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Evaluation of partial arytenoidectomy as a treatment for equine laryngeal hemiplegia

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Abbreviations used in paper and not given in legend of Table 1:

ARYT = arytenoidectomy with bilateral ventriculectomy; **HR** = heart rate; **LLH** = left laryngeal hemiplegia; **LRLN** = left recurrent laryngeal neurectomy; **TBFVL** = tidal breathing flow-volume loop.

Summary

The efficacy of partial arytenoidectomy was assessed in 6 Standardbred horses, with surgically induced laryngeal hemiplegia, at rest (Period A) and during exercise at speeds corresponding to maximum heart rate (Period C) and 75% of maximum heart rate (Period B). Peak expiratory and inspiratory airflow rate (PEF and PIF), and expiratory and inspiratory transupper airway pressure (P_{UE} and P_{UI}) were measured and expiratory and inspiratory impedance (Z_E and Z_I) were calculated. Simultaneously, tidal breathing flow-volume loops (TBFVL) were acquired using a respiratory function computer. Indices derived from TBFVL included airflow rates at 50 and 25% of tidal volume (EF_{50}, IF_{50}, EF_{25}, and IF_{25}) and the ratios of expiratory to inspiratory flows. Measurements were made before left recurrent laryngeal neurectomy (baseline), 2 weeks after left recurrent laryngeal neurectomy (LRLN) and 16 weeks after left partial arytenoidectomy coupled with bilateral ventriculectomy (ARYT).

After LRLN, during exercise Periods B and C, Z_I and the ratio of EF_{50}/IF_{50} significantly increased and PIF, IF_{50} and IF_{25} significantly decreased from baseline values. At 16 weeks after ARYT, Z_I returned to baseline values during Periods B and C. Although PIF, IF_{50}, IF_{25}, PEF/PIF, and EF_{50}/IF_{50} returned to baseline values during Period B, these indices remained significantly different from baseline measurements during Period C. After ARYT, TBFVL shapes from horses during Period C approached that seen at the baseline evaluation.

Partial arytenoidectomy improved upper airway function in exercising horses with surgically induced left laryngeal hemiplegia, although qualitative and quantitative evaluation of TBFVLs suggested that some flow limitation remains at near maximal airflow rates. These results indicate that, although the procedure does not completely restore the upper airway to normal, partial arytenoidectomy is a viable treatment option for failed laryngoplasty and arytenoid chondropathy in the horse.

Introduction

Partial arytenoidectomy, the removal of the arytenoid and corniculate cartilages while leaving the muscular process *in situ*, was first introduced as a treatment for left laryngeal hemiplegia (LLH) in 1845 (Liautard 1892). This procedure was considered unsatisfactory because it was associated with a high rate of post-operative complications. With the development of the ventriculectomy (Williams 1911) and later prosthetic laryngoplasty (Marks *et al.* 1970), the low morbidity and mortality of these procedures obviated the use of arytenoidectomy as a treatment for LLH. Subtotal arytenoidectomy, the removal of the arytenoid body leaving the muscular process and corniculate cartilage intact, and partial arytenoidectomy have been recommended as treatments for arytenoid chondropathy (Haynes *et al.* 1980; Tulleners *et al.* 1988), arytenoid malformations and failed prosthetic laryngoplasty (White and Blackwell 1980; Haynes *et al.* 1984). The merits of these two techniques have been evaluated subjectively based on assessment of performance and post-operative complications (Haynes *et al.* 1984; Speirs 1986; Tulleners *et al.* 1988).

In 1990, Belknap *et al.* quantitatively evaluated subtotal arytenoidectomy and demonstrated that subtotal arytenoidectomy failed to improve upper airway function in horses with surgically induced LLH exercising submaximally. To date, there has been no objective evaluation of the efficacy of partial arytenoidectomy.

Upper airway function in exercising horses has been quantitated by measurement of transupper airway pressure and airflow, and calculation of inspiratory and expiratory impedance (Derksen *et al.* 1986). Analysis of tidal breathing flow-volume loops (TBFVL) is a useful, sensitive, convenient and non-invasive technique for quantitation of upper airway obstruction in exercising horses (Lumsden *et al.* 1993). In the present study, the effect of partial arytenoidectomy on upper airway function was evaluated by TBFVL analysis, measurement of upper airway impedance and videoendoscopic examination of the larynx in strenuously exercising horses with surgically induced LLH.

