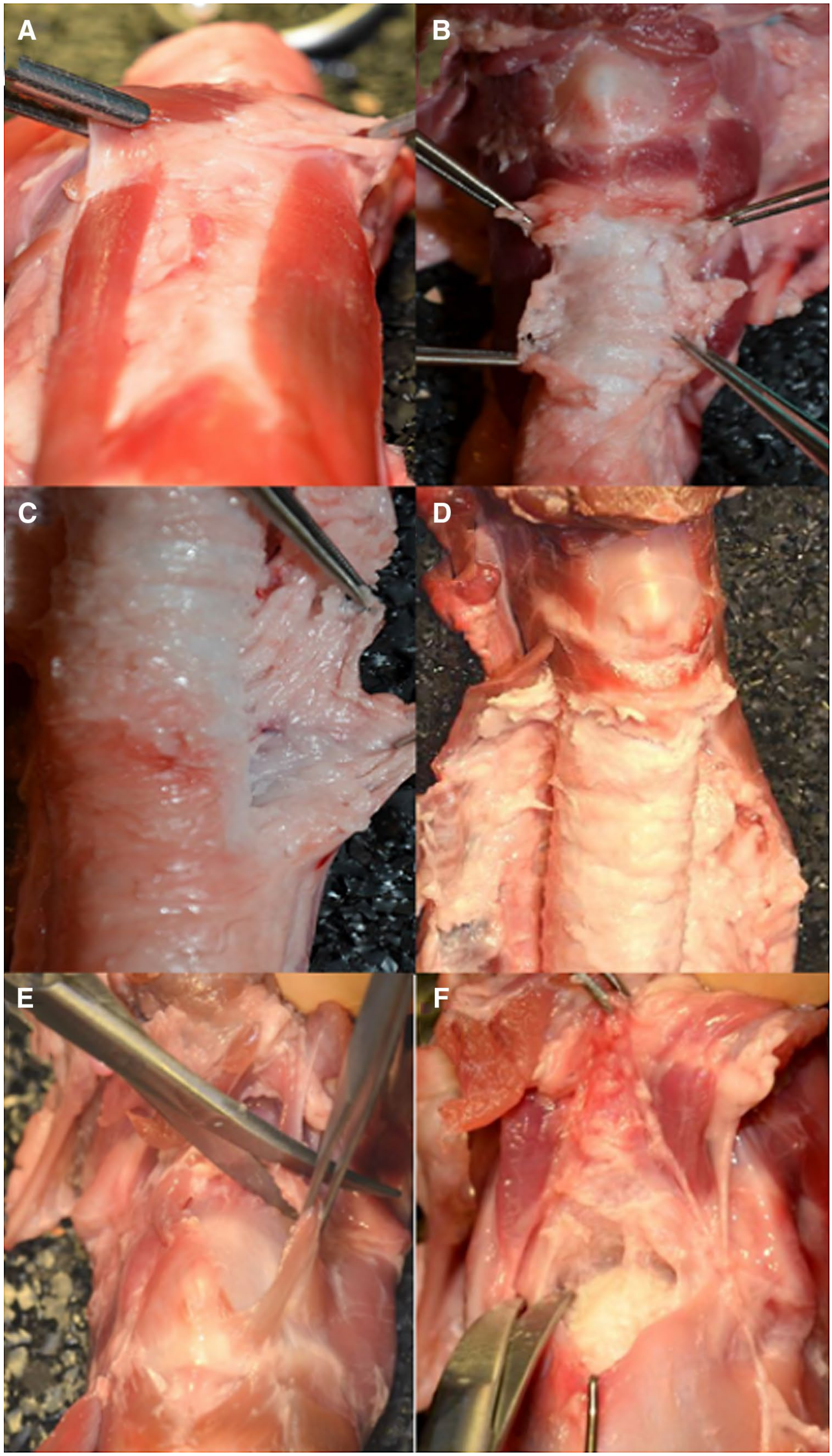

Fig. 2 Basic dissection approach for reconstructive airway surgery. **a** Dissection begins with longitudinal dissection along the midline. **b** Identification of the anterior aspect of the trachea. **c** Lateral dissection is performed subperichondrially to avoid damage to the RLNs. **d** Complete exposure of the trachea, up to the lower edge of the cricoid cartilage. **e** As first step for the infrahyoid laryngeal drop, when needed, the upper border of the thyroid alae is skeletonized and the thyrohyoid muscles are sectioned on either side. **f** The thyrohyoid membrane along the upper rim of the thyroid cartilage is incised up to the upper horn and can be divided on both sides if required

prefer to perform rather PCTR or ePCTR [11]. In the majority of cases, augmentation grafts are prepared using autologous costal cartilage, either as a single- or double-stage procedure [12].

Following anterior exposure of the trachea a typical incomplete or partial laryngofissure (LF) incision in a clinical setting extends in the midline through the lower third of the thyroid cartilage, the cricothyroid membrane, the anterior cricoid arch and the two upper tracheal rings, sparing the anterior commissure. Preserving the anterior commissure in the lamb model, however, is not possible due to the caudal insertion of the vocal cords. For LTR both cricothyroid muscles are to be preserved. The length of LF depends on whether the glottis is affected or not. In cases of transglottic and severe posterior glottic stenosis, or vocal cord synechiae, the incision is to be extended into a complete or full laryngofissure. The anterior LF must imperatively be performed along the midline at the anterior commissure. After completion of the LF, the length and width of the desired anterior expansion graft are measured (Fig. 3a). A regular office eraser is used in place of a costal cartilage and an anterior interpositional graft is prepared. The anterior graft is sutured using 4.0 Vicryl, either with simple interrupted or horizontal mattress sutures (3B-D). The perichondrium (marked with ink on the eraser) faces the lumen (Fig. 3e, f). Finally, fibrin glue is applied around the sutured graft.

