Effects of unilateral arytenoid lateralization technique and suture tension on airway pressure in the larynx of canine cadavers

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Objective—To evaluate effects of the arytenoid lateralization technique and suture tension on airway pressure in the canine larynx.

Sample—7 canine cadaver larynges.

Procedures—Negative pressure was elicited aboral to the larynx. Airway pressure was measured at airflows of 15 to 120 L/min before and after thyroarytenoid lateralization (TAL), cricoarytenoid lateralization (CAL), and combined TAL and CAL (cricothyroarytenoid lateralization [CTAL]) at 100 and 500 g of suture tension and with sectioning of the sesamoid cartilage (SSC) and disarticulation of the cricothyroid joint (DCTJ). Rima glottidis area (RGA) was measured. Effects of technique, modification, and suture tension on pressure and RGA were evaluated statistically.

Results—Increased suture tension significantly reduced airway pressure for TAL at 30 L/min, CAL at 45 to 120 L/min, and CAL after SSC and DCTJ at 60, 75, and 105 to 120 L/min. The CAL and CTAL caused significantly lower airway pressures than did TAL > 30 L/min, but SSC and DCTJ did not significantly reduce pressure. All procedures, except TAL at 100 g of tension, resulted in a significant RGA increase from baseline. The CAL and CTAL caused a significantly greater RGA than did TAL. For TAL at 100 g of tension, SSC significantly increased RGA.

Conclusions and Clinical Relevance—CAL and CTAL caused lower airway pressures than did TAL. No significant pressure differences were detected between CAL and CTAL; SSC and DCTJ had little effect on pressure. Pressure may be a more sensitive indicator of airflow than is RGA in the larynx of canine cadavers. (*Am J Vet Res* 2012;73:917–924)

Idiopathic laryngeal paralysis is a common disease that primarily affects large-breed dogs. Numerous surgical techniques, including unilateral and bilateral arytenoid lateralization,[1–3] creation of a castellated laryngofissure,[4] nerve-muscle pedicle grafting,[5] partial laryngectomy,[6] vocal fold excision with mucosoplasty,[7] and use of nitinol stents,[8] have been used for treatment of the condition. Unilateral arytenoid lateralization has emerged as a preferred technique because of the ease of the procedure and good clinical outcome.[1,9]

Lateralization techniques are broadly grouped into lateralization of the thyroid and arytenoid cartilages (ie, TAL)[10] and lateralization of the cricoiod and arytenoid cartilages (ie, CAL).[9] Both CAL and TAL result in a significant increase in RGA and alleviation of clinical signs associated with laryngeal paralysis.[6,10–12] In vivo, TAL increases RGA by a smaller proportion than does CAL,[10] and there have been similar findings in a cadaveric study.[12] It has been postulated that the combination of these 2 procedures (ie, CTAL) may lead to optimal positioning of the arytenoid cartilage within the rigid structure formed by the thyroid and cricoid cartilages.[13] Comparison between CAL and CTAL in live animals has revealed no significant difference in RGA and no detectable difference in postoperative clinical signs of dyspnea.[14]

The sesamoid cartilage provides a dorsal attachment between the arytenoid cartilages and prevents independent movement of the arytenoid cartilages in live animals.[9] It has been hypothesized that DCTJ combined with SSC allows dorsolateral movement of the arytenoid cartilage to cause a greater increase in RGA.[13]

Abbreviations

CAL	Cricoarytenoid lateralization
CTAL	Cricothyroarytenoid lateralization
DCTJ	Disarticulation of the cricothyroid joint
RGA	Rima glottidis area
SSC	Sectioning of the sesamoid cartilage
TAL	Thyroarytenoid lateralization

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The author of 1 study[12] found that SSC caused a significant decrease in the dorsoventral height of the rima glottidis but no significant increase in RGA. Because this intervention may cause misalignment of the rima glottidis and epiglottis, its role in altering airway pressure should be investigated.

The cricothyroid joint is a firm bilateral attachment that prevents translational motion of the cricoid and thyroid cartilages and maintains the dorsoventral height of the rima glottidis during abduction.[15] Although DCTJ has been recommended to increase surgical exposure, the necessity for this has been debated because no significant increase in RGA or change in rima glottidis geometry has been found after disarticulation.[11,12]

Another factor in arytenoid lateralization is the tension of the suture. For unilateral CAL, a low suture tension results in a lower percentage increase in RGA than does a high suture tension (increase in RGA of 82% and 129%, respectively), but misalignment of the rima glottidis and epiglottis in a high-tension CAL was postulated to play a role in an increased risk of aspiration pneumonia.[11] Investigators in another study[16] found no significant difference in laryngeal resistance between low and high suture tension. However, investigators in that study[11] did not measure tension objectively (low tension was classified as feeling resistance during knot tying, and high tension was classified as the maximum tension possible). Thus, the necessity or practicality of an optimum suture tension to balance a possible risk of aspiration pneumonia against increased airflow currently is unclear.

