



AKADÉMIAI KIADÓ

Acta Veterinaria
Hungarica

70 (2022) 3, 192–200

DOI:
[10.1556/004.2022.00018](https://doi.org/10.1556/004.2022.00018)
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RESEARCH ARTICLE



Retrospective analysis of tracheal hypoplasia in brachycephalic and non-brachycephalic dogs: Inter- and intra-observer agreement of measurements

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Received: 11 October 2021 • Accepted: 21 July 2022
Published online: 5 September 2022

ABSTRACT

This retrospective study was undertaken on the records of intraluminal diameter of the trachea in 185 dogs, in which hypoplasia of the trachea had been suspected. The relative size of the trachea was measured using the tracheal diameter (TD), thoracic inlet distance (TI), thoracic tracheal diameter (TT) and the width of the third rib (3R), expressed as ratios TD:TI and TT:3R. Thirty-five dogs were diagnosed as having tracheal hypoplasia. Bulldogs and non-bulldog brachycephalic dogs had significantly smaller measured trachea diameters compared to the predicted values calculated on the basis of their body weight. Radiographs of each dog were investigated by four observers. Inter- and intra-observer reliability (ICC_{inter} , ICC_{intra}) was based on the measurements taken by four observers to evaluate the reproducibility of the protocol. There was a good ICC_{inter} (0.8) and ICC_{intra} (0.89) agreement. Craniocaudal tangential radiographs, centred on the cranial thoracic aperture, did not show a significant difference in tracheal diameter measurements compared to the right lateral radiographs. In conclusion, our findings indicate that bulldogs and non-bulldog brachycephalic dogs have smaller tracheal diameters than non-brachycephalic dogs.

KEYWORDS

brachycephalic airway syndrome, bulldogs, diagnostic imaging, hypoplastic trachea, pugs

INTRODUCTION

Tracheal hypoplasia is a congenital condition described with high incidence in brachycephalic dog breeds and concurrent findings in many patients with brachycephalic obstructive airway syndrome (BOAS). English bulldogs have the highest incidence of hypoplastic trachea within brachycephalic breeds (55%) (Harvey and Fink, 1982; Mason, 2004; Clarke et al., 2011; Kaye et al., 2015). Apposed or overlapping tracheal cartilages and a shortened or absent dorsal tracheal membrane are common findings. This typically involves the whole trachea,

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with a uniformly narrowed lumen from the larynx to the carina which does not vary with dynamic pressure changes during respiration (Rudorf et al., 1997; Clarke et al., 2011; Coulson and Lewis, 2011). The described clinical signs are similar to those for BOAS and include dyspnoea, stridor, coughing, gagging, choking, exercise intolerance and syncope (Bartels et al., 2015; Liu et al., 2015). It is also important to evaluate the diameter of the trachea in dogs with brachycephalic syndrome, since the diagnosis of hypoplastic trachea worsens the prognosis. Tracheal shape is believed to have evolved in part toward minimising respiratory work. In dogs with small tracheal luminal diameter, linear velocity of air increases exponentially, and tracheal resistance increases as the diameter decreases (Liu et al., 2016).

The activity of the trachealis muscle has been reviewed (Leonard et al., 2009; Evans and Lahunta, 2013). Contraction of the trachealis muscle causes tracheal constriction. It has been suggested that the cartilaginous rings are the equivalent of a tracheal dilator muscle, causing an increase in tracheal lumen when the trachealis muscle relaxes because of a bow and bowstring mechanism. In dogs with congenital hypoplastic trachea, the tips of the tracheal rings overlap, eliminating the function of the trachealis muscle. A small trachea contributes less dead space but more turbulence because of greater linear velocity of the airflow.

Imaging modalities available for tracheal evaluation include radiography (Macready et al., 2007; Montgomery et al., 2015), ultrasonography (Rudorf et al., 1997; Eom et al., 2008), computed tomography (CT) (Kara et al., 2004; Standler et al., 2011), fluoroscopy (Macready et al., 2007; Weisse, 2015) and tracheobronchoscopy (Creevy, 2009). The latest studies in humans focus on magnetic resonance imaging (MRI) as the next imaging modality for evaluating the trachea (Priya and Mehra, 2014; Matsumoto and Ikeda, 2021). The benefits of the radiographic method are that it is able to show narrowing of whole tracheal lumen (Kneller, 2002; McConnell and Holloway, 2013), and it is independent of the size of the patient and phase of respiration; however, errors can occur if the patient is not properly positioned in lateral recumbency for the radiographic examination.

