The basic principle of the current static laryngoplasty procedure is to permanently affix the affected arytenoid in partial abduction. The “ideal” level of abduction should consider both of the major functions of the larynx: maintaining adequate airflow and deglutition. The most common postoperative complications can usually be attributed to over-abduction and upper airway contamination, or under-abduction and reduced airflow. There is currently no way to alter the level of abduction without having to perform a second revision laryngoplasty.

The dynamic laryngoplasty system (DLPS) has been developed with the overarching goal of being able to effectively alter the degree of arytenoid abduction postoperatively in horses. The ability to optimize arytenoid abduction may reduce the incidence of postoperative complications and maximize performance associated with a laryngoplasty procedure. The DLPS is composed of 2 polyether ether ketone (PEEK) discs with a central balloon that is incorporated into a standard laryngoplasty.

OBJECTIVE
Evaluate a prototype dynamic laryngoplasty system (DLPS) in horses; a feasibility study.

ANIMALS
7 healthy Standardbred adult horses.

METHODS
This was an in vivo experimental study. Horses had a standing surgical procedure to induce complete laryngeal hemiplegia, which was subsequently treated using the dynamic laryngoplasty system (DLPS). Activation of the DLPS was achieved using an injection port exiting through the skin (n = 2) or a subcutaneous injection port (n = 5). For each horse, endoscopic examinations of the upper respiratory tract were performed preoperatively, intraoperatively, and 7 days postoperatively. Left-to-right quotient ratios calculated during inactivated and activated states were obtained from still images of the rima glottidis acquired during day 7. In 3 horses, the device was intentionally overinflated to evaluate for device failure, and postmortem examinations were performed on day 7. For the remaining 4 horses, upper respiratory tract endoscopy was repeated at 1 month postoperatively, with no subsequent postmortem exam.

RESULTS
No perioperative complications occurred, and the DLPS was effectively delivered in all horses under standing sedation. The left-to-right quotient ratio at day 7 postoperatively could be altered from a resting position of 0.76 (± 0.06) to a maximum of 0.97 (± 0.06; P < .05). The degree of arytenoid abduction could not be significantly altered after 1 month of device implantation, suspected to be due to peri-implant fibrosis. No coughing nor tracheal contamination was observed at all time points or during inflation.

CLINICAL RELEVANCE
The ability to alter the degree of abduction at 7 days postoperatively with the DLPS may be beneficial in selective cases.

Keywords: equine, larynx, laryngeal hemiplegia, surgery, upper respiratory tract

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The discs sit between the 2 strands of the suture loop, and inflation of the central balloon allows functional shortening of the suture loop by displacing the suture strands outward, causing the suture loop to widen and shorten at the same time. By shortening the suture loop, the arytenoid is pulled back into greater abduction (Figure 1).

This developed prototype has been evaluated in vitro in 3 steps. The first step was mechanical testing of the device, demonstrating the device could cause an average of 7.1 mm of functional shortening of a suture loop (equivalent to 12% reduction in overall construct length) while under a static load likely to be seen in vivo of 10 N. The second step demonstrated an increased arytenoid abduction when the DLPS device was activated, with an increase in the left-to-right quotient angle ratio (LRQ) that was equivalent to 18.7 mm of shortening of the laryngoplasty suture loop. The final third step using a static airflow model demonstrated the device was able to significantly reduce translaryngeal impedance when the suture loop (Figure 2) was inflated, the suture loop around the balloon widens and shortens, resulting in arytenoid abduction.

Methods

All procedures performed on horses were approved by the IACUC (SVS/220/16). Seven university-owned Standardbred geldings aged between 4 and 10 years old were enrolled in this study. All horses’ larynges palpated normally, and an endoscopic examination at rest revealed normal laryngeal anatomy and function (Havemeyer grade 1 or 2.1) with no evidence of gross tracheal contamination.

