RESEARCH PAPER

Retrospective computed tomography analysis of endotracheal tube constriction and mispositioning in cats and dogs

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Abstract

Objective To discover the prevalence of endotracheal tube (ETT) constriction and rostral and caudal mispositioning in anaesthetized cats and dogs, and to identify associated risk factors.

Study design Retrospective analysis.

Animals A total of 146 cats and 670 dogs.

Methods Computed tomography images of the head/neck/thorax from orotracheally intubated cats and dogs were visually assessed for constriction or mispositioning of the ETT. If constriction was present, measurements of the cross-sectional area (CSA) of the ETT lumen at constricted and un-constricted locations were compared. Location and cause of constriction were noted and the expected increase in resistance to gas flow was calculated. Animal information was collected from clinical records. Normality of continuous variables was assessed via the Shapiro–Wilk test. Chi-square tests examined associations between variables. Kendall's tau-b test was performed between measured ETT size and degree of constriction.

Results The ETT extended rostrally beyond incisors in 52% of cases; the connector was within the oral cavity in 19% of cases. The ETT extended beyond the first rib in 25.5% of cases. The prevalence of ETT constriction was 22.7%. Median reduction in CSA was 7.68% (0.14–64.19%). Median increase in resistance assuming laminar and turbulent flow was 16.5% (0.3–680%) and 21% (0.3–1200%), respectively. The most common cause of constriction was the presence of a radiotherapy mouth gag. Significant associations existed between presence of constriction and rostral mispositioning, and caudal mispositioning and extreme brachycephaly. Increased severity of constriction was more likely in smaller ETT.

Conclusions and clinical relevance Constriction and mispositioning of ETT occurred very commonly in this population. Checking the ETT within the oral cavity for constriction and mispositioning is recommended. Radiotherapy mouth gags increase the risk of ETT compression. Smaller ETT are at greater risk of severe constriction. Brachycephalic dogs are at particular risk of caudal mispositioning.

Keywords anaesthesia, cats, complications, dogs, intubation, trachea.

Introduction

Orotracheal intubation is standard practice in canine and feline anaesthesia. Endotracheal tubes (ETT) facilitate the delivery of anaesthetic gases and oxygen, ensure patency of the upper airway, and can protect the respiratory tract from aspiration of gastric contents (Mosley 2015; Hughes 2016). However, endotracheal intubation is not a benign procedure. In humans, iatrogenic tracheal mucosal damage and stenosis are risks of orotracheal intubation (Evans et al. 2015), and obstruction of ETT and endobronchial intubation are reported (Szekely et al. 1993).

Complications with ETT may result in a risk to veterinary patient safety. A reduction in the size of the ETT lumen increases resistance to gas flow and consequently the work of breathing (Shapiro et al. 1986), and may lead to hypercapnia, hypoxaemia (via hypoventilation) and pulmonary oedema if severe (related to negative pressure in the alveoli) (Dicpinigaitis & Mehta 1995; Bhaskar & Fraser 2011). Endobronchial intubation can cause hypercapnia and hypoxaemia (Owen & Cheney 1987; Bissinger et al. 1989). An ETT that protrudes rostrally beyond the oral cavity produces unnecessary apparatus dead space, predisposing to rebreathing of carbon dioxide and hypercapnia (King & Feldman 2017). Conversely, an ETT with the connector residing within the oral cavity may cause handling difficulties for personnel when connecting breathing systems.

Case reports in cats and dogs describe incidents of tracheal injury from orotracheal intubation and ETT cuff overinflation (Alderson et al. 2006; Hofmeister et al. 2007). Tracheal rupture as a result of orotracheal intubation is also reported in cats (Mitchell et al. 2000). There are relatively few reports of ETT constriction and mispositioning in animals: ETT obstruction caused by kinking (Aguilar et al. 2017) and occlusion from blood clots (Küls & Murison 2015) are reported in dogs.

The utility of computed tomography (CT) imaging in assessment of ETT patency and detection of reductions in ETT cross-sectional area (CSA) has been demonstrated (Pinciroli et al. 2013; Mietto et al. 2014). Diagnostic CT imaging of the head, neck and thorax of orotracheally intubated cats and dogs provides a readily available resource for the evaluation of ETT constriction and mispositioning.

Knowledge of the prevalence of mispositioning and constriction of ETT in cats and dogs may inform clinical management. Awareness of the causes of ETT constriction presents an opportunity for prevention. The objectives of this study were to discover the prevalence of ETT constriction and rostral and caudal mispositioning in anaesthetised cats and dogs, and to ascertain risk factors for these problems. The authors expected to find rostral mispositioning and constriction caused by ETT ties in some cases (as observed clinically).