For complete or full LF, an incision is performed either using an inferior to superior or a superior to inferior approach. The inferior to superior approach starts in the midline at the inferior border of the thyroid cartilage and extends up to the thyroid notch. The reverse is done in the superior to inferior approach. Again, whichever the chosen approach it is critical to avoid an off-midline division that could damage the vocal ligaments. Needless to say, in a clinical setting, a partial LF is preferable to a total LF when possible.

Next, the anterior tip of each vocal ligament is sutured to the thyroid cartilage using 5.0 Vicryl to avoid it from getting detached from the cartilage during surgical manipulation (Fig. 4a). The posterior cricoid split (PCS) is then performed following infiltration with normal saline/tap water for hydro-dissection (in a clinical setting we use 2% lignocaine and adrenaline). A midline incision is performed on the posterior cricoid plate, reaching up to the median raphe of the posterior cricoarytenoid muscle without damaging the retrocricoid mucosa. An artery snap inserted into the oesophagus helps in performing the PCS. A paramedian

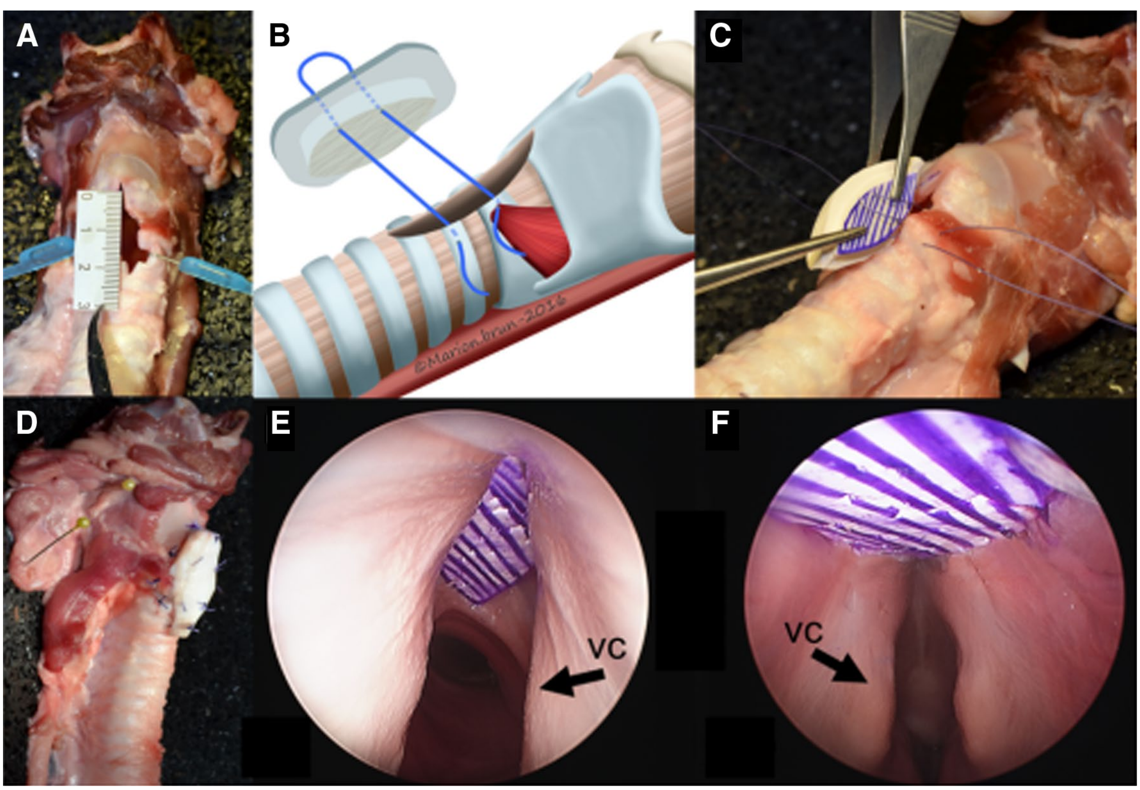

Fig. 3 Partial laryngofissure with anterior grafting. **a** Partial anterior laryngofissure from inferior third of the thyroid cartilage down to the second tracheal ring. Measurement for the expansion cartilage. **b, c** Horizontal mattress suture was used to fix the anterior graft seen in the schema (**b**) and in the model specimen (**c**). **d** Sutured graft in situ. **e, f** Anterograde (**e**) and retrograde (**f**) views at the end of the procedure. The perichondrium is marked with blue ink and faces the lumen. *VC* vocal cords