Effects of laryngeal surgery in cadavers have been measured via 2 protocols. Measurement of RGA has been used as a surrogate marker for airflow through the larynx because of the ease of measurement of RGA in cadavers and live animals.[6,10–12,15] More recently, the effect of suture tension during unilateral CAL on the pressure gradient and airflow in the larynx of a cadaver has been evaluated in a testing chamber.[16] Although the direction of airflow in the cadaver was in a physiologic direction, investigators in that study[16] relied on positive pressure oral to the larynx, whereas in live animals, negative pressure is elicited aborally.[17]

The purposes of the study reported here were to investigate the effect of 3 arytenoid lateralization techniques on airway pressure and RGA in the larynx of canine cadavers and to evaluate the effects of modifications of the technique (namely SSC and DCTJ) and different suture tensions on each technique. We hypothesized that use of the 3 techniques would cause differences in airway pressures and RGA and that the modifications would further decrease airway pressures and increase RGA.

Materials and Methods

Sample—Laryngeal specimens were obtained from cadavers of 7 young adult Greyhounds. Each dog was euthanized by IV administration of a pentobarbital-phenytoin solution for reasons other than laryngeal and tracheal disease. Each specimen comprised the larynx, caudal portion of the oropharynx, proximal portion of the esophagus, and proximal 5 tracheal rings. Grossly, all larynges were anatomically normal. Specimens were stored at –20°C and warmed to 18°C before use. Specimens were used within 1 day after thawing; specimens were periodically moistened throughout the experiments.

Excess cervical tissue was excised, and the dorsal aspect of the esophagus was incised to permit visual examination of the rima glottidis. Each larynx was secured to a wooden board with 2 stainless steel nails inserted at the articulation of the epihyoid and stylohyoid bones to stabilize the larynx without impeding motion of the arytenoid cartilage. A 20-gauge orthopedic wire was inserted through the epiglottis and pulled rostrally to keep the glottis open at all times. At the second tracheal ring, nylon cable ties were placed around the larynx and a rigid plastic tube connector was attached to a 25-cm-long piece of anesthetic tubing (28 mm in diameter), which created an airtight seal.

Airflow and pressure measurements—The laryngeal end of the construct was allowed to remain open to room air, and the 28-mm tubing was attached to a high-flow circuit (**Figure 1**). Airflow was created by application of a vacuum[a] in series with a variable flow regulator. Airflows and differential gas pressures were measured with a ventilator calibration analyzer[b] connected in series. Atmospheric pressure was used as the zero calibration for the pressure transducer. Airflow was set at a steady state for values between 0 and 120 L/min in increments of 15 L/min, and airway pressure was measured in triplicate for each surgical intervention.

Measurement of the rima glottidis—Digital photographs were obtained immediately after each surgical intervention; a 1-cm scale marker was placed between the arytenoid cartilages. Photography was performed at an airflow of 0 L/min. Specimen position was maintained to ensure consistent positioning of the camera with respect to the rima glottidis. All photographs were obtained for a fixed position and analyzed by 1 author (JRW). Computerized planimetric analysis[c] was used to measure the surface area of the RGA for each intervention, with the 1-cm scale marker used as a reference. An increase in RGA was expressed as a percentage of the original RGA measured in specimens before surgical intervention.

Arytenoid lateralization procedures—All procedures were performed on the left arytenoid cartilage by a single surgeon (JRW). For the TAL, CAL, and CTAL, 2-0 polypropylene[d] sutures were placed as described previously,[10] but the cricothyroid joint and sesamoid

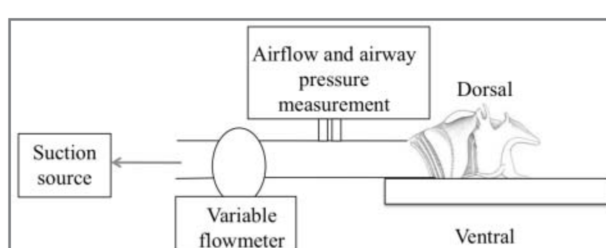

Figure 1—Schematic depicting the construct used to measure airway pressure and airflow in larynges obtained from canine cadavers.

cartilage were allowed to remain intact (standard technique). Sutures were passed through the ventral portion of the articular surface of the arytenoid cartilage, which has the greatest cartilage thickness.[18] Curved Halsted mosquito forceps were clamped on the sutures to maintain abduction during measurement; this allowed us to use the same suture in sequential interventions. Airflow and airway pressures were measured in each specimen after placing TAL, CAL, and CTAL sutures at 100 and 500 g of tension before and after SCC and DCTJ. For CTAL, the CAL suture was tightened prior to the TAL suture, as described elsewhere.[14]

Suture tension—Tension was measured with a digital scale.[e] In preliminary experiments, we found that for the experimental construct described, a tension of 10 N/1,000 g caused fracture in 1 of 3 arytenoid cartilages. Therefore, 500 g was set as the high tension. The low tension was set at 100 g (the tension at which the arytenoid cartilage moved to a fixed position with minimal resistance in preliminary experiments).