Materials and methods

This study received ethical approval from the University of Glasgow Research Ethics Committee (reference EA17/20). Retrospective analysis of CT images of anaesthetised cats and dogs from one University referral hospital between 2017 and 2019 inclusive was performed. A 3 year period was chosen to provide a representative sample of the hospital caseload and provide large numbers of images for analysis. Images were produced by a multislice scanner (Somatom Spirit; Siemens Healthineers, Germany) as Digital and Communication in Medicine (DICOM) files and reconstructed with bone windows for analysis by specialised medical imaging software (Clear Canvas; Synaptive Medical, ON, Canada). Inclusion criteria comprised any cat or dog undergoing CT imaging of the head and/or neck and/or thorax for any reason with an ETT *in situ*. A single observer (veterinary anaesthesia resident, trained in use of the software and targeted image interpretation by a Diplomate radiologist) assessed all images and performed all measurements in a transverse plane via the imaging software.

Rostral positioning was assessed in image sets of the entire head that included the tip of the nose and mouth. An ETT was defined as 'too rostral' when the body of the ETT extended beyond the incisors. Connectors of ETT positioned within the oral cavity were noted. An ETT was considered optimally rostrally positioned if the connector was present at the level of the incisors. Caudal mispositioning was assessed in image sets of the thorax showing the caudal tip of the ETT and was so defined if this extended beyond the first rib. The number of ribs each caudally mispositioned ETT extended to was counted, and ETT reaching the carina were noted. The ETT lumen was visually assessed for any constriction, and the location and apparent cause were noted. For cases showing constriction, measurements of the CSA of the ETT lumen were performed at the narrowest location and a normal (non-constricted) location that was free of image artefact. Degree of constriction was calculated as a percentage reduction in CSA between the two measurements. In cats, presence of a cuffed ETT was defined according to the detection of a pilot balloon or inflation tube within the ETT wall. A case was categorised as 'radiotherapy planning' if characteristic oral inserts - 'gags' — and a moulded plastic mask were visible in CT images of the head (Supplementary Figs S1a & b). This category was defined to facilitate separate analysis because in most of these cases, the ETT extended beyond the incisors deliberately to permit connection to the breathing system through a moulded mask.

For ETT exhibiting constriction, the expected increase in the magnitude of resistance to gas flow was calculated. This was achieved by comparing the constricted CSA with the non-constricted CSA, as an effect on ETT radius. The measured CSA was converted to a theoretical ETT radius via the following equation:

$$\text{Radius} = \sqrt{(CSA/\pi)}$$

Using the calculated radius, the expected change in magnitude of resistance was then estimated for both laminar and turbulent flow using the following equations:

For laminar flow: Resistance increase (%) $= [(\frac{1}{X})^4] \times 100 - 100$

For turbulent flow: Resistance increase (%) $= [(\frac{1}{X})^5] \times 100 - 100$

Where x = reduction in (calculated) radius due to (measured) constricted CSA.

Clinical and anaesthetic records were used to search for species, breed, age, body weight, presenting complaint, procedure, ETT size and recorded complications. French Bulldogs, Pugs and Bulldogs were classified as 'extreme brachycephalics' (Ladlow et al. 2018).

Statistical analysis

Data were analysed using SPSS Statistics for Mac 28.0 (IBM, NY, USA). Continuous variables were assessed for normal distribution using the Shapiro—Wilk test. Median (range) values and 95% confidence intervals (CIs) are reported. Chi-square tests were used to assess for associations between too-

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Table 1 The breeds and number (*n*) of individual animals included in a retrospective cohort of 816 cats and dogs undergoing computed tomography imaging of the head/neck/thorax with endotracheal tubes *in situ* from 2017 to 2019 inclusive at the University of Glasgow Small Animal Hospital. 'Other breeds' include those represented by fewer than three individuals.

Dogs	n
Labrador Retriever	78
Pug	50
Cocker Spaniel	38
Border Collie	30
French Bulldog	28
Staffordshire Bull Terrier	24
Springer Spaniel	24
Boxer	22
Labradoodle	19
Jack Russell Terrier	19
Golden Retriever	18
West Highland White Terrier	18
British Bulldog	18
Cavalier King Charles Spaniel	13
Lhasa Apso	13
Border Terrier	11
Siberian Husky	11
German Shepherd	11
Shih-Tzu	10
Rottweiler	10
Miniature Schnauzer	8
Chihuahua	8
Whippet	7
Pomeranian	7
Bernese Mountain Dog	6
Yorkshire Terrier	6
Beagle	6
Bull Mastiff	6
German Pointer	6
Rhodesian Ridgeback	5
Bichon Frise	4
Weimaraner	4
Bearded Collie	3
Cairn Terrier	3
Miniature Poodle	3
Tibetan Terrier	3
Hungarian Vizsla	3
Bassett Hound	3
Münsterländer	3
Other	41
Cats	
Domestic Short Hair	92
Persian	5
Bengal	4
Crossbreed cat	5
Domestic Long Hair	8
British Short Hair	8
Maine Coon	6
Ragdoll	4
Havana	3

(*continued on next page*)

Table 1 (*continued*)

Dogs	n
Unspecified	7
Other	12

rostral and caudal mispositioning with species, constriction and extreme brachycephaly, constriction with radiotherapy planning status, and constriction with cuffed tube status in cats. Radiotherapy cases were excluded from the association between too-rostral positioning and constriction. Strength of association is reported as φ. Kendall's tau-b test (τb) was performed between measured ETT size and degree of constriction. Statistical significance p was set at < 0.05.

