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1 Caudal Articular Process Dysplasia of Thoracic Vertebrae in Neurologically Normal French
2 Bulldogs, English Bulldogs and Pugs: Prevalence and Characteristics

3

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13 Key Words: Brachycephalic, Vertebral malformation, Facet joint

14

15 Running head: Thoracic Caudal Articular Process Dysplasia

16 Abstract

17

18 The aims of this study were to evaluate the prevalence and anatomical characteristics of
19 thoracic caudal articular process dysplasia in French bulldogs, English bulldogs and Pugs
20 presenting for problems unrelated to spinal disease.

21 In this retrospective cross-sectional study, computed tomography scans of the thoracic
22 vertebral column of these three breeds were reviewed for the presence and location of caudal
23 articular process hypoplasia and aplasia and compared between breeds.

24 A total of 271 dogs met the inclusion criteria: 108 French bulldogs, 63 English bulldogs and
25 100 Pugs. 70.4% of French bulldogs, 84.1% of English bulldogs and 97.0% of Pugs showed
26 evidence of caudal articular process dysplasia. Compared to French and English bulldogs,
27 Pugs showed a significantly higher prevalence of caudal articular process aplasia, but also a
28 lower prevalence of caudal articular process hypoplasia, a higher number of affected
29 vertebrae per dog and demonstrated a generalized and bilateral spatial pattern more
30 frequently. Furthermore, Pugs showed a significantly different anatomical distribution of
31 caudal articular process dysplasia along the vertebral column with a high prevalence of
32 caudal articular process aplasia between T10 and T13. This area was almost completely
33 spared in French and English bulldogs.

34 As previously suggested, caudal articular process dysplasia is a common finding in
35 neurologically normal Pugs but this also seems to apply to French and English bulldogs. The
36 predisposition of clinically relevant caudal articular process dysplasia in Pugs is possibly not
37 only caused by the higher prevalence of caudal articular process dysplasia but also by the
38 breed specific anatomical characteristics.

39 Introduction

40

41 The cranial and caudal vertebral articular processes are located at the junction of the vertebral
42 pedicle and lamina. Together they form the synovial facet or zygapophysial joint which
43 together with the intervertebral discs are an important part of each functional spinal unit.

44 Their main function is to provide stability and restrict motion. They contribute up to 30% of
45 the stability of the vertebral column.^{1,2} A complete (aplasia) or partial (hypoplasia) absence
46 of articular processes is defined as vertebral articular process dysplasia³ which is considered a
47 congenital vertebral anomaly in the majority of documented cases.⁴⁻¹⁰

48 Whereas dysplasia of the cranial articular process seems very rare, dysplasia of the caudal
49 articular process is well-documented.³ Although multiple dog breeds can be affected^{4,6,9}

50 Pugs seem especially vulnerable for this condition with an anatomical predisposition for the
51 thoracic vertebral column.^{5,10,11} Caudal articular process dysplasia can be associated with
52 progressive signs of spinal cord dysfunction,^{3,5,11} including paraparesis, ataxia of the pelvic
53 limbs and urinary incontinence. Caudal articular process dysplasia can however occur in
54 neurologically normal dogs and recent research abstracts have indicated a prevalence of more
55 than 60% in neurologically normal Pugs and Pug crosses.^{10,11} It has further been suggested

56 that only 4% of Pugs diagnosed with caudal articular process dysplasia will demonstrate
57 neurological signs.¹¹ This is in agreement with the results of a recent study, which indicated
58 that thoracic vertebral malformations occur commonly in neurologically normal “screw-
59 tailed” brachycephalic dog breeds, such as Pugs, French bulldogs and English bulldogs.¹²

60 This high prevalence of vertebral malformations in neurologically normal dogs is clinically
61 important. Failure to recognize that vertebral malformations can be clinically irrelevant could
62 cause delay in reaching an accurate diagnosis and postpone initiation of appropriate treatment
63 in “screw-tailed” brachycephalic dogs with spinal disease. It is further unclear why most dogs

64 with vertebral malformations are clinically unaffected, while some dogs develop progressive
65 and debilitating clinical signs. If we want to increase our understanding about the
66 pathophysiology of vertebral malformations, it can be considered an important first step to
67 understand the prevalence and spectrum of such anomalies in clinically unaffected dogs.
68 The aims of this study were therefore to evaluate the prevalence and anatomical
69 characteristics of caudal articular process dysplasia in French bulldogs, English bulldogs and
70 Pugs presenting for problems unrelated to spinal disease. It was hypothesized that caudal
71 articular process dysplasia would be common in all three evaluated breeds and that breed
72 specific differences would exist in prevalence and anatomical location of such anomalies.

