The Veterinary Journal 304 (2024) 106095

Contents lists available at ScienceDirect

The Veterinary Journal

journal homepage: www.elsevier.com/locate/tvjl

# Vertebral and spinal malformations in small brachycephalic dog breeds: Current knowledge and remaining questions

Steven De Decker [a,*], Cecilia Rohdin [b,c], Rodrigo Gutierrez-Quintana [d]

[a] Department of Clinical Science and Services, Royal Veterinary College, University of London, Hatfield AL9 7TA, UK
[b] Swedish University of Agricultural Sciences, University Animal Hospital, Uppsala 75007, Sweden
[c] Anicura Albano Small Animal Hospital, Danderyd 18236, Sweden
[d] School of Veterinary Medicine, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow G61 1QH, UK

ARTICLE INFO

*Keywords:*
Caudal articular process dysplasia
Hemivertebra
Meningeal fibrosis
Spinal arachnoid diverticulum

ABSTRACT

Small brachycephalic dog breeds, such as the French bulldog, English bulldog and pug have become increasingly popular. These breeds are predisposed to a variety of vertebral and spinal malformations, including hemivertebra, caudal articular process dysplasia, transitional vertebra, cranial thoracic vertebral canal stenosis, spinal arachnoid diverticulum and meningeal fibrosis. Recent studies have provided new insights into the prevalence, anatomical characteristics, pathophysiology and treatment of these conditions. Thoracic hemivertebra, caudal articular process dysplasia, transitional vertebra, and cranial thoracic vertebral canal stenosis occur commonly in neurologically normal dogs. Although the clinical relevance of these vertebral anomalies has therefore been questioned, severe kyphosis and hemivertebra in pugs have been associated with an increased likelihood of neurological signs. Meningeal fibrosis is characterised by the formation of dense intradural fibrotic adhesions, constricting the spinal cord. This condition has been heavily associated with the pug breed. It is in pugs further common to observe multiple concurrent spinal disorder in association with chronic progressive pelvic limb gait abnormalities. This clinical presentation has been referred to as 'pug dog thoracolumbar myelopathy' and potential genetic risk factors have recently been identified. Despite our increased knowledge, many questions remain currently unanswered. This review discusses our current understanding and controversies surrounding vertebral and spinal malformations in small brachycephalic dog breeds.

## 1. Introduction

Small brachycephalic dog breeds, such as the French bulldog and pug have become increasingly popular. This popularity has been associated with an increased awareness of welfare concerns associated with the brachycephalic conformation (Waters, 2017a; Waters, 2017b; The Kennel Club, 2023). This is highlighted in a recent study, which suggested that French bulldogs have a shorter lifespan of 4.53 years compared to 11.23 years for the overall canine population (Teng et al., 2022). French bulldogs and pugs are commonly presented to veterinary professionals for further assessment of a spinal disorder (Mayousse et al., 2017; Rohdin et al., 2018a). One group of spinal conditions that has been associated with small brachycephalic dog breeds are vertebral and spinal malformations (Gutierrez-Quintana and De Decker, 2021). Vertebral malformations are however commonly seen on diagnostic imaging studies of neurologically normal and abnormal French bulldogs, pugs, and English bulldogs (Gutierrez-Quintana et al., 2014; Ryan et al., 2017; Bertram et al., 2019; Brown et al., 2021). Recent studies have discussed the prevalence, clinical relevance, treatment, and breed-specific anatomical aspects of a variety of vertebral malformations, such as thoracic hemivertebra and caudal articular process dysplasia (CAPD) (Ryan et al., 2017; Bertram et al., 2018; Rohdin et al., 2018b; Mathiesen et al., 2018; De Decker et al., 2019; Bertram et al., 2019; Ryan et al., 2019). Common spinal anomalies in small brachycephalic dogs are spinal arachnoid diverticulum (SAD) and meningeal fibrosis (MF) (Fisher et al., 2013; Mauler et al., 2014; Rohdin et al., 2020). Although recent studies have provided new insights into well-known spinal disorders, such as SAD, previous assumptions about more recently described conditions, such as MF, have been questioned (Alcoverro et al., 2018; Alisauskaite et al., 2019; Rohdin et al., 2020). This review will summarise our current knowledge, highlight new developments and discuss remaining questions about vertebral and spinal

* Corresponding author.
*E-mail address:* sdedecker@rvc.ac.uk (S. De Decker).

https://doi.org/10.1016/j.tvjl.2024.106095
Received 29 September 2023; Received in revised form 4 March 2024; Accepted 4 March 2024
Available online 6 March 2024

malformations in small brachycephalic dogs.

## 2. Vertebral malformations

Although vertebral malformations can cause spinal cord dysfunction, studies have demonstrated a high prevalence of thoracolumbar and lumbosacral vertebral malformations in neurologically normal small brachycephalic dogs (Table 1) (Moissonnier et al., 2011; Gutierrez-Quintana et al., 2014; Ryan et al., 2017; Bertram et al., 2018; Brocal et al., 2018a; Rohdin et al., 2018b; Bertram et al., 2019; Brown et al., 2021; Lackmann et al., 2022; Ban et al., 2023). Common vertebral body malformations in small brachycephalic dog breeds include defects in vertebral body formation or hemivertebra (Westworth and Sturges, 2010), CAPD, transitional vertebra, thoracic vertebral canal stenosis, spina bifida, and vascular canal dysplasia (Table 1). The high prevalence of vertebral malformations in clinically normal small brachycephalic dogs questions the clinical importance of some of these anomalies and complicates differentiation between clinically relevant and irrelevant findings on diagnostic imaging studies (De Decker et al., 2019).

### 2.1. Hemivertebra

#### 2.1.1. Pathology

Hemivertebrae are characterized by a partial to complete absence of the vertebral body (Dewey et al., 2016). Based on the severity and location of the defect within the vertebral body, up to 10 hemivertebra subtypes have been recognised in dogs (Fig. 1) (Gutierrez-Quintana et al., 2014; Ryan et al., 2019; Brown et al., 2021: Lackmann et al., 2022). Common hemivertebra subtypes include ventral aplasia or 'dorsal hemivertebra', ventral hypoplasia or 'wedged vertebra', and ventral and median aplasia or 'butterfly vertebra'.

Hemivertebra are most often found in the mid-thoracic vertebral column. Especially in French and English bulldogs, it is common to find multiple hemivertebrae along the vertebral column (Dewey et al., 2016; Ryan et al., 2017; Brown et al., 2021). Hemivertebra can result in an abnormal dorsoventral (i.e. kyphosis) or lateral (i.e. scoliosis) curvature of the vertebral column. The severity of spinal curvature can be determined by the Cobb angle, which is obtained by measuring the angle between a line drawn parallel to the cranial vertebral endplate of the first vertebra cranial and a line parallel to the caudal vertebral end plate of the first vertebra caudal to the hemivertebra (Guevar et al., 2014). Although the exact aetiology of hemivertebra is unclear, it is assumed to be hereditary (Schlensker and Distl, 2016; Mansour et al., 2018). In French bulldogs, there is an association between thoracic hemivertebra and the screw-tail morphology (Schlensker and Distl, 2016; Lackmann et al., 2022). The 'screw-tailed' morphology is caused by a variant in the *DISHEVELLED 2* gene and has been demonstrated to segregate with thoracic vertebral malformations (Mansour et al., 2018).

#### 2.1.2. Prevalence of hemivertebra in brachycephalic dogs

The prevalence of thoracic hemivertebrae in neurologically normal brachycephalic dogs is surprisingly high. Recent studies have

**Table 1**
Selected studies that have evaluated the prevalence of vertebral malformations in neurologically normal small brachycephalic breeds.

| Study | Study design | Animals | Evaluated vertebral malformations | Diagnostic technique neurologically normal dogs | Prevalence vertebral malformations in neurologically normal dogs |
|---|---|---|---|---|---|
| Moissonnier et al., 2011 | Retrospective, single institution | 41 FBDs without and 4 with neurological signs | HV | RX | 78% |
| Schlensker and Distl, 2016 | Retrospective, single institution | 105 FBDs | HV | RX | 85% |
| Ryan et al., 2017 | Retrospective, single institution | 171 neurologically normal dogs: 62 FBDs, 68 pugs, 41 EBDs 10 dogs with neurological signs | HV, TV, SB | CT | **FBD**: 93.5% HV, 4.8% TV, 1.6% SB **Pug**: 17.6% HV, 30.9% TV, 38.2% SB **EBD**: 73.2% HV, 9.8% TV, 2.4% SB |
| Rohdin et al., 2018b | Prospective and retrospective part, multi-institutional | 57 pugs: 30 with and 27 without neurological signs | HV, SB, TV, CAPD | CT | HV: 29.6%, SB: 25.9%, TV: 33.3%, CAPD: 88.9% |
| Bertram et al., 2018 | Retrospective, single institution | 271 dogs: 108 FBDs, 63 EBDs, 100 pugs | CAPD | CT | 70.4% of FBDs, 84.1% of EBDs, 97% of pugs |
| Bertram et al., 2019 | Retrospective single institution | 149 dogs: 53 FBDs, 37 EBDs, 59 pugs | Lumbosacral HV, SB, TV | CT | **FBD**: 32% HV, 9.4% SB, 26.4% TV **EBD**: 24% HV, 13.5% SB, 13.5% TV **Pug**: 1.7% HV, 8.5% SB, 54,2% TV |
| Brown et al., 2021 | Prospective, single institution | 49 dogs: 31 FBDs (15 with* and 16 without neurological signs), 18 pugs (4 with* and 14 without neurological signs) | HV and TV | CT | **FBD**: HV: 100% HV and 12.5% TV **Pug**: 36% HV and 57% TV |
| Lackman et al., 2022 | Prospective, single institution | 265 dogs: 199 FBDs, 54 pugs, 12 EBDs (55% with neurological signs**) | HV | RX | 79% FBDs, 3.7% pugs, 83% EBDs** |
| Conte et al., 2021 | Retrospective, multi-institutional | 175 neurologically normal dogs: 41 EBDs, 60 FBDs, 6 Boston terriers, 68 pugs 10 dogs with neurological signs | Thoracic vertebral canal stenosis | CT | 18.8% dogs overall: 39% EBDs, 28.3% FBDs, 0% Boston terriers and pugs |
| Santifort et al., 2022 | Retrospective, multi-institutional | Neurologically normal FBDs and EBDs in UK and Italy **UK**: 41 FBDs and 36 EBDs **Italy**: 106 FBDs and 23 EBDs 9 dogs with neurological signs | Vertebral vascular canal dysplasia | CT in UK and MRI in Italy | **UK**: 68.3% FBDs and 83.3% EBDS **Italy**: 6.6% FBDs and 21/7% EBDs |
| Ban et al., 2023 | Retrospective, multi-institutional | 717 dogs of various breeds (59 with T3-L3 myelopathy) | CAPD | CT | Overall 47%: 66.4% toy breeds, 39% small breeds, 20% medium breeds, 6% large breeds |

CAPD, caudal articular process dysplasia; CT, computed tomography; EBD, English bulldog; FBD, French bulldog; HV, hemivertebra; RX, radiography; SB, spina bifida; TV, transitional vertebra.
*Neurologically abnormal dogs diagnosed with variety of spinal conditions, including intervertebral disk disease.
**No final diagnoses for neurologically abnormal dogs. No separate results presented for neurologically normal dogs. 98% of vertebral malformations were not associated with neurological signs.