Results

The total number of cases meeting the inclusion criteria was 816, comprising 146 cats and 670 dogs. Across all cases, 380 imaging sets of the head region, 438 of the neck region and 523 of the thoracic region were available for evaluation. Of the head image sets, 277 permitted assessment of the rostral ETT. Of the thoracic image sets, 515 permitted assessment of the caudal tip of the ETT (Supplementary Fig. S2). Assessment of both rostral and caudal ETTs was possible in 65 cases. No continuous variables showed normal distribution and so are presented as median (range). Bodyweight was 14.5 (1.5−77.7) kg, 95% CI: 12.9−16.7 kg. Age was 8 (0.3−19) years; 95% CI: 8−9 years. Included dog and cat breeds are summarized in Table 1. Extreme brachycephalic breeds comprised 14% of all dogs. There were 59 radiotherapy planning cases identified.

The overall prevalence of too-rostral mispositioning was 52% (145/277) for the entire population and 44% (95/218) excluding radiotherapy cases. Of the radiotherapy planning cases, 50 (85%) exhibited too-rostral mispositioning. The overall prevalence of ETT connectors residing within the oral cavity was 19% (52/277). Optimal rostral positioning was exhibited in 29% (80/277) of cases. The overall prevalence of caudal mispositioning was 25.5% (131/515); see Fig. 1a for the distribution of rib numbers reached by the caudal tip of the ETT. Of these, three ETTs reached the carina (0.6%), which was present at rib 5, 6 and 7 in these animals. No instances of endobronchial intubation were found.

There was no statistically significant association between rostral mispositioning and species ($p = 0.244$) or extreme brachycephaly ($p = 0.148$). With radiotherapy cases excluded, there was a statistically significant association between rostral mispositioning and presence of constriction, $\chi2 = 34.45$, $\varphi = 0.398$ and $p < 0.001$. Table 2 shows the distribution of causes of constriction in this cohort.

There was a statistically significant association between caudal mispositioning and species, with dogs being more likely

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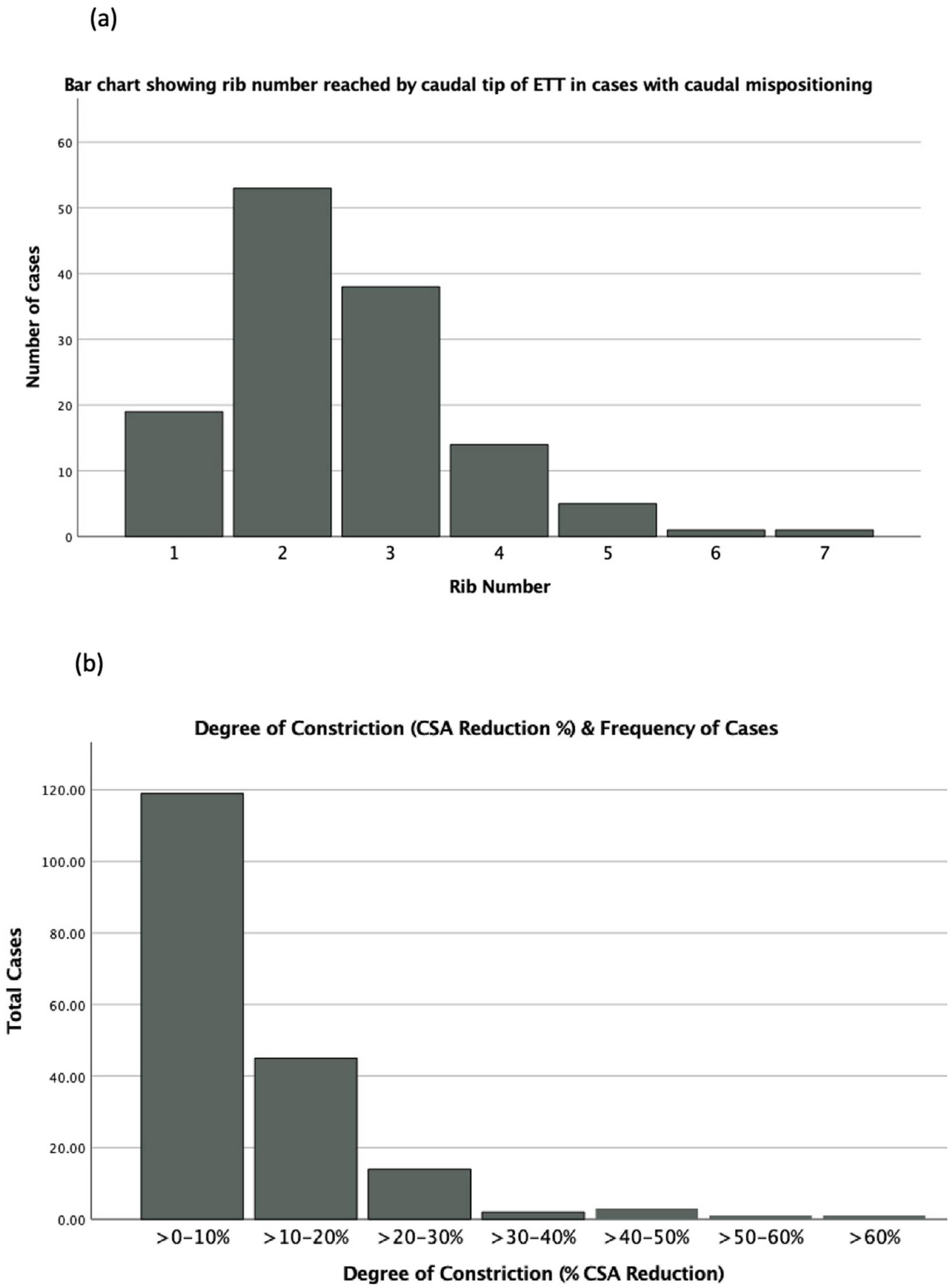