73 Material and Methods

74

75 This retrospective descriptive cross-sectional study was approved by the Clinical Research
76 Ethical Review Board of the Royal Veterinary College, University of London (URN 2017
77 1689-1). The electronic medical database of the Small Animal Referral Hospital, Royal
78 Veterinary College was searched for French bulldogs, English bulldogs and Pugs which
79 underwent computed tomography (CT), including the complete thoracic vertebral column, for
80 reasons unrelated to a spinal disease, from October 2010 to November 2016. Dogs were
81 included if the medical files and CT studies were available for review. Dogs were excluded if
82 a neurological or orthopaedic disease was the cause for investigation, if the CT studies were
83 not available for review or if the CT studies did not include the complete thoracic vertebral
84 column. This decision was made by the first author (S.B., Veterinary specialist-in-training in
85 Veterinary Neurology and Neurosurgery).

86 Information retrieved from the medical files included signalment, presenting clinical signs
87 and final diagnosis. CT images were reviewed by one investigator (S.B., under direct
88 supervision of a board-certified neurologist, S.D.D.) in a randomized order using a random
89 sequence generator (random.org) and blinded to any patient data. The investigator was aware
90 that none of the included dogs had recorded orthopaedic or neurological signs. After retrieval
91 from PACS to a workstation (MacBook Pro 13 inch, 2015, Apple Inc.) a commercially
92 available DICOM viewing software (Horos, version 1.1.7., www.horosproject.org) was used.
93 After transverse images were obtained, multiplanar sagittal and dorsal reconstructions as well
94 as 3D reconstructions were made and reviewed. The vertebrae from T1 to the last true
95 thoracic vertebra were individually and bilaterally assessed for presence of aplasia (complete
96 absence) or hypoplasia (incomplete formation) of the caudal articular process (Fig. 1 and 3).³

97 ⁵

98 The occurrence, number and location of hypoplastic and aplastic vertebral caudal articular
99 processes were recorded and compared between breeds. To enable further comparisons
100 included dogs were assigned to one group of two categories of CT characteristics by the
101 investigator (S.B.). The first category considered presence of caudal articular process
102 hypoplasia and aplasia. Dogs lacking any signs of caudal articular process hypoplasia or
103 aplasia were considered “unaffected” and dogs demonstrating caudal articular process
104 hypoplasia or aplasia were assigned to the group “caudal articular process dysplasia”. The
105 latter group was furthermore subdivided into the groups “caudal articular process hypoplasia”
106 (articular process hypoplasia without articular process aplasia) and “caudal articular process
107 aplasia” (articular process aplasia with or without articular process hypoplasia). In the second
108 category, the spatial distribution of the abnormalities was evaluated for the dogs with caudal
109 articular process dysplasia. Dogs were assigned to one of the three following groups by the
110 investigator (S.B.): focal (only one region of affected adjacent vertebrae, < 7 affected
111 vertebrae overall), multifocal (multiple regions of affected adjacent vertebrae, < 7 affected
112 vertebrae overall) or generalised (> 7 affected vertebrae overall) (Table. 1).