Data analysis—Normal distribution of the data was confirmed with the Shapiro-Wilk normality test. Data were reported as mean and SD and were analyzed with a 1-way repeated-measures ANOVA or paired *t* tests, as appropriate. Pressure data for each surgical intervention were compared with values obtained before intervention in all larynges. At high airflows at which laryngeal collapse occurred, only data from noncollapsing larynges were used for analysis. Measurements of RGA were analyzed in a similar manner. A statistical program[f] was used for all analyses. Significance was set at $P < 0.05$. Experimental groups evaluated were baseline (no surgical intervention), standard technique (TAL, CAL, or CTAL), suture tension (100 or 500 g), and modification (no modification, SSC alone, and a combination of SSC and DCTJ).

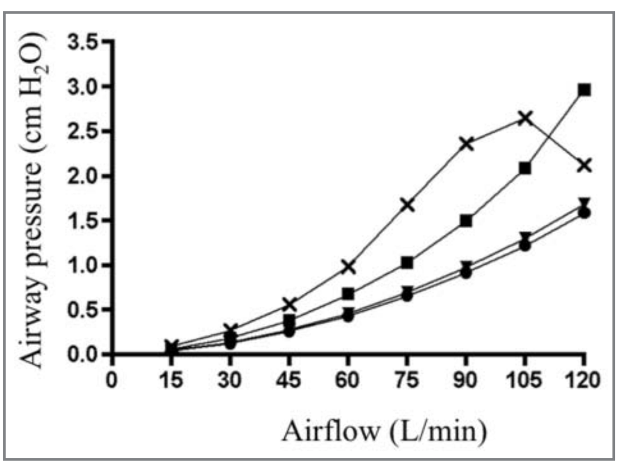

Figure 2—Mean airway pressure at various airflows for larynges obtained from canine cadavers. Results reported are for the larynges before surgical intervention (crosses) and the standard technique at 100 g of suture tension for TAL (squares), CAL, (inverted triangles), and CTAL (circles). Some larynges collapsed at high airflows; thus, values represent results for 7 larynges (0 to 75 L/min), 5 larynges (90 L/min), 4 larynges (105 L/min), and 3 larynges (120 L/min). Notice the increase in airway pressure at higher airflows for all larynges, regardless of surgical intervention or type of surgical intervention

Results

Laryngeal resistance and laryngeal collapse—In general, as airflow increased, the airway pressure increased exponentially both before and after surgical intervention (**Figure 2**). Laryngeal resistance was calculated for the unaltered larynges at each airflow in accordance with a method described in another study[16] (**Table 1**). Laryngeal resistance changed with airflow.

Before surgical intervention, collapse of the larynx was observed at higher airflows (ie, 90 L/min for 2 larynges, 105 L/min for 3 larynges, and 120 L/min for 4 larynges). However, laryngeal collapse was not observed after any surgical intervention.

Airway pressure data—Compared with values before surgical intervention, TAL at 100 g of suture tension resulted in a significant decrease in airway pressure for airflows between 30 and 75 L/min and TAL at 500 g of suture tension resulted in a significant decrease in airway pressure for airflows between 15 and 90 L/min (**Table 2**). Compared with values before surgical intervention, CAL at 100 g of suture tension resulted in a significant decrease in airway pressure at airflows between 30 and 90 L/min and CAL at 500 g of suture tension resulted in a significant decrease in airway pressure at all airflows, except for 120 L/min. Compared with values before surgical intervention, CTAL at 100 and 500 g of suture tension resulted in a significant decrease in airway pressure at all airflows, except for 120 L/min.

Compared with values for procedures at 100 g of suture tension, TAL at 500 g of suture tension resulted in a significant decrease in airway pressure at 30 L/min and CAL at 500 g of suture tension resulted in a significant decrease in airway pressure at airflows between 45 and 120 L/min (Table 2). There was no significant difference in airway pressure between CTAL at 100 and 500 g of suture tension at any airflow. Use of TAL and CAL at 500 g of suture tension was associated with a significant decrease in airway pressure, compared with baseline values, at airflows of 15 and 90 L/min; this decrease was not detected for sutures tied at 100 g of suture tension.

At both 100 and 500 g of suture tension, CAL and CTAL resulted in a significant decrease in airway pressure, compared with results for TAL, at airflows of 30 to 120 L/min. There was no significant difference in air-

Table 1—Mean ± SD laryngeal resistance at various airflows for noncollapsing larynges of canine cadavers.

Variable	Airflow (L/min) 15	30	45	60	75	90	105	120
No. of larynges	7	7	7	7	7	5	4	3
Laryngeal resistance (cm H_2O/L/s)	0.379 ± 0.213	0.546 ± 0.147	0.746 ± 0.189	1.040 ± 0.324	1.351 ± 0.530	1.696 ± 0.994	1.658 ± 0.876	1.820 ± 1.314

Table 2—Mean ± SD airway pressure (cm H_2O) before surgery and for TAL, CAL, and CTAL procedures with and without SSC and subsequent DCTJ at various airflows in larynges obtained from canine cadavers.