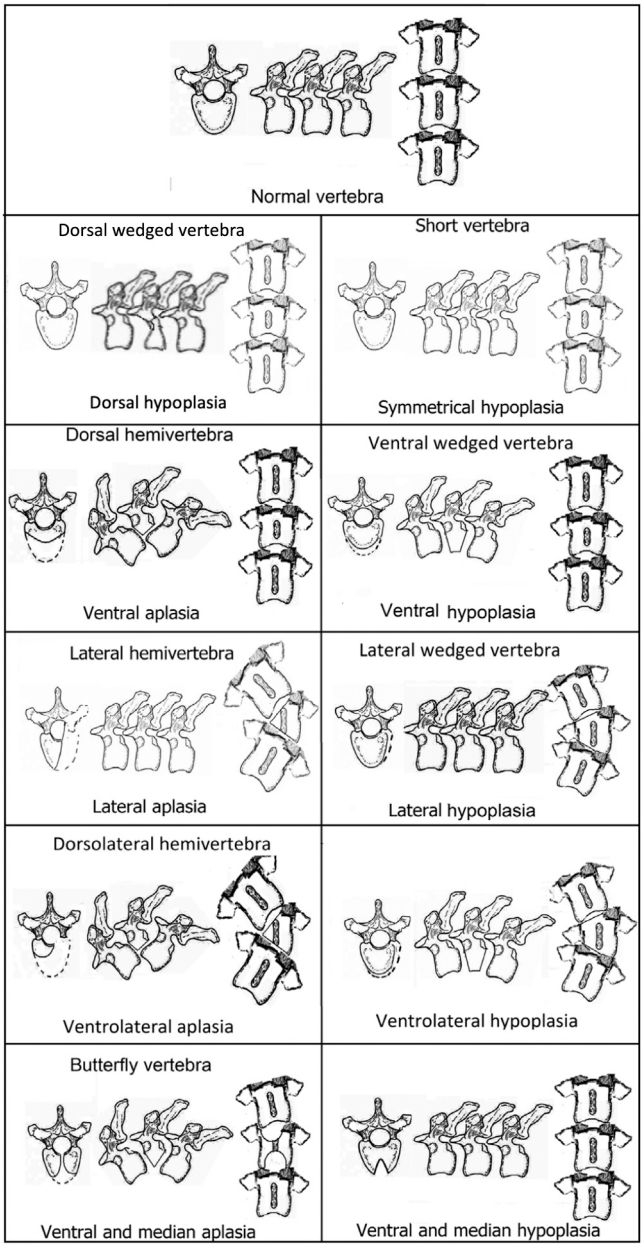


**Fig. 1.** Diagram of the 10 reported subtypes used to classify canine hemivertebra using computed tomography. This diagram is based on a previously published classification system (Ryan et al., 2019) and expanded to include the subtype dorsal wedged vertebra or dorsal hypoplasia.

demonstrated a prevalence of hemivertebrae in French bulldogs between 75% and 100% (Moissonnier et al., 2011; Schlensker and Distl, 2016; Ryan et al., 2017; Brocal et al., 2018a; Brown et al., 2021; Lackmann et al., 2022). Thoracic hemivertebra occur however also commonly in English bulldogs and pugs. One study demonstrated one or more thoracic hemivertebrae in 94% of neurologically normal French bulldogs, 73.2% of English bulldogs and 17.6% of pugs (Ryan et al., 2017). Vertebral malformations are also commonly observed in the lumbosacral region of small brachycephalic dogs with one study reporting lumbosacral hemivertebra in 32% of neurologically normal French bulldogs, 24.3% of English bulldogs and 1.7% of pugs (Bertram et al., 2019). The prevalence of thoracic and lumbosacral hemivertebrae is lower in neurologically normal pugs compared to French and English bulldogs (Ryan et al., 2017; Bertram et al., 2019; Brown et al., 2021). Furthermore, neurologically normal pugs are almost exclusively affected by one hemivertebra subtype; ventral hypoplasia (Ryan et al., 2019). In contrast, neurologically normal French and English bulldogs display a wider variation in hemivertebra subtypes with ventral and median aplasia and ventral and median hypoplasia being the most common hemivertebra subtypes (Ryan et al., 2019; Brown et al., 2021). Thoracic and lumbosacral hemivertebra are however only rarely reported in other dog breeds.

### 2.2. Clinical findings in dogs with hemivertebra

Some dogs with hemivertebra will develop signs of progressive pelvic limb ataxia and paraparesis. Although most affected dogs are younger than one year of age, clinical signs can occur later in life (Charalambous et al., 2014; Wyatt et al., 2018; Mathiesen et al., 2018). Spinal hyperaesthesia is only rarely present. Although it remains challenging to identify hemivertebra as the primary cause of clinical signs, hemivertebra in pugs and hemivertebra associated with kyphosis exceeding 35°, are two consistent clinical factors associated with an increased likelihood of neurological signs (Moissonnier et al., 2011; Guevar et al., 2014; Ryan et al., 2017; De Decker et al., 2019; Brown et al., 2021). It is unclear if hemivertebra subtype is associated with a higher likelihood of clinical signs. Although ventral aplasia or 'dorsal' hemivertebra is often observed in dogs with clinical signs (Charalambous et al., 2014; Gutierrez-Quintana et al., 2014), studies have not been able to identify a reliable association between hemivertebra subtype and likelihood of clinical signs (De Decker et al., 2019; Brown et al., 2021). Other factors that have been associated with a higher likelihood of clinical signs in some, but not in other studies, were the presence of vertebral subluxation or 'step formation', a lower number of hemivertebra along the vertebral column, and the degree of vertebral canal stenosis (Moissonnier et al., 2011; De Decker et al., 2019; Brown et al., 2021; Lackmann et al., 2022).

The increasing evidence that the severity of spinal kyphosis is a key factor in development of clinical signs, supports an important role of instability in the pathophysiology of hemivertebra and the importance of vertebral stabilisation in the surgical treatment of hemivertebra with kyphosis (Charalambous et al., 2014; Mathiesen et al., 2018; Mariné et al., 2021).

### 2.3. Diagnosis and treatment of hemivertebra with kyphosis

The diagnostic modality of choice is magnetic resonance imaging (MRI). MRI facilitates evaluation of spinal cord compression at the level of a hemivertebra and allows assessment of possible concurrent spinal conditions, such as intervertebral disc disease or SAD (Dewey et al., 2016). Although CT is superior to characterise the bony abnormalities associated with hemivertebra and provide information necessary for surgical planning, the spinal cord parenchyma and degree of spinal cord compression cannot be assessed with this diagnostic technique (De Decker et al., 2019).

Treatment of thoracic hemivertebra is challenging (Table 2). It has originally been suggested that mild clinical signs in young dogs could potentially stabilise when they would become skeletally mature (Dewey et al., 2016). A small retrospective study has however suggested that medical management of hemivertebra is associated with a poor prognosis. Progression of neurological signs occurred in all dogs, resulting in euthanasia or a non-ambulatory status in most dogs (Wyatt et al., 2018). It is therefore possible that surgery is the treatment modality of choice. Although initial surgical reports have described the combination of decompressive surgery with vertebral stabilisation (Aikawa et al., 2007), it has been debated if decompressive surgery should be considered indicated and appropriate. In most dogs, vertebral canal stenosis does not appear to be a primary factor in the pathophysiology of hemivertebra with kyphosis (Moissonnier et al., 2011; De Decker et al., 2019) and it is possible that creating a bony defect could contribute to already present vertebral instability. Several studies have reported

**Table 2**
Summary of publications reporting outcome after medical or surgical treatment for hemivertebra in small brachycephalic dogs.

| Study | Treatment modality | Study design | Number of animals | Outcome | Follow-up time | Comments |
|---|---|---|---|---|---|---|
| Aikawa et al., 2007 | Vertebral stabilization using threaded profile pins and PMMA Combined with Laminectomy or hemilaminectomy in 8 dogs | Retrospective, single centre | 9 dogs: 2 pugs, 2 FBD, 5 other small breeds | 8 dogs regained ambulatory status | Mean 39.8 months (range: 8–82) | 1 dog had SAD at site of surgery |
| Jeffery et al., 2007 | Dorsal laminectomy or hemilaminectomy in combination with vertebral stabilization using PMMA and K-wires or threaded external fixator pins | Retrospective, single centre | 3 dogs: 2 pugs, 1 EBD | All dogs regained ambulatory status with mild residual ataxia | 3 weeks to 3 months | |
| Charalambous et al., 2014 | Spinal segmental stabilisation with or without decompression 3 dogs also decompressive surgery; dorsal laminectomy in 2 and corpectomy in 1 | Retrospective, multi-institutional | 9 dogs: 6 pugs, 2 EBDs, 1 pomeranian | 4 neurologically normal, 3 mild residual ataxia, 1 moderate ambulatory paraparesis, 1 relapsed 3.5 years after surgery | Range 1.5 – 5.5 years | Long-term complications associated with technique in Mavrides et al., 2021 |
| Wyatt et al., 2018 | Medical management | Retrospective, multi-institutional | 13 dogs: 9 pugs, 3 FBDs, 1 EBD | Progression of signs in all dogs: 4 euthanized, 2 underwent surgery, 7 alive | Median 518 days (range 55–1730) | Medical management not standardized |
| Mathiesen et al., 2018 | Transthoracic bilateral ventral stabilization with SOP (String of Pearls) | Retrospective, single institution | 6 pugs | All improved to mild residual ataxia and excellent quality of life | Median 9 months (range 6–16) | |
| Elford et al., 2020 | Dorsal bicortical pedicle screws and PMMA. Use of 3D-printed patient-specific drill guides | Retrospective, single institution | 6 dogs; 5 pugs and 1 FBD | No clinical outcome reported | No follow-up recorded | Study focused on accuracy implant placement |
| Farré Mariné et al., 2021 | Unilateral transthoracic vertebral distraction and stabilization using monocortical screws and PMMA | Retrospective, multi-institutional | 10 dogs: 7 pugs, 2 FBDs, 1 cross-breed | One died within 24hrs postoperatively 7 recovered full function, 2 improved to ambulatory paraparesis | Median 26.5 months (range 12–50) | |

EBD, English bulldog; FBD, French bulldog; PMMA, polymethylmethacrylate

positive outcomes after stabilisation without additional decompression (Table 2) (Charalambous et al., 2014; Mathiesen et al., 2018; Mariné et al., 2021). The role of partial realignment of the vertebral column is currently unclear. Two surgical approaches that have been associated with successful outcomes are a transthoracic approach to the ventral and lateral aspects of the vertebral column (Mathiesen et al., 2018; Mariné et al., 2021) and a dorsal approach requiring more extensive dissection of the paravertebral muscles (Charalambous et al., 2014; Elford et al., 2020).

