12 Balloon dilation of the airway

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Historical overview

Airway dilation for the management of patients with laryngotracheal stenosis has been a mainstay of airway surgery for at least a century. For most of that period, dilation involved the passage of rigid or semirigid devices through the stenotic area. These devices included Jackson, cat-tail, and Maloney dilators, rigid bronchoscopes, and endotracheal tubes. All of these instruments produced inexorable shearing forces that damaged mucosa in both healthy and stenotic segments of the airway. Despite this considerable downside, dilation using a bougienage technique remained appealing, as it offered avoidance of external incisions, short operative time, and quick recovery.

The specific use of balloon catheters to widen stenotic segments of the airway was first reported by Cohen and colleagues in 1984 (Cohen et al. 1984). These authors described the use of angioplasty balloons to salvage the distal trachea and right mainstem bronchus of an infant with recurrent stenosis after excision of complete tracheal rings. Over the past several decades, balloon technology and techniques have expanded (Noppen et al. 1997, Lee et al. 2002, Mayse et al. 2004), becoming an invaluable tool for the management of airway stenosis. This chapter presents an overview of the advantages of this management approach, the types of balloons available, candidate and balloon selection, dilation techniques, adjunctive procedures, complications, and outcomes.

Advantages of balloon dilation

Case series published to date (Hebra et al. 1991, Lee & Rutter 2008, Whigham et al. 2012, Guarisco & Yang 2013), combined with our own clinical experience, suggest that balloons offer a number of advantages over other dilation instruments. First and most importantly, correctly placed balloons exert a purely radial expansile force on the stenotic area. Radial expansion also distributes force evenly over the circumference of the stenosis, thereby minimizing the risk of airway rupture at any single point.

Second, balloons permit the surgeon to fine-tune the force applied to the stenosis. Balloons expand through the instillation of fluid, using a device that incorporates a pressure gauge. This design allows ongoing fine adjustment of the pressure exerted by the balloon. In contrast, rigid dilators exert a radial force once they are in place; however, this force can be adjusted only by removing the dilator and inserting a larger one.

Each removal and insertion exerts shearing forces on the stenosis and potentially on the normal mucosa of the airway above and below the stenosis, as well as on the vocal folds. This shearing may cause injury and may cause edema and scarring as well as mucosal bleeding.

A third advantage of balloon dilation catheters is their shape and flexibility. Since these catheters were initially designed for use in angioplasty, they are long, narrow, and flexible––properties that are all beneficial in the airway. A narrow, flexible balloon may be steered through a severe stenosis, while the catheter's length allows the surgeon to reach more distal stenoses.

Indications for balloon dilation

Patient selection

Appropriate patient selection is crucial to the success of airway balloon dilation. In general, ideal candidates are patients with adequate cardiopulmonary reserve to allow airway occlusion or those with a tracheostomy and stenosis above the tracheostoma. Stenoses that are likely to respond well to balloon dilation are thin or weblike and soft, and consist of immature scar tissue. Firm or mature scar tissue, cartilaginous airway narrowing, and structural problems of the airway exoskeleton (e.g. complete rings, subglottic lateral shelves, A-frame deformity, and missing cartilage) are less likely to respond to dilation. In addition, dilation is less likely to achieve desired outcomes in longer stenoses; however, there is no maximum length beyond which dilation should not be attempted. Also of note is that, in patients with second airway lesions, balloon dilation may be less likely to yield positive outcomes, as dilation of a single stenotic area may not provide an overall adequate airway (Whigham et al. 2012).

In general, balloon dilation requires the presence of an airway lumen large enough to permit entry of the deflated balloon. Stenoses with a pinpoint lumen may be gently dilated with a stylet and small cuffless endotracheal tubes until they are temporarily large enough for the surgeon to pass a balloon. Balloon dilation is therefore not generally suitable for the treatment of grade 4 stenosis.

