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Correlations among tracheal dimensions, tracheal stent dimensions, and major complications after endoluminal stenting of tracheal collapse syndrome in dogs

Nathaniel P. Violette[1] | Chick Weisse[1] | Allyson C. Berent[1] | Kenneth E. Lamb[2]

[1]Department of Diagnostic Imaging and Interventional Radiology, The Animal Medical Center, New York, New York

[2]Lamb Statistical Consulting LLC, West St. Paul, Minnesota

Correspondence
Chick Weisse, Department of Diagnostic Imaging and Interventional Radiology, The Animal Medical Center, 510 East 62nd Street, New York, NY 10065.
Email: chick.weisse@amcny.org

Abstract

Background: Endoluminal tracheal stenting can relieve signs associated with tracheal collapse syndrome (TCS) in dogs, but major complications can result.

Objective: To identify associations among tracheal dimensions, stent dimensions, and subsequent complications requiring additional stent placement after endoluminal stenting for TCS.

Animals: Fifty-two dogs from the hospital population.

Methods: Medical records of dogs that received an endoluminal self-expanding tracheal stent for TCS by the interventional radiology service between 2009 and 2014 were reviewed for relevant data. Signalment and clinical details, including tracheal collapse type, tracheal measurements, nominal stent dimensions, follow-up evaluation times, and stent complications, were recorded.

Results: Fifty-two dogs that received an endoluminal stent for TCS met the inclusion criteria. Major complications included stent fracture (13/52; 25%), obstructive tissue ingrowth (10/52; 19%), and progressive tracheal collapse (6/52; 12%). Natural tracheal taper ($P = .04$) and more stent diameter oversizing ($P = .04$) in the intrathoracic (IT) trachea were associated with caudodorsal stent fracture. Only stents with a 14-mm nominal diameter fractured. Progressive tracheal collapse was associated with smaller maximum tracheal diameters ($P = .02$). The majority of dogs with obstructive tissue ingrowth (7/10; 70%; $P = .30$) and all dogs with thoracic inlet fractures (3/3; 100%) had tracheal malformations.

Conclusions and Clinical Importance: A higher taper in tracheal diameter may lead to increased risk of fracture in the IT location. Dogs with tracheal malformations may have higher risk for thoracic inlet fracture and development of obstructive tissue ingrowth. Clinicians should be aware of the possible risk factors for tracheal stent complications.

KEYWORDS
collapsing trachea, dog, fluoroscopy, interventional radiology

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1 | INTRODUCTION

Tracheal collapse syndrome in dogs (TCS) is a chronic progressive respiratory disease most commonly seen in mature toy and small breed dogs.[1-4] Two processes that cause narrowing of the tracheal lumen have been observed in this syndrome.[5] Dynamic airway obstruction, the traditional form of collapse, is caused by chondromalacia of tracheal cartilages and weakening of the trachealis muscle.[2] Static airway obstruction has been noted more recently in dogs with malformed tracheal cartilages resembling the shape of a "W."[5,6] Clinical signs suggestive of TCS include a "goose honk" cough, raspy breathing, and occasionally dyspneic episodes and cyanosis. Dogs initially are managed with a combination of medications including antibiotics, antitussives, corticosteroids, and sedatives, with the goal of controlling clinical signs and maintaining reasonable quality of life.[1,2,4,5] If dogs display persistent signs of respiratory distress despite aggressive medical management, intervention may be required as a salvage procedure.

The most common procedures include surgical placement of extraluminal ring prostheses and endoluminal tracheal stent placement.[1,2] Both options aim to provide immediate resolution of life-threatening airway obstruction and associated clinical signs, but both also have the potential for major complications.[7] Extraluminal ring placement is limited mostly to the cervical trachea, and complications are reported more commonly in the perioperative and short-term periods.[3,5,8,9] Endoluminal tracheal stenting has benefits including infrequent serious perioperative complications, rapid and noninvasive placement, ability to treat the entire length of the trachea, and quick recovery times.[10-13] Complications with tracheal stent placement include aspiration pneumonia, bacterial and inflammatory tracheitis, intraluminal tissue ingrowth, progressive collapse, and stent fracture.[5,10,14-16] Minor complications may require further medical management, whereas major complications may require a second stenting procedure or result in death.[17]

Precise tracheal measurements and subsequent stent sizing decisions likely contribute at least in part to minimizing stent complications. Tracheal stents are self-expanding metallic stents (SEMSs) that must be oversized within the normal tracheal diameter to achieve sufficient outward radial force, to achieve complete mucosal apposition (to aid in complete epithelialization), and to prevent migration.[5,18] Abnormally shaped tracheal cross-sections or flattened tracheal segments associated with TCS can cause incomplete stent-to-tracheal mucosa contact and inconsistent tracheal stent expansion after deployment. This results in variable mechanical stress along the length of the stent.[19,20] Additionally, the common tapering diameter of the trachea in dogs from the cricoid cartilage toward the carina can lead to considerable oversizing of the stents, particularly within the often relatively smaller diameter intrathoracic tracheal segments.[5] Incompletely expanded stents may be predisposed to fracture because of relative weakness in the more collapsed, constrained position. Incomplete stent-to-mucosa apposition may be more likely to occur in malformed tracheas, leading to mucus trapping, infections, and tissue ingrowth.