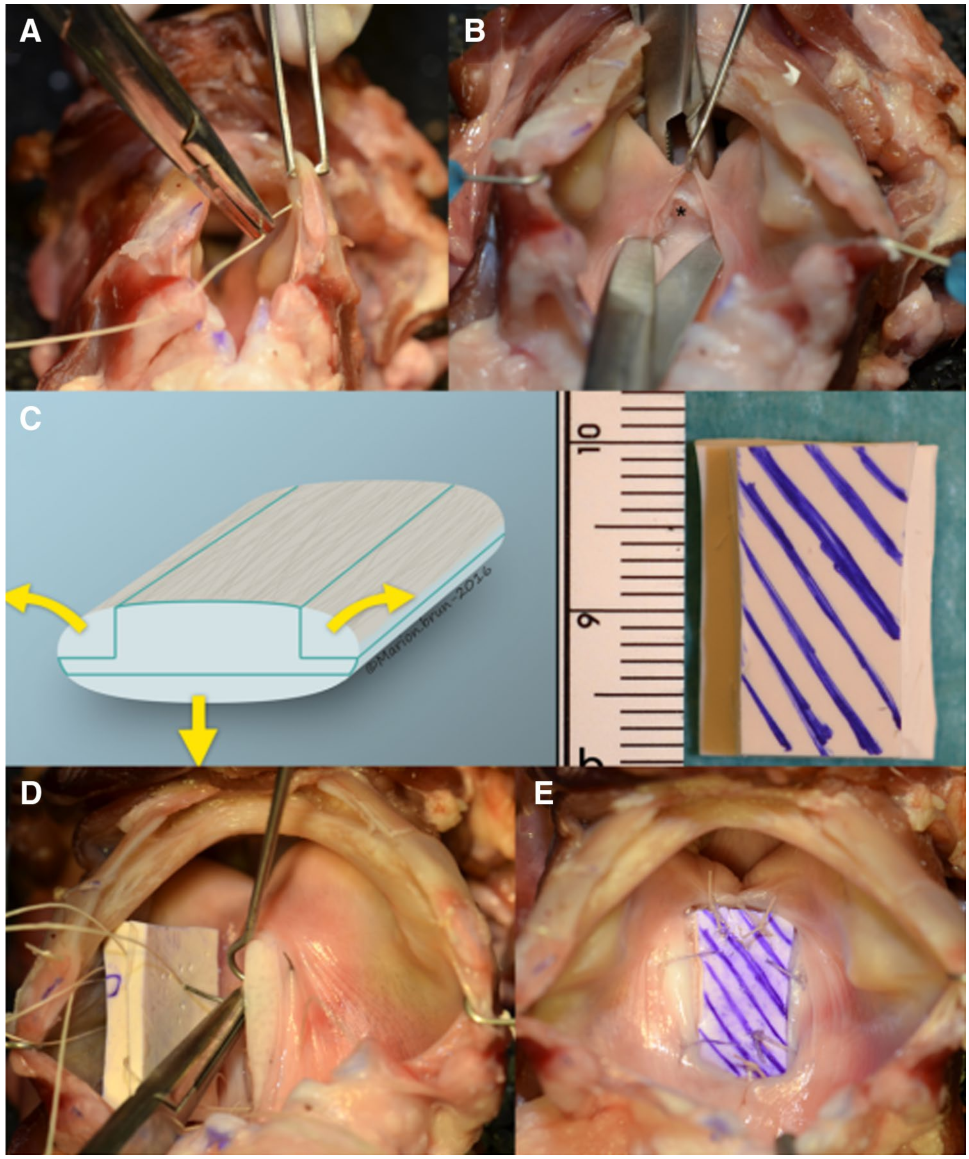

Fig. 4 Complete laryngofissure with posterior grafting. **a** Securing the left vocal ligament to the thyroid cartilage. **b** The transverse interarytenoid muscle (asterisk) is sectioned to avoid recurrence of posterior glottic stenosis. **c** Posterior graft fashioning in a schema (left) and on the eraser (right). The rounded posterior portion of the coastal cartilage is flattened in a clinical situation. **d** Posterior graft suturing technique. The suture is placed at the posterior and inferior edges of the cricoid plate, emerging at the mucosal edge to allow an optimal mucosa-graft perichondrium contact. **e** Suturing the posterior graft perichondrium with the interarytenoid (cranially) and tracheal (caudally) mucosae, respectively

PCS could potentially damage the cricoarytenoid joints, an eventuality which must be avoided. In a clinical setting of posterior glottic stenosis, the transverse interarytenoid muscle is fibrosed and should be transected up to the retroarytenoid mucosa (Fig. 4b). After completing the PCS, we measure the width for the interposition graft that is required to adequately expand the posterior cricoid and thereby the subglottis. The posterior graft is rectangular in shape with the lateral flanges measuring 2 mm wide and 1 mm thick (Fig. 4c). The flanges pass behind the posterior cricoid plate and would prevent medialisation of the graft. Using a skin hook, dissection is done up to 2–3 mm laterally and posterior to the posterior cricoid plate to accommodate these flanges. Vicryl 5.0 sutures are used to fix the graft with the posterior cricoid plate. The needle is passed through the posterior graft and emerges at the junction with the flanges. The stitch then passes through the sectioned edge of the posterior cricoid plate and emerges outside (Fig. 4d) ensuring a meticulous contact between the subglottic mucosa and the graft perichondrium (marked with ink). Two stitches are used on either side to fix the graft with the posterior cricoid plate. The posterior glottic and tracheal mucosae are sutured to the perichondrium on the upper and lower edges of the graft (Fig. 4e). In the absence of an anterior graft, the LF is closed with interrupted Vicryl 4.0 sutures. The petiole of the epiglottis is fixed with the upper edge of the thyroid cartilage.

Partial cricotracheal resection

PCTR is indicated for cases with severe SGS (Myer-Cotton classification grade III and IV, with over 70% of luminal obstruction) and as salvage surgery after failed LTR. The decannulation rate with both primary and salvage PCTR has been estimated to be above 90% [13–16]. Like LTR, PCTR is a suitable approach even for low-weight children (< 10 kg) [17, 18]. The PCTR procedure starts with exposure of the laryngotracheal cartilage frame and completion of the infrahyoid drop (Fig. 5a). The anterior aspect of the cricoid ring is then resected along with the affected tracheal rings. For this purpose, the upper incision is performed at the level of the inferior border of the thyroid cartilage, beginning in the midline and proceeding laterally and horizontally along the cricoid arch (Fig. 5b). The importance to remain anterior to the cricothyroid joints during cartilage incision to avoid RLN injury cannot be sufficiently stressed. The cricoid plate is then completely denuded of scar tissue and the membranous trachea is released from the oesophagus only over the distance required to resurface the denuded cricoid plate, as extensive dissection along the trachea–esophageal groove may result in vascular compromise of the trachea and further iatrogenic injury. Given that lambs have almost complete tracheal rings, we suggest creating a more membranous-like posterior trachea by removing a portion of the cartilaginous ring. An inferior midline thyrotomy (IMT) is created with an intention to widen the subglottis (Fig. 5d). In a clinical situation, the IMT should not cranially affect the anterior commissure to optimize voice outcomes.