Materials and methods

Experiments were approved by the All-University Committee for Animal Use and Care at Michigan State University.

Horses: Six adult Standardbred horses (3 geldings, 3 mares), 5.2 ± 2.0 (mean ± sd; range 3–8) years of age and weighing 437.8 ± 40.2 kg (range 390.0–490.0), were maintained at pasture for at least 30 days before experiments. Animals were treated with anthelmintics and vaccinated against tetanus, equine influenza and rhinopneumonitis. Before measurements or surgical procedures,

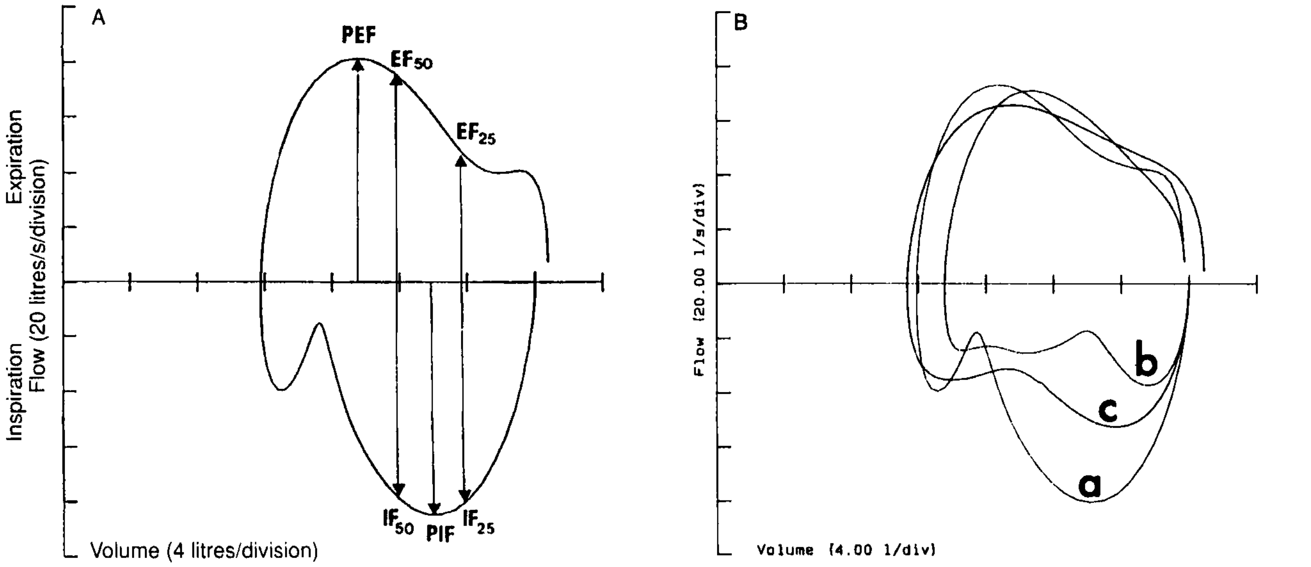

Fig 1: TBFVLs from (A) a horse exercising at maximal heart rate (Period C) before LRLN (baseline). The flow measurements used to calculate TBFVL indices are shown; and (B) a horse at baseline (a), after LRLN (b), and following partial arytenoidectomy and bilateral ventriculectomy (c). TBFVLs were generated at a speed corresponding to maximal heart rate.

clinical examination and endoscopic evaluation of the upper airway showed no abnormalities when horses were at rest. Wearing a face mask, animals were trained on a treadmill over a 3-day period before the start of the study. Between surgical procedures and measurement protocols horses were kept at pasture.

Measurement techniques: Airflow rates, tidal volume and transupper airway pressure were recorded as described by Shappell *et al.* (1988). Briefly, horses wore a mask to which was attached a pneumotachograph (Merriam Instruments, Grand Rapids, MI, USA). The mask covered both mouth and nostrils and allowed complete nostril dilation. The combined resistance of mask and pneumotachograph was 0.05 cmH_2O/litre/sec up to an airflow of 90 litres/sec. Pressure changes across the pneumotachograph were measured by a differential pressure transducer (Model DP45-22, Validyne Sales, Northridge, CA, USA) which produced a signal proportional to flow. The flow signal from the pressure transducer was fed into a respiratory function computer (Buxco LS-14, Buxco Electronics, Inc., Sharon, CT, USA) that digitally integrated flow with respect to time to give tidal volume (V_T).

