TITLE: Evaluation of radiography as a screening method for detection and characterisation of congenital vertebral malformations in dogs

AUTHORS: Winter, Brocal, J., De Decker, S., José-López, R., Guevar, J., Ortega, M., Parkin, T., Ter Haar, G., Gutierrez-Quintana, R.

JOURNAL TITLE: Veterinary Record

PUBLISHER: BMJ Publishing Group

PUBLICATION DATE: 8 March 2018

DOI: 10.1136/vr.104388

Evaluation of radiography as a screening method for detection and characterisation of congenital vertebral malformations in dogs.

J. Brocal[a], S. De Decker[b], R. José-López[a], J. Guevar[a], M. Ortega[c], T.Parkin[a], G. Ter Haar[b], R. Gutierrez-Quintana[a*].

[a]*School of Veterinary Medicine, College of Medical, Veterinary and Life Sciences, University of Glasgow, Bearsden Road, Glasgow G61 1QH, UK.*
[b] *Department of Veterinary Clinical Science and Services, The Royal Veterinary College, University of London, Hawkshead Lane, North Mymms, Hertfordshire AL97TA, UK.*
[c]*Centro Clinico Veterinario Indautxu, San Mames Zumarkalea 38, Bilbao, Bizkaia, 48010, Spain.*

*Corresponding author: College of Medical, Veterinary and Life Sciences, University of Glasgow, Bearsden Road, Glasgow G61 1QH, UK phone: +44(0)141 330 5848, fax: +44 (0)141 330 3663, email: Rodrigo.GutierrezQuintana@glasgow.ac.uk

Abstract

Congenital vertebral malformations (CVM) are common in brachycephalic “screw-tailed” dogs; they can be associated with neurological deficits and a genetic predisposition has been suggested. The purpose of this study was to evaluate radiography as a screening method for congenital thoracic vertebral malformations in brachycephalic “screw-tailed” dogs by comparing it with computed tomography (CT). Forty-nine dogs that had both radiographic and CT evaluations of the thoracic vertebral column were included. Three observers retrospectively reviewed the images independently to detect CVM’s. When identified, they were classified according to a previously published radiographic classification scheme. A CT consensus was then reached.

All observers identified significantly more affected vertebrae when evaluating orthogonal radiographic views compared to lateral views alone; and more affected vertebrae with the CT consensus compared to orthogonal radiographic views. Given the high number of CVM’s per dog, the number of dogs classified as being CVM free was not significantly different between CT and radiography. Significantly more midline closure defects were also identified with CT compared to radiography. Malformations classified as symmetrical or ventral hypoplasias on radiography were frequently classified as ventral and medial aplasias on CT images. Our results support that CT is better than radiography for the classification of CVM’s and this can be important if further evidence of which CVM’s are clinically the most relevant is identified. These findings are of particular importance for designing screening schemes of congenital vertebral malformations that could help selective breeding programs based on phenotype and future studies.

Keywords: vertebral malformation, computed tomography, radiography, dog, hemivertebra

Introduction

Congenital vertebral malformations (CVM) are relatively common in dogs. Although they can occur in any breed and location, they appear to be more common in the thoracic vertebrae of brachycephalic “screw-tailed” breeds, such as French bulldogs, English bulldogs, Boston terriers and Pugs (Done and orthers 1975; Gutierrez-Quintana and others 2014; Moissonnier and others 2011; Ryan others 2017; Westworth and Sturges 2010). They can be single or multiple, and although most of them are incidental, they can be associated with neurological deficits. These deficits are thought to be secondary to a combination of vertebral instability and vertebral canal stenosis (Done and others 1975; Gutierrez-Quintana and others 2014; Moissonnier and others 2011; Westworth and Sturges 2010). However, the long-term effects of these malformations on the biomechanics of the vertebral column are currently unknown, and they could be responsible for early degenerative changes of the intervertebral discs and chronic spinal pain (Faller and others 2014; Khan and others 2012).

Although the true prevalence of clinical and non-clinical CVM’s among brachycephalic “screw-tailed” breeds is currently unknown, previous radiographic studies have reported a very high prevalence, with 64-85% of dogs having at least one CVM (Done and others 1975; Gutierrez-Quintana and others 2014; Moissonnier and others 2011; Ryan and others 2017; Westworth and Sturges 2010). In most cases the aetiology is unclear, but the familial occurrence of this condition suggests a heritable trait. Thoracic hemivertebrae in German Shorthaired Pointer dogs are believed to have an autosomal-recessive mode of inheritance and studies have suggested a genetic predisposition to the number and grade of hemivertebrae in French bulldogs (Kramer and others 1982; Schlensker and Distl 2013; Schlensker and Distl 2016).

French bulldogs and Pugs are within the five most popular breeds in the United Kingdom for years 2015 and 2016 (THE KENNEL CLUB 2016). The popularity of the French bulldog saw a 47% increase in the last year alone, a 368% rise in the past five years and has increased 30 fold in the past ten years. Breed programmes to reduce the prevalence of CVM’s and the number of clinically affected dogs could be used.

Canine radiographic screening schemes are currently well established and commonly used for hip and elbow dysplasia (Crispin and Turner 2010). More recently a Chiari-malformation/syringomyelia scheme using magnetic resonance imaging (MRI) has been implemented (Mitchell and others 2014). Although, no official screening scheme for congenital vertebral malformation exists, several breeding associations (French Bulldogs and Pugs) have already implemented different radiographic screening protocols based on a single lateral view, or in combination with ventro-dorsal/dorso-ventral views (Schlensker and Distl 2013; White 2013). Furthermore, some studies have evaluated heritability of CVM’s based on single lateral views (Schlensker and Distl 2013; Schlensker and Distl 2016). Thus, determining the best diagnostic imaging protocol for screening CVM’s is of great importance for future studies, and if selective breeding programs based on phenotype are initiated.