The posterolateral stitches on either side are the most crucial. On either side, this suture is passed submucosally on the tracheal side, subperichondrially through the cricoid plate and emerges out anterior to the cricothyroid joint avoiding damage to the RLN. Then, three or four 4.0 or 5.0 Vicryl interrupted sutures and knotted inside the lumen are placed to create the posterior anastomosis (Fig. 5c). The lateral and anterior thyro-tracheal stitches are placed submucosally (Fig. 5d–f) and alternatively through the 1st and 2nd tracheal rings on either side of the anastomosis to distribute tension over the entire suture line. While preparing the distal trachea, a pedicled triangular cartilage flap is fashioned in the

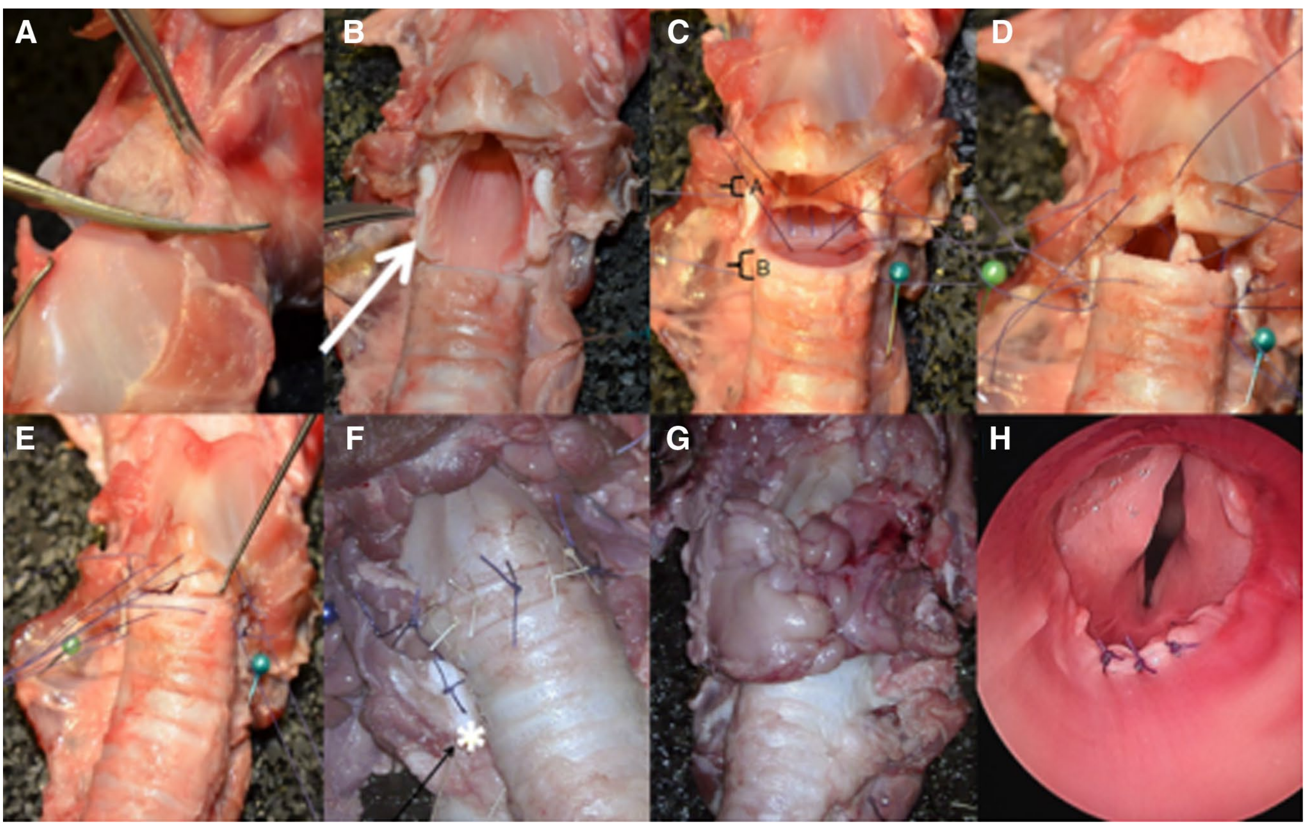

Fig. 5 Partial cricotracheal resection. **a** To complete the infrahyoid laryngeal drop, the upper horn of the thyroid cartilage may be sectioned with Mayo scissors. **b** Lateral cut passed horizontally on the cricoid arch in front of the cricotracheal joint (arrow). **c** Three or four interrupted 4.0 or 5.0 Vicryl sutures are placed to create the posterior anastomosis. The inferior margin (**b**) should be twice the length of the upper margin (**a**) to have an optimal tracheal and subglottic mucosal approximation. **d** Triangular cartilage flap sutured in the subcommissural defect after inferior midline thyrotomy. **e** Meticulous anastomotic alignment is achieved using a skin hook. **f** Tension-releasing stitch is taken between the inferior lateral cricoid arch (asterisk) and lateral edge of 2 tracheal rings distal to the inferior cricoid rim (white arrow). **g** Thyroid gland sutured around the anastomosis provides additional vascularity. **h** Retrograde endoscopic view. Perfect mucosal approximation is the only way to prevent granulations and subsequent restenosis at the anastomotic level

anterior trachea and sutured into the IMT (Fig. 5d). For all reconstructive airway procedures, the thyroid gland is used to reinforce the stenosis sutures during closure (Fig. 5g). Training the suturing technique is essential as incomplete mucosal coverage of the cartilage leads to aberrant scar tissue, potentially requiring re-operation and compromising outcomes (Fig. 5h).