Variable	Suture tension (g)	Airflow (L/min) 15	30	45	60	75	90	105	120
Before surgical intervention	NA	0.095 ± 0.053	0.273 ± 0.074	0.560 ± 0.142	0.987 ± 0.320	1.678 ± 0.726	2.363 ± 1.657	2.649 ± 1.773	2.123 ± 0.099
Standard technique									
TAL	100	0.061 ± 0.024	0.184 ± 0.047*	0.383 ± 0.097†	0.677 ± 0.175*	1.032 ± 0.302*	1.501 ± 0.502	2.088 ± 0.789	2.966 ± 1.366
	500	0.049 ± 0.008‡	0.152 ± 0.024†§	0.320 ± 0.052†	0.550 ± 0.107†	0.842 ± 0.174†	1.185 ± 0.275‡	1.616 ± 0.418	2.103 ± 0.587
CAL	100	0.053 ± 0.018	0.140 ± 0.023†	0.279 ± 0.033†	0.463 ± 0.064†	0.700 ± 0.099†	0.981 ± 0.147‡	1.301 ± 0.215	1.690 ± 0.317
	500	0.041 ± 0.010‡	0.121 ± 0.013†	0.255 ± 0.028†§	0.427 ± 0.057†§	0.641 ± 0.102†§	0.905 ± 0.153‡§	1.207 ± 0.223‡§	1.559 ± 0.308§
CTAL	100	0.043 ± 0.010‡	0.126 ± 0.014†	0.261 ± 0.034†	0.436 ± 0.063†	0.662 ± 0.096†	0.919 ± 0.144‡	1.222 ± 0.214‡	1.588 ± 0.298
	500	0.043 ± 0.005‡	0.128 ± 0.012†	0.263 ± 0.029†	0.436 ± 0.046†	0.649 ± 0.078†	0.909 ± 0.121‡	1.202 ± 0.180‡	1.557 ± 0.248
After SCC									
TAL	100	0.050 ± 0.006‡	0.155 ± 0.035†	0.327 ± 0.066†	0.568 ± 0.156†	0.866 ± 0.251*	1.226 ± 0.377	1.657 ± 0.541‡	2.181 ± 0.784
	500	0.049 ± 0.013‡	0.152 ± 0.032†	0.315 ± 0.066†	0.534 ± 0.122†	0.816 ± 0.197*	1.148 ± 0.298	1.548 ± 0.432	2.017 ± 0.581
CAL	100	0.042 ± 0.007‡	0.132 ± 0.022†	0.279 ± 0.038†	0.467 ± 0.072†	0.687 ± 0.099*	1.002 ± 0.170	1.321 ± 0.243	1.704 ± 0.320‡
	500	0.041 ± 0.009‡	0.125 ± 0.015†	0.259 ± 0.034†	0.443 ± 0.052†	0.668 ± 0.087*	0.938 ± 0.126	1.248 ± 0.182	1.621 ± 0.245‡
CTAL	100	0.040 ± 0.008‡	0.134 ± 0.016†	0.276 ± 0.035†	0.454 ± 0.059†	0.689 ± 0.093†	0.974 ± 0.145‡	1.315 ± 0.229	1.714 ± 0.312
	500	0.043 ± 0.008‡	0.127 ± 0.016†	0.275 ± 0.033†	0.453 ± 0.059†	0.684 ± 0.092†	0.957 ± 0.142‡	1.257 ± 0.186‡	1.555 ± 0.256
After SCC and subsequent DCTJ									
TAL	100	0.046 ± 0.005‡	0.151 ± 0.023†	0.329 ± 0.062†	0.528 ± 0.089†	0.796 ± 0.154†	1.115 ± 0.234‡	1.563 ± 0.382	1.969 ± 0.440
	500	0.043 ± 0.007‡	0.149 ± 0.027†	0.322 ± 0.058†	0.528 ± 0.096†	0.800 ± 0.160†	1.126 ± 0.235‡	1.518 ± 0.335	1.966 ± 0.467
CAL	100	0.042 ± 0.004‡	0.134 ± 0.018†	0.274 ± 0.043†	0.457 ± 0.063†	0.694 ± 0.105*	0.978 ± 0.169	1.317 ± 0.250	1.701 ± 0.333‡
	500	0.039 ± 0.006‡	0.128 ± 0.023†	0.259 ± 0.036†	0.438 ± 0.065†§	0.667 ± 0.109*§	0.940 ± 0.173	1.253 ± 0.249§	1.624 ± 0.331‡§
CTAL	100	0.041 ± 0.004‡	0.132 ± 0.018†	0.282 ± 0.042†	0.462 ± 0.058†	0.699 ± 0.100†	0.979 ± 0.159‡	1.301 ± 0.231	1.691 ± 0.314
	500	0.043 ± 0.005‡	0.131 ± 0.016†	0.272 ± 0.044†	0.443 ± 0.046†	0.676 ± 0.079†	0.940 ± 0.132‡	1.256 ± 0.195	1.616 ± 0.257

†‡Within a column, value differs significantly ($P = 0.01$, †$P < 0.001$, and ‡$P < 0.05$) from the corresponding value before surgical intervention. §Within a procedure, value differs significantly ($P < 0.05$) from the value for 100 g of suture tension.