The purpose of our study was to retrospectively investigate the relationships among tracheal anatomy, stent size, and stent-associated complications in TCS patients at a single interventional radiology service. We hypothesized that the higher the degree of stent oversizing, the more likely a stent fracture would occur. Additionally, we hypothesized that patients with tracheal malformation would suffer from higher rates of tissue ingrowth.

2 | MATERIALS AND METHODS

2.1 | Case selection

Medical records of all dogs with TCS evaluated by the Animal Medical Center Interventional Radiology service from September 1, 2009, to November 12, 2014, were reviewed retrospectively. Dogs that had a single tracheal stent placed by the Interventional Radiology service and had at least 30 days of follow-up were included. Exclusion criteria included death before 30 days of follow-up, a previous tracheal stent placed elsewhere, previous tracheal surgery, >1 tracheal stent placed at the first stenting procedure, a trimmed tracheal stent, absence of pre-stent positive pressure ventilation (PPV) radiographs with a marker catheter, or absence of post-stent radiographs. Stents were placed as a salvage procedure when dogs had failed aggressive medical management. Some stents, however, may have been placed as an emergency procedure before medical management, but these data were not readily available.

2.2 | Medical records review

Information gathered from the medical record included signalment; weight; tracheal collapse (TC) type; age at first stenting procedure; tracheal stent diameter, length, and type; time to follow-up examination; stent complications; and cause of death. Tracheal collapse type was noted as tracheal malformation if an appreciable W-shaped tracheal cartilage could be observed on tracheoscopy or radiography. Traditional collapse was noted if laxity of the dorsal tracheal membrane, decreased tracheal cartilage integrity (flattening), or both was observed. For dogs with a combination of collapse types, the predominant pathology was recorded.

2.3 | Stent placement and radiographic measurements

Tracheal dimension measurements and stent placement were performed as previously described.[5,6] Under general anesthesia, the dog was placed in lateral recumbency, its neck flexed ventrally to straighten the trachea, and the endotracheal tube cuff inflated directly caudal to the cricoid cartilage. A hydrophilic guide wire (Weasel wire; Infiniti Medical, Menlo Park, California) within a marker catheter (Measuring catheter; Infiniti Medical) was placed in the esophagus so that the marker catheter spanned the length of the trachea. The marker catheter allowed for calibration of radiographic magnification. Positive pressure ventilation of 20 cm H_2O was applied to expand the trachea to its maximum dimensions. A radiograph then was taken to measure tracheal dimensions, including diameter and length. Maximum tracheal diameters

were measured in the cervical, thoracic inlet, and intrathoracic (IT) regions. Negative pressure of −10 to −15 cm H_2O also was applied, and images were recorded to determine the length of collapse and the presence or absence of bronchial collapse. A tracheal stent with a nominal diameter (resting, fully expanded) approximately 2-3 mm larger than the largest tracheal diameter measured at PPV was selected. Oversizing the stent is required to prevent migration and decrease gaps between the stent and tracheal wall so as to encourage epithelialization and minimize mucus accumulation. Using a stent-shortening chart provided by the manufacturer (Weasel wire, Infiniti Medical), tracheal stent length was selected with the goal of the deployed stent extending approximately 10 mm caudal to the cricoid cartilage to 10 mm cranial to the carina. Using fluoroscopic guidance, the SEMS, either nitinol SEMS (Vet Stent-Trachea, Infiniti Medical) or elgiloy SEMS (Wallstent endovascular stent, Boston Scientific, Natick, Massachusetts), was placed as previously described.[5] A single board-certified surgeon placed or guided the placement of all stents (C.W.). Occasionally, after deployment, the endotracheal tube cuff was inflated within an incompletely expanded stent to achieve more extensive wall contact in certain cases, most commonly in dogs with tracheal malformations.

Maximum tracheal diameters at the cervical, thoracic inlet, and IT regions of the trachea were recorded using the 20 cm H_2O PPV, pre-stent, and lateral fluoroscopic images (Figure 1). Radiographic measurements were calibrated using the marker catheter (Measuring catheter, Infiniti Medical). All measurements were made by a single experienced observer (C.W.) using an imaging analysis software package (OsiriX DICOM viewer; Pixmeo, Geneva, Switzerland). Pre- and post-stent tracheoscopy now routinely performed was not always performed in the earlier cases.