### 2.4. Remaining questions

Do hemivertebra predispose to intervertebral disc disease?

Since hemivertebra are only rarely the primary cause of clinical signs in dogs with a gait abnormality, it has been suggested that hemivertebra, especially in French bulldogs, should be considered incidental findings on diagnostic imaging studies (Ryan et al., 2017). Thoracic hemivertebra with kyphosis alter however gait variables (Wyatt et al., 2019) and have been associated with accelerated intervertebral disc degeneration adjacent to the kyphotic vertebral segment (Faller et al., 2014), and a more caudal distribution of thoracolumbar intervertebral disc extrusions along the vertebral column (Aikawa et al., 2014; Inglez de Souza et al., 2018). One study reported that French bulldogs with kyphosis were at twice the odds of having a thoracolumbar intervertebral disc extrusion (Inglez de Souza et al., 2018). Further longitudinal studies are however necessary to assess if and to which degree kyphosis increases the risk of developing intervertebral disc disease.

Are hemivertebra more clinically important in pugs?

Studied have suggested that hemivertebra is of greater clinical concern in pugs compared to French and English bulldogs (Ryan et al., 2017; De Decker et al., 2019; Brown et al., 2021). Hemivertebra in pugs has also been associated with specific anatomical characteristics (Ryan et al., 2019). Although pugs and bulldogs share similar phenotypic characteristics, they should not be considered related breeds (Parker, 2012). Pugs should not be considered a 'screw-tailed' brachycephalic breed and do not carry the aforementioned *DISHEVELLED 2* variant (Mansour et al., 2018). It is therefore possible that the aetiology and pathophysiology of thoracic hemivertebra are different in pugs compared to 'screw-tailed' brachycephalic breeds.

Can we develop meaningful screening programs?

Radiographic screening programs, based on the number, subtype, and anatomic location of the hemivertebra have been considered (Schlensker and Distl, 2016). The prevalence of thoracic hemivertebra is however extremely high in neurologically normal French and English bulldogs, while the associated prevalence of neurological signs is low in these two breeds (Ryan et al., 2017). Studies have also not identified a clear relationship between the presence of neurological signs and the number (De Decker et al., 2019), subtype (Brown et al., 2021), and location (Lackmann et al., 2022) of the hemivertebra. Studies have suggested that a Cobb angle exceeding 35° is associated with an increased likelihood of clinical signs and measurement of Cobb angles on diagnostic imaging studies is relatively easy and reliable (Guevar et al., 2014; De Decker et al., 2019). Severe kyphosis does however also occur in neurologically normal dogs (Inglez de Souza et al., 2018) and kyphosis should not be considered a static anatomical factor (Fig. 2). This is illustrated in a case report describing neurological signs and marked thoracic kyphosis in a 6-month-old pug. Thoracic radiographs did however not disclose any kyphosis when the dog was only 2 months old (De Rycke et al., 2016).

### 2.5. Caudal articular process dysplasia

#### 2.5.1. Pathology

Caudal articular process dysplasia is characterised by complete (aplasia) or partial (hypoplasia) absence of one or more caudal vertebral articular processes (Fig. 3). When CAPD was initially reported, it was

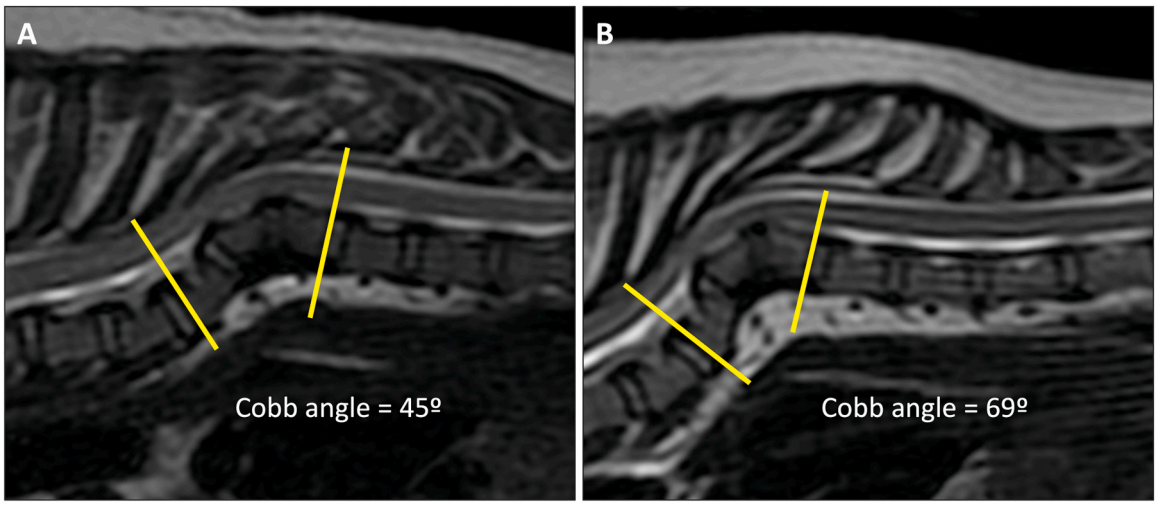


**Fig. 2.** (A) T2-weighted sagittal MR image of a 5-month-old pug with mild paraparesis and ataxia of the pelvic limbs. A thoracic hemivertebra with kyphosis can be seen. The measured Cobb angle is 45 degrees. (B) The same dog 2 months later. Although still ambulatory, more severe ataxia and paresis is seen. The measured Cobb angle is 69 degrees, indicating worsening of the previously diagnosed kyphosis. Although it is currently unknown how increased kyphosis results in progression of clinical signs, it is possible this is associated with increased instability or a more severe dynamic component of spinal cord compression.

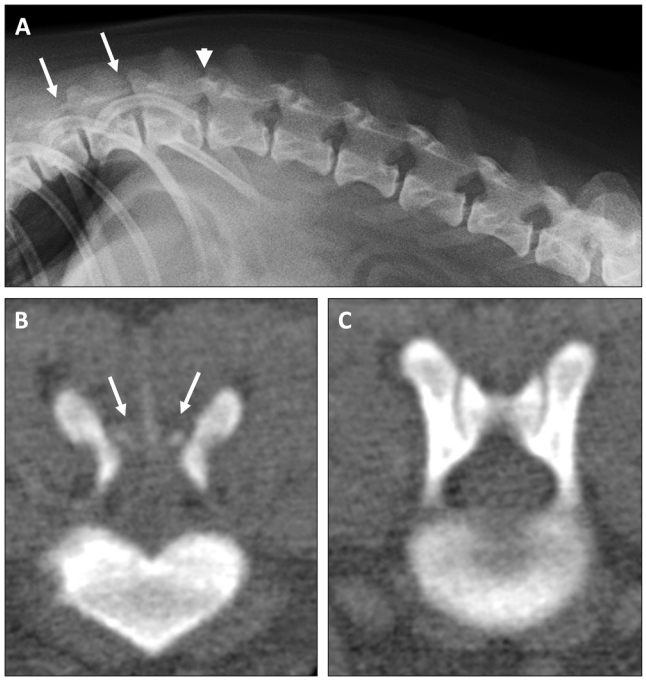


**Fig. 3.** (A) Lateral spinal radiograph of a 7-year-old pug with ambulatory paraparesis and ataxia of the pelvic limbs. The caudal articular process cannot be recognised at the levels of T11-T12 and T12-T13 (arrows). The caudal articular process can be recognised at the level of T13-L1 (arrowhead). Only 6 lumbar vertebrae are present. (B) CT image at the level of T12-T13 confirms bilateral caudal articular process aplasia (arrows). (C) CT image at the level of T13-L1 reveals presence of normally developed caudal articular processes.

suggested to cause low-grade repetitive vertebral instability, which could subsequently lead to reactive fibrotic tissue formation surrounding the spinal cord. The latter has been referred to as constrictive myelopathy or meningeal fibrosis (Fisher et al., 2013; Rohdin et al., 2020). CAPD has also been associated with other spinal disorders, such as intervertebral disc disease and SAD (Nishida et al., 2019; Driver et al., 2019).

#### 2.5.2. *Prevalence of CAPD in brachycephalic dogs*

In agreement with hemivertebra, there is a high prevalence of CAPD in neurologically normal French bulldogs (70.4%), English bulldogs (81.4%) and pugs (97%) (Bertram et al., 2018). Compared to French and English bulldogs, pugs demonstrate a higher prevalence of CAPD, a higher prevalence of caudal articular process aplasia (in contrast to hypoplasia), a higher number of affected vertebrae per dog, more often bilateral dysplasia, and CAPD localised in the caudal (vs. cranial) thoracic vertebral segments (Bertram et al., 2018). CAPD localised to the cranial thoracic vertebral segments occurs however also commonly in a variety of other brachycephalic and non-brachycephalic toy, small, and medium breed dogs (Ban et al., 2023).

### 2.6. *Remaining questions*

Is CAPD a clinically relevant vertebral malformation?