Use as an adjunct to open airway reconstruction

Balloon dilation can be a useful adjunct to planned airway expansion or reconstruction procedures. In this context, the aim of dilation is to maintain patency of the airway lumen until the definitive procedure can be carried out. In patients with progressive grade 3 subglottic stenosis (>70% narrowing), interval balloon dilations may prevent the development of a complete (grade 4) stenosis that might preclude reconstruction with grafts (Guarisco & Yang 2013). Similarly, dilation may reduce the severity of a stenosis, permitting a single-stage procedure rather than a double-stage procedure. Dilations may be performed repeatedly until the patient is old enough or has sufficient growth to undergo open reconstruction.

Balloon dilation may also be used after airway reconstruction. Although postoperative dilation cannot be performed with a stent in place, once the stent is removed and adequate time is allowed for the reconstruction to heal, the balloon can be used in several ways. More specifically, in cases of postoperative edema or granulation, dilation may be combined with topical antibiotic/steroid drops to promote healing and reduce the risk of restenosis. Dilation may also be used to gently reposition an anterior graft that has prolapsed into the airway. Given that this particular use of the balloon carries the risk of displacing the graft, and that dilation after reconstruction generally has the potential to damage the repair, it should be done judiciously, at low pressures and with relatively small balloons.

Balloon selection

Balloon catheter design

All balloon catheters currently used for airway dilation have two ports (**Figure 12.1**). The first port is the inflation port, which allows the introduction of fluid to inflate the balloon. This port is usually labeled *balloon* (Boston Scientific, Natick, MA) or *B* (Acclarent, Inc, Menlo Park, CA) and is designed for attachment to the inflation device. The second port is used to introduce a stylet. Inadvertent instillation of inflation fluid through this port results in lung lavage rather than balloon inflation.

Semicompliant balloons

Although semicompliant balloons are not used at the authors' institution, these balloons are preferred by many surgeons. In contrast to noncompliant balloons, they are capable of expanding to different diameters at different pressures. When the portion of the balloon within the stenosis reaches an outward pressure equal to the

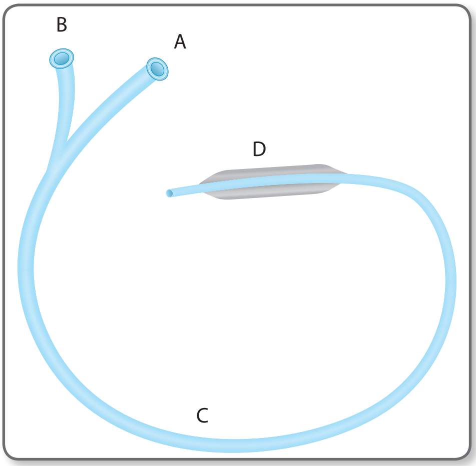

Figure 12.1 Basic schematic of an airway balloon catheter. Key components of the device are labeled. (A) Stylet port. (B) Inflation port. (C) Catheter shaft. (D) Balloon.

inward pressure exerted by the stenosis on the balloon, equilibrium is reached. As more fluid is introduced, the pressure at the stenosis and the balloon diameter at the stenosis remain relatively constant while the compliant balloon material allows the excess fluid to selectively fill the balloon above and below the stenosis. The result is an hourglass shape. Although these balloons have the advantage of exerting a constant pressure at the stenosis, they also have several important disadvantages. Most importantly, pressure equilibrium within the stenosis may be reached at a balloon diameter much smaller than the goal airway lumen diameter. In addition, the hourglass shape of the balloon may place excessive pressure on the mucosa above and below the stenosis, and these balloons cannot sustain as high a pressure at a given diameter as noncompliant balloons, as described subsequently.

Noncompliant balloons

Noncompliant balloons are designed to reach a uniform diameter over the full length of the balloon. This design allows the balloon to apply the greatest pressure and achieve full dilation at the narrowest point of the stenosis, thus avoiding the hourglass shape that may place undesirable pressure on adjacent areas of mucosa. These balloons may exert high pressures at the stenosis, making them more useful for dense scar tissue but raising the risk of airway rupture.