Two radiographic methods have been proposed for evaluating tracheal diameter dimensions in dogs. The first is based on the tracheal lumen diameter to thoracic inlet distance ratio (TD/TI), proposed by Harvey and Fink (1982), and the second on the ratio between the thoracic tracheal luminal diameter and the width of the proximal third of the third rib (TT/3R), proposed by Suter et al. (1972). Coyne and Fingland (1992) modified Suter's method by defining a ratio between the thoracic tracheal luminal diameter measured at the midpoint between the thoracic inlet and the carina (TT) and the width of the proximal third of the third rib (3R).

Comparison of the radiographic measurements of the thoracic inlet (TI) relative to the tracheal lumen (TD) and the width of the third rib (3R) to the tracheal lumen (TT) forms the basis for the diagnosis of tracheal hypoplasia. In normal English bulldogs the TD:TI ratio is 0.127, while it is 0.160 in non-bulldog brachycephalic dogs and 0.204 in non-

brachycephalic dogs. The ratio of the thoracic tracheal diameter to the width of the third rib in a small number of normal dogs in Suter's study was approximately 3:1. Values of either <2.0 or <3.0 are used in later literature as the definition of tracheal hypoplasia (Suter, 1984; Coyne and Fingland, 1992; Kaye et al., 2015).

Tracheal hypoplasia is most often diagnosed within the first year of life, with one study showing a median age of diagnosis of five months. Hypoplastic trachea may also be an incidental diagnosis in asymptomatic patients having thoracic radiographs taken later in life (Clarke et al., 2011).

Although tracheal hypoplasia is usually not accompanied with clinical signs in the absence of concurrent pulmonary disease, nor is it associated with unfavourable outcomes following corrective BOAS surgery, it is still seen as a negative prognostic indicator when found together with clinical BOAS, apart from in puppies affected with bronchopneumonia. For these reasons, it is not possible to predict what degree of hypoplasia might give rise to respiratory symptoms in brachycephalic breeds (Hendricks, 1992).

The objectives of this study were (1) to retrospectively determine and evaluate the TD:TI and TT:3R ratios in English bulldogs, in non-bulldog brachycephalic dogs and in non-brachycephalic dogs, also comparing the calculated predicted diameters of the tracheal lumen (2) to assess the reliability of the tracheal index relative to the actual size of the trachea and to compare our results with previously reported data; and (3) to evaluate intra-observer variability in the protocols developed for tracheal diameter measurements.

We hypothesised that there would be (1) significantly different size of the trachea in brachycephalic dogs and other dogs, (2) good intra-observer agreement for the values measured in this study, (3) a dependent relationship between the TD:TI and TT:3R ratios in dogs with hypoplastic trachea.

MATERIALS AND METHOD

This study was conducted at the Small Animal Clinic, University Veterinary Hospital in the University of Veterinary Medicine and Pharmacy in Košice, between November 2019 and December 2020.

Patients and data

Nine breeds (185 dogs) were included in this study: French Bulldog ($n = 35$), English Bulldog ($n = 13$), Pug ($n = 14$), Shih-tzu ($n = 16$), Boxer ($n = 18$), Rottweiler ($n = 15$), Yorkshire Terrier ($n = 25$), Chihuahua ($n = 30$), and Labrador Retriever ($n = 19$). The initial inclusion criterion in the study was dogs >12 months old. Patients were subsequently separated into three groups: category A (bulldogs and Pug, $n = 62$), category B (non-bulldog brachycephalic dogs, $n = 49$) and category C (non-brachycephalic dogs, $n = 74$). Predicted diameter of the tracheal lumen (TD_{pred}), determined on the basis of body weight, was calculated using the formula $(TD_{pred})_{cm} = 0.47 (Weight_{kg})^{0.39}$ (Leith, 1983) for 185 dogs with available body weight.



Tracheal measurements by radiography, computed tomography (CT) and magnetic resonance imaging (MRI)

Radiographs were acquired using a standard clinical X-ray unit (Gierth HF 200A, Gierth GmbH, Germany), digitised with a computed radiography viewing system (FCR Prima T2, CR-IR 392, Computed Radiography, Fujifilm Co., Tokyo, Japan) and saved as DICOM files. The neck was placed in an anatomically neutral position and the thoracic limbs were pulled cranially to minimise superimposition with the cranial thorax in right lateral recumbency using manual restraint without sedation or anaesthesia. The exposure settings were 45–80 kV, 1.20 mAs, and 4.20–10 ms. The focal distance was 110 cm. The radiographs were then divided into three categories: Category A (bulldogs and Pug), Category B (non-bulldog brachycephalic dogs) and Category C (non-brachycephalic dogs). The intraluminal tracheal diameters (TD, TT, TI) and third rib width (3R) were assessed by four observers. All radiographic measurements were repeated twice by all four observers, with a three-month interval. For each of the two assessments radiographs were presented in random order to help ensure on the second occasion that the observers were unaware of their initial values.