CAPD has been suggested to result in low grade vertebral instability, which could potentially contribute to the development of other spinal conditions, such as MF, SAD, and intervertebral disc protrusion (Fisher et al., 2013; Nishida et al., 2019; Driver et al., 2019; Aikawa et al., 2022). Dynamic spinal cord compression and intraoperative vertebral instability has also been demonstrated in dogs with CAPD at sites with or without articular process anomalies (Aikawa et al., 2022). This vertebral anomaly is however omnipresent in the overall pug population and is also commonly observed in other breeds (Bertram et al., 2018; Ban et al., 2023). Although concurrent spinal conditions often occur at the same site as CAPD (Driver et al., 2019), studies have been unable to conclusively confirm a causative relationship between CAPD and other myelopathies (Nishida et al., 2019; Driver et al., 2019; Ban et al., 2023; Wachowiak et al., 2023). Even if the contribution of CAPD to the development of other spinal conditions remains unclear, it is possible that the presence of vertebral instability should be considered when performing decompressive spinal surgery in dogs with CAPD (Aikawa et al., 2022).

### 2.7. *Transitional vertebrae*

#### 2.7.1. *Pathology*

Transitional vertebrae are located at the junction between two divisions of the vertebral column. Their morphology is variable as they combine features of two different vertebral types and occur most commonly at the thoracolumbar and lumbosacral junction. They also

can result in variations in the number of vertebrae found within a vertebral segment (Fig. 4A). (Westworth and Sturges, 2010; Brocal et al., 2018b).

#### 2.7.2. Prevalence of transitional vertebra in brachycephalic dogs

Transitional vertebrae are significantly more common in pugs than other small brachycephalic breeds, affecting cervicothoracic, thoracolumbar, and lumbosacral regions (Ryan et al., 2017; Brocal et al., 2018b; Bertram et al., 2019). Interestingly they are one of the only breeds to have frequent cervical ribs on C7 (Fig. 4A) (46% of neurologically normal pugs) (Brocal et al., 2018b). This is unusual, as the number of cervical vertebrae in mammals is almost constant at seven, implying that there is selection against variation in this number with pugs seeming to be breaking these evolutionary constraints. Thoracolumbar and lumbosacral transitional vertebrae are also common in this breed with multiple studies reporting a prevalence higher than 30% for both regions (Ryan et al., 2017; Brocal et al., 2018b; Bertram et al., 2019; Gong et al., 2020; Brown et al., 2021). In one study, pugs with a T3-L3 myelopathy presented more often a lumbosacral transitional vertebra compared to pugs without neurological deficits (Rohdin et al., 2018b).

The clinical relevance of transitional vertebrae remains however uncertain and somewhat controversial (Flückiger et al., 2006; Flückiger et al., 2017).

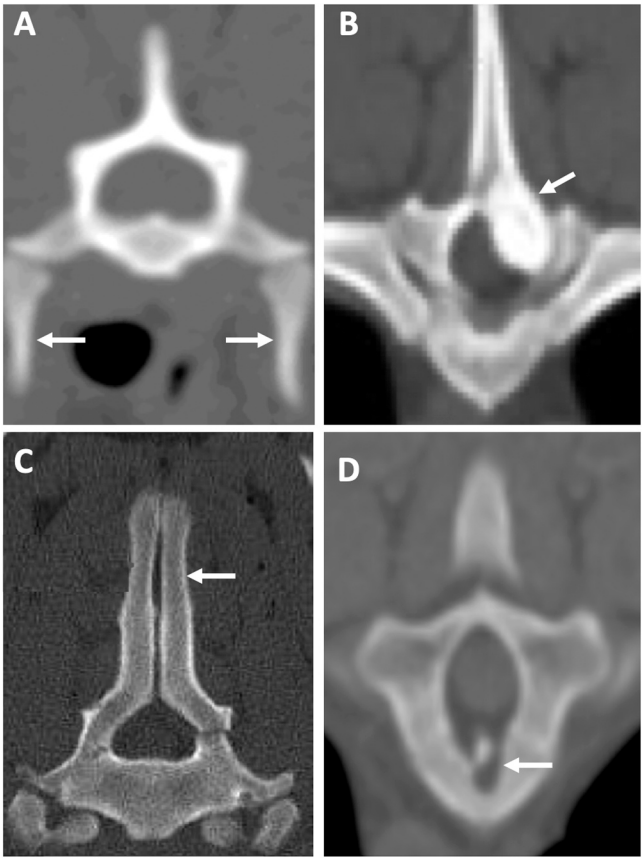


**Fig. 4.** (A) CT image at the level of the C7 vertebrae in a 2-year-old pug reveals a transitional C7 vertebrae with bilateral small ribs (arrows). (B) CT image at the level of T3-T4 in a 3-year-old French bulldog reveals presence of enlarged pedicle (arrow) causing vertebral canal stenosis. (C) CT image at the level of T1 in an 18-months-old pug reveals a bifid dorsal spinous process (arrows. (D) CT image at the level of T9 in a 4-years-old English bulldog showing vertebral vascular canal dysplasia (arrow) characterised by a defect in the ossification of the vertebral body centred around the vascular canal.

### 2.8. Thoracic vertebral canal stenosis

Cranial thoracic vertebral canal stenosis has been described in small brachycephalic breeds (Conte et al., 2021; Knecht et al., 1979;). It is observed predominantly in young male English and French bulldogs (Conte et al., 2021). The most common locations are T2-T3 and T3-T4 (Fig. 4B), emphasising the importance of including this region when performing diagnostic imaging investigations for bulldogs with paraparesis. Interestingly, not all stenoses are clinically relevant, and the degree of stenosis should be considered. Surgical and medical treatment have been reported with good outcomes (Conte et al., 2021).

### 2.9. Spina bifida

Spina bifida is the embryonic failure of fusion of one or more vertebral arches; it can happen as a single entity or be accompanied with spinal cord malformations (Song et al., 2016). As a single entity, it is commonly observed as an incidental finding on the first thoracic vertebra of pugs (Fig. 4C) (Ryan et al., 2017) and in the lumbosacral region of pugs, French and English bulldogs (Bertram et al., 2019). Spina bifida with concurrent meningocele or meningomyelocele in the lumbosacral region has been reported in English and French bulldogs causing urinary and faecal incontinence (Martin Muñiz et al., 2020). Little information is available regarding the best management for these cases, with early surgery preventing further neurological deterioration and potential improvement in some cases (Martin Muñiz et al., 2020).

### 2.10. Vertebral vascular canal dysplasia

Vertebral vascular canal dysplasia is a recently described vertebral malformation affecting French and English bulldogs. It has not yet been reported in pugs. Vertebral vascular canal dysplasia is characterised by a defect in the ossification of the vertebral body of variable extent, centred around the vascular canal (Fig. 4D). These defects are mainly identified using advanced imaging such as CT and MRI and are a frequent finding in English and French bulldogs (Santifort et al., 2022). Further studies are needed to understand the possible aetiology and clinical relevance.

#### 2.10.1. Remaining questions

Should transitional vertebra, cranial thoracic vertebral canal stenosis, spina bifida, and vertebral vascular canal dysplasia be considered ‘normal’ in small brachycephalic breeds?

The clinical relevance of these vertebral malformations is currently unclear. They occur commonly in neurologically normal small brachycephalic dogs and are only likely to cause neurological signs when there is particularly severe pathology or in specific locations. This is illustrated by the fact that clinical signs of cranial thoracic vertebral canal stenosis are more likely to occur when hypertrophy of the lamina and articular processes has resulted in severe vertebral canal stenosis (Conte et al., 2021). Furthermore, although spina bifida can be associated with meningocele or meningomyelocele in the lumbosacral region (Martin Muñiz et al., 2020), this malformation occurs commonly in the cranial thoracic region of neurologically normal pugs (Ryan et al., 2017). Finally, although lumbosacral transitional vertebra has been associated with and increased likelihood of degenerative lumbosacral stenosis (Flückiger et al., 2006), it remains unclear if this is also true in small brachycephalic dogs. Even if we accept that a variety of vertebral malformations occur commonly in neurologically normal brachycephalic dogs, it can be questioned if we should consider this high prevalence of anatomic variations normal and acceptable. It is further possible that we have not yet unravelled the complete spectrum of clinical abnormalities associated with vertebral malformations.

## 3. Spinal malformations

Benign meningeal proliferative disorders in dogs have been

described as two separate disorders. Focal dilations of the subarachnoid space containing cerebrospinal fluid (CSF) are described as SAD (Mauler et al., 2014; Smith and Guevar, 2020) and meningeal fibrous adhesions are described as meningeal fibrosis (MF) or constrictive myelopathy (Fisher et al., 2013; Rohdin et al., 2020). Dogs with SAD and MF present most often with a chronic onset of progressive ataxia and paresis. Urinary or faecal incontinence occurs in approximately 20% of cases and spinal hyperesthesia is typically not present (Fisher et al., 2013; Mauler et al., 2014; Rohdin et al., 2020). Especially in pugs, it is common to observe multiple concurrent thoracolumbar spinal conditions, such as SAD, CAPD, MF, and intervertebral disk herniation, when they are assessed for a chronic, progressive T3-L3 myelopathy (Fig. 5) (Wachowiak et al., 2023) This clinical phenotype has been referred to as 'pug dog thoracolumbar myelopathy' and multiple genetic risk factors have been identified. Identified candidate genes are implicated in bone homeostasis, fibrotic scar tissue, inflammatory responses, and the formation, regulation, and differentiation of cartilage (Brander et al., 2023).

### 3.1. Spinal arachnoid diverticula

#### 3.1.1. Pathology

Although SAD has been reported in a wide variety of breeds, pugs and French bulldogs are predisposed (Mauler et al., 2014). The underlying aetiology of SAD can be divided into congenital and acquired causes. Acquired SADs can occur secondarily to intervertebral disc herniation, vertebral malformations, trauma and inflammatory disorders (Smith and Guevar, 2020). Although French bulldogs and pugs with SAD often have a vertebral malformation near the SAD (Mauler et al., 2014), the causative relationship between both conditions remains unclear.

SADs occur most commonly in the cranial cervical or thoracolumbar region (Skeen et al., 2003; Gnirs et al., 2003). In small breed dogs, including the French bulldog, SADs occur most commonly in the thoracolumbar region (Skeen et al., 2003; Mauler et al., 2014). Pugs form an exception with SADs regularly being diagnosed in both the cervical and thoracolumbar region (Flegel et al., 2013; Rohdin et al., 2014; Alisauskaite et al., 2019) (Fig. 6). Pugs with thoracolumbar SADs develop clinical signs at an older age, while pugs with cervical SAD typically present at a younger age (Mauler et al., 2014; Rohdin et al., 2014). Cervical SADs have been reported in related pugs, suggesting a possible hereditary aetiology (Rohdin et al., 2014).