Figure 1 (a) Bar chart showing rib number reached by the caudal tip of the endotracheal tube (ETT) in 131/515 cats and dogs undergoing computed tomography (CT) imaging of the head/neck/thorax from 2017 to 2019 inclusive at the University of Glasgow Small Animal Hospital. In 384 cases, the caudal tip of the ETT did not extend beyond the first rib. (b) Bar chart showing severity of constriction of ETT lumen in 185/816 cats and dogs undergoing CT imaging of the head/neck/thorax from 2017 to 2019 inclusive at the University of Glasgow Small Animal Hospital. Degree of constriction measured by percentage reduction in ETT cross-sectional area (CSA). In 631 cases, there was no constriction of the ETT lumen.

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Table 2 Causes of constriction of the endotracheal tube (ETT) lumen with concurrent rostral mispositioning (ETT extends beyond rostral incisors) in 94/816 (*n*) cats and dogs undergoing computed tomography imaging of the head/neck/thorax from 2017 to 2019 inclusive at the University of Glasgow Small Animal Hospital.

Site/cause of constriction		Cases (*n*)
'Oral' (unidentified)		18
Larynx		10
Tie		11
Gag		20
Teeth	Incisors	16
	Canines	1
	Molars	18

to have too-caudally positioned ETT, $\chi 2 = 6.168$, $\varphi = 0.109$ and $p = 0.013$. There was a statistically significant association between caudal mispositioning and extreme brachycephaly, $\chi 2 = 14.232$, $\varphi = 0.183$ and $p < 0.001$. There was no statistically significant association between caudal mispositioning and constriction ($p = 0.345$).

Apparent constriction was present in 191/816 ETT; however, in six of these cases, no actual reduction in CSA was found, so they were excluded from all further analyses. The overall prevalence of true ETT constriction was 22.7% (185/816); with a prevalence of 22.4% in dogs (150/670) and 24% in cats (35/146). There was no statistically significant association between species and presence of constriction ($p = 0.679$). The frequency of constriction was similar in cuffed and plain (non-cuffed) ETT in cats. Constriction was exhibited in 46 (78%) radiotherapy planning cases. Prevalence and severity of constriction according to cause are presented in Table 3. The most common site for ETT lumen constriction was within the oral cavity, caused by the presence of a radiotherapy mouth gag, compression from the ETT tie or teeth. The larynx was the site of constriction in 27 cases. Severity of constriction for all causes is presented in Fig. 1b. Fig. 2 shows example images.

There was a significant association between severity of constriction and ETT size, $\tau b = -0.111$, $p < 0.001$: smaller ETTs showed an increased severity of constriction. Table 4 shows the median reductions in CSA and expected increase in resistance according to ETT size category. There was a statistically significant association between presence of a radiotherapy mouth gag and presence of constriction, $\chi 2 = 107$, $\varphi = 0.362$ and $p < 0.011$.

The median decrease in CSA due to constriction was 7.9% (0.14−64.2%), 95% CI: 6.0−9.0%. The median increase in expected resistance due to ETT constriction at laminar flow was 16.5% (0.3−680%); 95% CI: 12.2−19.2%, and at turbulent flow was 21% (0.3−1200%); 95% CI 15.5−24.5%.