For each radiograph in right lateral recumbency (RLR), the intraluminal tracheal diameter at the thoracic inlet (TD) and the thoracic inlet distance (TI) were measured according to Harvey and Fink (1982) and Coyne and Fingland (1992). A line denoting the boundary of the thoracic inlet was drawn from the ventral aspect of the vertebral column at the centre of the most cranial rib to the dorsal aspect of the manubrium at its point of minimal thickness (Fig. 3). The tracheal diameter was then measured between the inner tracheal margins angled perpendicularly to the long axis of the trachea at the point where the thoracic inlet line intersected the centre of the tracheal lumen (Hayward et al., 2008). The thoracic intraluminal tracheal diameter (TT) and the width of the proximal third of the third rib (3R) were measured according to Suter et al. (1972) and Coyne and Fingland (1992). Radiographic TD:TI and TT:3R ratios were calculated as previously described.

For dogs ($n = 15$) with severe trachea narrowing, craniocaudal tangential radiographs were made with the beam centred on the middle of the *apertura thoracica cranialis* (ATC). One dog with the most severe narrowing of the trachea was referred for MRI and CT examination. For comparative purposes, the internal tracheal widths and heights were measured on transverse X-ray, CT and MRI images (Figs 2, 4 and 5).

Statistical analysis

All statistical analysis was performed using IBM SPSS Subscription 27 statistical software (IBM Corp[®], Armonk, NY).

All data were evaluated for normality with the Shapiro–Wilk normality test. Mann–Whitney coefficients were obtained to evaluate relationships between TD_{Pred} and TD.

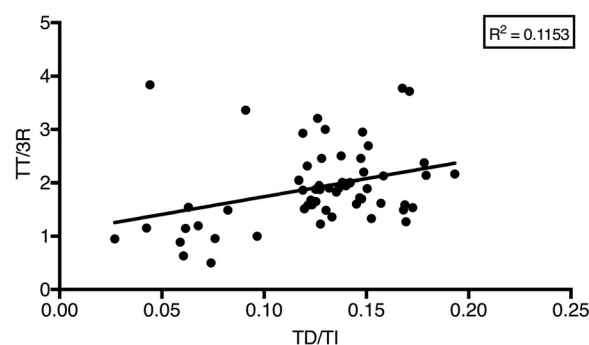


Fig. 1. Linear regression for ratios comparing radiographic tracheal parameters in dogs with hypoplasia of the trachea. TD = tracheal lumen diameter at the thoracic inlet, TI = thoracic inlet distance, TT = thoracic tracheal luminal diameter, 3R = width of the proximal third of the third rib

Statistical significance was set at $P = 0.05$. Linear regression analysis was performed to assess the relationships between TD:TI and 3R:TT, and was regarded as statistically significant when $P < 0.05$ and as very high when $R^2 > 0.900$ (Fig. 1).

Means and standard deviations (SD) for radiographic measurements TD, TI, TT, 3R and ratios TD:TI, TT:3R were calculated for each breed and group. Inter-observer and intra-observer variability in radiographic measurements was evaluated by means of two-way random single-measure intra-class correlation coefficients for absolute agreement (ICC 2.1). Inter-observer agreement was evaluated between observers separately according to breeds for all four radiographic measurements, for each breed separately, and total ICC_{inter} for each radiographic measurement (TD, TI, TT, 3R). Intra-observer agreement was evaluated for radiographic methods (TD, TI, TT, 3R) irrespective of breed. The purpose of intra-observer measurements in these methods was to evaluate their repeatability. The intra-class correlation coefficient (ICC 2.1) ranged from 0 (no agreement) to 1 (perfect agreement). The strength of agreement was interpreted as follows: <0.5 was regarded as poor reliability, values between 0.5 and 0.75 indicated moderate reliability, values between 0.75 and 0.9 indicated good reliability, and values greater than 0.90 indicated excellent reliability (Koo and Li, 2016).

RESULTS

Study population

The study involved 105 males and 80 females (a total of 185 dogs), aged between 1 and 18 years (6.16 ± 3.8 years) and weighing between 1.5 and 50 kg (18.25 ± 13.29 kg).

Tracheal measurements by radiography, CT and MRI

Radiographs from 185 dogs were evaluated during the study period. Radiographic measurements were performed by four observers. For the assessed breeds, means \pm SD for TD, TT, TI, 3R and ratios TD:TI, TT:3R are summarised in Tables 1 and 2. Calculated TD_{Pred} values are also shown in Table 1.