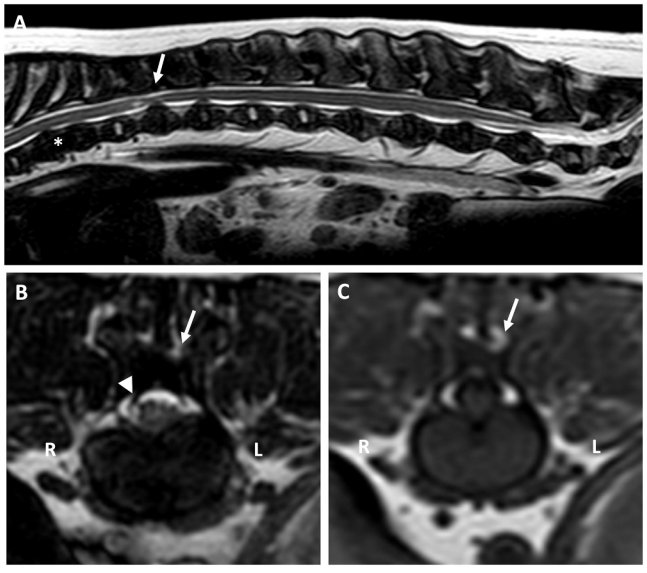


**Fig. 5.** (A) T2-weighted sagittal MR image of an 8-year-old pug with chronic progressive paraparesis and ataxia of the pelvic limbs. A vertebral body malformation is present at the level of T9 (asterisk). A mild widening of the dorsal subarachnoid space can be at the level of T11-T12 (arrow). An intraparenchymal hyperintensity and intervertebral disk protrusion can also be observed at this level. (B) T2-weighted and (C) T1-weighted transverse images at the level of T11-T12 reveal an irregular shaped and widened subarachnoid space with linear hypointense bands (arrowhead). A hypoplastic left sided caudal articular process (arrow) and an intervertebral disc protrusion are also present.

#### 3.1.2. Diagnosis of SAD

Spinal arachnoid diverticula can be diagnosed by myelography, CT myelography and MRI. The classic imaging appearance of SAD consists of a teardrop-shaped dilatation of the subarachnoid space (Galloway et al., 1999; Gnirs et al., 2003). Magnetic resonance imaging can demonstrate a focal widening of the subarachnoid space (Mauler et al., 2014) and allows visualization of the adjacent spinal cord parenchyma (Rohdin et al., 2014; Shivapour et al., 2019). It can, however, be difficult to reliably differentiate between a SAD and subarachnoid widening associated with MF on MRI sequences. The addition of a single-shot turbo spin-echo (Seiler et al., 2012) or three-dimensional constructive interference in steady state (3D-CISS) sequences (Tauro et al., 2018) can improve identification of SAD.

#### 3.1.3. Treatment of SAD

SAD can be treated medically or surgically. Medical management of SAD has been associated with long-term improvement in 30% and stabilisation of clinical signs in another 30% of cases (Mauler et al., 2017). Several surgical techniques have been described with no clear evidence of superiority of one technique over the others (Skeen et al., 2003; Spinillo et al., 2021; Jones et al., 2022). Surgical treatment of SAD has been associated with long-term improvement in 82% of cases (Mauler et al., 2017). Late-onset post-operative recurrence of signs has been reported (Alcoverro et al., 2018). Although surgery has been associated with good long-term results in most dogs, pugs with thoracolumbar SADs have been reported to have worse outcomes. A study demonstrated that, although 80% of pugs experienced a good short-term outcome after surgery, 85% of them experienced late-onset recurrence of neurological signs (Alisauskaite et al., 2019).

### 3.2. Meningeal fibrosis

#### 3.2.1. Pathology

Meningeal fibrosis is characterised by the formation of a dense, sometimes circumferential, band of fibrotic tissue, causing intradural adhesions between the arachnoid and pia mater and constriction of the spinal cord (Fisher et al., 2013). Although it can occur in other breeds, MF is heavily associated with the pug breed. Affected animals develop clinical signs later in life, with studies reporting a median age around 7.5 years (Fisher et al. 2013; Rohdin et al., 2020; Lourinho et al., 2020). Meningeal fibrosis typically affects the caudal thoracic vertebral column and was originally proposed to develop secondarily to CAPD. It was hypothesized that low-grade and repetitive vertebral instability associated with CAPD could result in development of fibrotic bands and eventually MF (Fisher et al., 2013). Meningeal fibrosis has however also been reported in pugs with other vertebral malformations, such as hemivertebra, and in pugs without concurrent vertebral anomalies (Lourinho et al., 2020; Rohdin et al., 2020). The causative relationship between MF and CAPD remains therefore unclear.

#### 3.2.2. Diagnosis of meningeal fibrosis

Meningeal fibrosis or constrictive myelopathy is diagnosed by MRI (Driver et al., 2019; Lourinho et al., 2020) (Fig. 7). Reported MRI abnormalities include: an irregular subarachnoid space with mixed signal intensity on T2-weighted images; multiple linear hypointense bands that transverse across the arachnoid to the pia across the arachnoid space; spinal cord distortion and compression; CSF in multiple pockets; and bilateral V-shaped ventrolateral extradural lesions (Driver et al., 2019;

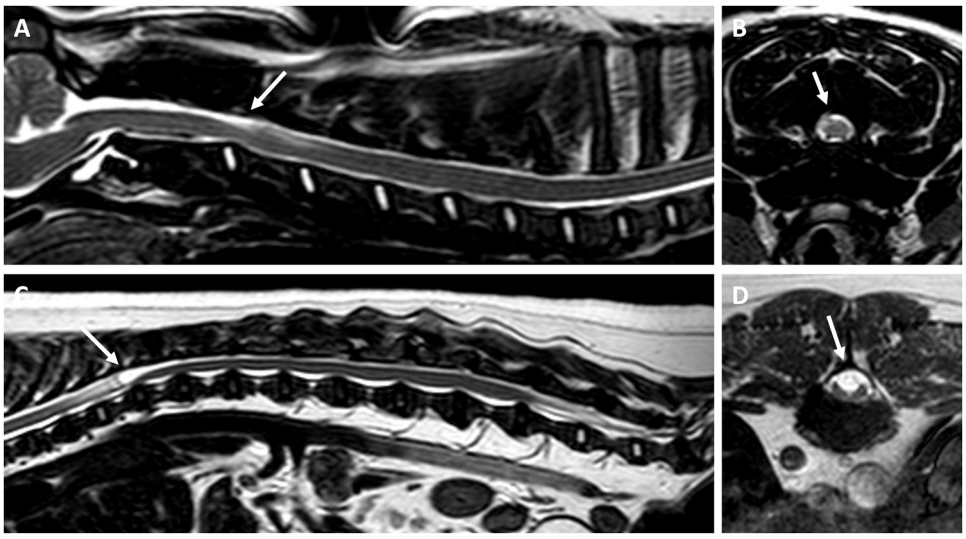


**Fig. 6.** (A) Sagittal and (B) transverse T2-weighted MR images of a 7-month-old pug with a SAD at the level of C2-C3. A focal widening of the dorsal subarachnoid space can be seen (arrow). (C) Sagittal and (D) transverse T2-weighted MR images of a 10-year-old pug with a spinal arachnoid diverticulum (SAD) at the level of T10-T11. A teardrop shaped enlargement of the dorsal subarachnoid space can be seen (arrow). Pugs with thoracolumbar SAD are often older, while pugs with cranial cervical SAD are often younger.

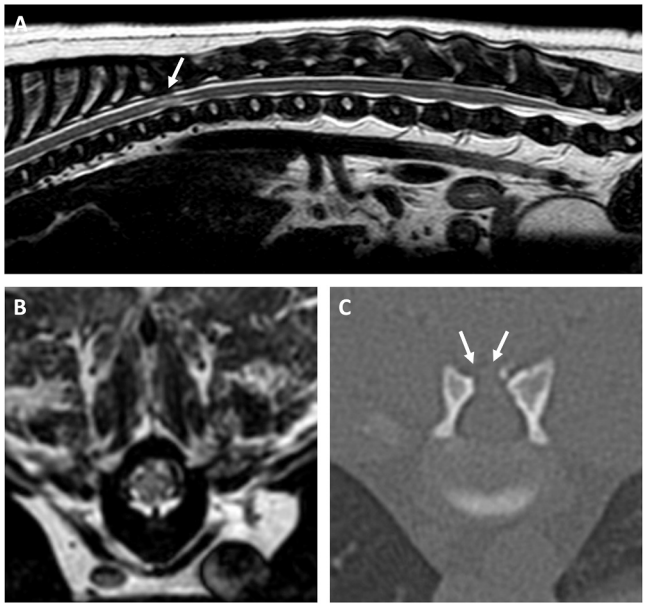


**Fig. 7.** (A) Sagittal T2-weighted image of a 9-year-old pug with meningeal fibrosis at the level of T10-T11. Dorsoventral narrowing of the spinal cord and an intraparenchymal hyperintensity can be seen (arrow). (B) Transverse T2-weighted image at the level of T10-T11 reveals circumferential spinal cord narrowing, an irregular subarachnoid space with mixed signal intensity and CSF in multiple pockets. (C) Computed tomography at the level of T10-T11 reveals bilateral caudal articular process aplasia (arrows).

Lourinho et al., 2020). An intraparenchymal hyperintensity is usually present at the site of spinal cord compression and post-contrast images can reveal circumferential or focal contrast enhancement (Rohdin et al., 2020; Lourinho et al., 2020).

### 3.2.3. *Treatment of meningeal fibrosis*

Little is known about the results of medical management (Rohdin et al., 2020). Surgical treatment consisting of decompressive surgery in combination with dissection of the pia-arachnoid adhesions has been associated with a poor outcome (Fisher et al., 2013). Vertebral stabilization with or without additional decompression has been associated with neurological improvement (Tauro et al., 2019; Aikawa et al., 2022). Concurrent urinary or faecal incontinence is, however, expected to resolve in fewer than half of affected cases (Tauro et al., 2019). A favourable outcome has also been reported after subarachnoid-subarachnoid shunt placement to bridge the site of CSF flow obstruction in dogs with pia-arachnoid fibrosis (Meren et al., 2017).