113 Data was recorded using a spreadsheet (Microsoft Excel for Mac, Version 15.33). Statistical
114 tests were performed by the first author (S.B.) and a statistical analysis software (SPSS
115 Statistics for OSx, Version 24.0, IBM Corp, Armonk, NY) was used to analyse the data. Data
116 was tested for normal distribution to enable selection of the correct statistical test using a
117 Kolmogorov-Smirnov test. Interaction between the occurrence of abnormalities in the
118 different breeds at each vertebral level was tested using a generalized estimating equation to
119 account for the repeated measures from the same dog (logistic link function and
120 exchangeable correlation matrix was implemented). Interbreed differences between the
121 occurrence of abnormalities at each individual vertebral level and the general lesion patterns
122 were tested using Fisher’s Exact test corrected for multiple comparison according to

123 Bonferroni. A binary logistic regression model was used to test age and sex as covariates for
124 the breed specific prevalence of articular process hypoplasia and aplasia. For comparison of
125 the number of affected vertebrae between breeds Kruskal-Wallis test and post hoc multiple
126 comparison with Bonferroni correction was applied. Statistical significance was defined as P
127 < 0.05.

128 Results

129

130 Included animals

131

132 A total of 271 dogs were included in the study, consisting of 108 French bulldogs, 63 English
133 bulldogs and 100 Pugs. Included animals underwent CT imaging for a variety of reasons,
134 including brachycephalic obstructive airway syndrome (n = 207), other respiratory disease,
135 neoplastic disease (n = 17 for both), gastrointestinal disease (n = 13), trauma (n = 7), cardiac
136 disease and ear disease (n = 5 for both). All CT scans were acquired using a 16-slice scanner
137 (Mx8000 IDT, Philips, Best, The Netherlands) with dogs in sternal recumbency under
138 anaesthesia or sedation. Following parameters were used: 16 × 1.5 mm collimation, helical
139 scan mode, 2 or 3 mm reconstruction slice thickness with 1 to 1.5 mm overlap, 2s tube
140 rotation time, 120 to 180 mA depending on patient size, 120 to 140 kVp, 500 mm acquisition
141 field of view, with reconstruction field of view dependent on patient body size (varying
142 between 200–250 mm), and 512×512 matrix.

143 Overall, 226 of 271 dogs (83.39%) and 1104 of 3506 (31.49%) vertebrae demonstrated
144 thoracic caudal articular process dysplasia. More specifically, 198 of 271 dogs (73.06%) and
145 476 of 3506 (13.58%) vertebrae demonstrated caudal articular process hypoplasia of which
146 42 of 271 dogs (15.50%) exclusively showed caudal articular process hypoplasia. 184 of 271
147 dogs (67.89%) and 628 of 3506 (17.91%) vertebrae demonstrated aplasia of the caudal
148 articular process (Fig. 1 and 2).

149 The group of 108 French bulldogs consisted of 79 males (27 neutered) and 29 females (10
150 neutered), aged between three and 133 months old (median 18 months). All dogs of this
151 breed had 13 thoracic vertebrae. 76 of 108 of French bulldogs (70.4%) showed dysplasia, 29
152 of 108 (26.9%) showed hypoplasia and 47 of 108 (43.5%) showed caudal articular process

153 aplasia (Table. 1). In 56 of the 76 (85.5%) affected dogs, multiple vertebrae demonstrated
154 caudal articular process dysplasia. Of the 1404 evaluated vertebrae, 224 (16.0%)
155 demonstrated caudal articular process dysplasia (of which 147 showed hypoplasia and 77
156 aplasia). A focal spatial pattern was seen in 27 (35.5%) French bulldogs, a multifocal pattern
157 in 45 (59.2%) and a generalised pattern in four of 76 dogs (5.3%). In five (8.9%) of the 56
158 dogs which had multiple affected vertebrae, caudal articular process dysplasia was seen on
159 one side of the vertebral column only. In the remaining 51 dogs (91.1%), caudal articular
160 process dysplasia was seen on both sides of the vertebral column. Finally, 87 of 224 (38.8%)
161 of the vertebrae showing dysplasia of the caudal articular process were affected bilateral. In
162 French bulldogs with caudal articular process aplasia, T9 (17 of 77 vertebrae (22.1%)) was
163 most often affected followed by T4 (16 of 77 vertebrae (20.8%)) (Fig. 3). Hypoplasia was
164 most often observed at T10 (22 of 147 vertebrae (15.0%)) followed by T11 (18 of 147
165 vertebrae (12.2%)).