Balloon size and pressure selection

The surgeon's choice of balloon length and diameter is dependent upon the clinical context of the stenosis and the patient to be treated. In general, when using balloon dilation as a definitive treatment for airway stenosis from the glottis to the carina, the first step is to determine the diameter of an age-appropriate normal airway. For the subglottis and trachea, this is easily accomplished using endotracheal tube sizes, using the following equation:

Tube size = (age in years/4) + 4

Once the appropriate endotracheal tube size is selected, 1 mm is added to the outer diameter of that tube to determine the appropriate balloon diameter for use in the larynx. For tracheal dilation, the surgeon should add 2 mm rather than 1 mm. The difference between laryngeal and tracheal diameters reflects the anatomic difference between the closed ring of the cricoid and the open rings of the trachea. From the starting point established by these calculations, the surgeon can make adjustments, using smaller balloons for initial dilation of severe stenoses or relatively fresh reconstructions.

The target inflation pressure is usually determined by the 'burst pressure' of the balloon (i.e. the pressure beyond which the balloon may fail), which is specified on the packaging for each balloon. Generally, burst pressure becomes lower as balloon diameter becomes larger. Unless the surgeon has a specific reason to use a lower pressure, it is reasonable to use the burst pressure as the target inflation pressure.

Technique

Anesthesia

In patients without a tracheostomy, we prefer to perform endoscopy and dilation with the patient spontaneously ventilating. This technique requires close cooperation and good communication between the surgeon and the anesthesiologist. General anesthesia is typically induced with propofol and maintained with insufflated sevoflurane. If needed, the patient can temporarily be intubated above the stenotic area to allow maximal preoxygenation prior to dilation. Once the patient is adequately anesthetized, the surgeon should apply a weight-appropriate dose of topical laryngotracheal anesthetic. Prior to balloon insertion, the anesthesiologist should be informed that the airway will be fully occluded. In addition, the anesthesiologist should inform the surgeon when the oxyhemoglobin saturation drops to 90–92%, so that the balloon can be deflated and removed in a timely manner without excessive desaturation. The surgeon must be prepared to immediately provide mask ventilation once the balloon is removed in order to allow prompt reoxygenation. If the patient begins to 'cough' or 'buck' during balloon inflation, the balloon should be deflated and removed immediately and mask ventilation performed. Doing otherwise risks negative pressure pulmonary edema (NPPE) (as the patient attempts to inspire against the occluded airway), as well as barotrauma (when the patient forcefully exhales against the occluded airway). Once the patient is brought to a deeper level of anesthesia, dilation can be attempted again. The risk of NPPE is higher in adults and is rarely seen in children.

In patients with a tracheostomy and stenosis above the tracheostoma, airway management during dilation is much more straightforward. The tracheostomy tube may be left in place or replaced with a cuffed endotracheal tube through the stoma. The balloon can then be placed via direct laryngoscopy (described below) and inflated, while the anesthesiologist maintains oxygenation and ventilation via the tracheostoma. In this situation, the surgeon must ensure that the balloon does not ride under or next to the tracheostomy tube. Inflation with the balloon in such a position could force the tracheostomy tube against the tracheal wall and cause injury.

Dilation

The application of topical laryngotracheal anesthetic is strongly recommended, along with a diagnostic laryngoscopy and bronchoscopy immediately prior to dilation. This allows the surgeon to fully survey the airway and the stenotic area. Once this is done, the patient is preoxygenated and dilation can proceed. Under direct laryngoscopic visualization, the catheter is passed through the glottis to approximately the depth of the stenosis. The authors do not typically use a stylet, as the increased rigidity associated with the stylet raises the risk of airway perforation. The stylet may, however, be useful if a curve must be introduced into the catheter. If the catheter must be bent, it should be bent with the stylet in place to avoid kinking the inflation system.