### 3.2.4. *Pathology and histopathology in dogs with meningeal fibrosis*

Post-mortem examinations of pugs with MF show adhesions involving the dura and/or the leptomeninges that embrace the spinal cord circumferentially (Rohdin et al., 2020). The leptomeningeal proliferations (Fig. 8A) are often associated with formation of a diverticula of varying size, in some creating multiple compartments of the subarachnoid space (Fig. 8B). Spinal cord cavitations characterized by malacia, hydro- or syringomyelia commonly accompany the focal meningeal fibrous adhesions. The meningeal vessels and nerve roots are embedded, and appear constricted, in the MF. In addition, varying degrees of lympho-histiocytic inflammation of the central nervous system is commonly, but not always, present (Rohdin et al., 2020) (Fig. 8C). The lack of inflammatory cells on histopathology of some dogs with MF could suggest that focal arachnoiditis is not a primary factor in the development of meningeal proliferation or that it is no longer present at the time of examination. Pugs with focal intraparenchymal myelomalacia (Fig. 8D) have a more chronic duration of clinical sign and less often lympho-histiocytic inflammation (Rohdin et al., 2020). This could potentially indicate an early inflammatory phase and a later chronic proliferative state in which fibrosis and adhesions become permanent for the development of MF.

## 3.3. *Remaining questions*

Are SAD and MF separate conditions?

Although SAD and MF have traditionally been considered separate disorders, both conditions share some similarities. Both SAD and MF are meningoproliferative disorders but while SADs cause neurological deficits mainly through spinal cord compression, MF causes deficits mainly by obstructing the vascular supply to the spinal cord (Smith and Guevar, 2020; Rohdin et al., 2020). Imaging studies of dogs with SAD and MF demonstrate however some overlapping abnormalities and histopathological examinations of pugs with MF often reveal smaller diverticula

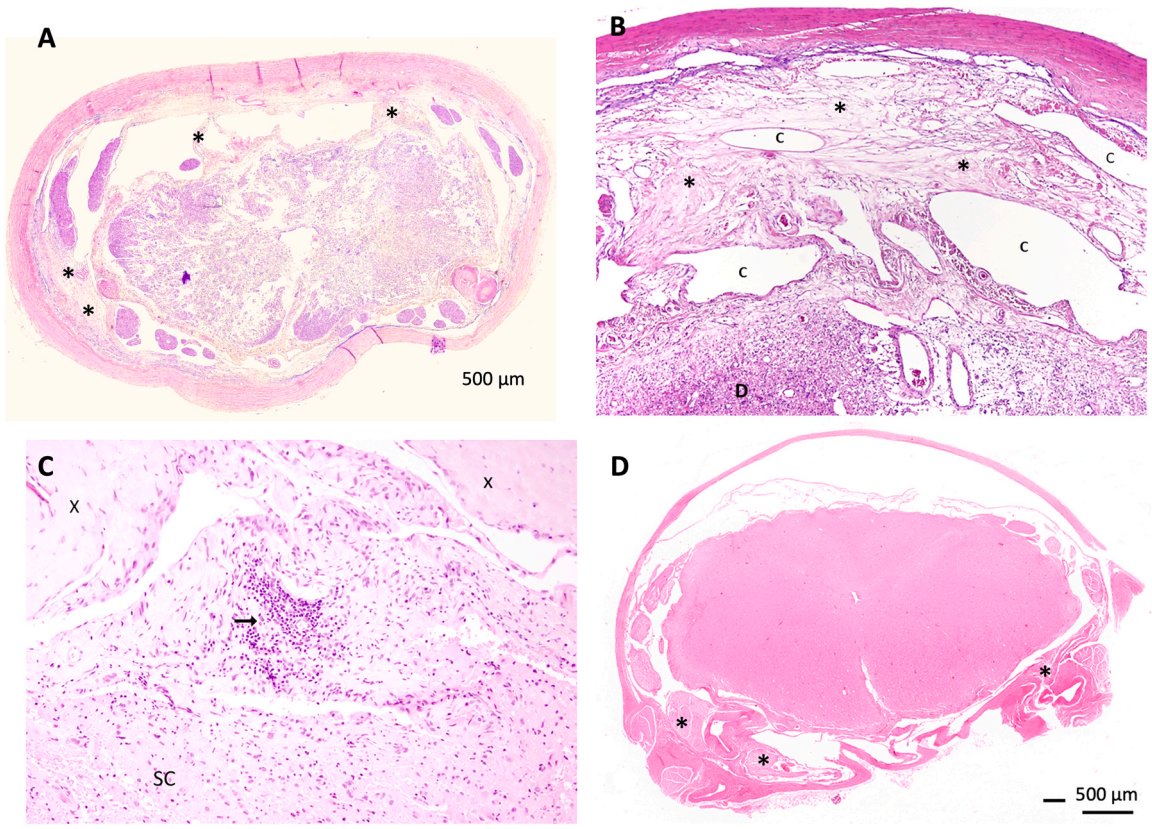


**Fig. 8.** Examples of histopathological findings in different pugs with meningeal fibrosis. (A) Focal malacia with almost total destruction of the spinal cord, leptomeningeal and subdural fibrosis (asterisk) with focal adhesions at the level of T13 where the pug also had caudal articular process hypoplasia; HE staining. (B) Formation of diverticula with multiple compartments (C) and leptomeningeal fibrosis (asterisk) of the subarachnoid space at the level of T10 where the pug also had caudal articular process hypoplasia. D = dorsal funiculus spinal cord; HE staining. (C) Moderate lympho-histiocytic leptomeningitis (arrows) adjacent to a thoracic, malacic, focal spinal cord (SC) lesion. X = pachymeninges; HE staining. (D) Prominent ventrolateral meningeal proliferation involving the pachymeninges with severely atrophied ventral horns at the level of C3; HE staining. This figure has been previously published in: Rohdin C. Phenotypic and genotypic characterization of a myelopathy in pugs. Doctoral thesis No. 2022:74. Faculty of Veterinary Medicine and Animal Science, Swedish University of Agricultural Sciences, Uppsala, Sweden.

with multiple compartments, of the subarachnoid space (Rohdin et al., 2020) (Fig. 8). The overlap of histopathological and MRI findings therefore potentially suggests that both conditions could represent a spectrum of the same disorder in pugs (Brander et al., 2023).

Does CAPD cause meningeal fibrosis?

Caudal articular process dysplasia has been suggested to lead to low grade vertebral instability and development of excessive fibrotic reactions (Fisher et al., 2013; Lourinho et al., 2020; Aikawa et al., 2022). Dogs with MF can also demonstrate neurological improvement after surgical stabilisation, suggestion a potential contributary role of instability (Tauro et al., 2019). Meningeal fibrosis has however also been reported in the absence of CAPD (Meren et al., 2017; Rohdin et al., 2020) and most animals with CAPD do not develop neurological signs (Bertram et al., 2018). It is therefore possible that this vertebral anomaly does not represent a primary or specific risk factor for the development of MF. The mechanism for the development MF remains incompletely understood and is possibly multifactorial. The body continuously responds to tissue damage and abnormal load, where fibrosis and inflammation are part of the normal physiological repair process. The distinction between physiology and pathology could be defined by matters of degree; enough repair can heal and restore, whereas excessive repair could lead to tissue dysfunction and ongoing excessive proliferation (White and Mantovani, 2013). It is therefore possible that MF represents an abnormal response of predisposed dogs to any type of meningeal irritation or compression, regardless of site or diagnosis (Wachowiak et al., 2023).

Why are pugs and French bulldogs predisposed for SAD?

Despite their physical similarities, pugs and French bulldogs are not closely related breeds (Parker, 2012). It is therefore likely that common genetic factors do not play a major role in the development of SAD in these breeds. Pugs and French bulldogs with SAD are often diagnosed with concurrent vertebral malformations, which has been associated with the formation of SAD (Mauler et al., 2014). Vertebral anomalies, including hemivertebra, CAPD, transitional vertebra, and spinal bifida occur however commonly in neurologically normal pugs and French bulldogs (Ryan et al., 2017; Rohdin et al., 2018b; Bertram et al., 2018). Conformational characteristics may potentially predispose pugs and French bulldogs to health problems not previously associated with the brachycephalic syndrome (Santifort et al., 2022). Brachycephalic breeds are prone to respiratory problems, predisposing the pug and French bulldog to hypoxia (Hendricks et al., 1987). Maternal hypoxia can result in vertebral defects in mammals (Farley et al., 2001; Sparrow et al., 2012) and hypoxia is also linked to a decreasing ability to maintain normal spinal cord function (Hendricks et al., 1987; Tarnoki et al., 2021). Furthermore, an association has been shown between an abnormal gait (ataxia and paresis) and dyspnoea in pugs (Rohdin et al., 2018a).

Why are pugs affected by meningeal fibrosis?

Vertebral malformations, including CAPD and hemivertebra occur commonly in French and English bulldogs, while these breeds are not predisposed for MF. It is therefore possible that vertebral malformations do not represent a major biomechanical risk factor for the development of MF in pugs. Pugs are prone to inflammatory CNS disease, such as necrotizing meningoencephalitis (NME) (Levine et al., 2008). Pugs with

focal fibrous adhesions may present with lympho-histiocytic inflammation, similar to dogs with NME (Rohdin et al., 2020). A recent study also recognized a strong inflammatory cytokine expression in a group of older pugs. (Windsor et al., 2021). A dysregulated immune response could potentially interfere with the normal physiological repair process resulting in excessive fibrous tissue. In people it has been suggested that some patients are predisposed for the development of fibrous adhesions caused by various factors including autoimmune-related mechanisms (Idris et al., 2014; Khan et al., 2016).

Why do pugs have a worse long-term prognosis after surgery for SAD?

Various pathophysiological mechanisms for the less favourable prognosis in pugs have been proposed including spinal deformity, vertebral column hypermobility, and abnormal CSF flow (Alisauskaite et al., 2019). There is also a degree of overlap in pathological and diagnostic imaging findings in pugs with SAD and MF. It is therefore possible that thoracolumbar SAD formation in this breed is associated with a multifactorial aetiology and a variety of pathological mechanisms.

Objective outcome assessment for SAD and MF is difficult in pugs

There is wide variation in clinical features and imaging findings in pugs with SAD and MF. It is further common to observe multiple concurrent spinal conditions affecting the same spinal segment in pugs with chronic spinal disease (Meren et al., 2017; Tauro et al., 2019; Wachowiak et al., 2023). This complicates clinical decision making and limits objective comparison of outcome data between studies.

This review summarised our current understanding of vertebral and spinal malformations in pugs, French, and English Bulldogs. It was unfortunately not possible to provide and in-depth and detailed discussion of each condition. Despite the publication of various studies in recent years, questions remain about the etiology, clinical relevance, and ideal treatment modality for several of these malformations. It is obvious that our increased knowledge has generated new clinically relevant questions, which will hopefully be answered in future studies.

## Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

## CRediT authorship contribution statement

**Rodrigo Gutierrez-Quintana:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Cecilia Rohdin:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Steven De Decker:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Conceptualization.