Tracheal pressure was measured via a lateral tracheal catheter placed percutaneously at the mid-cervical level. Inspiratory and expiratory transupper airway pressure (P_{UI} and P_{UE}) were measured as the pressure difference between tracheal and mask pressure. Inspiratory and expiratory impedance (Z_I and Z_E) were calculated as the ratio of peak inspiratory and expiratory transupper airway pressure (P_{UI} and P_{UE}) and peak inspiratory and expiratory airflow (PIF and PEF) over 10 consecutive breaths. Minute ventilation ($\dot{V}_E$) was calculated as the product of respiratory rate (f) and V_T. Heart rate (HR) was recorded using a telemetry system (Digital UHF Telemetry System, M1403A, Hewlett Packard, Palo Alto, CA, USA).

In addition to measurements of airway impedance, TBFVL were constructed from 10 breaths out of each exercise period and were analysed using computer software (Buxco LS-14). The criteria for TBFVL selection were reported by Lumsden *et al.* (1993). The shape of the TBFVL was qualitatively evaluated. Measurements from TBFVL included f, V_T, inspiratory and expiratory time (T_I and T_E), total breath time (T_{TOT}), T_I/T_E, V_T/T_I, T_I/T_{TOT}, PIF and PEF, flow rates at 50% and 25% of tidal volume (IF_{50}, EF50, EF_{25} and IF_{25}) and ratios of these flow rates (Fig 1A).

Experimental design: Before upper airway function tests, maximum heart rate (HR_{max}) during exercise was determined by a single rapid incremental exercise test (Lumsden *et al.* 1993). From this information, the treadmill speeds at which HR_{max} and 75% of maximum heart rate ($HR_{0.75max}$) occurred were estimated.

All data were recorded during the last minute of each 2-min measurement period. Measurements were made while horses were at rest, standing next to the treadmill (Period A). Horses were then exercised on the treadmill with a 3-degree incline at 4 m/sec for 2 min, then at the treadmill speed corresponding to $HR_{0.75max}$ for 2 min (Period B). Horses rested for 1 min and then exercised at a treadmill speed corresponding to HR_{max} (Period C) for 2 min.

Measurements obtained before left recurrent laryngeal neurectomy (LRLN) (baseline) and 2 weeks after LRLN were reported in an earlier study designed to evaluate the usefulness of TBFVL indices for detection of upper airway obstruction (Lumsden *et al.* 1993). At 16 weeks after left partial arytenoidectomy and bilateral ventriculectomy (ARYT), horses underwent the same measurement protocol as for baseline and LRLN measurements. The day after measurement of upper airway function, the larynx was examined using videoendoscopy at rest and during exercise at HR_{max}.

Surgical procedures: Laryngeal hemiplegia was created by transection of the left recurrent laryngeal nerve (Derksen *et al.* 1986). Left partial arytenoidectomy was performed as follows. Anaesthesia was induced with guiafenesin (Aceto Chemical Co, Flushing, NY, USA) and thiamylal (Biotal, Bioceutic Division, Boehringer Ingelheim Animal Health Inc, St Joseph, MO, USA). The animals were intubated via a mid-cervical tracheotomy and anaesthesia was maintained with halothane (Fluothane, Ayerst Laboratories Inc, New York, NY, USA) in oxygen. Partial arytenoidectomy was performed as described by McIlwraith and Turner (1987), except that the corniculate cartilage and its mucosa were removed *en bloc*, and a bilateral ventriculectomy was performed. Via a ventral laryngotomy a fibreoptic retractor (Shea fibreoptic retractor, Stryker Corp, Kalamazoo, MI, USA) was used to illuminate the lumen of the larynx. The mucosa was incised, beginning at the ventral aspect of the junction of the corniculate and arytenoid cartilages and extending caudal along the ventral border of the arytenoid cartilage. This incision was continued along two-thirds of the caudal border of the arytenoid

TABLE 1: Effect of surgery on measured and calculated variables from 6 horses with surgically induced left laryngeal hemiplegia before (pre-operative) and after (post-operative) left partial arytenoidectomy and bilateral ventriculectomy