2.4 | Follow-up information

Information collection was based on either reevaluation examination or communication by telephone or e-mail with owner or referring veterinarian. These data included complications that occurred after hospital discharge until final follow-up examination, death, or last update by the referring veterinarian or owner. Major complications were defined as those requiring another stenting procedure and included stent fracture, obstructive tissue ingrowth, and progressive collapse (Figure 2). All complications were evaluated with cervical and thoracic radiographs by the interventional radiology service. Stent fracture was defined as loss of stent body structure because of breakage and disruption of stent wires. Fractures were further classified by location; specifically, either thoracic inlet stent body fractures or caudodorsal stent body fractures. Wire breakage at the stent ends was considered stent fraying and was not classified as a stent fracture because these events are not routinely associated with fracture propagation or clinical signs. Obstructive tissue ingrowth was defined as inflammatory tissue growth obstructing >50% of the tracheal lumen detectable on radiography or during tracheoscopy at the second stenting procedure. The percentage of tracheal lumen obstruction was a subjective estimate made by the clinician. Tissue ingrowth also was classified further by location based on radiography. Progressive collapse was defined as severe TC beyond the stent (cranially or caudally) leading to recurrence or considerable worsening of clinical signs not sufficiently palliated with aggressive medical management.

2.5 | Statistical analysis

Baseline descriptive statistics are presented as mean and SD for normally distributed variables, whereas nonnormally distributed variables are presented as median and range. The normality of the error residuals was deemed normal by visual inspection and by other formal tests where appropriate. Between-group analyses of baseline variables were performed using analysis of variance or the Wilcoxon test as appropriate for the data distribution. Analyses for proportions of categorical variables were evaluated using a chi-square or Fisher's exact test. Fisher's exact test was used when a group of n ≤ 5 was being evaluated. Time-to-event analyses were carried out in univariate by way of Kaplan-Meier product limit estimates. All statistical analyses were performed using commercially and publicly available statistical software (SAS, version 9.3, SAS Institute Inc, Cary, North
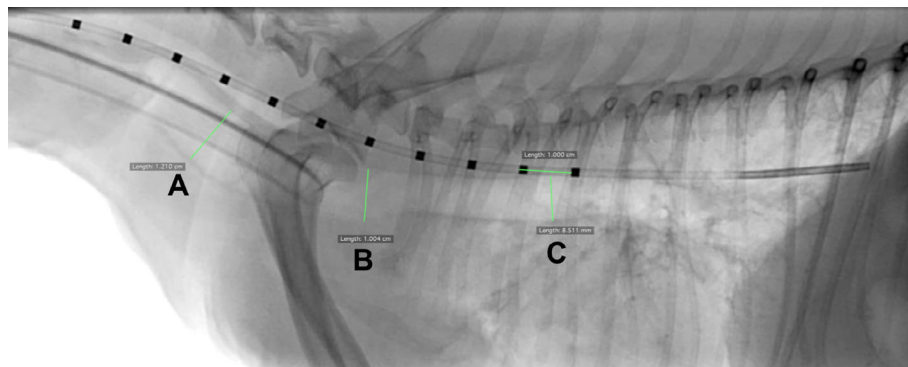