A human vertebral malformation classification was recently adapted for its use in dogs. Vertebral malformations were classified as defects of segmentation if adjacent vertebral elements failed to divide (block vertebrae) or defects of formation if a portion of the vertebral body was deficient. Defects of formation were then sub-classified into symmetrical hypoplasia, ventral aplasia, lateral aplasia, ventro-lateral aplasia, ventral and median aplasia, ventral hypoplasia and lateral hypoplasia of the vertebral body (Gutierrez-Quintana and others 2014).

The primary aim of this study was to evaluate radiography as a screening method for detection and classification of CVM's in brachycephalic "screw-tailed" dog breeds, by comparing it with computed tomography (CT). The secondary aim was to determine the intra and inter-observer agreement of the previously described radiographic classification scheme using both radiography and CT independently (Gutierrez-Quintana and others 2014). It was hypothesized that CT would identify more CVM's and more midline closure defects, and that the intra- and inter-observer agreements on the presence and classification of CVM's would be higher compared to radiography.

Materials and Methods

Ethical approval from the University of Glasgow, School of Veterinary Medicine was obtained for this study.

The medical records from 2010 to 2016 of the Royal Veterinary College Small Animal Referral Hospital, University of Glasgow Small Animal Hospital and Centro Clinico Veterinario Indautxu were retrospectively reviewed to identify French bulldogs, English bulldogs, Boston terriers and Pugs with lateral and ventro-dorsal or dorso-ventral digital radiographs as well as complete CT studies of the thoracic vertebral column. Only well positioned radiographs in which there was no major rib-vertebrae superimposition and had a good bone exposure were selected. Dogs underwent imaging investigations under sedation or general anaesthesia for a variety of clinical indications (related or unrelated to spinal disease). Information retrieved from the medical records included age, breed, signalment, reason for presentation and diagnosis.

Radiographs and CT studies for all dogs were retrieved and evaluated independently by three board-certified veterinary neurologists (RGQ, RJL, JG). All observers were blinded to any clinical history. Images were displayed using an open-source Workstation DICOM viewer (Osirix Imaging Sofware, v 3.9.2, Pixmeo, Geneva, Switzerland). Observers were asked to count the number of thoracic vertebrae, classify each thoracic vertebra into normal or abnormal, and to classify the CVM according to a previously published radiographic classification scheme (Gutierrez-Quintana and others 2014). For vertebrae unable to be classified according to this classification, such as bifid spinous process, pedicle overgrowth, incomplete cleft or transitional vertebrae, observers were asked to describe the vertebral abnormality. For vertebrae unable to be properly evaluated due to superimposition of structures, observers could classify the vertebrae as normal or abnormal, but no further sub-classification was required. This process was performed with lateral radiographs alone, with both lateral and ventro-dorsal or dorso-ventral radiographic views (orthogonal radiographic views), and CT independently. A CT consensus between the three observers was then reached. Two observers had previous experience in the use of the classification scheme. All CT images were reviewed in a bone window using multi-planar reconstruction (MPR) methods and observers had the option of using 3D [volume rendering (VR)] methods if considered necessary. To evaluate intra-observer agreement, imaging studies were reviewed again two weeks later by one observer (RGQ). CT was chosen as the gold standard as it provides cross-sectional images with excellent bony detail and the ability of performing three-dimensional volume reconstructions (Crawford and others 2003; Stieger-Vanegas and others 2015a).

As radiographs and CT's of the lumbar vertebrae were not available in all dogs, reviewers were only asked to review thoracic vertebrae. Dogs with no malformation and no ribs in T13 were considered to have 12 thoracic vertebrae and no malformation. Abnormal vertebrae unable to be classified were removed from analysis when looking at the agreement on the type of CVM.

Radiographs and CT images were obtained using three different machines for each modality. All radiographs were obtained with digital machines (Canon, Soundeklin, CXDI control software NE (n=28); Multifix top Siemens Camberley, (n=11) and Sedecal Compact Vet SHF 330 (n=10)). CT images were obtained using a 16-slice CT scanner (Q 500, Universal Systems, Solon, OH (n=28)), and two dual slice CT scanners (Siemens Somatom Spirit (n=11) and GE Brivo CT 325 (n=10)).

A commercially available statistics software program was used (SPSS statistics v22, IBM SPSS Inc., Chicago, IL). Intra-observer agreement for the classification of CVM's was calculated using the data of the observer who reviewed the images twice (RGQ). Inter-observer and intra-modality agreements for the presence and classification of CVM's were calculated with the data of all three observers and the CT consensus. When one observer identified less than five abnormal vertebrae with a specific CVM, the kappa value for that CVM and observer was not calculated. To calculate if the number of affected vertebrae, the number CVM free dogs, midline closure defects (bifid spinous process, incomplete cleft and ventral and medial aplasia) or a specific malformation was significantly different when comparing lateral radiographs alone to orthogonal radiographic views, and orthogonal radiographic views to CT, Mcnemar's analysis test was performed. P-value was considered significant if <0.05.

The strength of the agreement was determined based on the κ value results as previously described elsewhere (1.00, perfect; 0.93 to 0.99, excellent; 0.81 to 0.92, very good; 0.61 to 0.8, good; 0.41 to 0.6, fair; 0.21 to 0.4, slight; 0.01 to 0.2, poor; and ≤ 0, none) (Byrt 1996).