## References


Aikawa, T., Kanazono, S., Yoshigae, Y., Sharp, N.J., Muñana, K.R., 2007. Vertebral stabilization using positively threaded profile pins and polymethylmethacrylate, with or without laminectomy, for spinal canal stenosis and vertebral instability caused by congenital thoracic vertebral anomalies. Veterinary Surgery 36, 432–441.

Aikawa, T., Shibata, M., Asano, M., Hara, Y., Tagawa, M., Orima, H., 2014. A comparison of thoracolumbar intervertebral disk extrusion in French Bulldogs and Dachshunds and association with vertebral anomalies. Veterinary Surgery 202, 267–273.

Aikawa, T., Miyazaki, Y., Kihara, S., Saitoh, Y., Nishimura, M., Stephan, S.L., Dewey, C. W., 2022. Vertebral stabilisation for thoracolumbar vertebral instability associated with cranial and caudal articular process anomalies in pugs: Seven cases (2010–2019). Journal of Small Animal Practice 63, 699–706.

Alcoverro, E., McConnell, J.F., Sanchez-Masian, D., De Risio, L., De Decker, S., Gonçalves, R., 2018. Late-onset recurrence of neurological deficits after surgery for spinal arachnoid diverticula. Veterinary Record 182, 380.

Alisauskaite, N., Cizinauskas, S., Jeserevics, J., Rakauskas, M., Cherubini, G.B., Anttila, M., Steffen, F., 2019. Short- and long-term outcome and magnetic resonance imaging findings after surgical treatment of thoracolumbar spinal arachnoid diverticula in 25 Pugs. Journal of Veterinary Internal Medicine 33, 1376–1383.

Ban, J., Park, J., Kim, H., Yoon, K., Oh, M., Lee, Y., Lee, M., Chang, J., Kim, B., Kim, J., Chang, D., 2023. Investigation of canine caudal articular process dysplasia of thoracic vertebrae using computed tomography: prevalence and characteristics. Frontiers in Veterinary Science 10, 1066420.

Bertram, S., Ter Haar, G., De Decker, S., 2018. Caudal articular process dysplasia of thoracic vertebrae in neurologically normal French bulldogs, English bulldogs, and Pugs: prevalence and characteristics. Veterinary Radiology and Ultrasound 59, 396–404.

Bertram, S., Ter Haar, G., De Decker, S., 2019. Congenital malformations of the lumbosacral vertebral column are common in neurologically normal French Bulldogs, English Bulldogs, and Pugs, with breed-specific differences. Veterinary Radiology and Ultrasound 60, 400–408.

Brander, G., Rohdin, C., Bianchi, M., Bergvall, K., Andersson, G., Ljungvall, I., Jäderlund, K.H., Häggström, J., Hedhammar, Å., Lindblad-Toh, K., Tengvall, K., 2023. Multiple genetic loci associated with pug dog thoracolumbar myelopathy. Genes 14, 385.

Brocal, J., De Decker, S., José-López, R., Guevar, J., Ortega, M., Parkin, T., Ter Haar, G., Gutierrez-Quintana, R., 2018a. Evaluation of radiography as a screening method for detection and characterisation of congenital vertebral malformations in dogs. Veterinary Record 182, 573.

Brocal, J., De Decker, S., José-López, R., Manzanilla, E.G., Penderis, J., Stalin, C., Bertram, S., Schoenebeck, J.J., Rusbridge, C., Fitzpatrick, N., Gutierrez-Quintana, R., 2018b. C7 vertebra homeotic transformation in domestic dogs – are Pug dogs breaking mammalian evolutionary constraints? Journal of Anatomy 233, 255–265.

Brown, J.D., Podadera, J., Ward, M., Goldsmid, S., Simpson, D.J., 2021. The presence, morphology and clinical significance of vertebral body malformations in an Australian population of French Bulldogs and Pugs. Australian Veterinary Journal 99, 378–387.

Charalambous, M., Jeffery, N.D., Smith, P.M., Goncalves, R., Barker, A., Hayes, G., Ives, E., Vanhaesebrouck, A.E., 2014. Surgical treatment of dorsal hemivertebrae associated with kyphosis by spinal stabilisation with or without decompression. The Veterinary Journal 202, 267–273.

Conte, A., Bernardini, M., De Decker, S., Ricco, C., Behr, S., Sanchez-Masian, D., Cherubini, G.B., De Risio, L., Gutierrez-Quintana, R., 2021. Thoracic vertebral canal stenosis associated with vertebral arch anomalies in small brachycephalic screw-tail dog breeds. Veterinary and Comparative Orthopaedics and Traumatology 34, 191–199.

De Decker, S., Packer, R.M.A., Capello, R., Harcourt-Brown, T.R., Rohdin, C., Gomes, S. A., Bergknut, N., Shaw, T.A., Lowrie, M., Gutierrez-Quintana, R., 2019. Comparison of signalment and computed tomography findings in French bulldogs, pugs, and English bulldogs with and without clinical signs associated with thoracic hemivertebra. Journal of Veterinary Internal Medicine 33, 2151–2159.

De Rycke, L.M., Crijns, C., Chiers, K., van Bree, H.J.J., Gielen, I., 2016. Late-onset wedge-shaped thoracic vertebrae in a six-month-old pug. Veterinary Record Case Reports 4, e000317.

Dewey, C.W., Davies, E., Bouma, J.L., 2016. Kyphosis and kyphoscoliosis associated with congenital malformations of the thoracic vertebral bodies in dogs. Veterinary Clinics of North America: Small Animal Practice 46, 295–306.

Driver, C.J., Rose, J., Tauro, A., Fernandes, R., Rusbridge, C., 2019. Magnetic resonance imaging in pug dogs with thoracolumbar myelopathy and concurrent caudal articular process dysplasia. BMC Veterinary Research 15, 182.

Elford, J.H., Oxley, B., Behr, S., 2020. Accuracy of placement of pedicle screws in the thoracolumbar spine of dogs with spinal deformities with three-dimensionally printed patient-specific drill guides. Veterinary Surgery 49, 347–353.

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.

Farley, F.A., Loder, R.T., Nolan, B.T., Dillon, M.T., Frankenburg, E.P., Kaciroti, N.A., Miller, J.D., Goldstein, S.A., Hensinger, R.N., 2001. Mouse model for thoracic congenital scoliosis. Journal of Pediatric Orthopaedics 21, 537–540.

Fisher, S.C., Shores, A., Simpson, S.T., 2013. Constrictive myelopathy secondary to hypoplasia or aplasia of the thoracolumbar caudal articular processes in Pugs: 11 cases (1993-2009). Journal of the American Veterinary Medical Association 242, 223–229.

Flegel, T., Müller, M.K., Truar, K., Löffler, C., Oechtering, G., 2013. Thoracolumbar spinal arachnoid diverticula in 5 pug dogs. Canadian Veterinary Journal 54, 969–973.

Flückiger, M.A., Steffen, F., Hässig, M., Morgan, J.P., 2017. Asymmetrical lumbosacral transitional vertebrae in dogs may promote asymmetrical hip joint development. Veterinary and Comparative Orthopaedics and Traumatology 30, 137–142.

Flückiger, M.A., Damur-Djuric, N., Hässig, M., Morgan, J.P., Steffen, F., 2006. A lumbosacral transitional vertebra in the dog predisposes to cauda equina syndrome. Veterinary Radiology and Ultrasound 47, 39–44.

Galloway, A.M., Curtis, N.C., Sommerlad, S.F., Watt, P.R., 1999. Correlative imaging findings in seven dogs and one cat with spinal arachnoid cysts. Veterinary Radiology and Ultrasound 40, 445–452.

Gnirs, K., Ruel, Y., Blot, S., Begon, D., Rault, D., Delisle, F., Boulouha, L., Colle, M.-A., Carozzo, C., Moissonnier, P., 2003. Spinal subarachnoid cysts in 13 dogs. Veterinary Radiology and Ultrasound 44, 402–408.

Gong, H., Slunsky, P., Klass, L.G., Brunnberg, L., 2020. Prevalence of lumbosacral transitional vertebrae in dogs in Berlin. Polish Journal of Veterinary Science 23, 261–265.

Guevar, J., Penderis, J., Faller, K., Yeamans, C., Stalin, C., Gutierrez-Quintana, R., 2014. Computer-assisted radiographic calculation of spinal curvature in brachycephalic "screw-tailed" dog breeds with congenital thoracic vertebral malformations: reliability and clinical evaluation. PloS One 9, e106957.