Table 1. Determined predicted tracheal lumen diameter and radiographic tracheal measurements (all dogs)

	Breed	n	Mean \pm SD				
			TD _{Pred}	TD	TI	TT	3R
Bulldogs – brachycephalic	French Bulldog	35	12.05 (\pm 1.02)	9.43 (\pm 2.83)	51.74 (\pm 10.56)	9.32 (\pm 2.89)	3.73 (\pm 1.13)
	English Bulldog	13	16.45 (\pm 1.17)	11.44 (\pm 6.68)	65.99 (\pm 14.04)	11.44 (\pm 3.33)	5.42 (\pm 1.12)
	Pug	14	10.19 (\pm 0.59)	6.68 (\pm 0.95)	43.48 (\pm 4.69)	7.05 (\pm 1.58)	3.06 (\pm 0.82)
Non-bulldog brachycephalic dogs	Shih-tzu	16	10.35 (\pm 0.70)	8.14 (\pm 2.58)	51.19 (\pm 5.86)	7.50 (\pm 1.25)	3.47 (\pm 0.82)
	Boxer	18	18.18 (\pm 1.05)	16.85 (\pm 4.16)	82.05 (\pm 16.67)	14.78 (\pm 4.92)	6.23 (\pm 2.35)
	Rottweiler	15	19.95 (\pm 0.10)	14.45 (\pm 2.74)	87.75 (\pm 5.31)	14.20 (\pm 4.90)	6.96 (\pm 2.62)
Non-brachycephalic dogs	Yorkshire Terrier	25	6.97 (\pm 0.93)	5.45 (\pm 2.40)	31.71 (\pm 9.44)	6.96 (\pm 2.59)	2.70 (\pm 1.23)
	Chihuahua	30	7.57 (\pm 1.05)	7.55 (\pm 2.12)	32.79 (\pm 5.59)	7.31 (\pm 1.48)	2.23 (\pm 0.53)
	Labrador	19	18.37 (\pm 1.67)	17.19 (\pm 1.25)	77.93 (\pm 17.54)	17.82 (\pm 5.47)	6.42 (\pm 1.71)
	Retriever						

Key: n = number in category, TD_{Pred} = predicted tracheal lumen diameter, TD = tracheal lumen diameter at the thoracic inlet, TI = thoracic inlet distance, TT = thoracic tracheal luminal diameter, 3R = width of the proximal third of the third rib, SD = standard deviation.

A total of 35 dogs (all of them from Groups A and B) were diagnosed with hypoplastic trachea, while 103 dogs were classified as those with non-hypoplastic trachea. Forty-seven dogs had varying classification and were from Group C (Yorkshire Terrier, n = 25 and Chihuahua, n = 22).

Tracheal internal width and height were measured at two points, in the thoracic inlet and the area of the third rib. Comparison of right lateral recumbency (RLR) radiography to craniocaudal radiography with the tangential beam centred on the ATC revealed no significant differences in measurements ($P < 0.18$). Figures 2 and 3 show representative radiographs in a female French bulldog from this study, obtained during the study period. Figures 4 and 5 show transverse CT and MRI images of the same dog, showing internal and external tracheal height and width measurements.

Statistical analysis

The predicted tracheal lumen diameter, compared to the measured tracheal lumen (TD_{Pred}), was significantly greater in all bulldogs ($P < 0.0001$), non-bulldog brachycephalic dogs ($P < 0.0001$) and in Yorkshire Terriers among the non-brachycephalic dogs (Table 3). Assessment of the relationships comparing TD:TI and TT:3R in dogs with hypoplastic trachea using linear regression was regarded as poor and not significant.

Table 2. Radiographic tracheal hypoplasia ratios (by breed)

Breed	Mean \pm SD	
	TD:TI*	TT:3R
French Bulldog	0.18 (\pm 0.04)	2.67 (\pm 0.78)
English Bulldog	0.17 (\pm 0.04)	2.12 (\pm 0.57)
Pug	0.15 (\pm 0.02)	2.47 (\pm 0.71)
Shih-tzu	0.16 (\pm 0.05)	2.33 (\pm 0.64)
Boxer	0.21 (\pm 0.03)	2.58 (\pm 0.57)
Rottweiler	0.16 (\pm 0.03)	2.15 (\pm 0.46)
Yorkshire Terrier	0.18 (\pm 0.06)	2.88 (\pm 0.76)
Chihuahua	0.23 (\pm 0.06)	3.64 (\pm 0.99)
Labrador Retriever	0.22 (\pm 0.04)	2.98 (\pm 0.74)

*Key: see Table 1.