FIGURE 1 Right lateral fluoroscopic image with positive pressure ventilation of 20 cm H2O and an esophageal marker catheter placed. Typical tracheal measurements are made including maximum cervical diameter (A), maximum thoracic inlet diameter (B), and maximum intrathoracic measurement (C) indicated by the vertical measuring line from the dorsal tracheal membrane to the ventral margin of the tracheal cartilages. Measurements are calibrated using the marker catheter (10 mm from the beginning of one marker to the next)
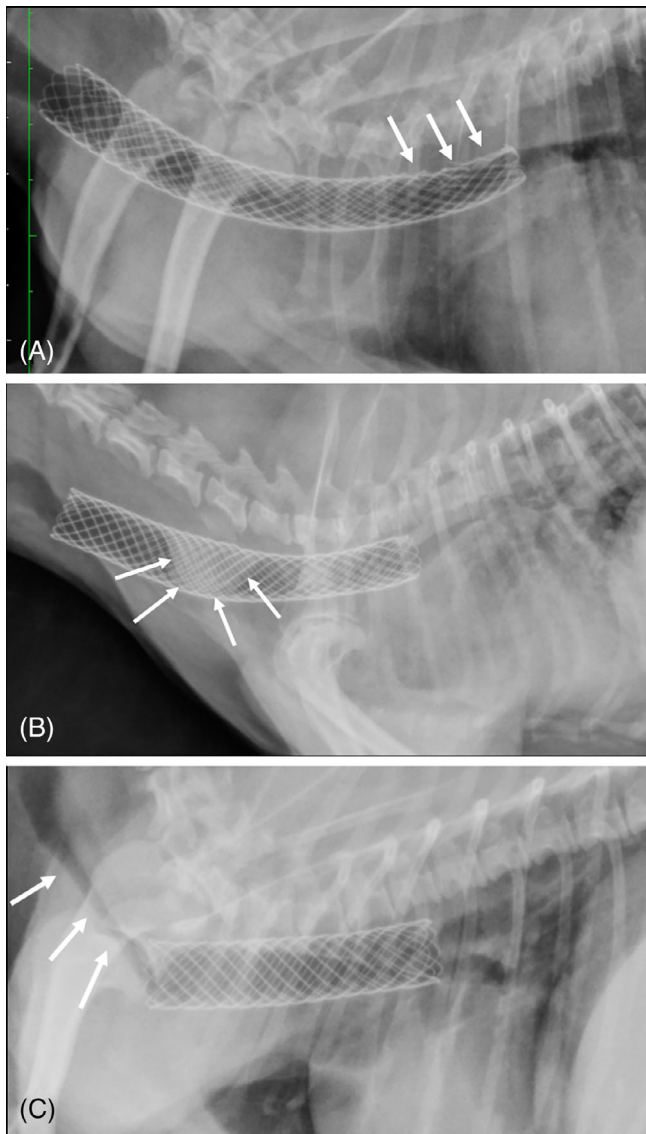
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FIGURE 2 Lateral thoracic radiographs of dogs with endoluminal tracheal stent complications including fracture of the caudodorsal stent margin (A), exuberant tissue ingrowth midway between the cranial and caudal stent margin (B), progressive tracheal collapse beyond the cranial margin of the stent (C). White arrows highlight the region of trachea where complications are occurring

Carolina; R, version 3.3.1, R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was set at $P < .05$.

2.6 | Data analysis

Oversize percentage (OP) was defined as:

$$OP = \left(\frac{\text{Nominal stent diameter} - \text{Maximum tracheal diameter}}{\text{Maximum tracheal diameter}} \right) \times 100,$$

or the percentage of the stent diameter was higher than the maximal tracheal diameter. Oversize percentage was used to evaluate stent oversizing between groups in univariate analysis. Tracheal taper was

quantified by dividing the maximum tracheal diameter by the maximal IT tracheal diameter, such that a higher value suggests more tracheal diameter taper along its length, and a value of 1 suggests a uniform or widening tracheal diameter along its length.

3 | RESULTS

During the study period, 84 dogs that received tracheal stents were identified, with 5 dogs having died sooner than 30 days post-stenting. Fifty-two of these dogs met the remaining criteria needed for inclusion in the study. The study population's mean (±SD) age at the time of first tracheal stenting procedure was 7.8 ± 3.4 years, sex was nearly evenly distributed (27 males; 52% and 25 females; 48%), and mean weight was 3.4 ± 1.1 kg. Six dog breeds were represented in the study including Yorkshire Terrier (36/52; 69%), Pomeranian (11/52; 21%), Maltese (2/52; 4%), Pug (1/52; 2%), Shih-Tzu (1/52; 2%), and Yorkie-Poo (1/52; 2%). The mean (±SD) maximal cervical, thoracic inlet, and IT tracheal diameters for the entire study population were 9.99 ± 1.46 mm, 8.70 ± 1.82 mm, 7.60 ± 1.20 mm, respectively. The maximum tracheal diameter (mean = 10.29 ± 1.55 mm) was measured in the cervical region in 42 dogs (81%), thoracic inlet location in 9 dogs (17%) and the IT region in 1 dog (2%). Twenty-five dogs had traditional collapse (48%) and 27 dogs had tracheal malformations (52%). Dogs with tracheal malformations had significantly smaller mean maximal cervical diameter (9.54 ± 1.39 mm, $P = .02$) and were significantly younger (6.6 ± 2.7 years, $P = .01$) compared to the mean maximal cervical diameter (10.5 ± 1.41 mm) and age (9.0 ± 3.8 years) of the traditional collapse dogs. Tracheal taper was not statistically significantly ($P = .54$) different in dogs with tracheal malformation (1.38 ± 0.19) compared to dogs with traditional collapse (1.35 ± 0.15). The stent type most commonly used was nitinol SEMS (49/52; 94%), and the remainder were elgiloy SEMS (3/52; 6%; Vet Stent-Trachea, Infiniti Medical; Wallstent endovascular stent, Boston Scientific). Nominal stent diameters ranged from 8 to 14 mm, and lengths ranged from 32 to 85 mm. The most common stents sizes were 14 mm × 58 mm (15/52; 29%), 12 mm × 52 mm (12/52; 23%), and 12 mm × 65 mm (10/52; 19%).