Variable	Exercise period	Baseline‡	Pre-operative‡	Post-operative‡
$\dot{V}_E$ (litres/min)	A	151.41 ± 15.01	140.75 ± 7.69	138.40 ± 12.12
	B	950.23 ± 59.02	808.40 ± 68.29	963.80 ± 39.60
	C	1,295.97 ± 127.52	1,027.60 ± 71.17*	1178.50 ± 38.58
P_{UI} (cmH_2O)	A	1.94 ± 0.22	2.16 ± 0.32	1.87 ± 0.23
	B	22.29 ± 1.15	49.40 ± 4.08*	26.12 ± 3.20†
	C	38.57 ± 3.93	62.73 ± 6.70*	39.99 ± 4.39†
PIF (litres/sec)	A	5.09 ± 0.34	5.84 ± 0.39	6.49 ± 0.55
	B	51.19 ± 4.05	36.58 ± 2.74*	43.28 ± 1.82
	C	75.52 ± 9.35	40.87 ± 3.23*	50.09 ± 2.16*
Z_I (cmH_2O/l/sec)	A	0.39 ± 0.03	0.38 ± 0.06	0.30 ± 0.04
	B	0.46 ± 0.06	1.41 ± 0.20*	0.62 ± 0.10†
	C	0.53 ± 0.04	1.63 ± 0.28*	0.81 ± 0.10†
IF_{50} (litres/sec)	A	5.24 ± 0.31	4.84 ± 0.18	5.82 ± 0.31
	B	39.86 ± 4.08	23.77 ± 1.61*	37.87 ± 1.95
	C	65.98 ± 8.47	24.09 ± 1.03*	36.24 ± 1.30*
IF_{25} (litrres/sec)	A	6.17 ± 0.56	5.17 ± 0.38	5.90 ± 0.31
	B	49.77 ± 2.70	34.34 ± 2.14*	42.03 ± 1.92
	C	70.78 ± 5.04	35.53 ± 1.64*	47.89 ± 2.17*
PEF/PIF	A	1.33 ± 0.07	1.35 ± 0.10	1.25 ± 0.07
	B	1.13 ± 0.06	1.58 ± 0.05*	1.19 ± 0.02*†
	C	0.97 ± 0.07	1.70 ± 0.03*	1.36 ± 0.02†
EF_{50}/IF_{50}	A	1.25 ± 0.11	1.11 ± 0.15	1.13 ± 0.12
	B	1.19 ± 0.11	2.15 ± 0.12*	1.27 ± 0.02†
	C	1.08 ± 0.07	2.56 ± 0.04*	1.72 ± 0.08*†
T_E/T_I	A	0.99 ± 0.05	0.97 ± 0.05	0.95 ± 0.06
	B	0.94 ± 0.03	0.70 ± 0.02*	0.83 ± 0.01
	C	0.98 ± 0.05	0.65 ± 0.01*	0.73 ± 0.01*
T_I/T_{TOT}	A	0.51 ± 0.01	0.52 ± 0.01	0.52 ± 0.02
	B	0.51 ± 0.01	0.59 ± 0.01*	0.55 ± 0.004
	C	0.51 ± 0.01	0.61 ± 0.01*	0.58 ± 0.004*
V_T/T_I	A	4.84 ± 0.34	4.40 ± 0.14	5.19 ± 0.27
	B	31.77 ± 2.08	23.87 ± 1.70*	29.98 ± 1.03
	C	44.78 ± 5.03	25.70 ± 1.02*	34.47 ± 1.38*

*Data significantly ($P<0.05$) different from baseline (before left recurrent laryngeal neurectomy) measurement at same speed.
†Data significantly different from pre-operative measurement at same speed.
‡Values represent mean and sem.
V_T = tidal volume, $\dot{V}_E$ = minute ventilation, P_{UI} = peak inspiratory pressure, PEF = peak expiratory flow, PIF = peak inspiratory flow, IF_{50} = inspiratory flow at 50% of V_T, IF_{25} = inspiratory flow at 25% of V_T, T_E = expiratory time, T_I = inspiratory time, T_{TOT} = total breath time, Z_I = inspiratory impedance.

