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Computed Tomography, Magnetic Resonance Imaging and a Novel Surgical Approach of Atlanto-Axial Instability with Incongruence in Dogs

Mario DOLERA^{*1}, Luca MALFASSI¹, Simone PAVESI¹, Sara FINESSO¹, Giovanni MAZZA¹, Silvia MARCARINI¹, Massimo SALA¹, Nancy CARRARA¹, Cristina BIANCHI¹, Jennifer M. GAMBINO².

¹ La Cittadina Fondazione Studi e Ricerche Veterinarie, Romanengo 26014 (CR), Italy

² Department of Clinical Science, College of Veterinary Medicine, Mississippi State University, 240 Wise Center Drive, Mississippi State, MS 39762

* CORRESPONDENCE TO: DOLERA, M., La Cittadina Fondazione Studi e Ricerche Veterinarie, Cascina Cittadina, 26014 Romanengo, Italy.

Tel.: +39 339 3516653

Fax: 037372227

E-mail: la Cittadina@alice.it

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ABSTRACT

Atlanto-axial (AA) instability due to ligament insufficiency is a common cause of cervical spinal cord compression in toy breeds. However, in some dogs a difference in size between the atlas and the axis leads to joint incongruence that exacerbates AA subluxation and makes surgical treatment challenging.

Twelve dogs with AA instability with incongruence were enrolled in a single institution prospective observational study. Computed tomography (CT) and magnetic resonance imaging (MRI) of the AA joint were compared to a retrospectively reviewed control group. A novel surgical approach consisting of a dorsal internal fixation technique was performed in six dogs. For affected dogs, the mean normalised difference between the dorso-ventral atlas canal and the dorso-ventral axis canal was 29.67% (median of 35.07%, standard deviation 25.64%), while in normal dogs a mean difference of 4.67% (median of 3.95%, standard deviation 5.21%) was observed. On MRI, 12/12 affected dogs had spinal cord compression, which was classified as reducible (3/12), partially reducible (6/12) and non-reducible (3/12). In surgically operated dogs, follow-up CT showed a partial or complete reduction of the previous spinal cord compression with a consistent amelioration or resolution of the presenting complaints. The proposed surgical technique was safe and effective in dogs with partially or completely reducible spinal cord compression.

Key words: atlanto-axial incongruence, atlanto-axial instability, atlanto-axial subluxation, dog, surgical stabilization

INTRODUCTION

Atlanto-axial (AA) instability with subluxation due to ligament insufficiency is a well-described congenital disease that predominantly afflicts toy breed dogs [2, 11, 26]. In contrast, traumatic AA subluxation may occur in any breed at any age. Irrespective of the aetiopathogenesis, AA instability causes acute and/or chronic spinal cord compression [1, 2]. Secondary lesions typically develop in affected individuals including spinal cord compression, contusions or haemorrhage which can predispose to hydromyelia, focal or diffuse syringohydromyelia and gliosis [9, 15, 17, 26]. The principal radiographic sign of AA subluxation is enlargement of the space between the tip of the spinous process of the axis and the dorsal arch of the atlas [26] on latero-lateral radiography. This finding is suggestive of ligamentous insufficiency but is non-specific [20].

In some dogs, concomitant other abnormalities of the craniocervical junction are present, such as atlanto-occipital overlapping, Chiari-like syndrome and dorsal constriction of the axis that could influence the clinical presentation, therapeutic options and prognosis [4, 5, 6, 11]. In particular, the so-called dorsal constriction of the axis is, in fact, a difference in size between the atlas and the axis that leads to joint incongruence that exacerbates AA subluxation and makes surgical treatment challenging.

Several works have been devoted to AA instability, but the role of AA incongruence between the atlas and the axis as well the treatment options remain poorly defined [2, 4, 5, 6, 7, 10, 11, 16, 18]. The specific aims of the current study were twofold. The first goal was to describe the clinical, computed tomography (CT) and magnetic resonance imaging (MRI) findings of AA instability with incongruence in dogs. The hypothesis was that this sub-group of dogs affected from AA instability would display a significant difference in size between the atlas and the axis when compared to a control population of similar morphology, weight and breed, leading to articular incongruence and, finally, AA instability. The second aim was to develop a novel surgical technique to treat this condition.