Results

Forty-nine dogs met the inclusion criteria (supplementary material). Twenty-six dogs were French bulldogs, 14 were Pugs, seven were English bulldogs, and two were Boston terriers. Age varied from two months to 12.5 years (mean and median were 4.17 and 3.08 years respectively). Eighteen were female and thirty-one were male. Seventeen and thirty-two dogs underwent investigations for neurological and non-neurological reasons respectively. Twenty-eight dogs presented with respiratory signs, one presented with gastrointestinal signs, one with recurrent ear infections, one with mandibular pain, one with a skin mass, 15 with signs of myelopathy and/or spinal pain and two with forebrain signs. Sixteen dogs were diagnosed with brachycephalic obstructive airway syndrome, eight with pneumonia, two with lung lobe torsions, one with tracheal hypoplasia, one with an idiopathic pleural effusion, one with an intestinal foreign body, one with bilateral middle ear disease, one with a mast cell tumour, one with mandibular osteomyelitis, 14 intervertebral disc extrusions, one with myelopathy secondary to CVM's, one with a extra-axial forebrain mass and one with methylmalonic aciduria.

Eight ventro-dorsal and 41 dorso-ventral radiographic views were available. A total of 630 vertebrae were reviewed. Seven dogs had 12 thoracic vertebrae and two dogs were considered skeletally immature. All observers identified significantly more vertebrae with malformations when evaluating orthogonal radiographic views compared to lateral views alone (*P*= 0.000, 0.007, 0.004 for observers RGQ, RJL, JG, respectively) and significantly less when compared to the CT consensus (*P*= 0.000, 0.001, 0.000). (Fig. 1).

Ventral hypoplasia and symmetric hypoplasia were the two most common CVM's identified with lateral radiographs alone (19.6-51.3%) by all observers and on orthogonal radiographic views by two observers (18.8-39.8%). Ventral and medial aplasias (28/132-21.2%) were the second most common CVM's identified with orthogonal radiographic views by the third observer, after symmetrical hypoplasia (50/132-37.9%), and the third most common CVM's for the other two observers (20/160-12.5 and 18/103-17.5%). Ventral and medial aplasia was the most common CVM's identified on the CT consensus (85/196- 43%). The CT consensus identified significantly more midline closure defects (*P*= 0.000) and ventro-lateral aplasias (P= 0.000, 0.006 and 0.000) compared to orthogonal radiographic views. Observers only identified a total of one midline defect on lateral radiographs. More ventral aplasias were identified with orthogonal radiographic views compared to the CT consensus, but this was only significant for one observer (P= 0.125, 0.003 and 0.250). When ventral and ventrolateral aplasias were considered together, they were identified on the CT consensus (compared to orthogonal radiographic views) more frequently by only one observer (P=0.057, 1, 0.022). All three observers identified more types of CVM's with orthogonal radiographic views compared to lateral radiographic views alone, and the CT consensus identified more types of CVM's compared to orthogonal radiographic views. Seventy-nine percent (155/196) of the CVM's identified on the CT consensus affected the vertebral body (Table 1).

On the CT consensus, 71% (35/49) of the dogs had more than one affected thoracic vertebrae and 17% (29/168) of all abnormal vertebrae had more than one malformation.

Eighty-one percent (9/11) of vertebrae classified as block vertebrae, 63% (14/22) classified as having fusion of the spinal process, and 33% (2/6) classified as having bifid spinous process also presented with another malformation within the same vertebra (Table 2).

Eight to 15 (mean: 11 (22.5%)), four to 11 (mean: 7.7 (15.6%)) and eight dogs (16%) were considered free of malformations on lateral radiographs alone, orthogonal radiographic views and CT consensus, respectively. The number of dogs identified as being malformation free was not significantly different when comparing lateral radiographic views alone to orthogonal radiographic views (*P*= 0.5, 1, 0.125); and orthogonal radiographic views to the CT consensus (*P*= 0.625, 0.687, 0.125).

Intra-modality agreement on the presence/absence of CVM's between lateral views alone and orthogonal radiographic views was very good-excellent and was higher than the agreement between lateral views or orthogonal radiographic views and the CT consensus, which was fair-good for all observers (Table 3).

The mean agreement on the type of CVM between orthogonal radiographic views and the CT consensus varied from poor to slight (κ: 0.32-0.41) and the agreement between CT and the CT consensus was good for all observers (κ: 0.72-0.79) (Table 4).

Inter-observer agreement on the type of CVM varied from poor (κ: 0.206) to perfect (κ: 1). The mean inter-observer agreement was slightly higher (good compared to fair) for all three techniques when the two observers with previous experience in the use of the classification were compared. The mean inter-observer agreement was higher on CT than on orthogonal radiographic views and higher on orthogonal radiographic views when compared to lateral radiographic views alone for all observers and varied from fair to good (κ: 0.46-0.792) (Table 5).

The intra-observer agreement on the type of malformation varied from good (κ: 0.62) to perfect (κ: 1). The mean intra-observer agreement of all malformations was very good for all three techniques (κ: 0.858-0.909) (Table 6).

Discussion

Significantly more vertebrae with CVM's were identified with orthogonal radiographic views compared to lateral views alone, suggesting that if a radiographic screening scheme for is to be implemented, it should include both lateral and ventro-dorsal/ dorso-ventral views.