With the assistant holding the balloon catheter in position, a narrow Hopkins Rod telescope is introduced and used to confirm that the balloon is centered within the stenosis. With the telescope still in place, the balloon is inflated to the target pressure. This telescopic visualization allows the surgeon to detect complications such as balloon failure or balloon displacement. Inflation is achieved using sterile saline. Water or air should not be used (**Figure 12.2**).

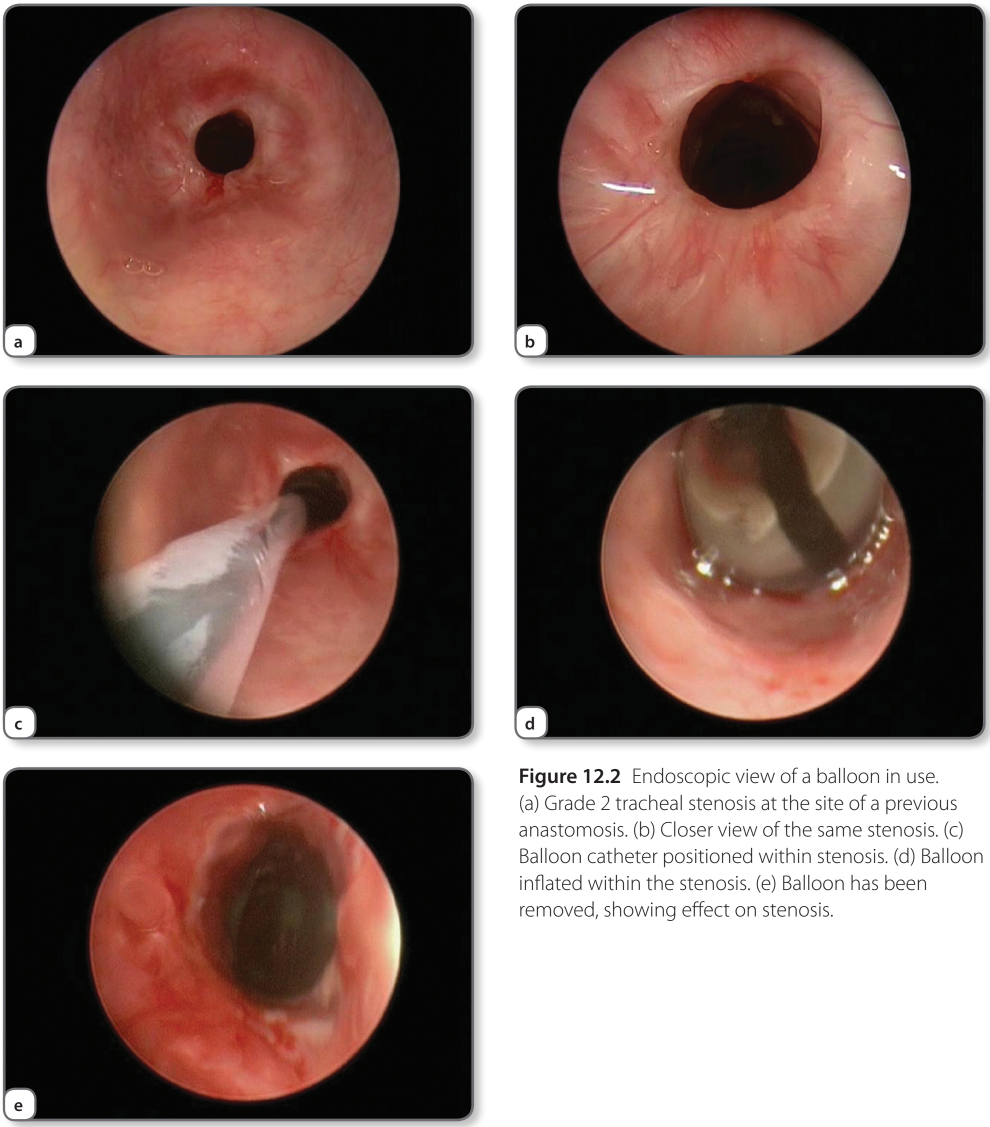

Figure 12.2 Endoscopic view of a balloon in use. (a) Grade 2 tracheal stenosis at the site of a previous anastomosis. (b) Closer view of the same stenosis. (c) Balloon catheter positioned within stenosis. (d) Balloon inflated within the stenosis. (e) Balloon has been removed, showing effect on stenosis.