Surgical procedure and postoperative care

All horses were restrained in stocks, sedated (using detomidine hydrochloride at 0.01 mg/kg, IV and butorphanol tartrate at 0.01 mg/kg, IV), and prepared for standing surgery. A video endoscope was placed via the right nostril and attached to the rope halter in a position to maintain the larynx in view throughout the procedure. Subsequently, an approach to the left side of the larynx was performed as previously reported for a standing laryngoplasty technique. In brief, a 10-cm-long subcutaneous (SC) line of local anesthetic was injected immediately ventral to the left linguofacial vein, and an incision was made along this line. A combination of sharp and blunt dissection ventral to the vein was performed to allow access to the left dorsolateral aspect of the larynx. At this point, the tendon of insertion of the left cricoarytenoideus (CAD) muscle was isolated and transected to induce complete left laryngeal hemiplegia, which was confirmed using the video endoscope. The DLPS was then placed as follows: using a trocar point half-circle needle, a single strand of No. 2 FiberWire suture was passed through the cricoid cartilage approximately 1.5 cm lateral to the midline and 1.5 cm from the caudal edge. For the arytenoid attachment, a FASTak II (AR-1524HF; Arthrex) suture anchor was placed in the muscular process of the arytenoid cartilage, 10-mm cranial to the insertion of the CAD muscle as described previously. The suture that was previously placed in the cricoid was then threaded through the eyelet of the anchor from medial to lateral creating a single suture loop. The balloon element of the DLPS was then placed in position between the resultant suture loop (Figure 1). The final placement of the DLPS was such that it was bordered by the muscular process of the arytenoid cartilage cranially, the caudal aspect of the cricoid cartilage caudally, the sagittal ridge of the cricoid dorsally, and the wing of the thyroid cartilage ventrally (Figure 2). At surgery, the suture loop was tied with the left arytenoid placed at an estimated LRQ of 0.7, equivalent to a Dixon grade 3 or slightly above resting position, when the DLPS was in an inactivated state. In the first 2 horses, the attached catheter was exited through a stab skin incision at the caudal aspect of the incision before routine closure in 3 layers. For the subsequent 5 horses, the DLPS was modified by adding a PEEK pillar in between the 2 PEEK discs, perpendicular to the suture direction, to prevent the sutures from prolapsing outward past the discs during balloon inflation. Additionally,
for these 5 horses, a catheter was tunneled SC and connected to an injection port (Vital-Port Titanium Vascular Access System; IP-S7110; Cook Medical) that was placed in an SC pocket via a 3-cm skin incision on the cranial lateral aspect of the neck (Figure 3). The catheters and the SC injection port were used to activate the DLPS by injection of saline into the exposed port or via a needle inserted transcutaneously. All horses received procaine penicillin (22,000 IU/kg, IM) twice a day, gentamicin (8.8 mg/kg, IV) once a day, and phenylbutazone (2.2 mg/kg, PO) once a day for 5 days postoperatively. Horses were fed soaked grass hay from the ground in a hospital box for the first 7 days and then turned out into a paddock for the remainder of the study.

Endoscopic examination of laryngeal function

Seven days postoperatively, the horses were restrained in stocks and an endoscopic examination of the larynx, and trachea was performed via the right nostril. Any gross evidence of tracheal contamination was noted as present or absent.

Whilst observing the larynx endoscopically, the DLPS was activated by injection of saline (range, 3 to 4 mL) to assess the range of arytenoid abduction attainable and during maximal right arytenoid abduction. Digital recordings were made of the endoscopic examination, and still images of the larynx were obtained pre- and postinflation at points of maximal left arytenoid abduction for measurement of the LRQ. In the first 3 horses, the DLPS was then intentionally overinflated with 6 mL of saline. Subsequently, these 3 horses were humanely euthanized via barbiturate overdose (pentobarbital sodium at 50 mg/kg, IV, bolus). The surgical sites were dissected to evaluate for any errors in device delivery (ie, if not located between the suture loop) or other types of failure (eg, anchor movement, balloon rupture, prolapse, or other construct failure).

For the remaining 4 horses, the devices were uninflated, and endoscopic examinations were repeated at 1 month postoperatively. Still images of the larynx were then obtained pre- and postinflation as previously described.

Left-to-right quotient angle ratio

Arytenoid LRQ was measured and calculated as previously described from each still image by an experienced observer (BJA) using ImageJ.6,7 In short, a digital image was acquired during maximal right arytenoid abduction obtained immediately after a stimulated swallow. A line was drawn from the ventral to the dorsal aspect of the rima glottidis and then extended by one-third to give a point that was used to measure the left and right arytenoid angles. The LRQ was then calculated by dividing the left arytenoid angle from the right arytenoid angle.