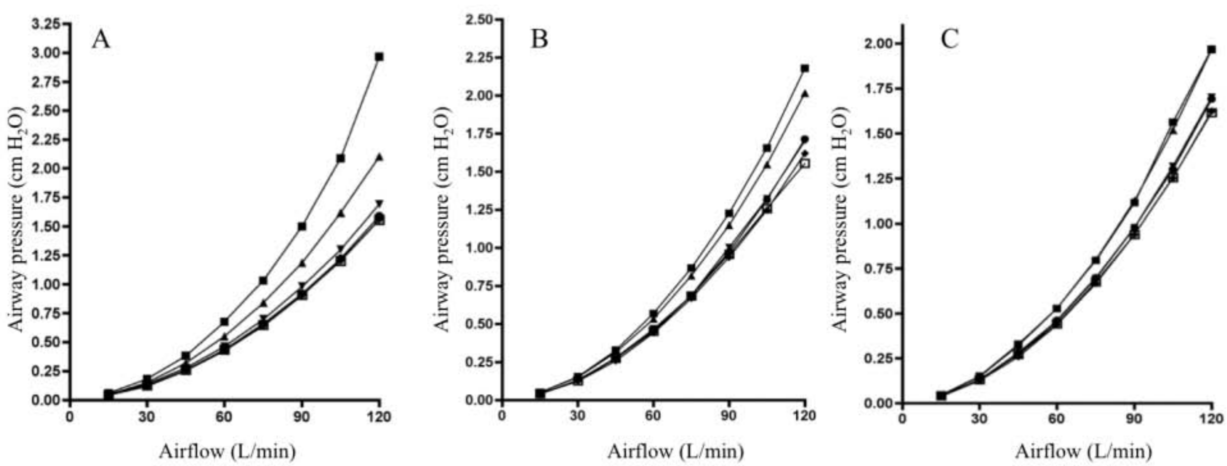

Figure 3—Mean airway pressure in larynges obtained from canine cadavers and subjected to various airflows before and after surgical intervention with standard techniques (A), the techniques performed after modification via SSC (B), and the techniques performed after modification via SSC and subsequent DCTJ (C). Notice that the scale on the y-axis differs among panels. *See* Figure 2 for remainder of key.

way pressure between CAL and CTAL at either suture tension for any airflow **(Figure 3)**.

After SSC, TAL at 100 g of suture tension resulted in a significant decrease in airway pressure, compared with values before surgery, at airflows of 15 to 75 L/min and 105 L/min. After SSC, TAL at 500 g of suture tension resulted in a significant decrease in airway pressure, compared with values before surgery, at airflows of 15 to 75 L/min (Figure 3). Modified CAL (ie, after SSC) at both 100 and 500 g of suture tension resulted in a significant decrease in airway pressure at airflows of 15 to 75 L/min and 120 L/min. Modified CTAL (ie, after SSC) at 100 g of tension resulted in a significant decrease in airway pressure, compared with values before surgery, at airflows of 15 to 90 L/min. Modified CTAL (ie, after SSC) at 500 g of suture tension resulted in a significant decrease in airway pressure, compared with values before surgery, at airflows of 15 to 105 L/min.

Increasing suture tension from 100 to 500 g was associated with a significant decrease in airway pressure, compared with baseline values. This decrease in airway pressure was not detected in sutures tied at 100 g for CTAL at 105 L/min. There was no significant difference in airway pressure for any of the modified techniques involving SSC when sutures were tied at 500 g of suture tension, compared with results when sutures were tied at 100 g of suture tension, at any airflow.

At 100 g of suture tension, the modified (ie, after SSC) CAL and modified CTAL resulted in a significantly lower airway pressure, compared with results for modified TAL, at 15 and 45 L/min. There was no significant difference in airway pressure between modi-

Table 3—Mean ± SD percentage change in RGA for TAL, CAL, and CTAL before and after SCC and subsequent DCTJ in larynges obtained from 7 canine cadavers.

Variable	100 g of suture tension			500 g of suture tension		
	TAL	CAL	CTAL	TAL	CAL	CTAL
Standard technique	114.8 ± 9.0	159.2 ± 27.5*	164.2 ± 38.3†	148.7 ± 36.0	179.3 ± 30.0‡	183.0 ± 36.3‡
After SSC	152.5 ± 35.8§	178.8 ± 51.6	173.2 ± 35.4	161.2 ± 36.2	183.7 ± 42.6	189.8 ± 27.6
After SSC and subsequent DCTJ	149.5 ± 31.2	176.2 ± 29.8	182.0 ± 34.0	154.7 ± 38.3	182.7 ± 26.7	188.3 ± 37.1

All values differ significantly ($P < 0.001$), compared with the corresponding values before surgical intervention, except for TAL at 500 g of suture tension (which differed significantly [$P < 0.01$]) and TAL at 100 g of suture tension (which did not differ significantly [$P \geq 0.05$]).