The median follow-up contact time was 790 days (range, 43-2119 days). Over the study period, 29 of the 52 dogs experienced major complications including stent fracture (13/52; 25%), obstructive tissue ingrowth (10/52; 19%), and progressive collapse (6/52; 12%). Forty-three of the 52 dogs (83%) had the presence or absence of bronchial collapse reported. Twenty-nine of the 43 dogs (67%) were affected by bronchial collapse and no statistically significant correlation was found between stent complications and bronchial collapse. Twenty-eight of the 29 dogs (97%) with major complications received an additional stent because of the complication. The dog that did not receive a second stent had a stent fracture and died soon after detection. At the conclusion of the study, 31 of 52 dogs (60%) had died. Fourteen dogs died of respiratory failure, 6 dogs died of reasons unrelated to the respiratory system, and 11 dogs died of unknown causes. Survival analysis indicated that dogs that experienced stent fracture had significantly ($P = .04$) shorter survival time (median survival time [MST],
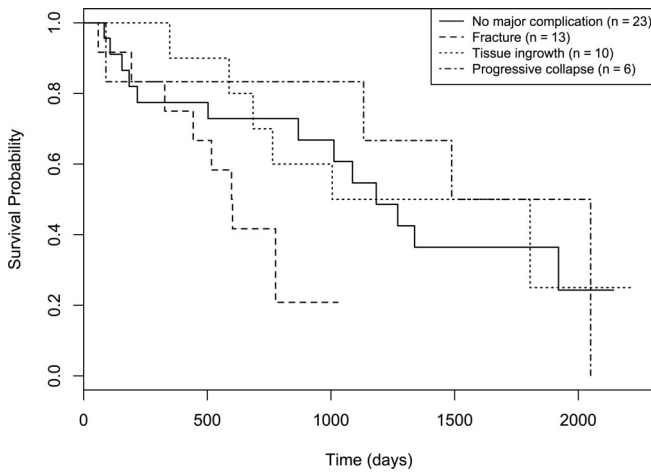
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FIGURE 3 Kaplan-Meier survival curves of 52 dogs that received tracheal stents for canine tracheal collapse syndrome comparing dogs without major complication (median survival time [MST] = 1183 days), dogs with fractured stents (MST = 600 days), dogs with obstructive tissue ingrowth (MST = 1405 days), and dogs that received a second stent for progressive collapse (MST = 1769 days). These median survival times excluded the 5 dogs excluded from the study that died within 30 days and may not be reflective of overall MST for all dogs undergoing endoluminal tracheal stenting

600 days) compared to the remainder of the 39 dogs (MST, 1270 days). Dogs that experienced stent fracture (MST, 600 days) had shorter, but not statistically significant, MST compared to dogs that experienced progressive collapse (MST, 1769 days; *P* = .11) and dogs that experienced obstructive tissue ingrowth (MST, 1405 days; *P* = .11). Also, dogs that experienced stent fracture (MST, 600 days) had shorter, but not statistically significant (*P* = .12), MST than did dogs without major complications (MST, 1183 days; Figure 3).

3.1 | Fracture

Of the 13 stent fractures, 10 (77%) were classified as caudodorsal fractures and 3 (23%) were classified as thoracic inlet fractures. The mean number of days post-stenting until fracture occurred was 289 ± 171 days, the earliest occurred 30 days post-stenting and the latest occurred 518 days post-stenting. The distribution of TC types within fracture cases (7 malformations and 6 traditional) was not significantly different from that observed in the cases without fracture (19 malformations and 20 traditional, *P* = .99). All 3 fractures at the thoracic inlet occurred in dogs with tracheal malformations. Tracheal dimensions were compared based on the presence or absence of stent fracture (Table 1). Mean maximum tracheal diameter for dogs with stent fractures was significantly larger compared to mean maximum diameter of the dogs without stent fractures (*P* = .01). Mean maximum IT tracheal diameter for dogs with stent fractures was not statistically different from mean maximum IT diameter of dogs without stent fractures (*P* = .45). The mean values of IT OP (*P* = .13) and tracheal taper (*P* = .05) for dogs with stent fracture were higher compared to dogs without fracture but these differences were not statistically significant. Oversize percentage at the cervical and thoracic inlet locations

TABLE 1 Characteristics of 52 dogs in a retrospective study to identify associations between tracheal dimensions and tracheal collapse type

| | Tracheal collapse type | | |
Variable	Malformation (n = 27)	Traditional (n = 25)	*P* value
Maximum tracheal diameter (mm)	9.99 ± 1.63	10.54 ± 1.41	.15
Cervical tracheal diameter (mm)	9.54 ± 1.39	10.48 ± 1.41	.02
Thoracic inlet tracheal diameter (mm)	8.73 ± 2.05	8.52 ± 1.60	.92
Intrathoracic tracheal diameter (mm)	7.32 ± 1.16	7.84 ± 1.21	.08

P values were calculated with analysis of variance.

was not significant. Stents measuring 14 mm × 58 mm were statistically overrepresented in stent fractures (10/13, 77% fractured) compared to all 52 stents placed (*P* < .01). The other 3 fractured stents measured 14 mm × 72 mm.