Discussion

Our results indicate that constriction and mispositioning of ETTs were observed very commonly in this population of cats and dogs. Caudal mispositioning of ETT risks endobronchial intubation, which can cause significant morbidity including hypoxaemia (Bissinger et al. 1989), hyperinflation of the intubated lung and pneumothorax (McCoy et al. 1997). The basis for defining caudal mispositioning in this study comes from the description of proper ETT placement in animals as outlined by Lumb & Jones (Mosley 2015). According to this description, the ETT should not extend beyond the thoracic inlet. The first rib designates the thoracic inlet and was easy to identify on CT imaging. It was uncommon for the caudal tip of the ETT to reach the carina, and most of the caudally mispositioned ETTs extended only to the second rib. However,

Table 3 Causes of constriction of the endotracheal tube (ETT) lumen in 185/816 cats and dogs undergoing computed tomography imaging of the head/neck/thorax. Severity of constriction was measured by percentage reduction in ETT cross-sectional area (CSA), with associated expected increase in resistance assuming laminar and turbulent flow. Prevalence (total cases = number of cats and dogs). In 631 cases, there was no constriction of the ETT lumen. CI = confidence interval.

			Reduction in CSA (%)			Increase in resistance assuming laminar flow (%)			Increase in resistance assuming turbulent flow (%)		
Type	Cause	Total cases	Median	Range	95% CI	Median	Range	95% CI	Median	Range	95% CI
All	**All**	185	7.9	0.1−64.2	6.0−9.0	16.5	0.1−680	12.2−19.2	21.0	0.3−1200	15.5−24.5
Intraluminal	**Material in ETT**	6	14.6	8.4−64.2	8.4−64.2	37.6	19−680	19−680	49.1	25−1200	25−1200
Extraluminal	**Radiotherapy mouth gag**	40	8.0	0.8−43.3	4.1−9.2	18.2	2−211	8.7−21.2	23.3	2−313	11−27.2
	Oral (unidentified)	39	11.1	0.6−36	4.8−14.6	26.8	1−144	10.4−37.2	34.5	2−206	13.1−48.5
	Tie	37	9.2	0.6−45.8	6.0−14.5	21.4	1−240	13.1−36.8	27.4	2−362	16.6−47.9
	Teeth	35	6.7	0.1−42.9	3.6−9.9	14.7	0.1−206	7.6−23.3	18.7	0.3−305	9.6−29.9
	Larynx	27	3.3	0.3−56.8	1.8−4.7	7.0	0.1−435	3.7−10.1	8.8	1−714	4.6−12.8

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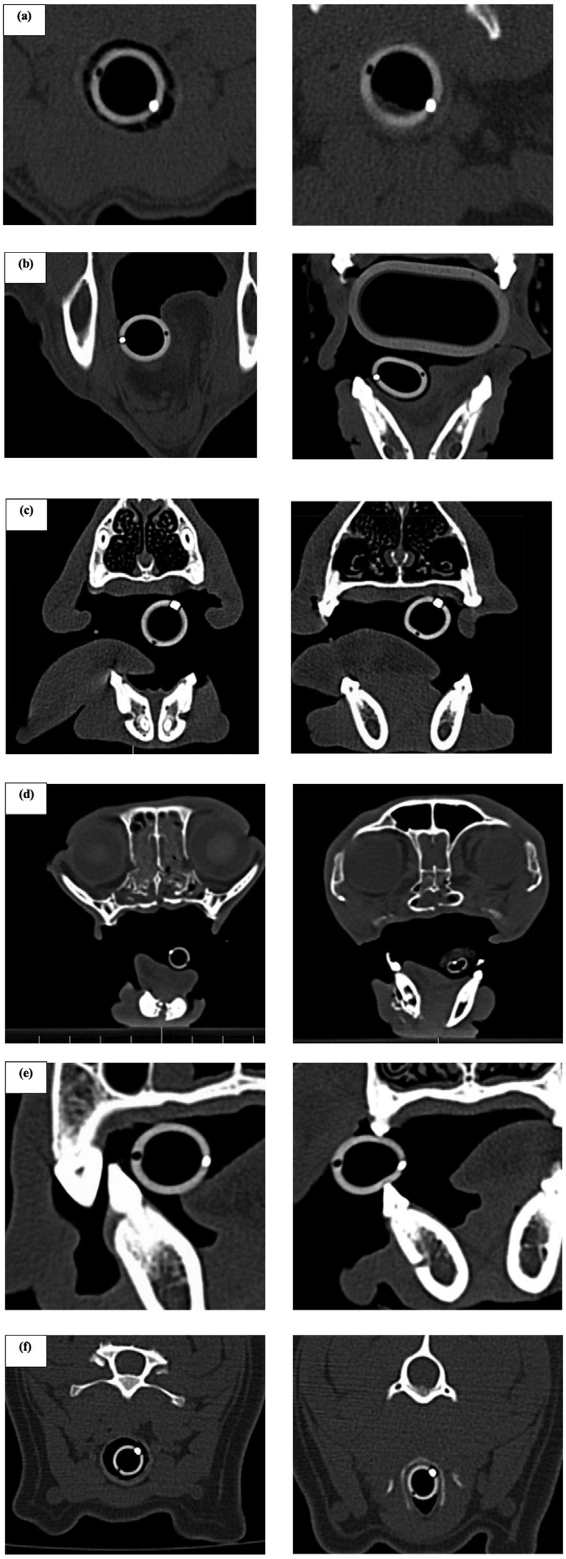