Several studies have demonstrated that CT provides better bone definition compared to radiography (Crawford and others 2003; Stieger-Vanegas and others 2015a). Furthermore, CT MPR allows images to be created from the original axial plane in transverse, sagittal and oblique planes with no additional time or labour required. In our study, the CT consensus identified more affected vertebrae and CVM's compared to radiography (Fig. 2) supporting the statement above and suggesting screening schemes should ideally use CT. Computed tomography is available at most referral hospitals, like radiography requires sedation or anaesthesia, is becoming less expensive and special prices could be agreed for screening schemes. The main disadvantages of using CT over radiography are the increase in radiation exposure and imaging interpretation time.

To the authors knowledge the prevalence of multiple malformations within the same vertebra has not been previously reported and was approximately 17% (29/168) in this study. The presence of block vertebrae, fusion of the spinal processes and bifid spinous process should raise the suspicion of possible additional concomitant malformation~~s~~ within the same vertebrae.

Despite the fact that more vertebrae with malformations were identified on CT compared to orthogonal radiographic views, and more with orthogonal radiographic views compared to lateral views alone, the number of dogs classified as being malformation free was not significantly different between these two comparisons. This was likely because the number of dogs identified with more than one CVM's in the thoracic vertebrae was high (71% on the CT consensus; 51% having three or more) and consistent with previous reports (Gutierrez-Quintana and others 2014; Ryan and others 2017). Furthermore, 17% of all abnormal vertebrae identified on the CT consensus had more than one malformation. The high number of CVM's per dog made it easy to recognise at least one CVM per dog even with radiography and small numbers of dogs were therefore considered malformation free, not reaching statistical significance.

Applying the radiographic classification scheme from Gutierrez-Quintana (Gutierrez-Quintana and others 2014), symmetrical hypoplasia (30.5%), ventral and medial aplasia (28.2%), and ventral hypoplasia (23.5%) were the most frequently identified CVM's on radiography in that study. Our radiographic results agreed with this previous study; however, ventral and medial aplasia was the most frequently diagnosed CVM using CT (85/196- 43%). Computed tomography identified significantly more midline closure defects compared to radiography; and malformations classified as symmetrical or ventral hypoplasias on radiography were frequently classified as ventral and medial aplasia on CT (Fig. 3). This was likely because CT provides cross-sectional images.

More types of CVM's and midline defects were identified and better inter and intra-observer agreements were obtained with CT compared to radiography. These results suggest that CT is superior for the detection and classification of CVM's compared to radiography.

Two observers had previous experience in the classification of CVM's. Inter-observer agreement on the classification of CVM's was slightly higher when these two observers were compared (good versus fair); suggesting that experience and training in the use of the classification may improve the agreement and possibly the correct classification of CVM's. Observer three consistently had the lowest agreements when radiography was compared to the CT consensus and this probably reflects radiological interpretative experience. None of the observers was board-certified in diagnostic imaging and including observers board-certified diagnostic imaging could have potentially improved the agreement in this study. If a selective breeding programme was to be implemented, board-certified in diagnostic imaging would most likely be standard of scrutineer used.

Overall, intra-observer agreement for the classification of CVM's was higher than the inter-observer agreement. This is in concordance with previous studies as regardless of the imaging modality being assessed, the intra-observer agreement is typically greater than inter-observer agreement (De Decker and others 2010; De Decker and others 2011; Fenn and others 2016).

Despite using a previously reported classification, the presence or absence of certain vertebral body malformations is subjective and observer dependent (Gutierrez-Quintana and others 2014). Unfortunately, establishing objective measurements would be challenging because the measurements are likely to be breed, size and vertebrae dependent. This might be one of the reasons why the agreements on the presence and type of malformation was so variable in the present study.

Although radiography provides good bone definition, it does not provide information regarding the presence and degree of spinal cord compression or the presence of other possible parenchymal lesions. CT and/or myelography provide limited detail and diagnostic accuracy on myelopathies, for which MRI provides better parenchymal detail. The presence of kyphosis is readily appreciated on radiography and CT and most dogs with neurological deficits secondary to CVM's have a kyphotic Cobb angle higher than 35° (Guevar and others 2014). The present study included dogs presented for a variety of clinical indications and only one dog in our study had a myelopathy secondary to CVM's. Kyphotic angles were not measured but maybe of interest if an official screening scheme was to be implemented.

Based on MRI, ventral and ventro-lateral vertebral body aplasias were the cause of spinal cord compression in 5/12 (41.6%) of dogs with neurologic deficits in a previous study (Gutierrez-Quintana and others 2014). It is likely that dogs with these malformations are therefore more likely to develop neurological deficits. More vertebrae with ventro-lateral aplasia (statistically significant) and fewer vertebrae with ventral aplasia (not statistically significant) were identified on the CT consensus compared to radiography in the present study. The inter- and intra-observer agreement for the presence of ventrolateral aplasia could only be calculated for CT (due to low numbers) and was slight-good (κ: 0.309, 0.374 and 0.798) and good (κ 0.62) respectively. The inter-observer agreement for the presence of ventral aplasia was calculated for lateral radiographs alone and one comparison on orthogonal radiographic views, and varied from slight-fair (κ: 0.346-0.567). Intra-observer agreement was only available for radiography and was very good-excellent (κ: 0.908-0.933). Due to the high prevalence of CVM's within the brachycephalic population (Ryan and others 2017; Schlensker and Distl 2016), and in an attempt to avoid a significant reduction of the genetic pool, selective breeding programs to eradicate CVM's that are more likely to cause neurological signs might be recommended as an initial starting point. Furthermore, some CVM's appear to be of greater clinical importance in certain breeds compared to others (Ryan and others 2017). Appropriate classification of the CVM would therefore become crucial for an effective breeding program. Due to the lack of CT kappa results for ventral aplasia, the variability and overall low inter-observer agreement, further studies to assess the classification of CVM's if this selective breeding approach is elected will be necessary.