After dilation is achieved, the balloon is completely deflated and removed. The telescope is left in place to visualize complete balloon deflation and to evaluate the dilated area for improved patency and for any complications such as tracheal injury.

Duration of dilation

The duration of dilations is ultimately limited by the inability to ventilate and oxygenate the patient while the balloon is inflated; within these limits, the optimal duration is unclear. Some surgeons prefer to use a fixed, arbitrary target time such as 2 minutes per dilation; however, data supporting this duration are lacking. An alternative method is to closely observe the pressure gauge on the balloon inflator. After the balloon is inflated to target pressure, the pressure will slowly drift downward as collagen crosslinks within the scar give way. The balloon can then be briefly inflated back to the target pressure for a total of 2 minutes and then deflated and removed.

Repeat dilation

Balloon dilation may be used repeatedly on the same lesion. In many cases, the initial dilation will achieve the full desired effect. Edema, granulation, and collapse may recur after dilation, and dilation itself may promote recurrent scarring. Accordingly, reassessment and patient and family education regarding the possibility of repeat dilation is essential.

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The number of dilation attempts beyond which benefits plateau is unknown, and this number likely varies among patients. The timing of repeat dilation also varies widely. At the authors' institution, however, dilation is generally performed at 1- to 2-week intervals. If a patient does not show incremental benefit with a fourth dilation, other strategies are typically investigated, including open reconstruction. Regardless of the strategy chosen, the surgeon must evaluate the patient carefully at each dilation, comparing images and videos of previous endoscopic procedures.

Adjunctive procedures

Multiple procedures may be used to augment the effects of dilation. In general, these procedures are best performed with suspension microlaryngoscopy, which allows the surgeon to use a microscope or telescope to visualize the procedure, while leaving both hands free.

Scar division

In patients with thicker cicatricial scar tissue or stenoses that are not cartilaginous but are refractory to dilation alone, radial incisions can be made immediately prior to dilation. The authors typically make three radial incisions with a Blitzer knife or laser in what is often referred to as a 'Mercedes-Benz' configuration; one incision is made anteriorly and one is made posterolaterally on each side (**Figure 12.3**). These incisions create weak points in the scar, allowing dilation to produce controlled tears through the scar tissue. To reduce the risk of tearing

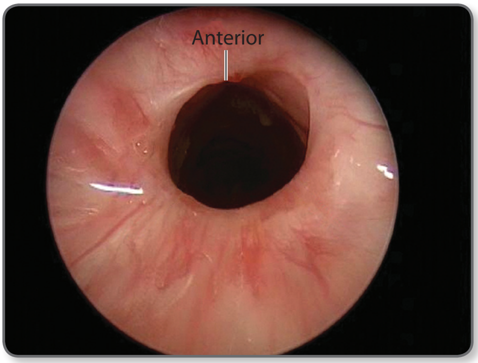

Figure 12.3 Typical radial incisions made in a 'Mercedes-Benz' configuration, shown as white lines on this grade 2 stenosis. To reduce the risk of tearing into the trachealis muscle or creating a tracheoesophageal fistula, no direct posterior incision is made.

into the trachealis muscle or creating a tracheoesophageal fistula, no direct posterior incision is made.

Steroid injection

Steroid injection may be a useful addition in cases of refractory stenosis, particularly when underlying inflammatory process is suspected. This combination has been beneficial in treating patients with Wegener's granulomatosis (granulomatosis with polyangiitis) who have subglottic stenosis (Hoffman et al. 2003) and is being used with increasing frequency in children. The authors prefer the use of triamcinolone (40 mg/mL) via an orotracheal injection device under telescopic visualization. Injection is best given prior to dilation, as dilation flattens the stenosis, making injection more difficult. Injection prior to dilation may also be preferable because the pressure from the balloon may distribute the steroid throughout the scar.