Extended partial cricotracheal resection

ePCTR is indicated for forms of combined severe subglottic stenosis with glottic involvement (such as posterior glottic stenosis or vocal fold synechiae/fusion), grade III and IV transglottic stenosis, and congenital laryngeal atresia [5, 11, 14]. PCTR and ePCRT differ in the fact that the latter is combined with a step of posterior glottic expansion by a posterior costal cartilage graft [5]. In addition to the surgical steps for PCTR, a full laryngofissure with posterior cricoid split is performed and the two arytenoids are spread apart with the divided cricoid laminae. Full section of the interarytenoid muscle is necessary at this point to avoid recurrence of posterior glottic stenosis. Then, the posterior costal cartilage graft is placed and sutured with four 4.0 Vicryl stitches. In the lamb model, we use regular office erasers instead of autologous cartilages to practice sculpting and shaping of the interposition grafts. At the level of tracheal stump, a generous pedicled flap of membranous trachea is preserved to resurface the costal cartilage graft of the expanded cricoid plate. Either running or interrupted sutures using 5.0 Vicryl are made between the posterior membranous tracheal flap and the posterior glottic mucosa (Fig. 6a, b). The important posterolateral anastomotic sutures are passed as described in the steps of PCTR. The full LF is closed up to the vocal ligaments using 3.0 Vicryl passed submucosally (Fig. 6d). The petiole of the epiglottis is fixed at the thyroid notch. Then, laryngotracheal measurements are made and the reconstructed glotto-subglottic area is stented with an appropriate

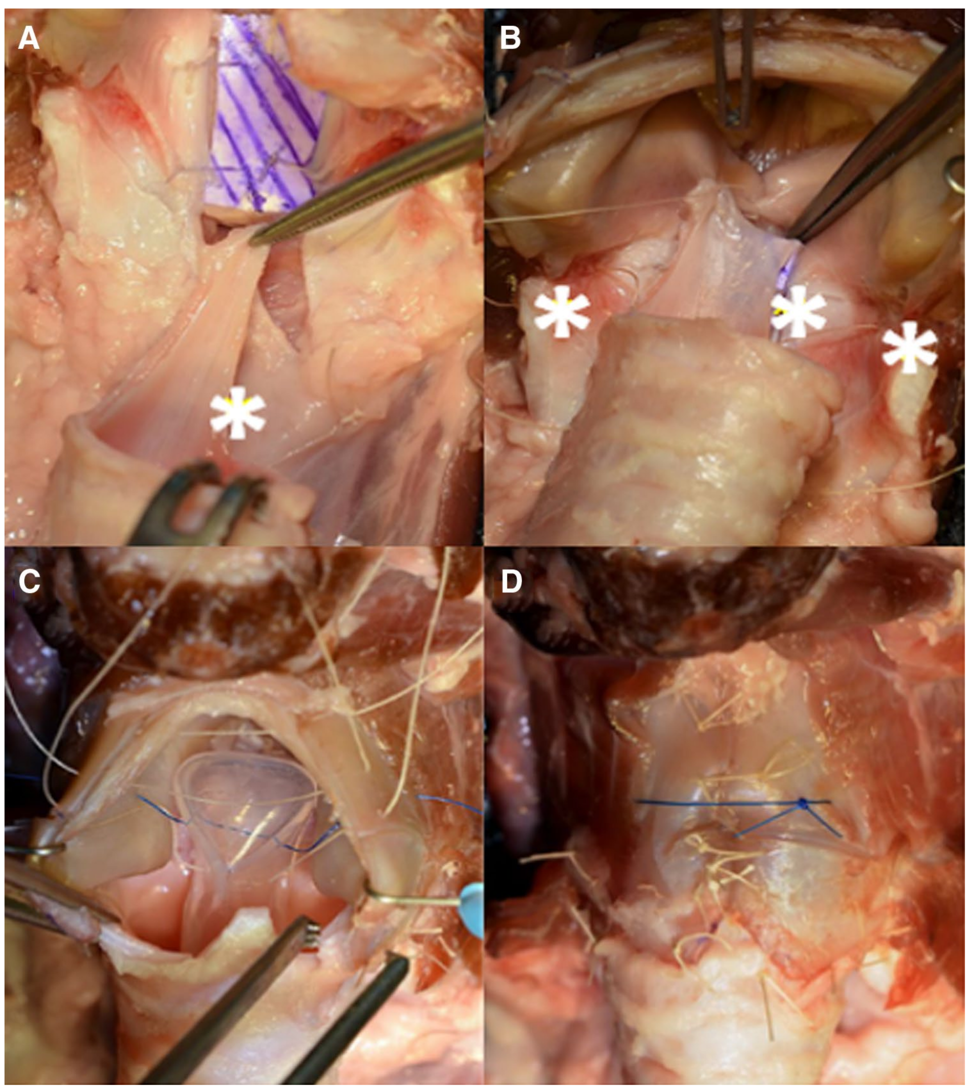

Fig. 6 Extended partial cricotracheal resection. **a** A full laryngofissure with posterior cricoid split is created, and the two arytenoids are spread apart with the divided cricoid laminae. Full section of the interarytenoid muscle is necessary to avoid recurrence of posterior stenosis. The posterior costal cartilage graft is then sutured with four 4.0 Vicryl stitches. Importantly, at the level of the tracheal stump, a generous pedicled mucosal flap (asterisk) is preserved. **b** Posterolateral stitches (lateral asterisks) are placed, while the posterior mucosal tracheal flap (medial asterisk) is used to resurface the costal cartilage graft of the expanded cricoid plate. **c** Insertion and fixation of an LT-Mold[R]. The size of the mold should correspond to the anteroposterior glottic length divided by 1.3, and its length to the distance between the anterior commissure and the superior edge of the tracheostoma. Please note that the selected LT mold is small for this model airway size. **d** Upon completion of the anterior stenosis, the LT-Mold[R] is secured with a 3.0 Prolene stitch tied on the external aspect of the thyroid cartilage. Tension releasing stitches are taken as discussed in the section of PCTR

size Monnier's LT-Mold^{R} fixed with two 3.0 non-resorbable Prolene stitches passed through the ventricular bands cranially and through the trachea caudally (Fig. 6c). Using 5.0 Vicryl, the beak of the LT mold^{R} is fixed with the vocal ligaments to ensure a sharp angle at the future anterior commissure. The lateral and anterior thyrotracheal anastomoses are made by placing stitches alternatively through the first and second tracheal rings as illustrated in Fig. 6b, c. In a clinical situation, a new tracheostomy replaces the old stoma that is resected concomitantly along with the anterior cricoid arch and the tracheal rings proximal to the stoma. If the original tracheostoma was close to the subglottis, a new tracheostomy must be performed three to four rings distal to the thyrotracheal anastomosis and an anterior pedicled triangular cartilage flap is created as in the case of PCTR. This flap will be sutured in the lower part of the LF below the anterior commissure and corresponds to the inferior midline thyrotomy as in PCTR. Thus, the ePCTR is always a 2-stage procedure. In the refashioned lamb tissue, we use the upper 1–2 tracheal rings to create the pedicled triangular cartilage flap.