MATERIALS AND METHODS

Internal ethical approval from our Foundation of Veterinary Research was obtained. (01/2008, recorded number 03/2008). All patients were enrolled in the study by way of a client consent form.

Definitions. Instability of the AA joint was defined as a variation in the normal relationship of the articular surfaces of the AA joint as evaluated on dynamic CT examinations. Incongruence was defined as a difference in shape and dimension of the corresponding articular surfaces of the AA joint resulting in different spinal canal diameters of the atlas and the axis.

Study design. A prospective cohort, single institution study was conducted.

Population. Dogs with clinical and radiological evidence of AA instability with incongruence were enrolled in this study from January 2008 to October 2013.

For the control-group, a retrospective review of similar breed dogs, of similar morphologic type as the prospective group of dogs, were evaluated. Dogs in the retrospective, control-group population underwent CT alone or CT and MRI examinations for a variety of non-neurologic pathologies. All dogs of this group were free of clinical signs for cervical disease and were included if CT and MRI of the neck were normal.

Imaging. All enrolled patients underwent both CT and MRI examinations. Sectional imaging was conducted under sedation with intramuscular dexmedetomidine (Dexdomitor, Elanco, Sesto Fiorentino, Italy) dosed at 1-5 µg/kg. The CT examinations were conducted with a multidetector CT (MDCT) scanner (Brilliance 64 Slice, Philips Medical Systems, Eindhoven, the Netherlands). Scan parameters were as follows: 200 mAs, 120 kV, pitch 0.625, rotation 1 sec, slice thickness 0.67 mm. Isotropic voxels of 0.67 mm were used to perform multiplanar reconstructions and to obtain transverse images of the C1-C2 spinal canal with a perpendicular orientation.

The MRI examinations were conducted with a 1.5 Tesla (T) MRI magnet (Intera 1.5 T, Philips Medical System, Eindhoven, the Netherlands). Standard image sequences were obtained with the patients in lateral recumbency with support under the neck and the nose in order to prevent flexion or rotation errors in positioning. A standard cervical spine coil (Sense Spine Coil, Philips Medical

System, Eindhoven, the Netherlands) was used. Images were acquired as follows: FOV 530 cm; slice thickness 2 mm; transverse and sagittal fast spin echo (FSE) T2-W (TE=130 msec, TR=3500 msec); transverse, reconstructable 3D T1 fast spoiled gradient echo (FSPGR), (TE=4.6 msec, TR=300 msec) and transverse T2-W turbo spin echo (TSE) (TE, TR). The total scan time for each patient was 14 min.

Affected and control dogs were placed in lateral recumbency with the head and neck in neutral positioning using a home-made, soft, padded positioning device that allowed for repeatability of neutral head positioning in dogs of different sizes and shapes. By definition, neutral positioning should result in a 120° angle and is easily obtained in the natural prone positioning in the anaesthetised patient [3]. Dynamic flexed (90°) and extended (170°) scans were performed using a cylindrical foam padding placed under the mandibular region or on the top of the nose, respectively.

Qualitative analysis and measurements. All MRI sequences were evaluated for the presence of spinal cord compression. The percentage of compression was evaluated on cross-sectional T2-W images by comparing the cross-sectional area of the spinal cord at the point of maximum compression with the closest site of normal appearance [22]. The compression was classified as dynamic if it was exacerbated by head flexion, and irreducible, partially or completely reducible by applying linear traction and extending the head and neck. On MRI, spinal cord morphology and integrity were evaluated, and abnormalities in T2-W and T1-W signal intensity, hydromyelia and syringohydromyelia if present, were documented. On both MRI and/or CT, conspicuous osseous morphologic abnormalities of the viewable caudal brain, caudal occiput, vertebral bodies, intervertebral foramina and associated intervertebral discs of the cervical spine were also considered.