Stenting

In cases of postreconstruction stenosis that is refractory to dilation alone, the combination of balloon dilation and stenting may be useful. Dilation is performed to achieve an age-appropriate airway lumen. Immediately following, a cut T-tube or Hood stent is placed endoscopically in patients without a tracheostoma, whereas a suprastomal stent or T-tube is placed in patients with a tracheostoma (Guarisco & Yang 2013).

Fluoroscopy

Historically, the use of balloon dilation catheters in the airway often involved fluoroscopy to confirm balloon placement. With the refinement of endoscopic balloon dilation techniques, this measure is no longer necessary for lesions of the larynx and trachea, as it not only carries the risks of radiation in pediatric patients but is also associated with additional costs, equipment, and staffing needs. Although fluoroscopy remains in use for lesions of the bronchi and more distal airways, continuous improvements in flexible bronchoscopic technology have made it comparatively less desirable.

Balloons via flexible bronchoscopes

Although lesions as distal as the mainstem bronchi are easily visualized with rigid telescopes, more distal stenoses and stenoses in patients with difficult airway access are better reached with flexible bronchoscopes. Flexible bronchoscopes currently provide excellent image quality and a working channel that allows the passage of a balloon catheter or other flexible instruments. Before passing the flexible bronchoscope into the airway, the surgeon should ensure that the working channel is wide enough to pass the catheter easily. For reference, 2.8- and 3.5-mm flexible bronchoscopes provide a 1.2-mm working channel, and 4.9-mm flexible bronchoscopes provide a 2.0-mm working channel. The latter is usually adequate to pass a balloon catheter. The balloon catheter must also be sufficiently long to pass entirely through the working channel, as inflation with the balloon partially within the channel may damage the bronchoscope. When dilating the bronchi, the surgeon should choose a balloon with a diameter equal to the normal airway lumen rather than upsizing by 1–2 mm, as is done for the larynx and trachea. Consideration may be given to the use of a guidewire to facilitate balloon placement through the working channel and stenosis; however, this may increase the risk of perforation.

Complications

Negative pressure pulmonary edema

As discussed earlier in this chapter, respiratory effort against an occluded airway may result in NPPE. In the case of balloon dilation, this complication is most likely to occur with attempted inspiration while the balloon is dilated. However, NPPE may also occur in patients with severe stenosis after dilation is completed and the balloon removed. In patients with a tracheostoma and stenosis above the stoma, this complication is rarely seen, as the stoma prevents development of significant negative pressure.

The cardinal sign of this complication is the production of copious, frothy, pinkish secretions from the airway. Lung compliance is reduced, and oxygenation and ventilation are compromised. Management includes immediately deflating and removing the balloon and providing positive-pressure ventilation. Subsequent management is medical. The patient should be transported to an intensive care setting, mechanical ventilation instituted, and consideration given to diuretics, morphine, nitrates, and supplemental oxygen therapy.

Airway rupture

Mechanical injury to the airway from balloon dilation may include mucosal abrasions and lacerations as well as full-thickness rupture. Perforation may result from direct trauma from the tip of the balloon catheter during catheter placement or from radial force exerted during dilation. Direct trauma can be avoided by placing the balloon under laryngoscopic or telescopic visualization and not advancing it blindly if resistance is met. Rupture can be avoided through appropriate selection of balloon type, diameter, and inflation pressure.