166 The group of 63 English bulldogs consisted of 39 males (nine neutered) and 24 females (eight
167 neutered), aged between three and 132 months old (median 14 months). All dogs of this
168 breed had 13 thoracic vertebrae. 53 of 63 of English bulldogs (84.1%) showed dysplasia, 12
169 of 63 (19.0%) showed hypoplasia and 41 of 63 (65.1%) showed caudal articular process
170 aplasia. In 40 of the 53 (75.5%) affected dogs, multiple vertebrae demonstrated caudal
171 articular dysplasia. Of the 819 evaluated vertebrae, 193 (23.6%) demonstrated caudal
172 articular process dysplasia (of which 116 showed hypoplasia and 77 aplasia). A focal spatial
173 pattern was seen in 22 (41.5%) English bulldogs, a multifocal pattern in 23 (43.5%) and a
174 generalised pattern in eight of 53 dogs (15.0%). In 10 (25.0%) of the 40 dogs which had
175 multiple affected vertebrae, caudal articular process dysplasia was seen on one side of the
176 vertebral column only. In the remaining 30 dogs (75.0%), caudal articular process dysplasia
177 was seen on both sides of the vertebral column. Finally, 60 of 193 (31.1%) of the vertebrae

178 showing dysplasia of the caudal articular process were affected bilateral. In English bulldogs
179 with caudal articular process aplasia, T4 (16 of 77 vertebrae (20.8%)) was most often
180 affected followed by T9 (15 of 77 vertebrae (19.5%)) (Fig. 3). Hypoplasia was most often
181 observed at T10 (20 of 116 vertebrae (17.2%)) followed by T11 (14 of 116 vertebrae
182 (12.1%)).

183 The group of 100 Pugs consisted of 54 males (24 neutered) and 46 females (29 neutered),
184 aged between seven and 151 months old (median 31.5 months). 17 of the 100 pugs (17.0%)
185 had only 12 thoracic vertebrae. 97 of 100 of Pugs (97.0%) showed dysplasia, one of 100
186 (1.0%) showed hypoplasia and 96 of 100 (96.0%) showed caudal articular process aplasia. In
187 94 of the 97 affected dogs (96.9%), multiple vertebrae demonstrated caudal articular
188 dysplasia. Of the 1283 evaluated vertebrae, 687 (53.5%) demonstrated caudal articular
189 process dysplasia (of which 216 showed hypoplasia and 471 aplasia). A focal spatial pattern
190 was seen in nine (9.3%) Pugs, a multifocal pattern in 33 (34.0%) and a generalised pattern in
191 55 of 97 dogs (56.7%). In two (2.1%) of the 94 dogs which had multiple affected vertebrae,
192 caudal articular process dysplasia was seen on one side of the vertebral column only. In the
193 remaining 92 dogs (97.9%), caudal articular process dysplasia was seen on both sides of the
194 vertebral column. Finally, 484 of 687 (70.4%) of the vertebrae showing dysplasia of the
195 caudal articular process were affected bilateral. In Pugs with caudal articular process aplasia,
196 T10 (65 of 471 vertebrae (13.8%)) was most often affected followed by T3 ((56 of 471
197 vertebrae (11.9%)), T11 and T12 (51 of 471 vertebrae (10.8%)) (Fig. 3). Hypoplasia was
198 most often observed at T4 (28 of 216 vertebrae (13.0%)) followed by T9 (26 of 216 vertebrae
199 (12.0%)).