Figure 2 Example images of different causes of constriction of endotracheal tubes (ETT) found in 185/816 cats and dogs undergoing computed tomography imaging of the head/neck/thorax from 2017 to 2019 inclusive at the University of Glasgow Small Animal Hospital. In 631, cases there was no constriction of the ETT lumen. Left hand image: 'normal' un-constricted ETT, right hand image: constricted ETT. (a) Intraluminal constriction due to material within the ETT lumen. (b) Constriction due to radiotherapy mouth gag. (c) Cause of constriction unidentified but within oral cavity. (d) Constriction due to ETT tie. (e) Constriction due to teeth. (f) Constriction at larynx.

caudal movement of ETTs within the trachea equalling the length of up to six vertebral bodies has been demonstrated with neck flexion in dogs (Quandt et al. 1993), so any ETT could migrate caudally, especially when an animal is repositioned.

Caudal mispositioning was more common in dogs, suggesting better estimation of appropriate ETT length in cats. This may be explained by the greater variability in body size and tracheal length in dogs, making ETT length selection more difficult. Measurement of the larynx to first rib distance is proposed for optimal ETT insertion length in cats (Rodriguez et al. 2022), but considerable variation in head and/or nose size might reduce the applicability of this measurement for dogs. Pugs, French Bulldogs and Bulldogs collectively showed a greater prevalence of caudal mispositioning. This may be a result of the combination of relatively larger heads, shorter noses and necks typical of these breeds leading to overestimation of appropriate ETT length. Assessing intended ETT against the nose to thoracic inlet distance is especially advised in these dogs.

Rostral mispositioning could only be assessed in cases including complete imaging of the rostral oral cavity, therefore the true prevalence could differ from our findings. The description of ETT placement in Lumb & Jones recommends that ETT do not emerge beyond the incisors (Mosley 2015). In practice, an ETT emerging rostrally from the oral cavity may facilitate handling and connection of the breathing system. This was indeed the case in most of the radiotherapy planning cases, where presence of a plastic head mask [see Supplementary Figure S1(b)] necessitated protrusion of the ETT beyond the incisors to enable connection to the breathing system. However, the convenience of rostral mispositioning should be weighed against the increased apparatus dead space, predisposing to the rebreathing of carbon dioxide and hypercapnia (King & Feldman 2017). It was not possible to quantify the length of the protrusion in our study, as many of the CT head images did not include the rostral part of the tube. If the connector of the ETT were situated within the oral cavity, as seen in 51 cases in this study, connecting the breathing system may be more difficult and accidental disconnection more likely to occur.

An association between too-rostral positioning and constriction of ETT was demonstrated in this study. There is more risk of compression by teeth when ETTs protrude from the mouth. Molars and incisors were similarly responsible for

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Table 4 Average constriction of the endotracheal tube (ETT) lumen in 185/816 cats and dogs undergoing computed tomography (CT) imaging of the head/neck/thorax as measured by percentage reduction in ETT cross-sectional area (CSA). Calculated increase in resistance assuming laminar and turbulent flow, according to size category of ETT. In 631 cases, there was no constriction of the ETT lumen. CI = confidence interval.

Size category (ETT internal diameter, mm)	Median (range) reduction in CSA (%)	95% CI for median reduction in CSA (%)	Median (range) increase in resistance assuming laminar flow (%)	95% CI for median increase in resistance assuming laminar flow (%)	Median (range) increase in resistance assuming turbulent flow (%)	95% CI for median increase in resistance assuming turbulent flow (%)
< 4.0	18.6 (1.9–43.5)	4.0–28.7	52.0 (4.0–210.0)	8.0–97.0	69.0 (5.0–313.0)	11.0–133.0
4.0–6.5	10.8 (0.4–45.8)	8.0–13.9	26.0 (1.0–240.0)	18.0–35.0	33.0 (1.1–362.0)	23.0–45.0
> 6.5–9.0	8.2 (0.3–56.8)	5.7–10.1	19.0 (1.0–435.0)	13.0–24.0	24.0 (1.1–714.0)	16.0–31.0
> 9.0	4.5 (0.1–64.2)	3.5–7.1	10.0 (0.1–680.0)	7.0–16.0	12.0 (0.3–1200.0)	9.0–21.0

constriction of ETT suggesting that rostrally mispositioned ETT may also be predisposed to lateral displacement. Optimal rostral positioning is achieved by ensuring the ETT connector is situated centrally within the oral cavity (thereby avoiding the molars) and sits at the level of the incisors. It eliminates the risk of compression by the teeth and minimizes apparatus dead space, whilst optimizing handling. A visual check of the ETT for optimal rostral positioning should be performed in every anaesthetised animal.