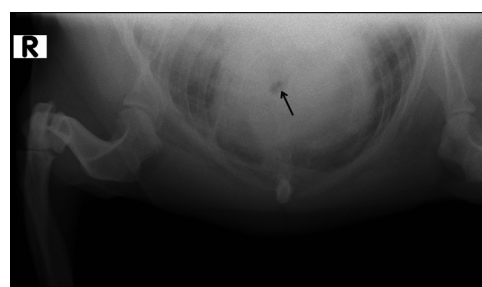


Fig. 2. Tangential radiographic view of a female French bulldog with severe hypoplasia of the trachea. Black arrow shows narrowed tracheal lumen; R: right side

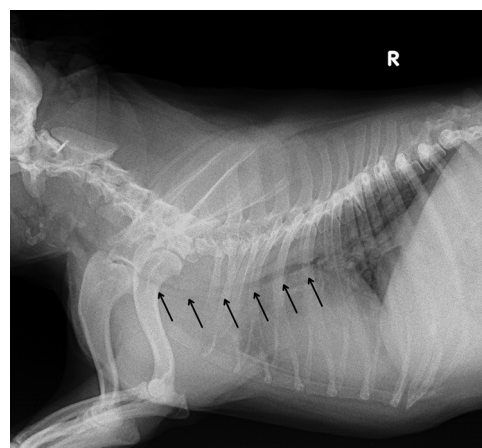


Fig. 3. Lateral radiographic view of a female French bulldog with severe hypoplasia of the trachea. Black arrows show narrowed tracheal lumen; R: right side

Inter-observer (ICC_{inter}) and intra-observer (ICC_{intra}) reliability of radiographic measurements

Estimates of the ICC_{inter} level comparing the four observers' results for each specific parameter (TD, TI, TT and 3R) of hypoplastic trachea (with cut-off ratios TD:TI < 0.127, 0.16, 0.20 and TT:3R < 2, respectively) are shown in Table 5. Overall ICC_{inter} was good (0.8). The overall ICC_{inter} was

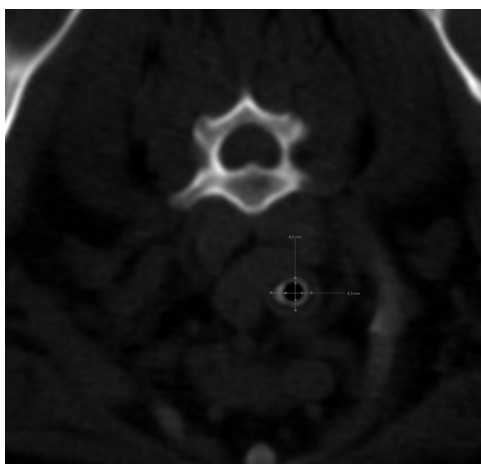


Fig. 4. Transverse computed tomographic (CT) image of the same female French bulldog. Figure showing internal and external tracheal height and width measurements at the *apertura thoracica cranialis* (ATC)

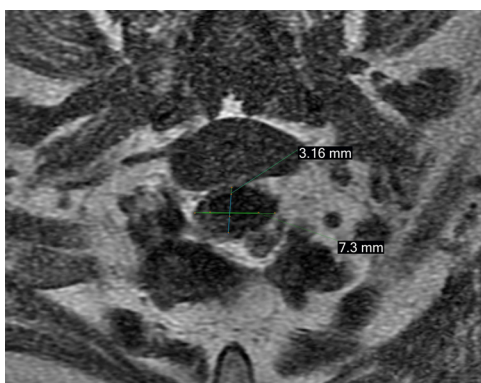


Fig. 5. Transverse magnetic resonance image (MRI) of the same female French bulldog. Figure showing internal and external tracheal height and width measurements at the *apertura thoracica cranialis* (ATC)

categorised as excellent for TI (0.94), good for TD (0.83) and TT (0.82), and moderate for 3R (0.61).

Table 5 summarises the values of ICC_{inter} for TD, TI, TT and 3R for each breed. For these radiographic parameters,

the overall ICC_{inter} was very good for the English Bulldog (0.94) and Rottweiler (0.94). For the Yorkshire Terrier (0.86), French Bulldog (0.81), Labrador Retriever (0.8), Shih-tzu (0.79) and Chihuahua (0.78) the ICC_{inter} values indicated good overall reliability. Moderate overall ICC_{inter} was assessed for Boxer (0.73) and Pug (0.62).

To assess the ICC_{intra} reliability for TD, TI, TT and 3R, the agreement between the two repeated measurements by each observer was determined. Table 5 summarises these values. The overall ICC_{intra} was very good for TD (0.93), TI (0.90) and TT (0.92), while for 3R it was 0.83, which indicated good overall reliability. Overall ICC_{intra} for these radiographic parameters was 0.89 and assessed as good (Table 4).

