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INTRODUCTION

Posterior glottis stenosis (PGS) is a life-threatening condition that is often difficult to treat. The disease is characterized by severely hypomobile or completely immobile vocal folds resulting in compromise of the glottic airway and respiratory distress. PGS occurs most commonly as a result of injury from endotracheal intubation, although it may less commonly be caused by inflammatory conditions, autoimmune disease, radiation therapy, tumors, and laryngeal trauma. The incidence following intubation has been reported to be as high as 12% in patients intubated between 11 and 24 days. The mechanism of injury to the posterior glottis from endotracheal tubes has been well studied. The posterior displacement of the base of tongue, as well as the posterior angulation of the trachea, directs pressure to the posterior commissure as the endotracheal tube passes through the glottis into the upper airway. This region of the glottis consists primarily of a thin layer of mucosa overlying the cricoid lamina and arytenoid cartilages, making it particularly susceptible to injury. Mucosal ulceration within the posterior commissure leads to local inflammation and granulation tissue that can ultimately lead to fibrosis, scar contracture, and cricoarytenoid joint dysfunction characteristic of PGS.

Classification of PGS commonly follows the scheme proposed by Bogdansarian and Olson, with class I described as an interarytenoid synchiae, class II as posterior glottic scar with hypomobile arytenoids, class III as fixation of one arytenoid cartilage, and class IV as fixation of bilateral arytenoid cartilages. Factors influencing the severity of disease in PGS is an area of ongoing study. Using a canine model, the work of Courey et al. suggests that depth of mucosal injury is directly related to severity of resulting fibrosis. A recent multi-institutional study demonstrated that diabetes, ischemic states, duration of intubation, and large endotracheal tube size are independent risk factors for developing PGS following intubation injury. However, the time required for posterior commissure mucosal injury to progress to mature scar and cricoarytenoid joint fixation is not well described.

Mature PGS is a debilitating disease with few treatment options. Because the fibrotic process ultimately results in cricoarytenoid joint fixation, treatment options for late-stage PGS are limited, and restoration of vocal fold motion is unlikely. Standard surgical options include tracheostomy and/or destructive glottal enlargement.
procedures that inevitably result in sacrifice of vocal quality and swallowing safety. Rosen et al. recently investigated the value of early intervention with conservative balloon dilation to prevent progression to chronic PGS. All five patients in that study regained some degree of vocal fold mobility; four patients avoided tracheostomy altogether; and one patient was successfully decannulated without need for destructive laryngeal surgery. Early identification and prompt, conservative treatment may help preserve laryngeal function in this otherwise progressive, devastating disease of the glottic airway.

Currently available airway balloon dilators are round and optimally designed for treating subglottic and tracheal stenosis. Unlike these structures, however, the glottis is not round. In fact, the glottic aperture more closely approximates a teardrop in shape. In geometric terminology, this is called a circular sector. The capacity of round balloons to effectively dilate the posterior glottis is unclear. The authors hypothesize that round balloon dilators may subject the membranous vocal folds to a high degree of pressure while ineffectively applying pressure to the posterior commissure. The purpose of this study is to compare the amount of pressure placed on the anterior and posterior glottis during traditional balloon dilation and a novel, anatomically appropriate dilation technique in a three-dimensional (3D)-printed model.

MATERIALS AND METHODS

Image Acquisition

DICOM images of a previously acquired computed tomography (CT) of the cervical spine without contrast were retrospectively obtained. The scan was performed on a GE LightSpeed VCT 64 slice CT scanner (GE Healthcare, Milwaukee, WI) at 120 peak kilovoltage with automatic exposure control and a pitch of 0.97. The images were reconstructed in 1.25 mm axial sections using a soft tissue algorithm and 20% adaptive statistical iterative reconstruction algorithm (ASIR, GE Healthcare, Milwaukee, WI). The DICOM images were anonymized and exported from the picture archiving and communication system and sent to a secure DICOM receiver in the institutional 3D print lab.

Segmentation

The DICOM images were loaded into Mimics Medical v.20.0 (Materialise, Inc., Leuven, Belgium), where segmentation of the endoluminal surface of the larynx and trachea was performed by a threshold operation. Unwanted structures 1.5 cm above and below the glottis were manually deleted from the segmentation. A 3D model of the glottis was then computed and exported to 3-Matic Medical v.12.0 (Materialise, Inc.) CAD software, with which mesh optimization, smoothing, and mesh repair were performed. The larynx was aligned in the central portion of a 10-cm diameter disc, with the true vocal folds parallel to the upper surface and the laryngeal ventricle aligned axially along the upper surface of the solid disc (Fig. 1).

Three-Dimensional Printing

The stereolithography file was loaded into PreForm v.2.19 (FormLabs Inc., Cambridge, MA) and placed in an optimal configuration according to FormLabs guidelines. An axial print resolution of 0.1 mm was selected in white acrylic photosensitive resin (FormLabs Inc.). Support structures were automatically added to support the model during the printing process. The print file was then saved and sent to a Form2 SLA 3D printer (FormLabs Inc.). After print completion, the model was washed 99% Isopropyl alcohol and subsequently cured at 60°C for 60 minutes in an ultraviolet light-emitting CureBox (WickedEngineering, East Windsor, CT). The final printed model was 25 mm in anteroposterior length at the midline.