Gutierrez-Quintana, R., De Decker, S., 2021. Tail end of the brachycephalic problem: diagnostic and treatment options for spinal malformations. In Practice 43, 124–134.
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.
Hendricks, J.C., Kline, L.R., Kovalski, R.J., O'Brien, J.A., Pack, A.I., 1987. The English bulldog: a natural model of sleep-disordered breathing. Journal of Applied Physiology 63 (1985), 1344–1350.
Idris, Z., Ghazali, F.H., Abdullah, J.M., 2014. Fibromyalgia and arachnoiditis presented as an acute spinal disorder. Surgical Neurology International 5, 151.
Inglez de Souza, M.C.C.M., Ryan, R., Ter Haar, G., Packer, R.M.A., Volk, H.A., De Decker, S., 2018. Evaluation of the influence of kyphosis and scoliosis on intervertebral disc extrusion in French bulldogs. BMC Veterinary Research 14, 5.
Jeffery, N.D., Smith, P.M., Talbot, C.E., 2007. Imaging findings and surgical treatment of hemivertebrae in three dogs. Journal of the American Veterinary Medical Association 230, 532–536.
Jones, B., Behr, S., Shaw, T., Capello, R., Jeffery, N., Liebel, F.X., Harcourt-Brown, T., 2022. Surgical techniques used in the management of intra-arachnoid diverticula in dogs across four referral centres and their immediate outcome. Journal of Small Animal Practice 63, 520–525.
Khan, M.U., Devlin, J.A., Fraser, A., 2016. Adhesive arachnoiditis in mixed connective tissue disease: a rare neurological manifestation. BMJ Case Reports 2016, bcr2016217418.
Knecht, C.D., Blevins, W.E., Raffe, M.R., 1979. Stenosis of the thoracic spinal canal in English Bulldogs. Journal of the American Animal Hospital Association 15, 181–183.
Lackmann, F., Forterre, F., Brunnberg, L., Loderstedt, S., 2022. Epidemiological study of congenital malformations of the vertebral column in French bulldogs, English bulldogs and pugs. Veterinary Record 190, e509.
Levine, J.M., Fosgate, G.T., Porter, B., Schatzberg, S.J., Greer, K., 2008. Epidemiology of necrotizing meningoencephalitis in Pug dogs. Journal of Veterinary Internal Medicine 22, 961–968.
Lourinho, F., Holdsworth, A., McConnell, J.F., Gonçalves, R., Gutierrez-Quintana, R., Morales, C., Lowrie, M., Trevail, R., Carrera, I., 2020. Clinical features and MRI characteristics of presumptive constrictive myelopathy in 27 pugs. Veterinary Radiology and Ultrasound 61, 545–554.
Mansour, T.A., Lucot, K., Konopelski, S.A., Dickinson, P.J., Sturges, B.K., Vernau, K.L., Choi, S., Stern, J.A., Thomasy, S.M., Döring, S., et al., 2018. Whole genome variant association across100 dogs identifies a frame shift mutation in DISHEVELLED 2 which contributes to Robinow-like syndrome in Bulldogs and related screw tail dog breeds. PLOS Genetics 14, e1007850.
Mariné, A.F., De Risio, L., Mascort, J., Peláez, M.J., López, M., Stabile, F., Feliu-Pascual, A.L., 2021. Transthoracic vertebral distraction and stabilization in 10 dogs with congenital thoracic vertebral malformations. Veterinary and Comparative Orthopaedics and Traumatology 34, 367–374.
Martin Muñiz, L., Del Magno, S., Gandini, G., Pisoni, L., Menchetti, M., Foglia, A., Ródenas, S., 2020. Surgical outcomes of six bulldogs with spinal lumbosacral meningomyelocele or meningocele. Veterinary Surgery 49, 200–206.
Mathiesen, C.B., de la Puerta, B., Groth, A.M., Rutherford, S., Capello, R., 2018. Ventral stabilization of thoracic kyphosis through bilateral intercostal thoracotomies using SOP (String of Pearls) plates contoured after a 3-dimensional print of the spine. Veterinary Surgery 47, 843–851.
Mauler, D.A., De Decker, S., De Risio, L., Volk, H.A., Dennis, R., Van der Vekens, E., Goethals, K., Van Ham, L., 2014. Signalment, clinical presentation, and diagnostic findings in 122 dogs with spinal arachnoid diverticula. Journal of Veterinary Internal Medicine 28, 175–181.
Mauler, D.A., De Decker, S., De Risio, L., Volk, H.A., Dennis, R., Gielen, I., Van der Vekens, E., Goethals, K., Van Ham, L., 2017. Spinal arachnoid diverticula: outcome in 96 medically or surgically treated dogs. Journal of Veterinary Internal Medicine 31, 849–853.
Mavrides, D., Charalambous, M., Freeman, P., 2021. Long-term follow-up of spinal segmental stabilization for surgical treatment of dorsal hemivertebrae associated with kyphosis in brachycephalic dogs. Canadian Veterinary Journal 62, 1323–1327.
Mayousse, V., Desquilbet, L., Jeandel, A., Blot, S., 2017. Prevalence of neurological disorders in French bulldogs: a retrospective study of 343 cases (2002-2016). BMC Veterinary Research 13, 212.
Meren, I.L., Chavera, J.A., Alcott, C.J., Barker, A.K., Jeffery, N.D., 2017. Shunt tube placement for amelioration of cerebrospinal fluid flow obstruction caused by spinal cord subarachnoid fibrosis in dogs. Veterinary Surgery 46, 289–296.
Moissonnier, P., Gossot, P., Scotti, S., 2011. Thoracic kyphosis associated with hemivertebra. Veterinary Surgery 40, 1029–1032.
Nishida, H., Nakata, K., Maeda, S., Kamishina, H., 2019. Prevalence and pattern of thoracolumbar caudal articular process anomalies and intervertebral disk herniations in pugs. The Journal of Veterinary Medical Science 81, 906–910.
Parker, H.G., 2012. Genomic analyses of modern dog breeds. Mammalian Genome 23, 19–27.
Rohdin, C., Nyman, H.T., Wohlsein, P., Hultin Jäderlund, K., 2014. Cervical spinal intradural arachnoid cysts in related, young pugs. Journal of Small Animal Practice 55, 229–234.
Rohdin, C., Jäderlund, K.H., Ljungvall, I., Lindblad-Toh, K., Häggström, J., 2018a. High prevalence of gait abnormalities in pugs. Veterinary Record 182, 167.
Rohdin, C., Häggström, J., Ljungvall, I., Nyman Lee, H., De Decker, S., Bertram, S., Lindblad-Toh, K., Jäderlund, K.H., 2018b. Presence of thoracic and lumbar vertebral malformations in pugs with and without chronic neurological deficits. The Veterinary Journal 241, 24–30.
Rohdin, C., Ljungvall, I., Häggström, J., Leijon, A., Lindblad-Toh, K., Matiasek, K., Rosati, M., Wohlsein, P., Jäderlund, K.H., 2020. Thoracolumbar meningeal fibrosis in pugs. Journal of Veterinary Internal Medicine 34, 797–807.
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 221, 25–29.
Ryan, R., Gutierrez-Quintana, R., Ter Haar, G., De Decker, S., 2019. Relationship between breed, hemivertebra subtype, and kyphosis in apparently neurologically normal French Bulldogs, English Bulldogs, and Pugs. American Journal of Veterinary Research 80, 189–194.
Santifort, K.M., Gutierrez-Quintana, R., Bernardini, M., Kortz, G.D., Gomes, S.A., Lowrie, M., De Decker, S., Glass, E.N., Bergknut, N., 2022. Vertebral vascular canal dysplasia in French and English Bulldogs: Clinical, CT, and MRI characteristics and prevalence. Veterinary Radiology and Ultrasound 63, 281–291.
Schlensker, E., Distl, O., 2016. Heritability of hemivertebrae in the French bulldog using an animal threshold model. The Veterinary Journal 207, 188–189.
Seiler, G.S., Robertson, I.D., Mai, W., Widmer, W.R., Suran, J., Nemanic, S., Lamb, C.R., Lang, J., Johnson, J.L., Thrall, D.E., 2012. Usefulness of a half-fourier acquisition single-shot turbo spin-echo pulse sequence in identifying arachnoid diverticula in dogs. Veterinary Radiology and Ultrasound 53, 157–161.
Shivapour, S.K., Volk, H.A., Watts, V., De Decker, S., 2019. Cine balanced fast field echo magnetic resonance imaging of canine spinal arachnoid diverticulae pulsation. Veterinary Journal 248, 86–90.
Skeen, T.M., Olby, N.J., Muñana, K.R., Sharp, N.J., 2003. Spinal arachnoid cysts in 17 dogs. Journal of the American Animal Hospital Association 39, 271–282.
Smith, C.J., Guevar, J., 2020. Spinal subarachnoid diverticula in dogs: A review. Canadian Veterinary Journal 6, 1162–1169.
Song, R.B., Glass, E.N., Kent, M., 2016. Spina bifida, meningomyelocele, and meningocele. Veterinary Clinics of North America: Small Animal Practice 46, 327–345.
Sparrow, D.B., Chapman, G., Smith, A.J., Mattar, M.Z., Major, J.A., O'Reilly, V.C., Saga, Y., Zackai, E.H., Dormans, J.P., Alman, B.A., et al., 2012. A mechanism for gene-Environment Interaction in the etiology of Congenital scoliosis 149, 295–306.
Spinillo, S., Golini, L., Mariscoli, M., Motta, L., 2021. Retrospective evaluation of surgical outcomes after closure of durotomy in eight dogs affected by spinal subarachnoid diverticulum. Open Veterinary Journal 10, 384–391.
Tarnoki, A.D., Tarnoki, D.L., Oláh, C., Szily, M., Kovacs, D.T., Dienes, A., Piroska, M., Forgo, B., Pinheiro, M., Ferreira, P., et al., 2021. Lumbar spinal abnormalities in patients with obstructive sleep apnoea. Nature Scientific Reports 11, 16233.
Tauro, A., Jovanovik, J., Driver, C.J., Rusbridge, C., 2018. Clinical application of 3D-CISS MRI sequences for diagnosis and surgical planning of spinal arachnoid diverticula and adhesions in dogs. Veterinary and Comparative Orthopaedics and Traumatology 31, 83–94.
Tauro, A., Rose, J., Rusbridge, C., Driver, C.J., 2019. Surgical management of thoracolumbar myelopathies in Pug dogs with concurrent articular facet dysplasia. Veterinary and Comparative Orthopaedics and Traumatology Open 2, e60–e72.
Teng, K.T.-Y., Brodbelt, D.C., Pegram, C., Church, D.B., O'Neill, D.G., 2022. Life tables of annual life expectancy and mortality for companion dogs in the United Kingdom. Nature Scientific Reports 12, 6415.
The Kennel Club [Internet]. Tackling health and welfare issues in brachycephalic dogs. Available from: ⟨https://www.thekennelclub.org.uk/health-and-dog-care/what-we-do-for-dog-health/brachycephalic-dogs⟩ (accessed 30 June 2023).
Wachowiak, I.J., Patterson, J.S., Winger, K.M., Smiler, K.L., Cole, R., Moon, R., Kluz, M., Bartner, L.R., 2023. Thoracolumbar myelopathies in pug dogs. Journal of Veterinary Internal Medicine 37, 618–625.
Waters, A., 2017a. Brachycephalic tipping point: time to push the button? Veterinary Record 180, 288.
Waters, A., 2017b. At last! Action to stop brachy dog ads. Veterinary Record 181, 635.
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, E.S., Mantovani, A.R., 2013. Inflammation, wound repair, and fibrosis: reassessing the spectrum of tissue injury and resolution. Journal of Pathology 229, 141–144.
Windsor, R., Stewart, S.D., Talboom, J., Lewis, C., Naymik, M., Piras, I.S., Keller, S., Borjesson, D.L., Clark, G., Khanna, C., Huentelman, M., 2021. Leukocyte and cytokine variables in asymptomatic Pugs at genetic risk of necrotizing meningoencephalitis. Journal of Veterinary Internal Medicine 35, 2846–2852.
Wyatt, S., Gonçalves, R., Gutierrez-Quintana, R., De Decker, S., 2018. Results of non-surgical treatment for congenital vertebral body malformations: 13 dogs (2009-2016). Journal of the American Veterinary Medical Association 253, 768–773.
Wyatt, S., Lafuente, P., Ter Haar, G., Packer, R.M.A., Smith, H., De Decker, S., 2019. Gait analysis in French bulldogs with and without vertebral kyphosis. The Veterinary Journal 244, 45–50.