200

201 *Comparison between breeds*

202

203 Breed had a significant influence on the prevalence of thoracic caudal articular process
204 dysplasia ($P < 0.0001$) whereas age and sex had not ($P > 0.05$). More specifically, Pugs were
205 more often affected compared to French bulldogs ($P < 0.0001$, OR = 13.6 95% CI [4.0, 46.2])
206 and English bulldogs ($P < 0.05$, OR = 6.13 95% CI [1.64, 23.1]). There was no significant
207 difference between French and English bulldogs ($P > 0.05$). Breed also had a significant
208 influence on the prevalence of thoracic caudal articular process hypoplasia and aplasia ($p <$
209 0.0001 for both) whereas age and sex had not ($P > 0.05$). Pugs were significantly less often
210 affected by hypoplasia and more often affected by aplasia compared to French (hypoplasia: P
211 < 0.0001 , OR = 0.028 95%, CI [0.004, 0.206]; aplasia: $P < 0.0001$, OR = 31.2, 95% CI [10.7,
212 90.8]) and English bulldogs (hypoplasia: $P < 0.0001$, OR = 0.043, 95% CI [0.005, 0.339];
213 aplasia: $P < 0.0001$, OR = 12.9, 95% CI [4.23, 39.7]). There was no significant difference
214 between French and English bulldogs concerning hypoplasia ($P > 0.05$) but English bulldogs
215 were more often affected by aplasia compared to French bulldogs ($P < 0.05$, OR = 2.42, 95%
216 CI [1.25, 4.61]). Pugs had a significantly ($P < 0.001$) higher number of vertebrae affected per
217 dog by thoracic caudal articular process dysplasia (median 7, IQR 5-10) compared to French
218 (median 2, IQR 0-3) and English bulldogs (median 3, IQR 1-5). There was no significant
219 difference between French and English bulldogs ($P > 0.05$).

220 Pugs showed significantly more often a generalised spatial pattern of thoracic caudal articular
221 process dysplasia compared to French ($P < 0.0001$) and English bulldogs ($P < 0.0001$). There
222 was no significant difference between French and English bulldogs ($P > 0.05$). Multiple
223 vertebrae were affected by thoracic caudal articular process dysplasia significantly more
224 often in Pugs compared to French ($P < 0.0001$) and English bulldogs. If more than one
225 vertebra was affected, thoracic caudal articular process dysplasia was confined to only one
226 side significantly more often in English bulldogs compared Pugs ($P < 0.001$). There was no
227 significant difference between French bulldogs and Pugs ($P > 0.05$) and French and English

228 bulldogs ($P > 0.05$). Furthermore, Pugs had a significantly higher number of vertebrae
229 affected by bilateral thoracic caudal articular process dysplasia compared to French ($P <$
230 0.0001) and English bulldogs ($P < 0.0001$). There was no significant difference between
231 French and English bulldogs ($P > 0.05$).

232 Breed had a significant influence on the anatomical distribution of caudal articular process
233 hypoplasia ($P < 0.01$) and aplasia ($P < 0.001$) along the thoracic vertebral column. More
234 specifically, T4 and T9 in French and English bulldogs and T5 in English bulldogs were
235 significantly more often affected by caudal articular processes aplasia compared to Pugs (P
236 values < 0.01). In Pugs T10, T11 and T12 were significantly more often affected by caudal
237 articular processes aplasia compared to French and English bulldogs ($P < 0.05$, $P < 0.01$ and
238 $P < 0.001$ respectively). There was no significant difference between French and English
239 bulldogs ($P > 0.05$). Overall, 40.4% of the vertebrae showing caudal articular processes
240 aplasia in Pugs were located between T10 and T13 compared to 11.6% and 5.2% in French
241 and English bulldogs, respectively (Fig. 3, 4 and 5).

242 Moreover, T4 was significantly more often affected in Pugs compared to French bulldogs (P
243 < 0.05) and T10 was significantly less often affected by caudal articular processes hypoplasia
244 in Pugs compared to French and English bulldogs (P values < 0.01). There was no significant
245 difference between French and English bulldogs ($P > 0.05$). Overall, 25.9% of the vertebrae
246 showing caudal articular processes hypoplasia in Pugs were located between T10 and T13
247 compared to 42.2% and 42.9% in French and English bulldogs, respectively.

248 Discussion

249

250 This study evaluated and compared thoracic caudal articular process dysplasia in three
251 “screw-tailed” brachycephalic dog breeds. Our results did not only demonstrate a very high
252 prevalence of caudal articular process dysplasia in Pugs (97.0%) presenting for problems
253 unrelated to spinal disease, but additionally in French (70.4%) and English bulldogs (84.1%)
254 which, to the authors knowledge, has not been reported previously.