Small ruptures may be asymptomatic and go undetected, whereas more significant ruptures perforations may become evident with the use of positive-pressure ventilation. Signs and symptoms may include dyspnea, crepitus, or subcutaneous air; diminished lung sounds in the case of associated pneumothorax; or hypotension and tachycardia with a large pneumothorax or pneumomediastinum. Posterior perforations may also result in tracheoesophageal or bronchoesophageal fistulae. Management includes endotracheal intubation beyond the level of the perforation, return to spontaneous (negative-pressure) ventilation as soon as possible, serial imaging, and placement of a chest tube if needed. A nasogastric tube may be useful in cases of tracheoesophageal fistula, although placement should be done under endoscopic visualization to avoid propagating the fistula. In many patients, nonoperative management is sufficient to allow healing of the perforation. However, in patients with more severe injuries or injuries that do not heal spontaneously, operative repair may be necessary.

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Airway obstruction

Airway obstruction may result from postdilation edema, a clot in the airway from dilation-related bleeding, or from actual detachment or fracture of the balloon catheter with retention of the balloon in the airway. In the setting of edema, if positive pressure cannot achieve ventilation, prompt introduction of a small endotracheal tube or rigid bronchoscope may be lifesaving. In the setting of a clot in the airway, suctioning with or without saline lavage may be useful. For a retained balloon, the surgeon should puncture the balloon with a sharp instrument and then withdraw the balloon using an endoscopic grasper. If the balloon is high in the airway, a large-bore needle may also be used to transcutaneously puncture and deflate the balloon.

Balloon displacement (‘watermelon seeding’)

If the balloon is not centered within the stenosis prior to inflation, it will tend to slide proximally or distally as it is inflated. This problem is more likely to occur with noncompliant balloons and balloons that have a large diameter. It is particularly apparent when the rounded ‘shoulders’ at the ends of the balloon are within the stenotic segment. The surgeon must resist the temptation to put traction or pressure on the catheter to hold it in place, as this maneuver may kink the catheter and impede balloon deflation. Rather, the balloon should be fully deflated, repositioned, and reinflated once it is centered on the narrowest portion of the stenosis. Nonslip balloons currently under development may reduce or obviate this problem.

Inadvertent airway lavage

Inadvertent introduction of inflation fluid through the noninflation port will result in the escape of that fluid from the distal end of the catheter, filling the lower airways. The same complication may occur if the balloon fails, releasing fluid into the airway. Inadvertent airway lavage is easily recognized by the introduction of inflation fluid with no resulting inflation of the balloon or rupture of the balloon. Both possibilities can easily be detected by using a telescope to visualize the balloon during inflation. Management includes removal of the balloon catheter and suctioning of the trachea and lower airways to clear the fluid. Dilation can usually be attempted after suctioning is completed.

Balloon failure

For the most part, balloon failure can be avoided by taking care not to inflate the balloon beyond its specified burst pressure. Placing the end of the illuminated telescope close to the balloon during endoscopy may result in heat transfer to the balloon, with weakening and failure of the balloon wall. Balloon failure may be recognized by a sudden loss of pressure on the inflation gauge or rapid deflation visible under the telescope. As described above, balloon failure may result in airway lavage, requiring suctioning and another attempt at dilation with a fresh balloon. In this clinical scenario, consideration should be given to using a larger balloon to allow dilation to a larger diameter at lower pressure. Unlike endotracheal tube or tracheostomy tube cuffs, balloon catheters should not be tested by inflation prior to insertion, as their shape may change when deflated again, making insertion difficult.

Conclusion

Balloon dilation is an invaluable tool for managing airway stenosis in children. Whether used adjunctively or as the sole approach to maintaining or improving airway patency, it enables the airway surgeon to endoscopically manage a wide spectrum of laryngotracheal lesions. Sequential dilations can be performed, and these do not preclude later open reconstructive procedures. Dilation may also be used as a bridge to open reconstruction in appropriately selected cases. It is important to note that it can influence endoluminal scarring but is not as effective for problems of the laryngotracheal exoskeleton. The overall success of this approach therefore rests on careful patient selection and the use of balloons that are appropriate in regard to both size and design.

Acknowledgment

The authors would like to thank Aliza P Cohen for her assistance in writing this chapter.

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