The main limitation of the present study, due to its retrospective nature, was that CT images and radiographs were obtained with three different CT and radiographic machines and were performed for a variety of clinical indications. CT and radiographic parameters (including slice thickness) and quality varied between dogs and machines. Ventro-dorsal radiographs are considered better than dorso-ventral radiographs to evaluate the vertebral column (Thrall and Widmer 2007) and only eight ventro-dorsal views were available for analysis in our study. Furthermore, not all radiographs analysed had perfectly aligned vertebral columns and superimposition of structures occurred due to kyphotic/scoliotic deformities. Even though observers had the possibility of using advanced 3D-CT methods, it was used only in rare occasions and the possible additional benefit to 2D-CT methods when analysing CVM's is therefore unknown. In a previous study 3D-CT only improved sacral and pelvic fracture diagnosis when added to 2D-CT (Stieger-Vanegas and others 2015b).

Conclusions

Interpretation of CT was considered more time consuming by all observers but allowed identification of significantly more affected vertebrae and CVM's when compared to radiography. On the other hand, radiography is a less expensive and more readily available technique that did not identify significantly less CVM free dogs compared to CT. If CT is not available or considered too expensive, significantly more affected vertebrae will be identified with orthogonal radiographic views compared to lateral radiographs alone. The presence/absence and type of malformations can be subjective and therefore observer dependent and may explain the generally low and variable kappa interobserver agreements results obtained. The fact that the highest inter and intraobserver agreements on the type of CVM were obtained with CT and that CT identified more types of CVM's and significantly more midline closure defects compared to radiography, supports that CT is a better imaging modality for the classification of CVM's. Until further evidence exist of which CVM's are clinically the most relevant, CT may not provide any additional benefit to radiography. Selective breeding programs for some brachycephalic breeds have already been initiated and our study illustrates the importance of selecting the appropriate imaging technique for the detection and classification of CVM's (White 2013).

Conflict of interest statement

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

An abstract with some of the results of this study was submitted to the European College of Veterinary Neurology Annual Symposium, September 2016, Edinburgh, United Kingdom.

References

Byrt, T., (1996). How good is that agreement? Epidemiology (Cambridge, Mass.) 7, 561

Crawford, J.T., Manley, P.A., Adams, W.M., (2003). Comparison of computed tomography, tangential view radiography, and conventional radiography in evaluation of canine pelvic trauma. Veterinary Radiology and Ultrasound 44, 619-628

Crispin, S.M. & Turner, B.M, (2010). Changes to the BVA/KC Canine health schemes. Veterinary Record 166, 28

De Decker, S., Gielen, I.M., Duchateau, L., Lang, J., Dennis, R., Corzo-Menéndez, N., van Bree, H.J., Van Soens, I., Binst, D.H., Waelbers, T., (2011). Intraobserver and interobserver agreement for results of low-field magnetic resonance imaging in dogs with and without clinical signs of disk-associated wobbler syndrome. Journal of the American Veterinary Medical Association 238, 74-80

De Decker, S., Gielen, I.M., Duchateau, L., Polis, I., Van Bree, H.J., Van Ham, L.M., (2010). Agreement and repeatability of linear vertebral body and canal measurements using computed tomography (CT) and low field magnetic resonance imaging (MRI). Veterinary Surgery 39, 28-34

Done, S.H., Drew, R.A., Robins, G.M., Lane, J.G., (1975). Hemivertebra in the dog: clinical and pathological observations. Veterinary Record 96, 313-317

Faller, K., Penderis, J., Stalin, C., Guevar, J., Yeamans, C., Gutierrez-Quintana, R., (2014). The effect of kyphoscoliosis on intervertebral disc degeneration in dogs. The Veterinary Journal 200, 449-451

Fenn, J., Drees, R., Volk, H.A., Decker, S.D., (2016). Inter- and Intraobserver Agreement for Diagnosing Presumptive Ischemic Myelopathy and Acute Noncompressive Nucleus Pulposus Extrusion in Dogs Using Magnetic Resonance Imaging. Veterinary Radiology and Ultrasound 57, 33-40

Gutierrez-Quintana, R., Guevar, J., Stalin, C., Faller, K., Yeamans, C., Penderis, J., (2014). A proposed radiographic classification scheme for congenital thoracic vertebral malformations in brachycephalic "screw-tailed" dog breeds. Veterinary Radiology and Ultrasound 55, 585-591

Guevar, J., Penderis, J., Faller, K., Yeamans, C., Stalin, C., Gutierrez-Quintana, R., Computer-assisted radiographic calculation of spinal curvature in brachyocephalic “screw-tailed” dog breeds with congenital thoracic vertebral malformations: reliability and clinical evaluation. Public Library of Science 8, 2014

Khan, A., Barrey, C., Massourides, H., Perrin, G., (2012). Lumbar hemivertebra in an adult treated by transpediculer osteotomy. World Neurosurgery 77, 592

Kramer, J.W., Schiffer, S.P., Sande, R.D., Rantanen, N.W., Whitener, E.K., (1982). Characterization of heritable thoracic hemivertebra of the German shorthaired pointer. Journal of the American Veterinary Medical Association 181, 814-815

Mitchell, T.J, Knowler, S.P, van den Berg, H., Sykes, J., Rusbridge, C., (2014). Syringomyelia: determining risk and protective factors in the conformation of the Cavalier King Charles Spaniel dog. Canine Genetics Epidemiology Jul 29;1:9