cartilage. The cranial aspect of the incision was extended along the entire junction of the corniculate and arytenoid cartilages. The laryngeal mucosa was elevated from the luminal side of the arytenoid cartilage using a blunt Asheim knife. A separate incision was then made extending from the left laryngeal ventricle dorsally along the rostral border of the corniculate cartilage. The arytenoid and corniculate cartilages were separated. The corniculate cartilage and attached luminal mucosa were removed *en bloc*, after dissecting the laryngeal musculature from its lateral aspect. The body of the arytenoid cartilage was similarly dissected from its lateral musculature and transected from its muscular process and removed, leaving the muscular process and intact luminal mucosa. Bilateral ventriculectomy was performed, and all free mucosal edges were apposed with 2-0 polydioxanone (PDS, Ethicon Inc, Somerville, NJ, USA) in a simple continuous pattern. Horses were treated pre-operatively and post-operatively with procaine penicillin (Procaine penicillin G, Pfizer Inc, New York, NY, USA) (10,000 IU/kg im, twice/day for 5 days), and phenylbutazone (Butazolidin paste, Coopers Animal Health Inc, Kansas City, MO, USA) (3 mg/kg po, twice/day for 5 days). Food was withheld for 48 h after surgery and tracheotomy tubes (Dyson self-retaining tracheal tubes, Coopers Animal Health Inc, Mishawaka, IN, USA) were removed after endoscopic confirmation of an adequate airway at 24 h. The larynx of each horse was endoscopically examined at rest 1, 4, 8 and 16 weeks post-operatively.

Statistical analysis: A 3-way analysis of variance was used to determine the effect of exercise and surgical treatment according to the model Yijk = Ai + Bj + ABij +_ Ck = ACik + BCjk + error (Gill 1978); where Ai was the fixed effect of exercise (3 levels), Bj was the fixed effect of surgical procedure (2 levels), and Ck was the random effect of 6 horses. When F values were significant at $P<0.05$, treatment means were compared by use of Tukey's test.

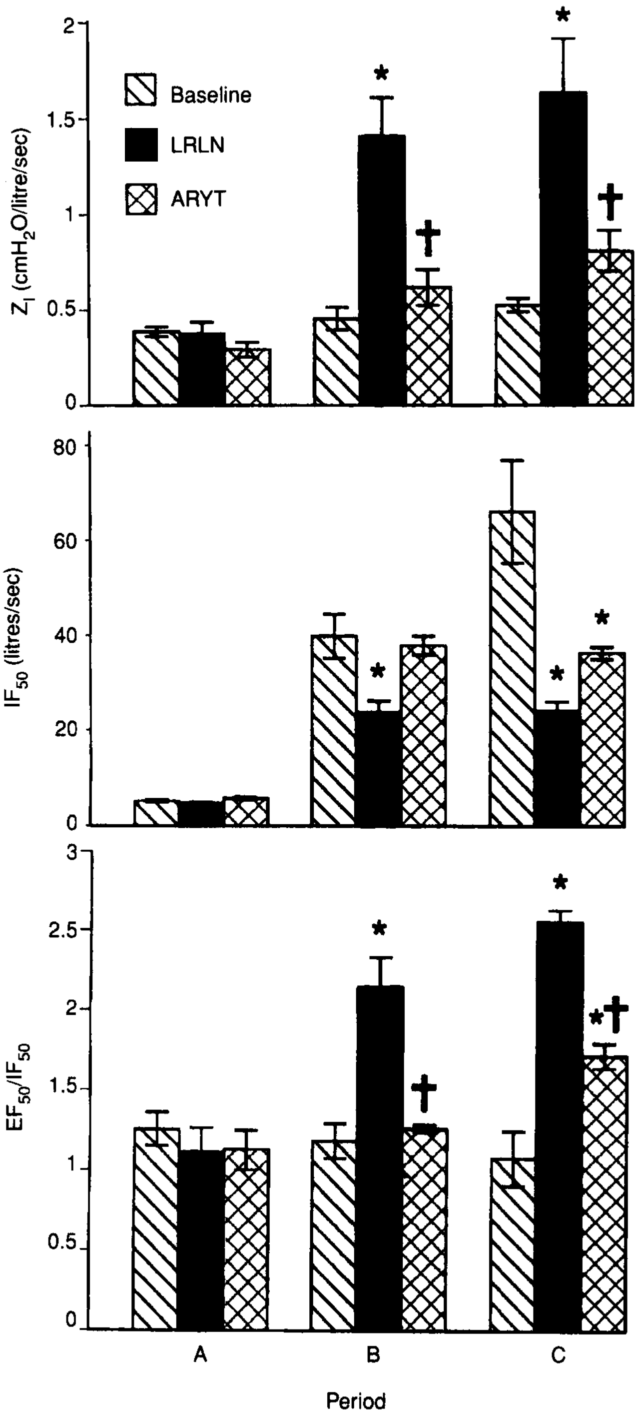

*Fig 2: Peak inspiratory impedance (Z_I), inspiratory flow at mid-tidal volume (IF_{50}) and expiratory/inspiratory flow ratio at mid-tidal volume (EF_{50}/IF_{50}) before and after LRLN, and after partial arytenoidectomy at rest (Period A) and during moderate (Period B) and strenuous (Period C) exercise. Baseline = before LRLN; LRLN = 2 weeks after LRLN; ARYT = 16 weeks after partial arytenoidectomy *Value significantly different from baseline measurement at same speed ($P<0.05$). †Value significantly different from LRLN measurement at same speed ($P<0.05$).*