255 Compared to the suggested prevalence in previously published research abstracts of caudal
256 articular process dysplasia in Pugs presenting for problems unrelated to spinal disease, which
257 were 64.4% and 76.2%, the prevalence in this study was remarkably higher.^{10, 11} Although
258 other reasons cannot be excluded, this discrepancy could possibly be explained by differences
259 in the chosen imaging modality. In one study, dogs underwent mainly survey radiographs,¹²
260 while in the other study dogs underwent a combination of magnetic resonance imaging (MRI)
261 and survey radiographs.¹¹ Cross sectional imaging techniques and especially CT scans enable
262 a more detailed evaluation of small changes in bony structures compared to radiographs.³

263 Thoracic caudal articular process dysplasia has been considered a breed-specific disorder in
264 Pugs.^{5, 10, 11} The results of this study show that not only Pugs have a high prevalence of
265 caudal articular process dysplasia but that this seems to be also true for other brachycephalic
266 “screw-tailed” breeds. If compared to French and English bulldogs Pugs showed a
267 significantly higher prevalence of caudal articular process dysplasia, a significantly higher
268 number of affected vertebrae per dog, Pugs had significantly more often caudal articular
269 process aplasia, significantly less often hypoplasia, demonstrated significantly more
270 frequently a generalized spatial pattern and vertebra being affected bilateral. Furthermore,
271 Pugs showed a significantly different anatomical distribution of caudal articular process
272 dysplasia along the vertebral column with a high prevalence of articular process aplasia

273 between T10 and T13. This area was almost completely spared in the two other breeds (Fig. 3
274 and 5).

275 Although the exact mechanism is currently unknown, there are multiple hypotheses about the
276 pathogenesis of articular process dysplasia. It is generally accepted that a failure of
277 ossification in the neural arch ossification center leads to a failure of articular process
278 formation.¹³ A mutation of a Hox gene which plays a major regulatory role in chondrocytic
279 proliferation and differentiation,^{5,6} dysgenesis of the neural arch ossification centre itself¹⁴ or
280 a lack of development or union of an accessory ossification centre with the lamina are
281 considered possible underlying mechanisms.^{9, 14, 15}

282 It is currently unclear why only a minority of dogs with caudal articular process dysplasia
283 will develop clinical signs of spinal cord dysfunction, while this vertebral anomaly seems to
284 be an incidental finding in the majority of affected dogs. It is further unclear why this
285 vertebral anomaly has been associated with clinical disease especially in Pugs,⁵ while the
286 results of this study suggest also a high prevalence in other “screw-tailed” brachycephalic
287 dogs. It can be hypothesised that the high prevalence of caudal articular process dysplasia
288 should not be considered the only factor causing a predisposition of clinical disease in Pugs.
289 It has been proposed that hypoplasia and especially aplasia of the caudal articular process can
290 result in instability of the vertebral column^{2, 3, 16} whereby the location of the defect is thought
291 to be of importance due to the regionally differing biomechanical properties of the facet
292 joints.¹³ This could be of importance when trying to explain why Pugs seem to be more prone
293 to suffer from clinical sequelae compared to other breeds.

294 Depending on the segmental location the synovial facet joints contribute up to 30% of the
295 stability of the vertebral column.^{1,2} The degree of motion of the different partition of the
296 vertebral column is dictated by the differing orientation of the caudal and cranial articular
297 processes to each other.³ The more opposing the incline of articulation, the higher is the

298 achieved stability.¹³ Based on the differing anatomical and biomechanical characteristics of
299 the vertebral column and especially the facet joints, the thoracic vertebral column can be
300 divided into a cranial (T1 to T9) and a caudal compartment (T11 to T13) which is separated
301 by the diaphragmatic vertebra T10. The cranial thoracic vertebral column shows a very
302 similar anatomy with the facet joints between T3 and T9 being almost confluent in the
303 median plane with a horizontal orientation overlapping each other in a loft tile manner.^{3, 4}
304 Based on their arrangement the facet joints in this region do not play a major role in
305 restricting motion but are suspected to have mainly weight bearing functions.^{3, 4} Another
306 important difference compared to the caudal thoracic vertebral compartment is the presence
307 of the costovertebral joints, which provide a high degree of stability against axial rotation and
308 lateral bending.¹⁷ Overall, this part of the vertebral column is very rigid with the facet joints
309 having mainly weight bearing and little stabilizing functions.