Moissonnier, P., Gossot, P., Scotti, S., (2011). Thoracic kyphosis associated with hemivertebra. Veterinary Surgery 40, 1029-1032

Ryan, R., Gutierrez-Quintana, R., ter Haar, G., De Decker, S., (2017). Prevalence of thoracic vertebral malformations in French bulldogs, Pugs and English bulldogs with and without associated neurological deficits. The Veterinary Journal, In press

Schlensker, E. & Distl, O., (2013). Prevalence, grading and genetics of hemivertebrae in dogs. European Journal of Companion Animinal Practice 23, 119-123

Schlensker, E. & Distl, O., (2016). Heritability of hemivertebrae in the French bulldog using an animal threshold model. The Veterinary Journal 207, 188-189

Stieger-Vanegas, S.M., Senthirajah, S.K., Nemanic, S., Baltzer, W., Warnock, J., Bobe, G., (2015a). Evaluation of the diagnostic accuracy of four-view radiography and conventional computed tomography analysing sacral and pelvic fractures in dogs. Veterinary and Comparative Orthopaedics and Traumatology 28, 155-163

Stieger-Vanegas, S.M., Senthirajah, S.K., Nemanic, S., Baltzer, W., Warnock, J., Hollars, K., Lee, S.S., Bobe, G., (2015b). Evaluation of the Diagnostic Accuracy of Conventional 2-Dimensional and 3-Dimensional Computed Tomography for Assessing Canine Sacral and Pelvic Fractures by Radiologists, Orthopedic Surgeons, and Veterinary Medical Students. Veterinary Surgery 44, 694-703

THE KENNEL CLUB (2016) Top twenty breeds in registration order for the years 2015 and 2016. http://www.thekennelclub.org.uk/media/1098176/top_20_breeds_2015_-_2016.pdf Accessed March 1, 2017

THE KENNEL CLUB (2017) Top twenty breeds in registration order for the years 2015 and 2016. http://www.thekennelclub.org.uk/press-releases/2017/february-2017/french-bulldogs-set-to-overtake-labradors-as-uk%E2%80%99s-most-popular-dog-breed/ Accessed March 1, 2017

Thrall, D.E. & Widmer, W.R., (2007) Physics of diagnostic radiology, radiation protection, and darkroom theory. In Textbook of veterinary diagnostic radiology. 5th Ed. Thrall, D.E. Saunders Elsevier. pp14

Westworth, D.R., Sturges, B.K., (2010). Congenital spinal malformations in small animals. Veterinary Clinics of North America Small Animal Practice 40, 951-981

White, D., (2013). Screening for hemivertebra in pugs. Veterinary Record 173, 23-24

Table 1. Number and type of malformations identified individually by the three observers on lateral radiographs alone, with orthogonal radiographic views and computed tomography (CT) and in the CT consensus.

	Observer									
	1	2	3	1	2	3	1	2	3	
Type of congenital vertebral malformation	**Lateral radiograph alone**			**Orthogonal radiographic views**			**CT**			**CT consensus**
Bifid spinous process	0	0	0	2	3	2	6	5	6	6
Transitional vertebra	1	5	0	6	9	2	10	6	10	11
Ventral hypoplasia	38	47	27	25	43	23	15	19	1	15
Ventral aplasia	7	19	7	5	12	4	1	5	0	1
Ventral and medial aplasia	0	1	0	28	20	18	78	64	82	85
Lateral hypoplasia	0	0	0	3	1	1	5	2	0	2
Lateral aplasia	0	0	0	0	0	1	3	0	2	3
Ventrolateral aplasia	0	0	0	1	3	1	8	18	7	13
Symmetrical hypoplasia	61	27	45	50	30	41	2	18	0	10
Block vertebra	2	23	0	2	25	0	7	19	2	11
Incomplete cleft	0	0	0	0	0	0	19	0	8	15
Pedicle overgrowth	0	0	0	0	0	0	2	0	3	3
Fusion of the spinal process	10	10	10	10	10	10	15	12	16	22
Vertebrae classified as abnormal without further subclassification	0	6	0	0	4	0	0	0	0	0
Total number of affected vertebrae	116	127	85	128	139	93	158	149	126	168
Total number of congenital vertebral malformations	119	138	89	132	160	103	171	168	137	196
Number of types of congenital vertebral malformations	6	7	4	10	10	10	13	10	10	13

Table 2. Number, type and percentage of vertebrae identified with the computed tomography (CT) consensus with more than one congenital vertebral malformation.

Type of congenital vertebral malformation	**Number of congenital vertebral malformations**	**Number (percentage) of vertebrae with more than one congenital vertebral malformation**	**Type of additional congenital vertebral malformation**
Bifid spinous process [a]	6	2 (33)	e
Transitional vertebra [b]	11	3 (27)	e,j
Ventral hypoplasia [c]	15	2 (13)	m
Ventral aplasia [d]	1	0 (0)	-
Ventral and medial aplasia [e]	85	22(26)	m,j,a,b,k
Lateral hypoplasia [f]	2	1 (50)	m
Lateral aplasia [g]	3	0 (0)	-
Ventrolateral aplasia [h]	13	2 (15)	k,j
Symmetrical hypoplasia [i]	10	0 (0)	-
Block vertebra [j]	11	9 (81)	e,b
Incomplete cleft [k]	15	3 (20)	e,h,m
Pedicle overgrowth [l]	3	0 (0)	-
Fusion of the spinous process [m]	22	14 (63)	e,c
Total	196	58 (17)	-

Table 3. Intra-modality agreement for the presence of congenital vertebral malformations.