Data analysis

All data are reported as mean ± SD throughout unless otherwise stated. Data were checked for normality using a Shapiro-Wilks test. Data analysis was performed using commercial statistical software
AJVR

(GraphPad Prism). A paired t test was used to compare the LRQ pre- and postinflation at 7 days. Statistical significance was set at $P < .05$.

**Results**

All surgical procedures were completed without complications. All surgeries were less than 45 minutes in duration and did not require additional doses of sedation. The DLPS device was readily positioned without complication.

Postoperatively all horses were clinically normal with no evidence of excessive pain or swelling of the surgical site and maintained a normal appetite for the duration of the study. During the postoperative period, no coughing or nasal discharge was noted. Routine wound management was required for the 2 cases with catheters exiting the skin, with mild serous drainage being cleaned daily. The SC portal in the remaining 5 horses was visible and easily palpated. Injection into the portal was easily performed with routine restraint. The LRQ at day 7 postoperatively could be varied from a mean resting position of 0.76 ($\pm$ 0.06) to a maximum of 0.97 ($\pm$ 0.06) as the balloon was inflated with 3 to 4 mL of saline (Figures 4 and 5; Supplementary Figure S1). There was a significant difference between pre- and postinflation LRQ at day 7 ($P < .05$). Endoscopic examinations of the trachea revealed no gross contamination or evidence of food aspiration in any of the horses.

Intentional overinflation of the balloon using 6 mL of saline caused a sudden loss of abduction in the first 2 horses. This loss of abduction did not occur in the third horse, and in this horse, additional injections of saline caused no apparent effect on the

**Figure 4**—Endoscopic images of the 7 horses (top to bottom) at day 7 postoperatively preinflation (A) and postinflation (B) of the dynamic laryngoplasty system in each horse, respectively. Note that these images were selected to best demonstrate the effect of the activated dynamic laryngoplasty system on arytenoid abduction. These were not the images used to calculate the left-to-right quotient ratio, which would be obtained with the right arytenoid in maximal abduction after a swallow.

**Figure 5**—Mean left-to-right quotient ratio (LRQ; ± SD) at 7 days postoperatively, pre- and postinflation of the dynamic laryngoplasty system.
observed maximal arytenoid abduction. When the saline was removed, after overinflation, the arytenoid returned to the resting position.

At postmortem, for the first 2 horses, the device was displaced from the suture loop and sitting immediately adjacent and dorsal to the suture loop. The balloons were intact, and the DLPS unit was functional but out of position. For the third horse, the DLPS was in place, and activation of the device caused changes in arytenoid abduction as expected. Overall, the remainder of the construct (suture loop and anchor) was in place without evidence of failure in all 3 horses. There was a smooth lined tissue space at the surgical site with a small amount of serous fluid that would be expected at 7 days post-operatively. For the remaining 4 horses, a 1-month follow-up endoscopy showed minimal left arytenoid movement when the device was inflated and no true appreciable increase in the LRQ was possible.

**Discussion**

We aimed to evaluate the feasibility of delivering a prototype DLPS in standing horses that was able to selectively alter arytenoid abduction. Based on the results from this limited number of horses, we partially supported our first hypotheses in that the prototype DLPS allowed for effective controllable alteration in arytenoid abduction at 7 days post-operatively but not at 1 month. Regarding our second hypothesis, no postoperative complications were identified in any of the horses related to the surgical site throughout the study. Intentional overinflation of the device in the first 2 horses led to displacement of the suture, leading to a failure to abduct the arytenoid cartilage on subsequent attempts. A postmortem examination found the DLPS was not in the correct position between the suture loop (displaced), which prompted a minor device modification for the third horse to prevent this displacement of the suture loop from occurring. As a result of this modification and despite intentional overinflation, the third device was in the correct position and able to cause changes in arytenoid abduction. The balloon and PEEK components remained intact in all cases.