310 The diaphragmatic vertebra T10 and the anticlinal space between T10 and T11 have a unique
311 anatomical conformation with a very high degree of opposing angles of the articular
312 processes leading to a very high degree of stability.³ The adjacent caudal thoracic vertebral
313 column between T11 and T13 resembles the lumbar vertebrae with the articular processes
314 being almost vertically aligned.^{3, 18} Their main function is restricting lateral flexion and axial
315 rotation making them an important stabilizing factor.^{3, 6, 19, 20} Additionally to that they are also
316 involved in weight bearing and the transmission of loading forces.^{3, 20} Therefore, this part of
317 the vertebral column shows a higher degree of flexibility with the facet joints playing a very
318 important part in restriction of excessive motion compared to the cranial thoracic
319 compartment.

320 A lack of normal functioning facet joints, such as in caudal articular process dysplasia, is
321 thought to cause a regional instability of the vertebral column. Furthermore, it can be
322 hypothesized that an association exists between the degree of regional instability and the

323 degree of regional caudal articular process dysplasia. This would suggest that Pugs, which
324 show a higher prevalence of caudal articular process aplasia, bilaterally affected vertebrae
325 and a more generalized pattern often affecting multiple adjacent vertebrae would suffer from
326 a higher degree of vertebral column instability compared to the other two investigated breeds.
327 The different anatomical distribution of aplasia in Pugs could be an even more important
328 difference. Due to the discussed anatomical and biomechanical differences, articular process
329 aplasia of the caudal compartment of the thoracic vertebral column can be hypothesized to
330 cause greater instability compared to the same defect in the cranial thoracic compartment
331 (Fig. 4 and 5). The results of this study have shown an up to 8fold higher prevalence of
332 articular process aplasia between T10 and T13 in Pugs affected by caudal articular process
333 aplasia compared to affected French or English bulldogs (Fig. 3). It is therefore possible that
334 this breed specific difference in the anatomical distribution of caudal articular process aplasia
335 could be an important reason to explain the higher prevalence of clinical sequelae in Pugs.
336 This hypothesis can be supported by a previous anatomic study looking at the incidence of
337 articular process dysplasia in different large, chondrodystrophic and small non-
338 chondrodystrophic breeds (eight Maltese and 27 Yorkshire Terriers).⁴ Thoracic articular
339 process dysplasia was exclusively detected in the examined Maltese and Yorkshire Terriers.
340 The presented anatomical distribution was similar to that of French and English bulldogs in
341 our study, with T11 to T13 being only affected in 6 to 14% of all of the examined Maltese
342 and Yorkshire Terriers compared to 26 to 63% between T1 and T10.⁴
343 It has been hypothesized previously, that vertebral instability resulting from articular process
344 dysplasia and a consequent increase in micromotion can lead to a condition termed fibrous
345 constrictive myelopathy^{5, 11} which has been well documented in Pugs^{5, 21} and occasionally in
346 other breeds.^{6, 9, 21} The increase in motion results in the formation of a dense band of fibrotic
347 tissue which can cause adhesions between the arachnoid and pia mater resulting in a

348 constriction of spinal cord.^{5, 21} This condition clinically manifests as a slowly progressive
349 myelopathy which is generally not painful and can be associated with urinary or fecal
350 incontinence.⁵ Treatment options for this disease include medical-palliative options,
351 decompressive surgery which can be combined with vertebral stabilization or placement of a
352 shunt tube bridging the site of constriction.^{5, 21}

353 This study was limited by its retrospective design. While all dogs with a documented
354 neurological abnormality were excluded from this study the majority of the included dogs
355 did not undergo a neurological examination. Therefore, there is the probability that subtle
356 gait abnormalities or neurological deficits were missed and we cannot exclude that the
357 affected dogs could develop clinical signs later in life. Another limitation is that only three
358 “screw-tailed” brachycephalic breeds were included in this study which makes it impossible
359 to make any statements about the overall prevalence in the canine population. Additionally,
360 this study was limited to CT scans with no MRI studies available for a detailed investigation
361 of soft tissue structures and possible subtle myelopathies.