	Observer		
	1	**2**	**3**
Lateral radiograph vs orthogonal radiographic views	0.939	0.9	0.879
Lateral radiograph vs CT consensus	0.64	0.674	0.485
Orthogonal radiographic views vs CT consensus	0.675	0.712	0.551

Table 4. Radiographic and computed tomography (CT) agreement on the classification of congenital vertebral malformations with the CT consensus.

	Observer 1		**Observer 2**		**Observer 3**	
Type of congenital vertebral malformation	**Orthogonal radiographic views vs CT consensus**	**CT vs CT consensus**	**Orthogonal radiographic views vs CT consensus**	**CT vs CT consensus**	**Orthogonal radiographic views vs CT consensus**	**CT vs CT consensus**
Bifid spinous process	0.553	1	-	0.908	0.617	0.908
Transitional vertebra	0.702	0.952	0.695	0.583	-	0.952
Ventral hypoplasia	0.433	0.659	0.4	0.72	0.295	-
Ventral aplasia	0.332	-	-		-	-
Ventral and medial aplasia	0.384	0.81	0.331	0.81	0.256	0.758
Lateral hypoplasia	-	-	-	-	-	-
Lateral aplasia	-	-	-	-	-	-
Ventrolateral aplasia	-	0.565	-	0.636	-	0.493
Symmetrical hypoplasia	0.076	-	0.078	0.708	0.092	-
Block vertebra	-	0.775	0.386	0.727	-	-
Incomplete cleft	-	0.819	-	-	-	0.514
Pedicle overgrowth	-	-	-	-	-	
Fusion of the spinal process	-	0.805	0.553	0.698	-	0.837
Mean	0.413	0.798	0.407	0.723	0.315	0.743

Table 5. Inter-observer agreement on the classification of congenital vertebral malformations for lateral radiographs alone, orthogonal radiographic views and computed tomography (CT) images.

	Observer 1 & 2			**Observer 1 & 3**			
alformation	**Lateral radiograph alone**	**Orthogonal radiographic views**	**CT**	**Lateral radiograph alone**	**Orthogonal radiographic views**	**CT**	**Lateral radiograph alone**
ess	-	-	0.908	-	-	0.922	-
ra	-	0.663	0.494	-	-	1	-
a	0.592	0.576	0.409	0.489	0.61	-	0.406
	0.453	0.346	-	0.567	-	-	0.453
plasia	-	0.625	0.699	-	0.755	0.771	-
a	-	-	-	-	-	-	-
	-	-	-	-	-	-	-
sia	-	-	0.374	-	-	0.798	-
asia	0.342	0.324	-	0.383	0.531	-	0.211
	-	-	0.531	-	-	-	-
	-	-	-	-	-	0.359	-
h	-	-	-	-	-	-	-
rocess	0.593	0.594	0.432	1	0.898	0.901	0.593
	0.495	0.521	0.55	0.61	0.7	0.792	0.416

Table 6. Intra-observer agreement on the classification of congenital vertebral malformations for lateral radiographs alone, orthogonal radiographic views and computed tomography (CT) images.

	Observer 1		
Type of congenital vertebral malformation	**Lateral radiograph alone**	**Orthogonal radiographic views**	**CT**
Bifid spinous process	-	-	1
Transitional vertebra	-	0.663	1
Ventral hypoplasia	0.893	0.87	0.744
Ventral aplasia	0.933	0.908	-
Ventral and medial aplasia	-	0.809	0.879
Lateral hypoplasia	-	-	0.798
Lateral aplasia	-	-	-
Ventrolateral aplasia	-	-	0.62
Symmetrical hypoplasia	0.811	0.792	-
Block vertebra	-	-	1
Incomplete cleft	-	-	0.837
Pedicle overgrowth	-	-	-
Fusion of the spinal process	1	1	0.843
Mean	0.909	0.804	0.858

Figure legends

Fig. 1**.** Histogram illustrating the number of vertebrae with congenital vertebral malformations identified by each observer with each imaging technique.