Tracheal resection and anastomosis and cervical slide tracheoplasty

Congenital and acquired tracheal stenosis is rare and can be short or long segmental. Acquired tracheal stenosis arises most often from blunt trauma to the neck, intubation-related injuries, and tracheotomy-induced granuloma or suprastomal collapse. Congenital tracheal stenosis is very rare and is often seen in a context of associated cardiovascular, pulmonary and gastrointestinal malformations [19]. Surgical treatment of tracheal stenosis is challenging and needs meticulous planning according to the length and site of the stenotic segment.

TRA is indicated for cases of stenosis involving up to six tracheal rings [20, 21], though we have excised up to 9 rings in one child with optimal anastomosis after performing a laryngeal drop procedure and adequate mobilisation of the thoracic trachea. Conversely, in adults however, the anastomosis is under tension if more than 4–5 rings are excised. For TRA, following classical dissection and exposure of the trachea, prior to any transverse incision on the trachea, mobilization of the larynx caudally and of the trachea cranially must confirm that approximation of the two tracheal ends will be possible after resecting the diseased airway segment (Fig. 7a). This technique can also be used in PCTR and ePCTR. After defining the site of maximal stenosis according to the endoscopic findings, the trachea is opened transversally and sliced cranially and caudally, until normal-sized luminal sections are obtained on both sides (Fig. 7b). The posterior trachea is minimally separated from the oesophagus to allow resection of the stenotic segment (Fig. 7c). Two considerations are important. First, posterior dissection in the trachea–esophageal groove is to be avoided beyond the borders of the resected segment. Second, in complex cases requiring PCTR, ePCTR and TRA, the airway should be opened vertically to assess the extent of the resection rather than transecting it transversely—as in case of an error, the situation would be then irreversible or likely lead to excessive anastomotic tension. Posterolateral stitches (2.0, 3.0 or 4.0 Vicryl, depending on the patient's age in a clinical situation) are placed in a submucosal fashion (Fig. 7d). Then, the posterior anastomosis is made with a 5.0 Vicryl or a 5.0 double arm PDS running suture (Fig. 7e) that is knotted on the outside (Fig. 7f). The lateral and anterior stitches are placed submucosally and alternatively through the 1st and 2nd tracheal rings on either side of the anastomosis to distribute tension over the entire suture line. Correct stitch placement for tracheo-tracheal anastomosis implies that the needle should pass submucosally to preserve vascular supply to the anastomosis (Fig. 7g). If these sutures are not passed submucosally, then a vascular compromise might happen secondary to a cheese-wire mechanism with the sutures cutting through the tracheal microcirculation. This will lead to an anastomotic dehiscence. The thyroid isthmus is sutured over the anastomotic site to reinforce vascularity. Endoscopic view of the inside of the airway after anastomosis is useful for assessing operative results as well as for educational purposes (Fig. 7h).

ST is indicated for cases of long-segment congenital tracheal stenosis with complete "0" rings as well as acquired long tracheal stenosis when segmental TRA is not possible. ST allows doubling the tracheal circumference at the level of the stenotic segment by shortening the trachea at most in half [22]. For ST, dissection of the trachea anteriorly over the whole distance of the stenotic segment and extending distally (tracheal mobilisation) is performed maintaining close contact with the tracheal rings and preserving the critical posterolateral vascular supply (Fig. 8a). Trachea is then divided transversally in the mid portion of the stenosis, after which the posterior tracheal wall is incised vertically on the lower trachea while anterior tracheal wall is incised vertically on the upper trachea (Fig. 8b). In a clinical situation, all complete tracheal rings should be incised—either in the front or in the back. Needless to say, the most distal or proximal ring(s), if left uncut leads to dangerous recurrence of symptoms. The two tracheal stumps on either end are spatulated (i.e. trim down the lateral sharp edges of the proximal and distal tracheal stumps) and slid over one another, which shortens the trachea by half but technically doubles the circumference and thereby quadruples the luminal cross-sectional area (Fig. 8c, d). The oblique, oval-shaped anastomosis is performed with two 4.0 Vicryl running sutures from posterior (caudal end) to anterior (cranial end) direction