Dilation Testing

The 3D-printed laryngeal model was secured to the lab bench using C-clamps at multiple points of fixation. Ultralow profile force sensors (FlexiForce B201-L, Tekscan, South Boston, MA) were applied to the bilateral membranous vocal folds and the posterior commissure (Fig. 2). A series of dilations were carried out under...
two test conditions: In the first condition, standard round balloon airway dilators (CRE 10-11-12, 12-13.5-15, 15-16.5-18, and 18-19-20 mm Pulmonary Balloon Dilator; Boston Scientific, Marlborough, MA) were placed in the lumen of the model and inflated using the manufacturer’s included inflation device to achieve the goal diameter according to the manufacturer’s internal-pressure guidelines.

The balloon-only dilations were performed at 10, 13, 15, 18, and 20 mm. In the second condition, the novel dilation technique was used. Triangular metal Jackson laryngeal dilators (#507501, 18-32 French, Teleflex, Morrisville, NC) were placed at the anterior commissure, whereas the aforementioned dilation balloons were placed posteriorly and inflated (Fig. 3). The anteriorly placed triangular stent with posteriorly placed balloon was conceptualized to more optimally address the true configuration of the glottic aperture and is referred to as teardrop-shaped glottic dilation (TSGD).

Thirty unique combinations of balloon and metal dilator sizes were tested (Table I) and repeated in triplicate. Maximum force measured in newtons (N) applied to each force sensor was captured in real-time using a digital force data acquisition system (FlexiForce ELF system, Tekscan, South Boston, MA). Force measurements were imported and analyzed in a spreadsheet program (Excel 2011 v.14.5.6, Microsoft, Redmond, WA). The mean force for each combination of dilators across all trials was calculated. Comparison between groups was performed by 2-tailed Mann-Whitney U test.

**RESULTS**

During standard balloon dilation, mean force applied to the vocal folds (VF) ranged from 0 to 23.7 N, and mean force applied to the posterior commissure (PC) ranged from 0 to 3.9 N. During TSGD, mean force applied to the VF ranged from 0 to 51.4 N, and mean force applied to the PC ranged from 0 to 20.4 N. The mean force across all trials for each combination of dilators is depicted in Figure 4. The ratio of force applied to the posterior commissure compared to the vocal folds (ForcePC/ForceVF) is greater during TSGD compared to standard balloon dilation at every balloon size tested \( (P = 0.03) \). During TSGD, optimal targeting of the PC occurred when the sum of the anteroposterior (AP) dimensions of the metal and balloon dilators approached the AP length of the glottic model. Larger sized dilators resulted in excessive force placed on the VFs without increased force exerted on the PC.

**DISCUSSION**

Additive manufacturing techniques have been described for fabrication of laryngeal models for use in
surgical simulation and preoperative planning, as well as numerous other applications in the broader otolaryngology literature. This study is the first to objectively measure the force applied to the glottis during balloon dilation in a 3D-printed model. Furthermore, this article describes a novel, anatomically appropriate dilation technique that is conceptually designed to optimize dilatory force directed toward the posterior glottis to treat PGS. This was accomplished by placing a rigid triangular stent at the anterior commissure and inflating a round balloon dilator posteriorly, taking into account the teardrop shape of the glottis. The simulated dilation trials performed in this investigation demonstrated that, regardless of balloon size used, the novel dilation method resulted in a superior ratio of force applied to the posterior commissure compared to the vocal folds. Force applied to the posterior commissure was maximized once the combined diameters of the Jackson and balloon dilators reached the AP length of the glottic model. The authors hypothesize that, when the glottis is filled in the AP dimension, the triangular metal dilator is able to leverage off of the anterior commissure and direct dilatory force toward the posterior commissure. Interestingly, dilators larger than the total glottic diameter resulted in increased force applied to the vocal folds without concurrent increase in force at the posterior glottis. In this preliminary investigation, it appears that optimal posterior glottic dilation occurs when teardrop shaped dilators match the AP length of the glottis.

The findings are important for several reasons. The glottis is not round, and dilation strategies in the treatment of PGS should effectively target the posterior glottis while minimizing trauma to the sensitive membranous vocal fold tissue. Furthermore, new evidence suggests that early identification and prompt, conservative treatment with balloon dilation may help prevent early fibrosis within the posterior commissure from progressing to chronic PGS. Analogous findings have been reported in the treatment of tracheal and subglottic stenosis by Nouraei et al., who showed that earlier intervention with balloon dilation is associated with significantly fewer endoscopic treatments and avoidance of open surgical reconstruction. Therefore, there is significant potential value in developing optimized dilation techniques for addressing early PGS in hopes of preventing its debilitating chronic form.

In this study, only an adult male glottis was used in the dilation force testing. Although the female larynx is smaller in size, the overall glottic configuration is essentially identical to that of males. Although it is unlikely that use of a smaller larynx would substantially alter the ratio of force distribution in the anterior and posterior glottis, future investigations using this model may include adult female and pediatric source images. Additionally, our model was fabricated from solid acrylic resin that does not account for the pliability of the true vocal folds; thus, the lack of soft tissue representation is a limitation. The inability of the print material to yield to the dilating instruments is likely to overestimate the force that would actually be applied to the vocal folds in vivo. However, this effect would likely be the same regardless of dilation technique used, and the outcome of interest remains the ratio of force applied to the posterior glottis versus the vocal folds rather than absolute force values. The novel TSGD technique resulted in a superior force ratio compared to standard balloon dilation, irrespective of balloon size.

CONCLUSION

Use of a novel, anatomically appropriate dilation technique that targets the true shape of the glottis maximizes the ratio of force applied to the posterior commissure compared with the vocal folds. This study demonstrates that a novel teardrop-shaped dilation method maximizes dilation of the posterior glottis while minimizing potential trauma to the sensitive vocal fold tissue. This technique may play a
major role in treating early PGS and preventing laryngeal stenosis associated with chronic PGS.

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BIBLIOGRAPHY