DISCUSSION

The diagnosis of hypoplastic trachea is expressed on the basis of radiographic values for the ratios TD:TI and TT:3R, and defined as TD:TI 0.127 for bulldogs, 0.16 for non-bulldog brachycephalic breeds and 0.20 for non-brachycephalic breeds, with TT:3R < 2 for all dogs. These relations have been previously reported and are easily identifiable (Harvey and Fink, 1982). This study provides comprehensive quantitative radiographic data which can be used for future objective analyses of the trachea in brachycephalic and non-brachycephalic dogs.

The trachea of dogs of different breeds and different ages was assessed by Harvey and Fink (1982) on 82 dogs and then by Coyne and Fingland (1992) on 103 dogs. The authors concluded that brachycephalic dogs have a significantly smaller trachea than non-brachycephalic dogs, and bulldogs have a significantly smaller trachea than other brachycephalic dogs. The ratios TD:TI reported by Harvey and Fink (1982) are lower than the mean TD:TI values found in our study, namely 0.17 for category A, 0.18 for category B and 0.21 for category C.

Tracheal lumen diameter is proportional to the 3/8 power of body mass in mammals over a wide range of size, with variability among species, based on the formula (D_{pred}) $cm = 0.47 (Weight_{kg})^{0.39}$ (Leith, 1983). The value TD_{Pred}

Table 3. Predicted tracheal lumen diameter compared with radiographic tracheal lumen measurement

	Breed	n	Mean ± SD		
			TD _{Pred}	TD	P
Bulldogs	French Bulldog	35	12.05 (±1.02)	9.43 (±2.83)	<0.0001 ^a
	English Bulldog	13	16.45 (±1.17)	11.44 (±6.68)	<0.0001 ^a
	Pug	14	10.19 (±0.59)	6.68 (±0.95)	<0.0001 ^a
Non-bulldog brachycephalic dogs	Shih-tzu	16	10.35 (±0.70)	8.14 (±2.58)	<0.009 ^a
	Boxer	18	18.18 (±1.05)	16.85 (±4.16)	<0.007 ^a
	Rottweiler	15	19.95 (±0.10)	14.45 (±2.74)	<0.0011 ^a
Non-brachycephalic dogs	Yorkshire Terrier	25	6.97 (±0.93)	5.45 (±2.40)	<0.012 ^a
	Chihuahua	30	7.57 (±1.05)	7.55 (±2.12)	0.68
	Labrador Retriever	19	18.37 (±1.67)	17.19 (±1.25)	0.14

^a Differences were considered significant at $P < 0.05$.

Table 4. Intra-observer reliability and overall intra-observer reliability for radiographic tracheal parameters

	ICC				
	Intra-observer				Overall ICC _{intra}
	Observer 1	Observer 2	Observer 3	Observer 4	
TD	0.96	0.94	0.91	0.9	0.93
TT	0.94	0.96	0.9	0.87	0.90
TI	0.92	0.94	0.89	0.86	0.92
3R	0.88	0.85	0.79	0.8	0.83
Overall ICC _{intra}	0.93	0.92	0.86	0.86	0.89

Table 5. Inter-observer reliability and overall inter-observer reliability of the radiographic tracheal parameters for assessed breeds

		ICC				
		Inter-observer				Overall ICC _{inter}
		TD	TI	TT	3R	
Bulldogs	French Bulldog	0.88	0.9	0.88	0.59	0.81
	English Bulldog	0.97	0.97	0.97	0.85	0.94
	Pug	0.63	0.95	0.46	0.44	0.62
Non-bulldog brachycephalic dogs	Shih-tzu	0.9	0.93	0.83	0.53	0.79
	Boxer	0.92	0.91	0.61	0.48	0.73
	Rottweiler	0.95	0.93	0.98	0.9	0.94
Non-brachycephalic dogs	Yorkshire Terrier	0.89	0.89	0.95	0.3	0.86
	Chihuahua	0.84	0.94	0.84	0.51	0.78
	Labrador Retriever	0.53	0.94	0.9	0.85	0.8
Overall ICC _{inter}		0.83	0.93	0.82	0.61	0.81

was calculated to determine the tracheal diameter relative to the predicted tracheal diameter. Ideally, the TD_{Pred} values should be close to the actual measured values. The TD_{Pred} for bulldogs and non-bulldog brachycephalic dogs were significantly higher than the values we measured. Based on TD_{Pred} calculations, Group A had 36% and Group B 26% lower tracheal diameter, while Group C (except for the Yorkshire Terrier, discussed below) did not have significant differences between TD_{Pred} and measured values. These findings support the previous conclusion that bulldogs and brachycephalic dogs have a smaller tracheal lumen diameter than other breeds. The TD_{Pred} calculation appears suitable for evaluating tracheal lumen diameter when body weight data are available. However, all dogs included in this study had weight corresponding to their breed standard and the effect of overweight is unknown. A further study would be appropriate here since we are dealing with many overweight dogs in recent years.