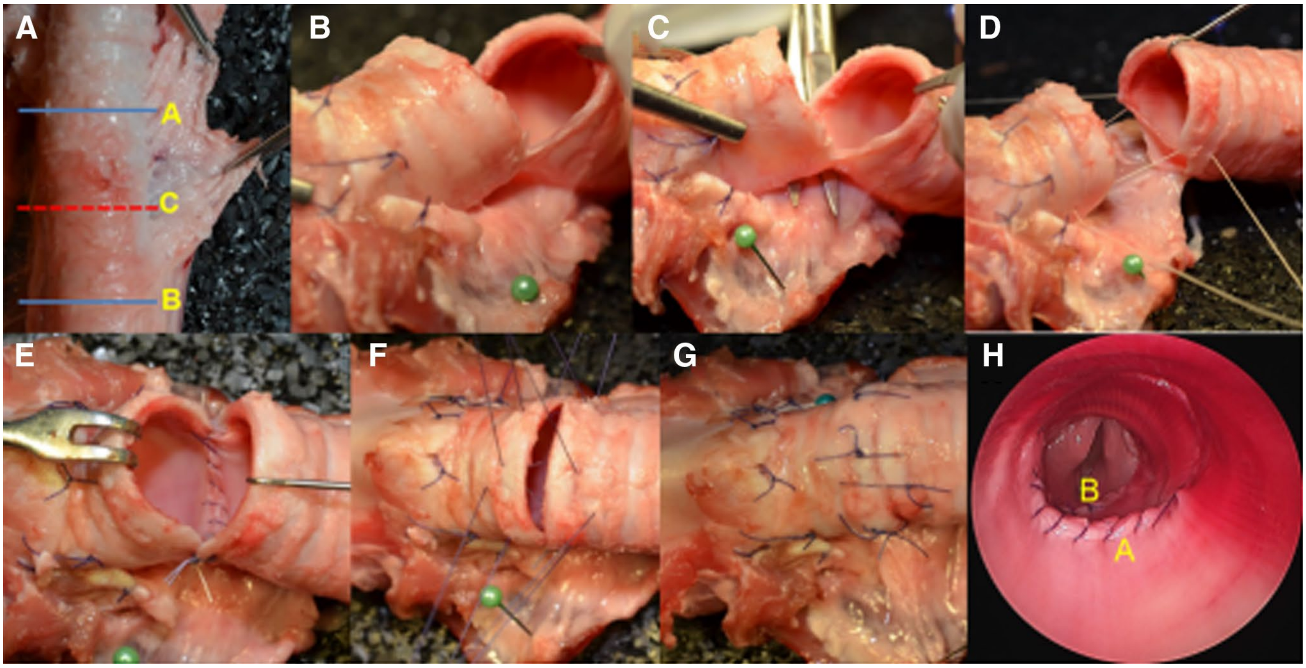

Fig. 7 Tracheal resection and anastomosis. **a** Prior to resection of the stenotic segment, it must be confirmed that the tracheal edges can be mobilized without undue anastomotic tension. For this purpose, after laryngeal release and full tracheal mobilization, it will be evaluated whether points A and B can be mobilized, caudally and cranially respectively, to point C without excessive tension. **b** Transversal incision and opening of the trachea is performed according to endoscopic findings. Peroperative fiberoptic guidance can help localizing the area of maximal stenosis by inserting a fine-needle through the tracheal wall. Note that this same specimen was used earlier for PCTR training. **c** Minimal separation of the membranous posterior trachea from the oesophagus should be performed on either tracheal stumps to maximally preserve the vascular supply to the trachea. **d** Following removal of the stenotic segment, posterolateral stitches (2.0, 3.0 or 4.0 Vicryl, depending on patient's age) are submucosally placed. **e** The posterior anastomosis is made with a 5.0 Vicryl or PDS running suture knotted on the outside. **f** The rest of stitches are placed submucosally and alternatively through the 1st and 2nd rings on either side of the anastomosis to evenly distribute tension along the suture line. **g** Correct stitch placement for tracheo-tracheal anastomosis implies that the needle should go through the submucosal plane to preserve vascular supply and avoid damage to the tracheal microcirculation by cheese-wire mechanism. **h** Retrograde endoscopic view showing the anastomosis after tracheal resection (**a**) and the PCTR anastomosis (**b**)

(Fig. 8e, f). Fibrin glue is smeared over the anastomotic line and an endoscopic examination is performed to visualize the extent of expansion inside the airway lumen (Fig. 8g, h).

Overall discussion

In this article, we present a brief surgical guide of open approaches for laryngotracheal stenosis using refashioned lamb tissue. Animal models have been key to learn, master and develop technical variants of established surgical procedures. For instance, while the technique of anterior and posterior cricoid split was first reported by Réthi in 1956 [23], the current standard technique of LTR was established in a seminal animal study by Fearon and Cotton [24]. These authors performed extensive trials on African green monkeys, whose anatomy closely resembles the human anatomy.

Even though the role of animal and more specifically primate research undeniably represent a precious tool for preclinical validation of new technical approaches, the ethical standards understandably limit the use of living animals for the purpose of training. Moreover, the use of fresh human cadavers is limited due to several factors, including availability, medico-legal, financial and ethical issues. In this context, the use of *ex vivo* models as training tools in the field of head and neck surgery is increasingly recognized. In this sense, Naseer et al. [8] suggested the use of the porcine larynx for training endolaryngeal microsurgery. Similarly, Propst et al. [25] published a manual on open airway surgery in a porcine model. Effat [26] reported the experience with 33 bovine larynges for diverse phonosurgical approaches and partial laryngectomy.

Regarding the use of ovine models, several studies have equally described their usefulness for laryngological approaches. Indeed, comprehensive comparison between the human and the sheep larynx have previously established the suitability of such a model [27–29].

Lamb larynges are widely available, cheap, resemble small human airways and are easy to preserve. This model allows the training and improvement of skills by acquiring