The basic premise of a traditional laryngoplasty is to affix the arytenoid to a predetermined position by utilizing a prosthetic material to replace the compromised CAD muscle. Alternative surgical treatment options for recurrent laryngeal neuropathy include ventriculotomy and ventriculocordectomy, partial arytenoidectomy, and reinnervation of the cricoarytenoideus dorsalis muscle. However, neither ventriculotomy and ventriculocordectomy nor partial arytenoidectomy improve airflow dynamics as significantly as a prosthetic laryngoplasty. Reinnervation procedures aim to restore physiological function of the CAD muscle and avoid postoperative complications like coughing and dysphagia associated with a laryngoplasty. However, evidence of successful reinnervation can take 4 to 12 months, which may not be a logistically feasible option for the majority of Thoroughbred racehorses with a relatively short athletic career. In comparison, horses undergoing a prosthetic laryngoplasty can resume normal training within 2 to 3 months. Additionally, reinnervation is not suitable for horses diagnosed with complete paralysis. Therefore, the current static prosthetic laryngoplasty remains the treatment of choice for the majority of cases despite the list of potential complications.

Over the years, there have been numerous variations in the standard static laryngoplasty techniques (eg, suture type, suture position and configuration, suture number, and method of anchorage on the muscular process, methods to promote fusion of the cricoarytenoid joint). Reported success rates are highly variable, especially for high-level athletes performing at maximal speeds where outcomes are moderate at best, and no single technique has been universally adopted as the gold standard. Clearly, there is significant scope for improvement and many of the complications associated with the procedure are either due to over- or under-abduction of the permanently affixed arytenoid.

Coughing is the most common complication following a laryngoplasty, with reported incidence rates of up to 57% of cases. In particular, over-abduction of the arytenoid can lead to tracheal contamination and subsequent coughing, although this is not always a direct linear relationship. Other causes of postoperative coughing with or without dysphagia include development of perilaryngeal adhesions, perilaryngeal inflammation and seroma formation, excessive retraction during surgery, laryngeal fistula formation, tracheal inflammation, damage to the periesophageal adventitia and the muscles, or innervation of the larynx, proximal oesophagus, or caudal pharynx. The ability to alter the level of arytenoid abduction postoperatively with a device such as the developed DLPS may help to optimize the degree of abduction to reduce the incidence of postoperative complications and maximize performance.

The intraoperative target abduction varies depending on the study and discipline of the horse and has been reported to be between 90% and 90% degree of abduction, or more specifically, a Dixon grade 2 in racehorses (ie, 80% to 90% abduction) and Dixon grade 3 in sport horses and draft horses (ie, slightly above resting position). A computational model identified that a surgical target of 88% abduction of the maximal cross-sectional area of the rima glottidis (equivalent to a Dixon grade 2) is the most appropriate for restoring airflow. However, the “optimal” degree of abduction that balances both improved airflow dynamics and the ability to obtain normal laryngeal closure during swallowing is likely highly variable and often needs to be determined on a case-by-case basis. When excessive abduction is present with concurrent coughing and dysphagia, revision surgery to remove, loosen, or replace the prothesis is often recommended. Depending on the timing of the second surgery, the formation of fibrous adhesions may distort normal anatomical landmarks, making it hard to place the prosthesis accurately and
requiring extensive dissection, which may increase the risk of seroma formation. Therefore, having a dynamic prosthesis may allow the surgeon to fine-tune the degree of arytenoid abduction within the early postoperative days to a position that the horse can tolerate with minimal coughing.

Postoperative loss of abduction is also a common occurrence with a loss of at least 1 grade of abduction often seen in the first 1 to 6 weeks after surgery. Suboptimal abduction leads to decreased cross-sectional area of the rima glottidis with subsequent increase in negative collapsing pressure across the larynx and may result in poor athletic performance. This can induce dynamic collapse of other unsupported soft tissue structures such as the aryepiglottic folds, vocal folds, and nasopharyngeal walls. Note that secondary fibrosis at the surgical site will most likely preclude the ability to alter the degree of abduction in the long term; however, the initial loss of abduction most commonly occurs within the first 7 days after static laryngoplasty.

Delivery of the DLPS in vivo during a standing procedure was readily achieved in this pilot study, but it could be performed under general anesthesia at the surgeon's discretion. Surgical familiarity with the DLPS and technique is essential before attempting effective delivery. Standing laryngoplasty allowed for a more accurate intraoperative assessment of the degree of abduction, better exposure of the surgical landmarks (ie, muscular process and cricoid cartilage), and placement of sutures in the correct position.