To our knowledge this is the first study in which craniocaudal tangential radiographs have been made with the beam centred on the ATC. Craniocaudal tangential radiographs were performed in 15 dogs from category A (bulldogs – brachycephalic) based on the values of tracheal diameter and measured in right lateral recumbency. These 15 dogs had the most pronounced tracheal hypoplasia. Comparing our results, no significant difference was found ($P < 0.18$).

One of the hypotheses we wanted to prove was whether there was a relationship between the ratios TD:TI and TT:3R

as a cut-off value for hypoplasia of the trachea. Based on the assumption that hypoplasia involves the whole trachea, the direct dependence of TD:TI on TT:3R was suspected, but the result of our linear regression analysis indicated poor reproducibility ($R^2 = 0.11$).

When TD:TI was used in combination with <2 for TT:3R as the cut-off limit for tracheal hypoplasia, 35 dogs were classified as hypoplastic by all observers using both methods, 103 dogs were classified as non-hypoplastic, and the remaining 47 dogs had varying classifications. The tracheal ring has the smallest diameter and thickness at the thoracic inlet in the dog. Using the narrowest diameter to define whether a trachea is hypoplastic, this study suggests that the TD:TI ratio previously used for the assessment of tracheal hypoplasia is most sensitive at the thoracic inlet, compared to the thoracic tracheal luminal diameter. For this reason, 47 dogs had varying classifications in this study, with smaller thoracic tracheal inlet diameter than thoracic tracheal diameter. Yorkshire Terriers made up 53% ($n = 25$) of the dogs with varying classifications, which is due to the fact that Yorkshire Terriers are very often affected by tracheal collapse at the ATC (Macready et al., 2007), which should be ruled out before assessing the narrowest diameter of the trachea.

We used ICC for the evaluation of observer reliability, and interpretation of ICC values is a non-trivial task. There are different forms of this test which can produce different results even when evaluating the same values, and the results



may give the impression of high agreement. Precise definition of the statistical method should be the standard. It is impossible to compare the results of studies where the statistical method is not precisely defined; in addition, where different evaluation scales are used a more critical approach was used in this study, and the total ICC_{inter} was 0.8, indicating good overall reliability. Differences in the individual observers' radiological experience probably contributed to the varying agreements in this study. Four observers with different experience evaluated the radiographs. One observer was a doctor with 19 years' experience in veterinary diagnostic imaging, the second was a third-year PhD veterinary student in radiology, the third observer was an orthopaedic surgeon with 20 years' experience working with small animals, and the fourth was a Diplomate of the ECVS. The measurement methods were new for observers 3 and 4, but not for the first and second observers. Observer 4 in this study had the lowest level of experience of all the observers, but he practiced taking measurements before the study using several non-related radiographs. Comparing all radiographic parameters, there was no significant difference between measurements made by observers 1 vs. 2 and 3 vs. 4. They had similar levels of experience, which supports the well-known statement that the experience of observers influences the results of studies and subsequent clinical decisions. The greatest differences were found in measuring parameter 3R (0.61). This was probably due to several factors. Any rotation in combination with congenitally malformed vertebrae and magnification or distortion of position sometimes made it difficult to assess which ribs formed the third pair, and sometimes only one of the third ribs could be confidently identified. Superimposition of ribs also obscured their margins. The normal shape of the *os costale* is caudolaterally convex. Due to varying convexity, it can appear shorter or longer in a two-dimensional radiograph, and much of the dorsal part of the ribs is superimposed on the spine in many radiographs (Ingman et al., 2014).

A previous study comparing the tracheal diameter obtained by radiography and computed tomography in canine cadavers revealed that CT-based tracheal diameter measurements were on average 1.03 mm larger than those obtained from radiographs (Montgomery et al., 2015; Williams et al., 2016). One French Bulldog in this study was diagnosed radiographically with severe hypoplasia in all tracheal points and was referred for CT and MRI examinations (Fig. 2). Values of the inner tracheal diameter obtained from these imaging modalities were 29% (1 mm) larger on average than the corresponding radiographic dimensions. We cannot draw firm conclusions based on the results from one dog, but they seem to be consistent with previous findings (Kaye et al., 2015; Montgomery et al., 2015).