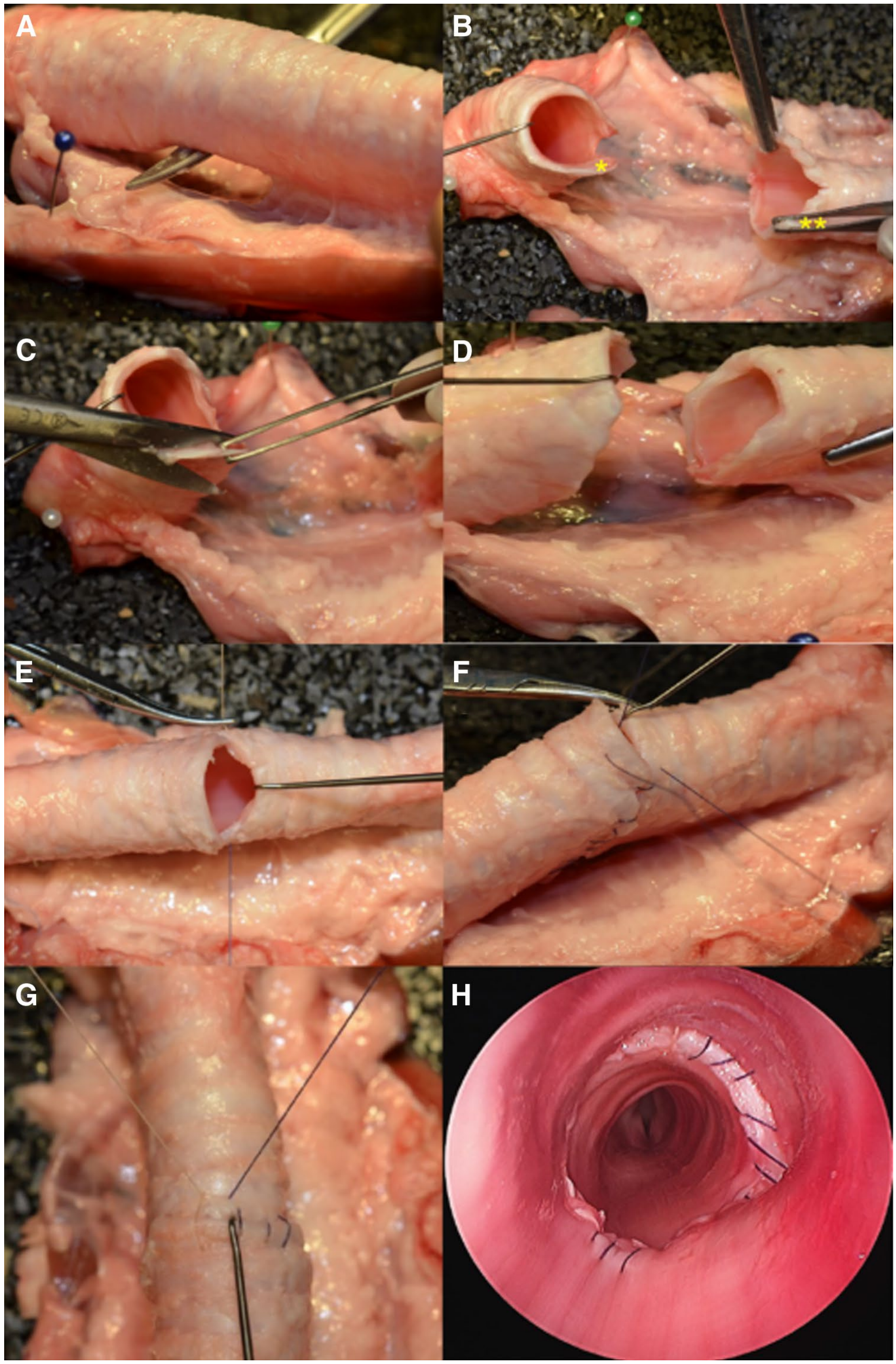

Fig. 8 Slide tracheoplasty. **a** Anterior and lateral dissection of the trachea, preserving vascular supply from the tracheoesophageal groove over the lower one-half of the stenosis. **b** Following transverse section of the trachea in the mid portion of the stenosis, the lower stump is vertically incised on its posterior wall (asterisk), while the cranial stump is anteriorly incised (**). **c** The lateral sharp edges of the proximal and distal tracheal stumps are trimmed down (spatulated). **d** The tracheal segments are slid over one another. **e** Oblique, oval-shaped anastomosis with two running Vicryl 4.0 sutures from caudal to cranial. **f** Oblique tracheo-tracheal anastomosis. **g** Final step of the anastomosis. **h** Retrograde endoscopic view of the anastomosis suture

the essential hands-on experience for a variety of surgical approaches, as well as the possibility for a "dry-run or warm-up" prior to the actual surgery for the trained airway surgeon [30]. Relevant to this last point, in their only case report on laryngeal transplantation, Farwell et al. [31] mentioned extensive training for two years on an established porcine model prior to performing their successful surgery.

In our experience, refashioned laryngotracheal lamb tissue is suitable for a wide range of reconstructive airway procedures (including placement of a laryngeal stent), even allowing the possibility to perform two surgeries (involving the trachea) in the same specimen (e.g. PCTR or ePCTR combined with TRA or ST). This is because of the long trachea that can be harvested in the model allows additional hands-on dissection. The lamb ribs are mostly bony and harvesting the costal cartilages is time-consuming. We found that use of regular office erasers to be a simple and cheap alternative, providing a similar tactile feedback. Moreover, sculpting anterior and posterior grafts on erasers and practicing various suturing techniques relatively mimics the actual working with human costal cartilage.

Finally, the lamb model has been used during dissection courses recently held at our institution. More than 100 beginner surgeons have practised hands-on reconstructive airway approaches with success on this model, giving a very positive feedback. High definition videos of these dissections are being created at our institution and are expected to serve as important training tools for young surgeons.

Conclusion

Reconstructive airway surgery is complex and requires development and maintenance of very fine surgical skills and expertise, especially in the context of pediatric LTS. However, the low incidence of LTS cases requiring such approaches and rarity of centres able to concentrate meaningful number of cases leads to scarce opportunities of hands-on training in these procedures. As a result, proper training in laryngotracheal airway reclaiming surgeries is challenging, time consuming and its complexity further lengthens its learning curve. An alternative to overcome these limitations is the implementation of training programs using fresh animal models. In our experience, the lamb is a versatile training model for these kinds of interventions. Its availability, harvesting, preparation, low cost, and anatomical similarity to humans make of it an ideal dissection model. In addition, the lamb tissue carries a low risk of cross infection and is ethically adequate.

Compliance with ethical standards

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Conflict of interest No conflict of interest.

Ethical standards All applicable institutional guidelines for the care and use of animals were followed.

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