Results

The mean ± sem HR_{max} and $HR_{0.75max}$ averaged 225.5 ± 4.92 and 166.8 ± 3.9 beats/min at treadmill speeds of 11.0 ± 0.2 and 6.2 ± 0.7 m/sec, respectively. The effect of exercise on all physiological parameters was previously reported (Lumsden *et al.* 1993).

The flattened shape of the inspiratory flow curve of the TBFVL observed after LRLN (b) was altered after partial arytenoidectomy (c), to a shape that approached the inspiratory flow curve (a) generated at baseline evaluation (Fig 1B).

The effects of LRLN on the indices of upper airway function included: significant increases in P_{UI} and Z_I, and decreases in PIF (Table 1; Fig 2), with no significant change in PEF, P_{UE}, or Z_E at Periods B and C. After LRLN, at Period C, $\dot{V}_E$, and at Periods B and C, IF_{50}, IF_{25}, T_E/T_I and V_T/T_I significantly decreased, and PEF/PIF, EF_{50}/IF_{50}, T_I/T_{TOT} significantly increased compared to baseline values at the same exercise period (Table 1; Fig 2).

At 16 weeks after partial arytenoidectomy and bilateral ventriculectomy, P_{UI} and Z_I were not significantly different from baseline values during Periods B and C (Table 1; Fig 2). Furthermore, all indices describing TBFVL returned to baseline (pre-LRLN) values at Period B (Table 1; Fig 2). However, PIF, IF_{50}, IF_{25}, PEF/PIF, EF_{50}/IF_{50}, T_E/T_I, T_I/T_{TOT}, V_T/T_I and f remained significantly different from the baseline value at Period C (Table 1; Fig 2).

In all horses, left laryngeal hemiplegia was confirmed using videoendoscopic evaluation of the larynx at rest and during exercise. After partial arytenoidectomy and bilateral ventriculectomy, no post-operative complications were encountered other than minor dehiscence of the sutured mucosa in 2 horses. Neither dysphagia nor coughing were observed. At 16 weeks post-operatively, endoscopic examination showed complete mucosal healing and the right corniculate cartilage appeared rotated towards the left side in all horses at rest and during exercise. Videoendoscopy during exercise at HR_{max} revealed an apparently adequate airway in all horses. Slow motion playback of the video recording revealed minor inspiratory centripetal movement of the left side of the larynx in 4 horses and more pronounced inward movement in 2 horses which had more abundant mucosa and the highest Z_I values during Period C.

Discussion

The aim of arytenoidectomy is to provide an airway of maximal cross-sectional area during exercise while preserving normal swallowing (Speirs 1986). Although Haynes *et al.* (1984) suggested that these objectives can best be achieved using subtotal arytenoidectomy, dynamic inspiratory collapse of the remaining corniculate cartilage may result in continued airway obstruction during exercise (Stick and Derksen 1989; Belknap *et al.* 1990). Partial arytenoidectomy reportedly eliminates the collapsing corniculate cartilage (Stick and Derksen 1989) and may allow return to racing in approximately 50–75% of cases (Speirs 1986; Tulleners *et al.* 1988). The technique has been associated with an unacceptably high incidence (36%) of dysphagia and/or coughing (Speirs 1986), but a large recent study found a much lower incidence of these complications (Tulleners *et al.* 1988). Therefore, partial arytenoidectomy may be the preferred treatment for arytenoid chondritis and failed prosthetic laryngoplasty in performance horses, and was chosen for evaluation in the present study. We evaluated our horses 16 weeks after surgery, because preliminary studies, using endoscopic examination of the larynx with horses standing, confirmed that the diameter of the rima glottidis appeared to continue to enlarge for up to 4 months after partial arytenoidectomy (Speirs 1986).