Comparing only the 10 dogs with caudodorsal fractures to the other 42 dogs, the mean tracheal taper (*P* = .04) and IT OP (*P* = .04) for caudodorsal fracture dogs were both significantly higher than the mean tracheal taper and IT OP for the remaining dogs. The dogs with caudodorsal fracture had no statistically significant difference when comparing the mean of IT tracheal diameter (7.72 ± 1.02 mm) and the maximum tracheal diameter (11.20 ± 1.03 mm) to the mean IT tracheal diameter (8.20 ± 0.84 mm; *P* = .48) and the mean maximum tracheal diameter (11.31 ± 0.79 mm; *P* = .87) of the 3 dogs with fractures at the thoracic inlet.

3.2 | Obstructive tissue ingrowth

Of the 10 dogs with obstructive tissue ingrowth, 4 dogs had focal lesions near the cranial margin of the stent, 3 had focal lesions in the middle of the stent, and 3 had tissue growing diffusely throughout the stent. The mean number of days post-stenting until obstructive tissue ingrowth occurred was 717 ± 463 days; the earliest occurred 193 days post-stenting and the latest occurred 1601 days post-stenting. Tracheal dimensions were compared based on the presence or absence of tissue ingrowth (Table 2). A higher proportion of dogs with malformation-type collapse developed tissue ingrowth (7/27, 26%) compared to the proportion of traditional collapse dogs that developed tissue ingrowth (3/25, 12%), but this difference was not statistically significant (*P* = .30). Stent dimensions and tracheal diameter measurements did not have statistically significant correlations with regard to the occurrence of obstructive tissue ingrowth.

3.3 | Progressive collapse

The 6 dogs that required another stenting procedure because of progressive collapse showed evidence of collapse beyond the stent at both

TABLE 2 Characteristics of 52 dogs in a retrospective study to identify associations between tracheal dimensions and tracheal stent fracture

	All stent fractures			Caudodorsal stent fracture		
Variable	Occurred (n = 13)	Did not occur (n = 39)	P value	Occurred (n = 10)	Did not occur (n = 42)	P value
Maximum tracheal diameter (mm)	11.22 ± 0.95	9.98 ± 1.59	.01	11.20 ± 1.03	10.07 ± 1.58	.04
Intrathoracic tracheal diameter (mm)	7.82 ± 0.97	7.53 ± 1.28	.45	7.72 ± 1.02	7.58 ± 1.26	.75
Intrathoracic OP[a] (%)	77.0 ± 24.5	64.8 ± 25.9	.13	87.9 ± 24.1	63.7 ± 22.6	.04
Tracheal taper	1.45 ± 0.16	1.34 ± 0.17	.05	1.49 ± 0.16	1.34 ± 0.16	.04

Values are reported as mean ± SD for tracheal diameters, intrathoracic OP (oversize percentage), and tracheal taper (maximum tracheal diameter divided by intrathoracic tracheal diameter). *P* values were calculated with analysis of variance.

[a]$OP = \left(\frac{\text{Nominal stent diameter} - \text{Maximum tracheal diameter}}{\text{Maximum tracheal diameter}} \right) \times 100$.

TABLE 3 Characteristics of 52 dogs in a retrospective study to identify associations between tracheal dimensions and obstructive tissue ingrowth or progressive collapse

	Obstructive tissue ingrowth			Progressive collapse		
Variable	Occurred (n = 10)	Did not occur (n = 42)	P value	Occurred (n = 6)	Did not occur (n = 46)	P value
Maximum tracheal diameter (mm)	10.48 ± 1.67	10.25 ± 1.53	.67	8.88 ± 1.37	10.48 ± 1.48	.02
Intrathoracic tracheal diameter (mm)	8.15 ± 1.01	7.47 ± 1.23	.11	7.08 ± 1.03	7.67 ± 1.22	.26
Intrathoracic OP[a] (%)	56.2 ± 22.0	70.6 ± 25.6	.11	71.7 ± 24.8	67.3 ± 25.7	.69
Tracheal taper	1.30 ± 0.16	1.38 ± 0.17	.18	1.26 ± 0.095	1.38 ± 0.17	.09

Values are reported as mean ± SD for tracheal diameters, intrathoracic OP (oversize percentage), and tracheal taper (maximum tracheal diameter divided by intrathoracic tracheal diameter). *P* values calculated with analysis of variance.