The severity of ETT constriction (CSA percentage reduction) varied considerably both within and between cause categories. It is difficult to predict the clinical effects of a reduction in ETT CSA, as they will depend on an individual animal's characteristics, but the implications are probably dictated by their effect on resistance to gas flow. Calculation of the expected increase in the magnitude of resistance was therefore performed to illustrate a theoretical correlation between the degree of constriction and the clinical implications. In laminar gas flow, resistance is proportional to the fourth power of the radius of the ETT lumen (Bock et al. 2000), whereas in turbulent flow, resistance is proportional to the fifth power of the radius (Lofaso et al. 1992). The nature of gas flow is predicted by the Reynold's number (Re), a dimensionless characteristic as given by the following equation (Davis et al. 1995):

$$Re = \nu \rho d / \eta;$$

Where ν = linear velocity of gas, ρ = density of gas, d = internal diameter of ETT and η = viscosity of gas.

If Re < 2000, flow is likely laminar, while turbulent flow is probable at Re > 4000 (Henderson & Runcie 2017). Due to the retrospective nature of this study, exact values for the Reynold's number are unknown, although it is assumed that tracheal gas flow is likely turbulent (Dekker 1961). Sites of constriction further increase the likelihood of turbulent flow (Ahmed & Giddens 1983). Calculations were performed for each case of constriction assuming both laminar and turbulent flow to illustrate both possible scenarios.

Using experimentally derived data from El-Khatib et al. (2008), ETT of 7.5–8.0 mm internal diameter (ID) showed a baseline resistance of ~15 cm H_2O at the proximal end, and a clinically significant increase in resistance was designated as > 5 cmH_2O. With these values, an increase in resistance of approximately 33% (i.e. from 15 to 20 cmH_2O) would be considered 'clinically significant'. Using this definition, 24% of cases in this study exhibiting constriction assuming laminar flow and 32% of cases exhibiting constriction assuming turbulent flow would qualify as having a 'clinically significant' increase in resistance. Many cases had expected resistance increases of much more than 33% (the highest being a 1200% increase for one individual) despite modest median increases in resistance for the population. It is important to state that the

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calculations of resistance are theoretical and unlikely to reflect the situation *in vivo*, since the radius measurement derived from the measured CSA assumed a circle. This was not the case, as constriction of ETT was not concentric. Additionally, the range of ETT sizes in this study was much wider than those evaluated by El-Khatib et al. (2008), therefore the variables defining clinical significance may differ considerably. Clinically, even modest increases in resistance could exert deleterious clinical effects, and any degree of constriction of an ETT is undesirable (Redding et al. 1979). If very severe, complete obstruction of the ETT may occur, leading to hypoxaemia, pulmonary oedema (Dicpinigaitis & Mehta 1995; Bhaskar & Fraser 2011) and possible fatality.

The measured ETT size was negatively associated with the severity of constriction: ETTs with smaller IDs were more vulnerable to higher degrees of constriction (ETT ID was calculated from the measured non-constricted CSA). Table 4 shows the median decreases in CSA according to ETT size category: ETT < 4.0 mm ID showed the highest median reduction in CSA, and this decreased as ETT ID increased. Smaller diameter ETT are associated with an increased work of breathing (Bolder et al. 1986). Reducing the tube radius further in small-sized ETT is therefore likely to have a considerable impact on the work of breathing and produce a clinically detrimental effect.

Maximising the diameter of ETT placed in every animal would reduce the risk of constriction as well as the work of breathing exerted by the ETT itself, but this must be balanced against the risk of tracheal mucosal damage. The larynx was the site of constriction in 27 cases, suggesting insertion of an ETT that was too large in these individuals. Prediction of ETT size has received considerable attention in the veterinary literature, with several methods of estimation proposed including using body mass (Haider et al. 2019), nasal septal width, tracheal palpation (Lish et al. 2008) and cervical radiography (Shin et al. 2018) to inform choice. None of the methods tested produced perfect results and differences in suitability were evident between breeds, particularly for brachycephalic dogs. Using an ETT that fits through the larynx and advances into the trachea comfortably remains the most sensible approach to tracheal intubation.

In six cases out of 816, there was a change in shape of the ETT lumen, which gave an initial impression of constriction. However, subsequent measurements of normal and misshapen sections of these ETT had the same CSA. In five of the six cases, this occurred within the oral cavity and represented a distortion of the ETT lumen without any associated effect on lumen CSA. Distortion of the ETT is therefore possible without accompanying constriction of the lumen. However, this remains an uncommon finding.