During moderate and strenuous exercise (Periods B and C, respectively), after partial arytenoidectomy, the airflow-generating transupper airway inspiratory pressures and inspiratory impedance did not differ from baseline values (Table 1; Fig 2), suggesting that partial arytenoidectomy restored upper airway function in horses with induced LLH. Additionally, during Period C, partial arytenoidectomy reversed the decrease in $\dot{V}_E$ observed after LRLN (Table 1). However, although Z_I and P_{UI}

returned to baseline values after partial arytenoidectomy, PIF remained significantly reduced, suggesting that this operation did not completely restore upper airway geometry. This became apparent only at the higher exercise level (Period C). Lack of tissue support may have allowed partial dynamic collapse of the left side of the larynx after partial arytenoidectomy.

Further information regarding the effects of partial arytenoidectomy on upper airway function was obtained using TBFVL analysis. After partial arytenoidectomy, measurements of inspiratory airflow during period B did not differ significantly from baseline measurements (Table 1; Fig 2). In contrast, during more strenuous exercise (Period C), PIF and the TBFVL indices describing airflow throughout inspiration (IF_{50} and IF_{25}) remained significantly less than baseline values. Although PEF/PIF and EF_{50}/IF_{50} (Table 1; Fig 2) were less than values obtained after LRLN, they remained significantly greater than baseline values.

The TBFVL in Figure 1(B) illustrates the reduced airflow throughout inspiration and preservation of airflow during expiration after LRLN. After partial arytenoidectomy, the TBFVL shape at Period C was characterised by an inspiratory curve intermediate between those observed post-LRLN and at baseline. Therefore, TBFVL evaluation suggests that partial arytenoidectomy eliminated the LLH-induced dynamic upper airway obstruction at submaximal exercise (Period B), but that some inspiratory flow limitation persisted during more strenuous exercise. When extending these findings to racing conditions it may be concluded that partial arytenoidectomy does not completely restore upper airway function in horses with LLH.

The leftward displacement of the right corniculate cartilage observed at rest and during exercise may have resulted from caudal retraction of rostral mucosa of the left side of the larynx, while leaving the transverse arytenoid ligament intact (Speirs 1986). The varied degrees of centripetal movement of the left side of the larynx during inspiration was probably the result of the semi-rigid nature of the tissue of the left side of the larynx after partial arytenoidectomy and the lack of left side abductor function. This centripetal movement, which appeared more pronounced in horses with more abundant mucosa, in conjunction with an airway of less than normal cross-sectional area, may explain the partial inspiratory flow limitation. The results of the present study support previous observations by others (Stick and Derksen 1989; Belknap *et al.* 1990) that unsupported structures, such as the corniculate cartilage after subtotal arytenoidectomy, are a significant cause of upper airway obstruction. Therefore, we recommend removal of as much laryngeal mucosal as practical during surgery while permitting primary closure under minimal tension.

Although the decrease in Z_I that followed partial arytenoidectomy parallelled the decrease in Z_I after prosthetic laryngoplasty (Shappell *et al.* 1988), accurate comparison of the efficacy of these two techniques in improving upper airway function in horses with LLH is impossible due to the higher treadmill speeds, higher peak airflows and lower treadmill incline reported in the present study. Despite these differences in exercise conditions, comparisons of upper airway impedance between these two studies would suggest that the two different surgical techniques have similar efficacy. In the present study, there were obvious discrepancies in the results from TBFVL and the calculation of Z_I during Period C. Detection of persistent partial inspiratory obstruction after partial arytenoidectomy using TBFVL analysis, but not by evaluation of Z_I, indicates that the former technique is a more sensitive measure of upper airway function. Re-evaluation of prosthetic laryngoplasty for the treatment of LLH using TBFVL analysis may provide more detailed assessment of the ability of this surgical technique to restore upper airway function.

The horses in our study showed no evidence of coughing or dysphagia. However, in clinical cases, pre-existing laryngeal and peri-laryngeal pathology associated with arytenoid chondropathies and failed prosthetic laryngoplasty may influence the incidence of serious post-operative complications and the efficacy of partial arytenoidectomy in restoring upper airway function (Speirs 1986; Tulleners *et al.* 1988). Based on studies of upper airway flow mechanics, videoendoscopy in exercising horses and minimal post-operative complications, we recommend partial arytenoidectomy as the treatment of choice for arytenoid chondropathy and failed prosthetic laryngoplasty.

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