[a]$OP = \left(\frac{\text{Nominal stent diameter} - \text{Maximum tracheal diameter}}{\text{Maximum tracheal diameter}} \right) \times 100$.

the cranial and caudal margins of the stent. The mean number of days post-stenting until progressive collapse occurred was 811 ± 605 days; the earliest occurred 45 days post-stenting and the latest occurred 1433 days post-stenting. Malformation-type collapse in the dogs with progressive collapse (5/6, 83%) was more common compared to the malformation-type dogs without progressive collapse (22/46, 48%), but this difference was not statistically significant (P = .19). Tracheal dimensions were compared based on the presence or absence of progressive TC (Table 3). The maximum tracheal diameter in dogs with progressive collapse was significantly smaller than that of the remaining dogs (P = .02). Dogs with progressive collapse did not have a significantly different (P = .46) average weight (3.6 ± 1.6 kg) compared to the remainder of the study population (3.1 ± 1.1 kg). Yorkshire Terriers (5/6, 83%) made up most of the group, although the breed was not significantly overrepresented (P = .65). No other significant associations were found among tracheal diameter measurements, stent dimensions, and dogs with progressive collapse.

4 | DISCUSSION

The age and breed composition of the study population was consistent with previous studies of dogs treated for TCS with endoluminal SEMS.[6,10,11,21] As previously described, the overall trend in tracheal measurements indicated a natural taper from the cervical trachea (largest diameter) to the IT trachea (smallest diameter).[22] Nine dogs had maximum tracheal diameter at the thoracic inlet, which likely represents normal tracheal variation. One dog had an IT diameter as the largest measurement, which may be the result of error in PPV at the time of radiography, or a rare tracheal abnormality.

The complication rates in the study population may not be an accurate representation of the actual complication risk associated with endoluminal tracheal stenting because of the exclusion of 32 cases. Nonetheless, the major complication rate (29/52; 56%) was similar to that reported previously (9/18; 50%).[10] The MST cannot be compared to previously reported results because 5 dogs that died before 30 days post-stent were excluded.[10-13] The 5 excluded dogs experienced perioperative death secondary to respiratory failure and did not have any of the complications evaluated in our study. Excluding these dogs affects the overall survival times but does not affect stent sizing and complication comparisons. The reason for exclusion of these dogs was the potential for too short a time period for many of the major complications to occur. Thirty days ultimately was chosen because it was the earliest time point for 1 of the recorded major complications (fracture), whereas progressive collapse and tissue ingrowth first occurred at 45 and 193 days, respectively. These events could have occurred earlier but escaped detection.

Survival analysis showed that stent fracture decreased survival time, whereas tissue ingrowth and progressive collapse did not. These results indicate that having to place a second stent for tissue ingrowth or progressive collapse does not have a detrimental effect on survival. If a second stent could not be placed for stent fracture, progressive collapse, and tissue ingrowth refractory to medical management, euthanasia may be the only option. Despite 12 of the 13 dogs with fractured stents having a second stent placed, survival ultimately was

decreased after this complication with an MST of 600 days compared to an MST of 1270 days in dogs that did not experience fracture. Therefore, minimizing the risk of stent fracture should be a priority. Although 2 types of commercial stents were used, only 3 of 52 stents were elgiloy SEMS, and no meaningful statistical comparisons could be made based on stent type (Wallstent endovascular stent, Boston Scientific), although no fractures occurred in the elgiloy stents. Elgiloy SEMS were used in dogs earlier in the study and were phased out because of the perceived benefits of nitinol SEMS. Nitinol is a biocompatible, superelastic material that can withstand considerable strain without plastic deformation.[23]

Similar to previous studies, stent fracture was the most common major stent complication.[2,10,13] The IT and thoracic inlet locations of stent fracture were similar to the locations documented in previous studies.[10,16,17] The 3 cases of thoracic inlet fracture occurred in dogs with tracheal malformations, characterized by inverted, W-shaped cartilage rings at the thoracic inlet.[6] This abnormal structure as well as the high motion characteristic of the area likely result in uneven pressure and increased strain on the stent.[20] The malformation prevents even distribution of force 360 degrees around the tracheal mucosa because of formation of gutters or folds in the trachea. The gutters may cause the stent to exert its outward force on a smaller diameter and increase pressure where the stent does contact the mucosa. Intrathoracic fractures, more specifically noted in our study as caudodorsal fractures, are hypothesized to occur dorsally because of the structurally weak dorsal tracheal membrane providing no stent support compared to the arguably decreased but present cartilage ring support laterally and ventrally. These fractures presumably occur intrathoracically because of the typically narrower tracheal diameter resulting in less stent expansion and subsequent decreased outward radial force to resist compressive forces. Greater OP of an SEMS previously has been found to increase stent strain and decrease fatigue resistance.[19] These 2 anatomical characteristics (narrower tracheal diameter and weak dorsal membrane) likely contribute to fatigue that leads to stent fracture in this particular location.