Several causes of a reduced ETT CSA were identified. The largest median CSA reduction (and hence largest expected increase in resistance) was caused by the presence of material within the ETT lumen, but this was also the least frequent cause. The retrospective nature of this study meant the material identified on CT was unknown, but it was probably respiratory secretions or possibly saliva aspirated during induction. Identifying animals at risk of aspiration and identifying airway fluid via auscultation and suction of the ETT if appropriate are recommended to reduce the adverse effects of this complication.

The most common cause of ETT constriction was the presence of a radiotherapy mouth gag within the oral cavity. This finding represents a specific sub-population of animals in this study, undergoing CT planning for radiotherapy treatment of intracranial, intranasal or oral tumours. Solid plastic inserts ('gags') are placed in the mouth to separate the soft tissues in the oral cavity [see Supplementary Fig S1(a)] and create a uniform tissue field for the radiotherapy beam to penetrate (Larue & Gordon 2013). Additionally, custom-moulded plastic head 'masks' are applied, ensuring uniform positioning for each radiotherapy session [see Supplementary Fig S1(b)]. The combined presence of both structures poses a significant risk of compression of the ETT. These tools are required for successful and safe radiotherapy, but the ETT should be checked for constriction. Use of metallically reinforced ('armoured') ETT could be considered, but distortion of the metal structures can lead to permanent constriction (Aguilar et al. 2017) which could itself pose an additional risk. Armoured ETT may also cause artefact in CT images, making them unsuitable for the planning stage.

Compression of the ETT by the securing tie is avoidable, and personnel applying the tie should be mindful of its potential to constrict the tube. In 39 cases exhibiting constriction within the oral cavity, the cause was not evident from evaluation of the CT images and the cases were categorised as 'oral' (unidentified). In these cases, there was no contact with the teeth and no gag was present. The most plausible cause was therefore the ETT tie, but this could not be confirmed because of the lack of visual evidence. The prevalence of ETT tie constriction is therefore possibly higher than reported. Performing a visual check of the ETT once the tie is in place is recommended.

At our hospital, ETT are typically secured with stretch bandage material ('Knit-firm'; Millpledge Veterinary, UK) that is knotted onto the ETT or connector and then secured around the muzzle or behind the ears of the animal. There is no standard operating procedure for ETT size (ID) or length selection and the choice of ETT and orotracheal intubation differs between personnel. Management of ETT and tracheal intubation practices may differ amongst other institutions, which could result in different complication rates with ETT and reduce the applicability of our findings to wider populations, representing a limitation of this study.

An important limitation of this study was the fact that the entire length of the ETT could not be assessed in all animals due

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to a lack of CT images of all anatomical areas. As a result, findings for rostral and caudal mispositioning and constriction may not reflect the true prevalence in this population. Additionally, it was not possible to assess the impact of the rostral ETT connector on CSA reduction because this was infrequently included in the available images. Connectors are inserted into the ETT lumen, thereby reducing the CSA at this location. It is possible that the connector itself presented a greater impact on resistance than some of the more modest reductions in CSA found in this study, rendering them clinically insignificant when compared with an un-constricted ETT.

The material composition of the ETT may influence their vulnerability to constriction. At our hospital, silicone, polyvinyl chloride and (infrequently) red rubber tubes are utilised. Information regarding ETT material was not available for individual cases, and it was not possible to identify through CT imaging, although no armoured ETT were found.

The identification of constriction was made before measurements were taken, but the detection of very small CSA reductions suggests an adequate visual sensitivity for subtle cases. There were missing animal data for many cases in this study (such as body weight, procedure and presenting complaint), preventing meaningful assessment of these variables. Although no complications recorded were directly attributed to the ETT, clinical abnormalities noted on the anaesthesia records such as hypercapnia and hypoxaemia were not assessed, preventing the opportunity to link observed constriction and mispositioning of ETT with potential clinical effects.

The images evaluated in this study only represent a single point in time that is not necessarily reflective of the entire anaesthetic period, so results are unlikely to reflect the true prevalence of complications in the population studied. Although the prevalence of tube tie compression is unlikely to have changed after CT imaging, intraluminal narrowing could occur later in anaesthesia with accumulation of respiratory secretions, and dental compression could occur or resolve following animal repositioning. Gradual warming of ETT from body temperature could lead to softening of the tube material (Busaidy et al. 2011), which may predispose to deformity from compressive forces. Tube constriction associated with gag placement will have resolved on removal.

Conclusions

Constriction and mispositioning of the ETT occurred very commonly in this population of dogs and cats. The use of radiotherapy mouth gags carries a significant risk of ETT compression. Smaller ETTs carry a greater risk of severe constriction. Brachycephalic dogs are at increased risk of caudal mispositioning of the ETT.

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Authors' contributions

FL: study design, data collection, statistical analysis, data interpretation, preparation of manuscript. JR: data interpretation, preparation and critical appraisal of manuscript. PJM: study design, data interpretation, preparation and critical appraisal of manuscript.

Conflict of interest statement

Authors declare no conflict of interest.

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Supporting Information

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