†Value differs significantly ($P = 0.01$ and †$P < 0.001$) from the value for TAL at 100 g of suture tension. ‡Value differs significantly ($P < 0.001$) from the value for TAL at 500 g of suture tension. §Value differs significantly ($P < 0.05$) from the value for the standard technique of TAL at 100 g of suture tension.

fied CAL and modified CTAL at any airflow at 100 g of suture tension. At 500 g of suture tension, modified CTAL resulted in a significantly lower airway pressure, compared with that for modified TAL, at 120 L/min. There was no significant difference in airway pressure between modified TAL and modified CAL and between modified CAL and modified CTAL at any airflows at 500 g of suture tension (Figure 3).

After SSC, TAL and CTAL resulted in a significant decrease in airway pressure, compared with values obtained before surgery, at airflows of 15 to 90 L/min at both 100 and 500 g of suture tension. After SSC and subsequent DCTJ, CAL resulted in a significant decrease in airway pressure at airflows of 15 to 75 L/min and 120 L/min at both 100 and 500 g of suture tension.

We did not detect a significant difference in airway pressure between sutures tied at 100 and 500 g of tension for TAL and CTAL after SSC and subsequent DCTJ at any airflow. After SSC and subsequent DCTJ, CAL at 500 g of suture tension resulted in a significantly lower airway pressure at airflows of 60 to 75 L/min and 105 to 120 L/min, compared with results for CAL at 100 g of suture tension (Figure 3). There was no significant difference in airway pressure between CTAL after SSC and subsequent DCTJ at 100 and 500 g of suture tension at any airflow.

After SSC and subsequent DCTJ, CAL and CTAL resulted in a significantly lower airway pressure, compared with the airway pressure for TAL after SSC and subsequent DCTJ, at airflows of 30 to 120 L/min for both 100 and 500 g of suture tension. There was no significant difference in airway pressures between CAL and CTAL after SSC and subsequent DCTJ at either suture tension at any airflow. No significant changes in airway pressure were detected when comparing the standard TAL, CAL, and CTAL techniques with values after SSC and subsequent DCTJ at any suture tension and any airflow.

RGA—All surgical techniques and their modifications resulted in a significantly greater RGA, compared with values obtained before surgery, except for the standard TAL technique tied at 100 g of suture tension (**Table 3**). At 100 and 500 g of suture tension, CAL ($P = 0.01$) and CTAL ($P < 0.001$) resulted in a significantly greater RGA than did TAL. There was no significant difference in the RGA between CAL and CTAL at either tension. Increasing tension from 100 to 500 g did not significantly increase RGA for any surgical technique and modification. Modification of the standard surgical technique did not result in a significant difference in the RGA for any technique, except with SSC for TAL at a suture tension of 100 g, which was associated with a significant ($P = 0.01$) increase in RGA from the baseline value (from 114.8% at baseline to 152.5%).

Discussion

Studies in cadavers[8,12,15,16] and live animals[1,7,10] have been used to determine the effects of surgical intervention on the larynx. However, it has not been possible to detect significant differences in clinically relevant variables among surgical techniques in live animals,[10] and most clinical studies relate to postoperative complications rather than to effects on airflow or airway pressure. Tidal breathing flow-volume loops[19] and plethysmography[20] currently are limited to only resting animals. Investigators in another study[21] found that the mean airflow in a population of resting dogs was approximately 30 L/min; this value increases to approximately 60 L/min for dogs with laryngeal paralysis.[20] Although the use of such airflows is clinically applicable in resting healthy dogs, the airway pressure achieved in dyspneic animals with laryngeal paralysis may vary widely and may require the investigation of supranormal flows and pressures.

In the present study, airway pressure differed on the basis of surgical technique, modification of surgical technique, and suture tension. The presence and magnitude of these differences differed with changes in airflow through the larynx.

To our knowledge, the present study is the first in which negative pressure was elicited aboral to the larynx, which is similar to the situation in live animals. It involved the use of a cadaver larynx as a dynamic model of obstruction and was intended to mimic peak inspiratory flow in a patient with laryngeal paralysis. Some authors[6,12] claim that the arytenoid cartilages of excised cadaver larynges maintain a similar paramedian position to that in live patients with bilateral laryngeal paralysis.

A change in diameter of a single airway passage greatly influences resistance measurement, as indicated by the following equation[17]: $R = 8nl/\pi r^4$, where R is resistance, n is gas viscosity, l is length of the passage, and r is radius of the passage. If the gas viscosity and length of the passage remain the same, decreasing the radius by one-half results in a 16-fold increase in resistance. In a passage at low flow rates, airflow is laminar and airflow is proportional to pressure, presuming gas viscosity and length of the passage remain the same. At higher flow rates, airflow becomes turbulent and pressure is proportional to the square of the airflow. It is considered likely that airflow is only laminar in small bronchioles and that airflow orad to the trachea is more likely to be turbulent.[17] In another study,[16] laryngeal resistance was calculated by recording airflow at a pressure gradient of 1 cm H_2O. By use of a similar calculation in the present study, it was found that laryngeal resistance changed with airflows between 15 and 120 L/min (Table 1), which suggested that airflow does not remain laminar or that there is deformation in the larynx to reduce the airway radius at high flows. For this reason, the use of raw data (airway pressure and airflow) was deemed a more accurate measure than was airway resistance for the present study.