362 In conclusion, this study demonstrated that articular process dysplasia has not only a high
363 prevalence in Pugs presenting for problems unrelated to spinal disease but also in two other
364 “screw-tailed” brachycephalic breeds. It can be hypothesized that not only the higher
365 prevalence but also the more generalized pattern and especially the high prevalence of this
366 abnormality in the caudal thoracic vertebral column contribute to the predisposition of Pugs
367 to develop clinical signs compared to the other two evaluated breeds. It is currently unknown
368 why this very common abnormality is only rarely associated with development of clinical
369 signs of spinal cord dysfunction. Further studies are therefore needed to investigate this
370 abnormality in different breeds and to compare imaging findings of neurological normal and
371 abnormal Pugs.

372

373	List of Author Contributions
374	
375	Category 1
376	(a) Conception and Design: Steven De Decker, Gert ter Haar and Simon Bertram
377	(b) Acquisition of Data: Simon Bertram
378	(c) Analysis and Interpretation of Data: Simon Bertram
379	
380	Category 2
381	(a) Drafting the Article: Simon Bertram and Steven De Decker
382	(b) Revising Article for Intellectual Content: Simon Bertram, Gert ter Haar and Steven De
383	Decker
384	
385	Category 3
386	(a) Final Approval of the Completed Article: Simon Bertram, Gert ter Haar and Steven De
387	Decker

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- 447

448 Tables

449

450 Table 1: Imaging Findings of Included Dogs

	French Bulldogs	English Bulldogs	Pugs
	(n = 108)	(n = 63)	(n = 100)
Evidence of caudal articular process			
dysplasia (%)	76 (70.4%) ¹	53 (84.1%) ³	97 (97.0%) ^{1,3}
hypoplasia (%)	29 (26.9%) ¹	12 (19.0%) ²	1 (1.0%) ^{1,2}
aplasia (%)	47 (43.5%) ^{1,3}	41 (65.1%) ^{2,3}	96 (96.0%) ^{1,2}
Spatial pattern			
focal (%)	27 (35.5%) ³	22 (41.5%) ¹	9 (9.3%) ^{1,3}
multifocal (%)	45 (59.2%)	23 (43.4%)	33 (34.0%)
generalized (%)	4 (5.3%) ¹	8 (15.0%) ²	55 (56.7%) ^{1,2}

451 Note: Superscript letters indicate a statistical significant difference between two breeds (¹ and

452 ² = P < 0.0001, ³ = P < 0.01)

453 Figure legends

454

455 Figure 1: Transverse CT images at the level of the T4/T5 facet joint showing the difference
456 between an anatomical correct facet joint (A,C), consisting of normally developed cranial
457 (arrow, red outline) and caudal (arrowhead, blue outline) articular processes, and a case of
458 right sided unilateral caudal articular process aplasia (B,D).

459

460 Figure 2: Transverse CT images at the level of the T11/12 facet joint showing the difference
461 between an anatomical correct facet joint (A,C), consisting of normally developed cranial
462 (arrow, red outline) and caudal (arrowhead, blue outline) articular processes, and a case of
463 bilateral caudal articular process aplasia (B,D).

464

465 Figure 3: Spatial distribution of caudal articular process aplasia between T1 and T13. The
466 stated percentage is the number of dogs with caudal articular process aplasia at a specific
467 vertebra divided by the overall number of vertebra affected by articular process aplasia in this
468 breed (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$).

469

470 Figure 4: 3D reconstructed CT study of the cranial (T1 to T7) thoracic vertebral column and
471 ribs with evidence of hypoplasia (arrowhead) and aplasia (arrows) of the caudal articular
472 processes of T2, T3 and T4. The caudal articular processes of T1, T5 and T6 are developed
473 normally (asterisks).

474

475 Figure 5: 3D reconstructed CT study of the caudal (T10 to T13) thoracic vertebral column
476 and ribs with evidence of hypoplasia (arrowhead) and aplasia (arrows) of the caudal articular
477 processes.