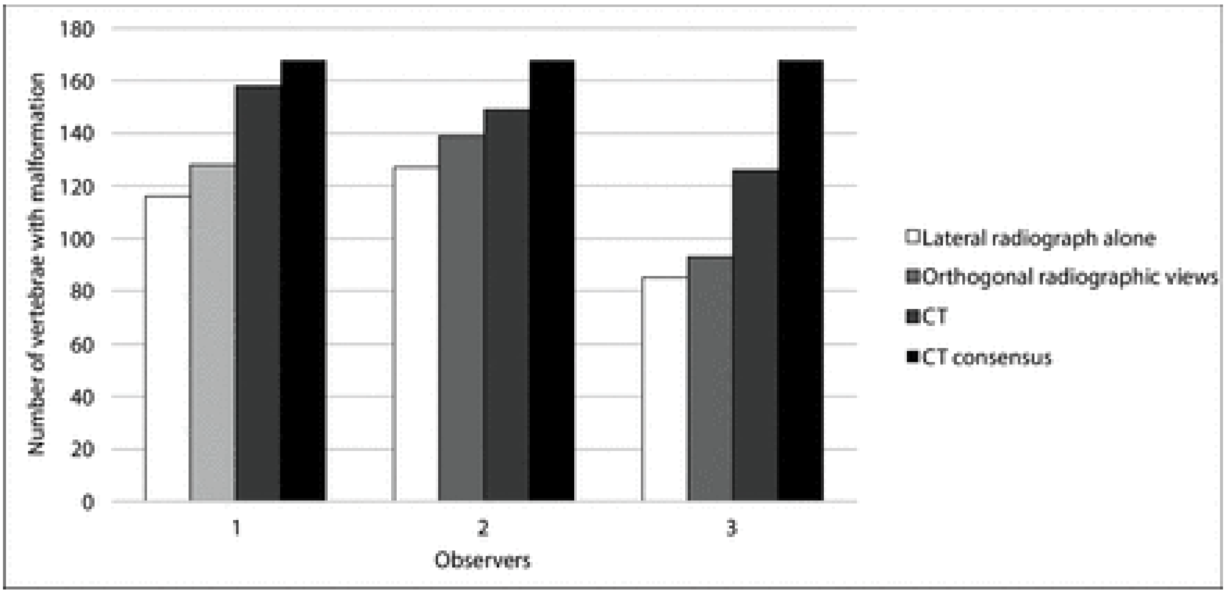

Fig. 2. Lateral (A) and ventrodrosal (B) radiographs of the thoracic vertebral column and CT transverse (C) image of T1 vertebra of a dog in which bifid spinous process (arrow) was missed by the 3 observers using radiography and identified using CT. (R: right)

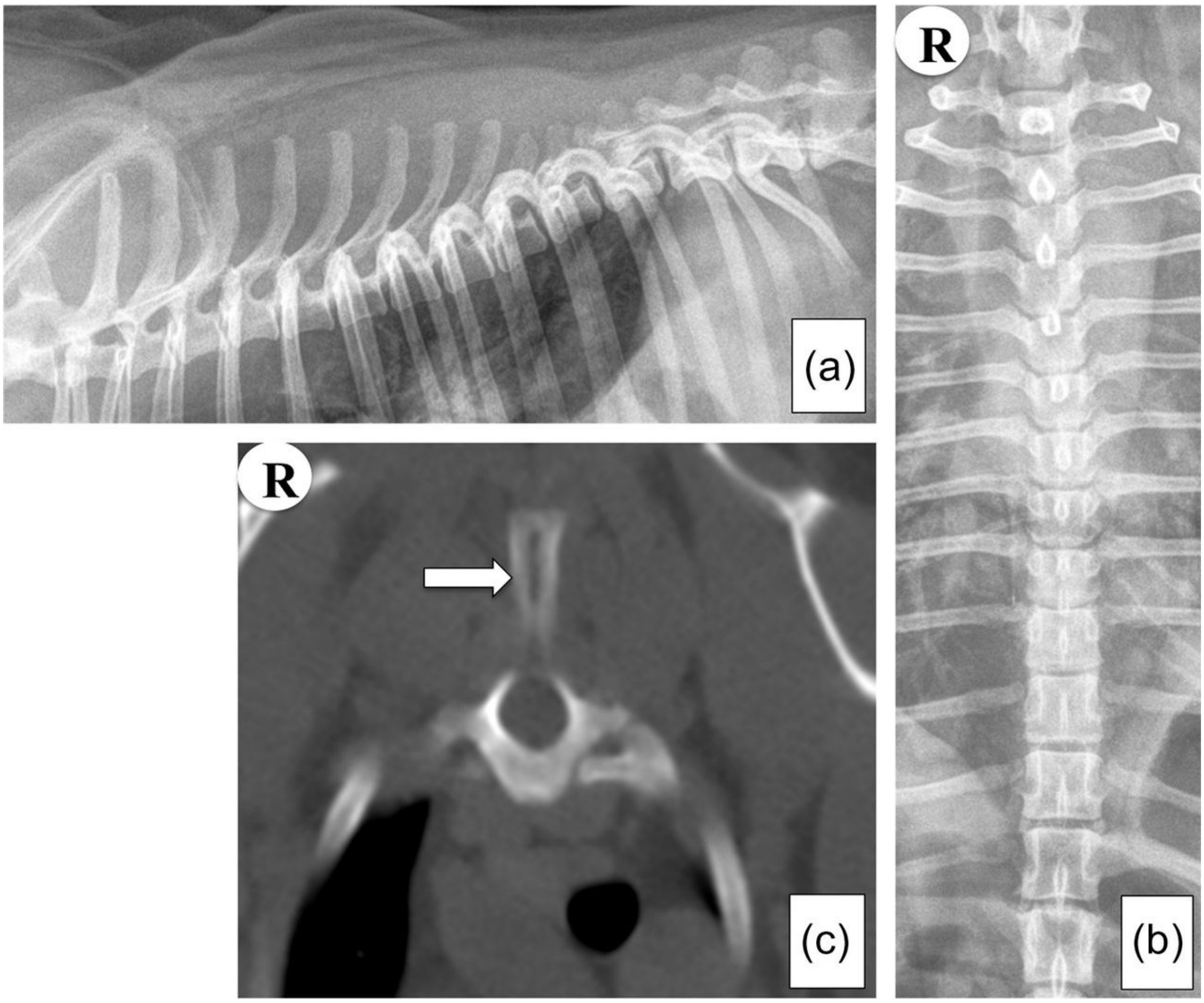

Fig. 3. Lateral (A) and dorsoventral (B) radiographs and CT tranverse images (C) of the vertebral column of a dog in which T5, T9, T11 and T12 were respectively classified as ventral hypoplasia, symmetrical hypoplasia, symmetrical hypoplasia and ventral hypoplasia on radiography (with both lateral alone and orthogonal radiographic views) and were all classified as ventral and medial aplasia on CT images. The transverse CT image corresponds to T11. The arrow points the midline defect, (R: right)