At airflows ≥ 90 L/min in the present study, there was collapse in a mediolateral direction in some larynges before surgical intervention. This was assumed to be attributable to pressure exerted across the walls of the airway, which leads to a reduction in airway diameter and then an increase in pressure, thus causing a cycle that ends in complete collapse and lack of airflow. Because pressure across the airway wall would presumably affect airway diameter before collapse occurs, particularly at higher airflows, a linear relationship no longer exists between airway pressure and airflow. Smaller larynges may be more prone to collapse in this experimental apparatus. At flow rates ≥ 90 L/min, there were fewer larynges with baseline values because of laryngeal collapse and because certain techniques resulted in inherent stability of the larynx. Laryngeal collapse has not been reported in studies that involved the use of cadavers, and this may be a property of the cadaver construct or supraphysiologic airflows. Furthermore, laryngeal collapse has not been reported in live dogs with laryngeal paralysis, although dynamic laryngeal collapse is seen in exercising horses with laryngeal paralysis.[22]

Dynamic laryngeal collapse during breathing in animals with laryngeal paralysis (ie, animals with a rima glottidis that is already narrowed) may increase airway pressure. Thus, if this phenomenon occurs in a live animal, reduced resistance to airflow may not be found after surgery in animals that appear to have an airway of satisfactory diameter, as determined on the basis of a single inspection of the rima glottidis diameter at low airflows in anesthetized animals immediately after surgery.

In the present study, CAL and CTAL were associated with a significantly greater relative change in RGA, compared with results for TAL; this finding is in agreement with results of other studies.[10,12] No significant differences were detected in the percentage increase in RGA between CAL and CTAL in the present study, which was in agreement with results of only 1 other study.[14] The CTAL procedure resulted in the most consistent improvement in airway resistance, compared with baseline values, for airflows up to 105 L/min. It is suggested that CAL acts to replace the cricoarytenoideus dorsalis muscle, thus abducting and rotating the arytenoid cartilage caudally and in a more physiologic manner, whereas TAL fixes the arytenoid cartilage to the wing of the more lateral thyroid cartilage.[12] This may explain the reason that CAL (and therefore CTAL) more successfully decreased airway pressure than did TAL. In this respect, sutures for CTAL act more similar to CAL than to TAL (which is perhaps not surprising if the CAL suture is tied first). In this assessment, the addition of a TAL suture to a CAL suture did not have a significant positive or negative effect on airway pressure.

Investigators in 1 study[16] found no significant difference in laryngeal resistance between low- and high-tension CAL procedures with an open glottis; however, tension was subjectively classified, and the low- and high-tension procedures also involved the use of differing amounts of dissection. In the present study, a significant difference in airway pressure was detected for CAL at both 100 and 500 g of suture tension with identical amounts of dissection. This was at 45 to 120 L/min, which involved a range of airway pressures between 0.255 and 1.690 cm H_2O, rather than a single pressure gradient of 1 cm H_2O. In another study,[11] investigators found that there was a significant difference in the RGA increase for CAL with low-tension (82%) or high-tension (129%) sutures. This effect of tension was not detected in the present study. This difference in the effect of tension on RGA and airway pressure between the present study and previous studies may reflect the need to control the amount of dissection as well as to obtain objective measurement of tension, rather than the use of a subjective marker of tension (eg, resistance to knot tightening).

In 5 larynges for the standard TAL, standard CAL, and CTAL after SSC, use of 500 g of suture tension resulted in a significant decrease in airway pressure, compared with baseline values, which was not detected with 100 g of suture tension. Thus, at least in these configurations, suture tension had an effect on airway pressure in this construct, although this was only evident at low (15 L/min) or high (90 and 105 L/min) airflows, which may not be encountered in live animals.

On the basis of the range of airflows affected by increases in suture tension and the superiority of CAL over TAL, the lateralizing effect of the sutures for TAL may be achieved with little tension and overall little improvement may be achieved by increasing suture tension. In contrast, increasing suture tension will reduce airway pressure for CAL in some configurations. It may be hypothesized that similar to TAL, sutures in CTAL (possibly because of 2 points of fixation) achieve their lateralizing effect at a low tension and further increases in tension have no additional effects.

Classifying suture placement as low or high tension is useful for research, but application to clinical practice would require the use of a tensionometer incorporated into the suture loop as it is tied. Possible complications of the use of high-tension sutures include suture failure, fracture of arytenoid cartilage,[23] and avulsion from the arytenoid cartilage or from the thyroid or cricoid cartilage.[18] In preliminary investigations for the study reported here, suture pullout was seen at a lower force than has been reported previously.[18] This may have indicated the lack of repeatability in application of tension, perhaps because of differences in apparatus or treatment of cadaver material.