In our study, larger maximum tracheal diameter was found to be associated with fracture, but IT diameter alone was not a significant risk factor. Higher degree of tracheal diameter taper was associated with caudodorsal fracture. Correlation of IT OP with caudodorsal fracture indicated that higher OP of tracheal stents in dogs leads to a higher risk of stent failure. Therefore, stent fracture risk is highest in dogs with large maximum tracheal diameters and smaller IT diameters. This supports the hypothesis that tracheal diameter taper contributes to stent oversizing and increased risk of fracture in the location of the highest strain. Calculation of IT OP and tracheal taper can be performed while selecting the appropriate stent size based on the intraoperative PPV radiograph. A possible solution for cases with high IT OP and large degree of tracheal taper is a recently developed tapered nitinol SEMS (Duality Vet Stent, Infiniti Medical). These newer stents were not used in our study.

Exuberant inflammatory tissue growth into the lumen of the trachea after stent placement is a fairly common complication.[7,10,11,24] Tissue ingrowth can be detected by radiography before it becomes clinically

evident and may regress with treatment using antibiotics and high doses of corticosteroids.[5,21] If not detected early, dogs may require intubation and restenting.[25] Tissue ingrowth can occur >4 years after stent placement, which indicates the need for life-long survey radiography (currently recommended every 3 months). We hypothesize that dogs with malformation type collapse are more likely to develop inflammatory tissue because of the persistence of gaps or gutters between the stent and the tracheal mucosa. These gaps may prevent complete epithelialization of the stent, allow buildup of mucus, and predispose to a hyperinflammatory and possibly infected environment. Malformation-type collapse dogs that were affected by tissue ingrowth (7/10) were not a significantly higher proportion (P = .30) compared to the malformation-type collapse dogs without tissue ingrowth (20/42). No predictive associations were identified among tracheal dimensions, stent size, and tissue ingrowth.

Although stent shortening has been reported as a major complication that may be related to progressive collapse in other studies,[10,21] a subgroup of the 52 study dogs was previously evaluated for stent shortening and long-term mean shortening was found in <10%.[18] In our study, progressive collapse was because of stent selection not secondary to shortening of the stents. Early in the study period, dogs with tracheal malformations were treated with shorter stents spanning only the region of the malformation. These dogs were younger, and over the course of years, the collapse progressed beyond the stent margins. The 6 severe cases, 5 of which were tracheal malformations, ultimately required another longer stent to be placed. Later in the study period, dogs with malformation were treated using longer stents during the first procedure to prevent this complication. In the single traditional TC case, collapse was severe beyond the stent and a longer stent had to be placed.

Our study had limitations inherent in a retrospective study including inconsistent follow-up examinations and unknown causes of death in many cases. Stent complications were assumed to be mutually exclusive, which generally has been our experience clinically, but some patients do experience >1 major complication. Another limitation of the study is that calculations are based on the assumption that the stents expanded to the diameter of the trachea measured on prestent PPV radiographs. It is possible that stents actually may have expanded more or less than expected, which may be a source of error. Although tracheoscopy was not performed in all cases, complete obliteration of the tracheal lumen was identified on fluoroscopic imaging during negative pressure ventilation, which indicates that all dogs were affected with grade 4 TC.

Our results supported the hypothesis that risk of stent fracture, specifically in the caudodorsal region of the stent, is increased with a higher degree of stent oversizing in that region. Tapered stents offer a possible solution to caudodorsal stent fracture and warrant further assessment. We also hypothesized that tracheal malformation would be a risk factor for exuberant tissue ingrowth, which was not confirmed by the data, perhaps because of the small number of cases or the emphasis placed on eliminating any gaps or gutters during stent placement. A higher power study is required to further evaluate the effect of TCS type on stent-related complications. Stents are oversized throughout the

tracheal lumen to prevent migration and decrease gaps between the stent and tracheal wall so as to encourage epithelialization and minimize mucus accumulation. Tapered tracheas inevitably will result in considerably oversized stents within the IT trachea unless tapered stents are utilized in the more severely affected dogs.

CONFLICT OF INTEREST DECLARATION

Dr. Weisse is a consultant for Infiniti Medical, LLC.

OFF-LABEL ANTIMICROBIAL DECLARATION

Authors declare no off-label use of antimicrobials.

INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE (IACUC) OR OTHER APPROVAL DECLARATION

Authors declare no IACUC or other approval was needed.

HUMAN ETHICS APPROVAL DECLARATION

Authors declare human ethics approval was not needed for this study.

ORCID

Nathaniel P. Violette https://orcid.org/0000-0002-7108-2774

Chick Weisse https://orcid.org/0000-0001-5202-9962

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