Mechanical in vitro evaluation using limited cyclical and ramp-to-failure testing was performed on the DLPS construct (ie, PEEK discs, balloon, and sutures) leading up to this in vivo pilot study. The DLPS system was able to withstand 1,800 cycles without failure with an average minimum and maximum load of 9.82 and 15.4 N, respectively. The average stiffness of 9 out of 10 constructs that were tested was 11.35 N/mm when loaded to 100 N without failure. Note that the constructs were ramped to failure or up to 100 N load (due to load cell restrictions), whichever occurred first. Only 1 construct failed at 38.6 N due to the balloon pinching against the DLPS and rupturing, which has since been resolved by smoothing the PEEK discs. Based on a previous in vivo study, laryngoplasty sutures are subject to a mean increased loading of 1,152 cycles over a 24-hour rest period with a peak load reported to be 46.6 N during swallowing. Thus, further research on whether the DLPS construct can withstand long-term cyclical loading at physiologically relevant in vivo loads is warranted.

PEEK is an organic, thermoplastic polymer that is commonly used in medical devices such as nonmetallic surgical implants due to the fact that it is biocompatible, easily manufactured via 3-D printing software, has a high strength-to-weight ratio, and is impervious to moisture and degradation. The biocompatible nature of PEEK means it is not toxic to cells or tissue, and no adverse immune reactions have been reported upon implantation. In previous prototype evaluations, 4 other thermoplastic materials that have been used for medical implants were tested but were either too easily deformed and unable to constrain the balloon (nylon, avyonitrile butadiene styrene, and polylactic acid) or too brittle such that the pillars between the discs would break with balloon inflation (Polymax PLA). Unlike the other prototypes, the PEEK material was considerably stronger and stiffer and thus most suited to this application. The second component, the catheter and injection port (used in the last 5 horses), is an SC portal system already used routinely in human medicine. These components have proven to be very robust for use as a delivery system for IP chemotherapy in human medicine. On the other hand, the final balloon component, while used in medical settings in an indwelling location, is the relative point of weakness in the DLPS prototype due to the cyclical functionality required (ie, repeated cycles of inflation and deflation while being constrained between the 2 PEEK discs). This component will warrant evaluation regarding longer term in vivo performance as it has not been used previously in a similar setting that we are aware of.

At postmortem, the DLPS in the first 2 horses had been displaced from between the suture loops by intentional overinflation of the balloon. This was done in an effort to determine if the balloon would rupture or how the device would fail. At postmortem, the overinflated balloon could be seen to have caused the suture loop to displace from its intended location between the PEEK discs, which restrained the direction of balloon inflation. As such, for the third horse, the PEEK element of the DLPS had a pillar of PEEK added at both peripheries of the device at 180° to each other and perpendicular to the suture loop to prevent the suture from displacing from within the confines of the device. At postmortem, this device was still in location and functioning. This modification to prevent overinflation was used in the final 5 horses.

How the DLPS will perform in an exercising pressurized larynx is unknown at this time. An in vitro evaluation of the DLPS using a static airflow model showed that the DLPS could achieve an increase in and maintain arytenoid abduction that resulted in a significant reduction in translaryngeal impedance during airflow of 55 L/s. As a result of the previous in vitro evaluations and this in vivo proof-of-concept pilot, the DLPS may warrant further investigation or consideration as a means to alter the degree of postoperative abduction during exercise in vivo. This may be performed in conjunction with a cricoarytenoideus joint debridement to facilitate joint fusion in the optimal position.

This was a pilot study and clearly has the limitations of having only a small number of horses and a short survival period. Additionally, the model of this study suggests that the device is well tolerated and allows for variable adjustment of arytenoid positioning in 7 days postoperatively but not at 1 month. The failure to alter abduction at 1 month is hypothesized to be due to perilaryngeal fibrosis as some
movement was visible in all 5 cases, suggesting the device was functional but unable to overcome the fibrosis restricting free arytenoid movement. Future modifications of the device may involve a biologically inert sheath that envelopes the balloon or topical antifibrotics such as mitomycin C and caffeic acid phenethyl ester. Alternatively, periodic inflation of the device in the postoperative period may reduce the level of fibrosis that occurs to allow modification of the degree of arytenoid abduction for a longer period of time.

In summary, the primary goals of a prosthetic laryngoplasty are to maximize the rima glottidis area and stabilize the arytenoid cartilage, without compromising the protective mechanisms of the upper airway. Thus, the ability to modify the degree of arytenoid abduction for a longer period of time.

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References


**Supplementary Materials**

Supplementary materials are posted online at the journal website: avmajournals.avma.org