Because increases in suture tension did not have an effect on RGA for any technique or modification, this suggested that the decreases in airway pressure for sutures tied at a higher tension were not related to RGA but were instead related to another factor, such as rigid fixation of the arytenoid cartilage in a position that prevented medial encroachment on the airway during airflow. This was supported in part by the fact that the effect of suture tension on airway pressure was not detected at lower airflows. Measuring the RGA at various airflows could test this hypothesis. The airway pressure used in the present study may be a more sensitive indicator of laryngeal function than is RGA.

Analysis of data from the present study suggested that SSC and subsequent DCTJ are not detrimental and not necessary during lateralization procedures. However, SSC may have a role in increasing lateral mobility of the arytenoid cartilage, which allows TAL to increase RGA and negate the effects of higher suture tension on airway pressure (ie, less suture tension is required to decrease airway pressure, compared with baseline values). It has been suggested[9] that SSC is required to allow a CAL suture to sufficiently open the rima glottidis; however, the present study did not reveal a significant increase in RGA, which is in agreement with results of another study.[12] It has also been hypothesized that DCTJ paired with SSC allows dorsolateral movement of the arytenoid cartilage to cause a greater increase in RGA[13]; however, we did not detect a change in RGA or airway pressure in the present study, which is in agreement with findings on rima glottidis geometry in another study.[11]

The RGA data of the study reported here were similar to results reported in other studies,[12,15] although the upper limit of the percentage increase in RGA in the present study was higher for all TAL procedures and CAL after SSC and lower for CTAL and CAL after SSC and subsequent DCTJ. This may reflect breed differences in the larynges or the fact that there may be differences in the amount of dissection between procedures.

Mean upper airway resistance of 7.1 cm $H_2O/L/s$ was reported in another study.[21] Mean ± SD nares-to-larynx and open-glottis resistance for excised larynges was 2.10 ± 1.00 cm $H_2O/L/s$ for a population of large-breed dogs measured at an airflow of 60 L/min.[16] The lower mean ± SD resistance (1.04 ± 0.324 cm $H_2O/L/s$) measured at an airflow of 60 L/min in the present study may have been a reflection of the Greyhounds used, compared with the large-breed dogs used in the other study,[16] or of differences in the apparatus used.

Studies that involve the use of cadavers are subject to limitations, such as loss of supporting perilaryngeal tissues, loss of muscular tone, lack of response to tissue handling, and possible changes in mechanical properties as a result of loss of osmotic balance and specimen treatment. This may affect the amount of lateralization achieved with each type of suture. In the present study, we used a small number of larynges, although each larynx was subjected to all procedures and served as its own control specimen. Investigators in 1 study [18] stated that it was difficult to make comparisons between lateralization techniques because suture placement on the arytenoid cartilages greatly affects lateralization forces. Some of this uncertainty has been eliminated by maintaining consistent suture placement for CAL and TAL for each larynx and with the use of similar amounts of dissection between procedures.

Because all DCTJ procedures were performed only after SSC, another study would be needed to establish the effect of DCTJ without prior SSC. Similarly, all CTAL procedures were performed with the CAL suture tightened first,[14] and additional studies would be needed to establish whether performing a CTAL by tightening the TAL suture first would result in different effects. In the present study, experiments relied on steady-state airflow rather than on the dynamic situation that is evident with inspiration and expiration. Because inspiratory dyspnea is seen in live patients with laryngeal paralysis, this suggests that the inspiratory phase of respiration is most important in clinical outcome. In the study reported here, we used negative pressure elicited aborally, which is similar to the situation in live animals. Dynamic flow sampling has been used in an equine model[24] and could be applied to canine cadavers.

The TAL, CAL, and CTAL procedures had different effects on airway pressure and may have altered airflow by a more complex mechanism than simply by increasing the RGA. The RGA was not a reliable correlate of airway pressure in the present study.

At a given suture tension and flow rate, CAL and CTAL generally resulted in lower airway pressures than did TAL, which may have improved airflow in the larynx. No significant differences were detected between CAL and CTAL; however, CTAL resulted in a decrease in airway pressure over a larger range of airflows.

Clinical outcome may be improved by minimizing air pressure in the larynx. However, further investigation is required to successfully reconcile the decreases in airway pressure and clinical benefits without the potential for increased adverse effects.

a. Tesco VC406 bagged compact cylinder vacuum, Tesco, Cheshunt, Hertfordshire, England.
b. Timeter RT-200, Allied Health Products Inc, St Louis, Mo.
c. ImageJ 1.38x, National Institutes of Health, Bethesda, Md.
d. Prolene, Ethicon Ltd, Edinburgh, Scotland.
e. Bluefin Leisure Ltd, Crewe, Cheshire, England.
f. GraphPad Prism 4 for Macintosh, GraphPad Software Inc, San Diego, Calif.

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