The effects of CT vs. MR imaging on tracheal diameter measurements are so far unknown. The large airways are typically well visualised by MRI. The air filling the trachea and bronchi is hypointense compared with the airway walls and mediastinal structures, serving as a natural contrast agent (Fig. 4). This allows for easy evaluation of the tracheobronchial branching and airway diameters using

MRI. The wall of the trachea is thin and consists of two layers with different signal intensity, with each layer being approximately 1 mm thick in axial MRI scans. T1-weighted and T2-weighted pulse sequences can provide enough information for soft-tissue differentiation between healthy and pathological findings in the trachea.

Findings such as the thickness and irregularity of the tracheal wall, as well as the tracheal lumen diameter, were highly accurate using MRI compared to CT. The latest human medical study compared the sensitivity and specificity of MRI and CT with histopathology for evaluating the cartilages of the larynx and trachea. The results show that MRI provides better soft tissue resolution and multiplanar imaging, and it is more specific and sensitive than CT (89.5 vs. 78.9%) in the detection of cartilage invasion (Priya and Mehra, 2014). These findings could be used for future studies to evaluate tracheal hypoplasia in brachycephalic dogs (overlapping cartilages, narrowing or absence of dorsal tracheal muscle, thickness of the tracheal wall).

There were several limitations to this study. The first was related to the small sample size. The sample of English and French Bulldogs, Pugs and brachycephalic breeds in this study is too small to allow the data collected to be considered as representative of the population. Using more dogs would have provided greater statistical significance and more precise and reliable results. Another limitation was the reliability of thoracic radiographs for accurate measurement of the tracheal diameter. In addition, although the tracheal diameter does not change significantly between inspiration and expiration in normal dogs and cats, mild physiological changes may occur during respiration, and extension of the head and neck can result in compression and narrowing of the tracheal lumen (Hayward et al., 2008; Ettinger, 2010). To minimise the impact of these factors, all radiographs were obtained in this study during the maximum inspiratory phase with the head and neck in neutral position. A further limitation was that the thoracic radiographs were taken in only one radiographic view. Measuring the internal tracheal diameter using ventrodorsal, dorsoventral and left lateral thoracic radiographic images might have provided a range of measurements. Right lateral radiographs were selected for this study because the tracheal margins in ventrodorsal and dorsoventral views are difficult to measure accurately owing to superimposition of the trachea over the vertebrae and sternbrae (Schwarz and Johnson, 2008). In addition, because the trachea normally deviates slightly to the right at the thoracic inlet in dogs, measuring the internal tracheal diameter in left lateral views may produce higher values due to the larger magnification factor. Because the tracheal diameter (TD) of dogs is influenced by breed, body weight, age and conformation, large individual variations in TD exist among them (Thomas and Lerche, 2011). The last limitation of this study was that only one dog was referred for further MRI and CT examination. Including more dogs would have provided greater opportunity for comparing diagnostic imaging modalities (X-ray, MRI, CT).

The breeding regulations for the Pug, English Bulldog and French Bulldog do not describe this disease. The FCI



regulations state the following in the preamble of the International Breeding Rules ([Federation Cynologique Internationale, 1979](#)): The only dogs which are considered to be healthy in hereditary terms are those transferring breed standard features, breed type and temperament typical of that breed without displaying any substantial hereditary defects which could impair the functional health of their descendants. Hypoplasia of the trachea is known to be a congenital disease, but the heritability of tracheal hypoplasia is unknown, so further studies are needed to determine its heritability.

The breeding criteria for many breeds include X-ray examination for congenital diseases. Based on our findings we would recommend the use of X-ray as first-line investigation modality for evaluation of the trachea in bulldogs, pugs and other brachycephalic dogs, and the implementation of tracheal evaluation among the breeding criteria based on official screening for the size of the trachea in brachycephalic dogs.

In conclusion, our results indicate high reliability of the use of radiographic measurements to evaluate hypoplastic trachea in brachycephalic dogs. We found that the actual measured tracheal diameters in bulldogs and non-bulldog brachycephalic dogs tended to be significantly smaller compared to predicted tracheal diameters and to the tracheal diameters of non-brachycephalic dogs. Any of the variations discussed above and the choice of imaging modality can potentially influence the tracheal hypoplasia classification of individual dogs. For proper evaluation of the trachea and tracheal rings, more studies including MRI examinations are needed. These could also be used in cases of diseased tracheas, where irregular margins and hypoplasia of the trachea could further complicate accurate measurement.

ACKNOWLEDGEMENTS

The publication is supported by the Medical University Park in Košice project (MediPark, Košice) (project title: Operational Program Research and Development). The project was financed from the European Regional Development Fund (OPVaV-2012/2.2/08-RO), contract no. OPVaV/12/2013.

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