CT measurements were performed by the use of the console software (Console Workspace v 2.0, Philips Medical Systems, Eindhoven, the Netherlands). The comparison of CT images from the neutral and flexed positions were used to assess AA instability by evaluating the distance of the

dens from the corresponding articular surface (fovea) of the atlas, the distance of the cranial third of the spinous process of the axis from the arch of the atlas, and the position of the apex of the dens of the axis with respect to a line drawn from the opisthion to the cranial margin of the body of the atlas (Chamberlain line) [7].

Other measurements performed on the CT images were: the latero-lateral and the dorso-ventral diameter of the spinal canal, measured at the middle of the atlas and the axis on transverse CT images (Fig. 1), and the caudal opening of the atlas and the cranial opening of the axis, defined respectively as the vertebral foramen enclosed by the most caudal part of the atlas that meets the the most cranial part of the axis, measured in the reformatted sagittal image plane (Fig. 2A).

Statistical analysis. Statistical analysis were performed using commercial software (Matlab, R 2011, MathWorks, Natick, MA, USA). The distribution of the data was evaluated using the Shapiro-Wilk test. Non-normally distributed data were reported as normalised percentage differences. The normalised percentage data of the subsequent categories were organized as follows: from transverse images, latero-lateral atlas and axis diameter of the control-group dogs, latero-lateral atlas and axis diameter of the affected dogs, dorso-ventral atlas and axis diameter of the control-group dogs, dorso-ventral atlas and axis diameter of the affected dogs; and from sagittal images, the caudal opening of the atlas and cranial opening of the axis of the control-group dogs, caudal opening of the atlas and cranial opening of the axis of the affected dogs. The Mann-Whitney test was used to assess differences between the affected and control-group dogs. Statistical significance was defined as $p\text{-value} \leq 0.05$.

Surgical technique. Following CT and MRI evaluations, dogs with partially or completely reducible AA subluxation underwent surgical reduction and internal fixation. Six of 12 affected patients underwent a dorsal direct fixation technique. Perioperative cefazolin (Cefazolina Teva, Teva Italia, Milano) was administered (30 mg/kg intravenously). Following routine aseptic preparation, dogs were placed in ventral recumbency with the head placed on a home-made support in order to obtain maximal extension of the AA joint. For all procedures, a surgical microscope was

used (NC-4, Carl Zeiss, D-73446 Oberkochen, Germany). General anesthesia was induced with intravenous injectable propofol (Propofol Kabi, Fresenius Kabi Italia Srl, Isola della Scala, VR, Italy) (4 mg/kg, intravenously). Patients were intubated and maintained with a mixture of isoflurane (IsoFlo, Abbott House, Berkshire, U. K.) in oxygen and medical air. Ventilation was mechanically assisted. A dorsal cutaneous incision was performed from the bregma to the middle third of the neck. After the dissection of the subcutaneous planes and epaxial muscles, which were laterally reflexed with the aid of Gelpi retractors, the wings and the lamina of the atlas and the spinous process and lamina of the axis were exposed. Using a high-speed 1 mm burr, one or two holes were drilled into the center of each wing of the atlas. Three additional holes were drilled in the dorsal process of the axis. Each hole was countersunk to allow the perpendicular insertion of a completely treated screw (1.5-3.5 mm diameter, 15-25 mm length) according to the dimensions of the bone (orthopaedic screws) (Bioimpianti, Peschiera Borromeo, MI, Italy), which emerged 5 mm ventral to the ventral aspect of the wings of the atlas and half of the length across the dorsal process of the axis. Gentle traction and extension of the head assisted in positioning, such that the screws could be embedded in methyl methacrylate admixed with 3.8% gentamicin (Biogent, Bioimpianti, MI, Italy), which was allowed to cool and harden for internal fixation (Fig. 3). To dissipate the heat, saline solution was dropped continuously on the implant during the hardening time. For closure, the muscles were approximated to the median plane by using 3-0 absorbable monofilament suture, and the sub-cutaneous and cutaneous planes were routinely sutured. A semi-rigid neck brace was applied to each patient for one month. Postoperative analgesia was warranted by the administration of opioid drugs. In particular, dogs were treated with methadone (Semfortan, Eurovet Animal Health, Bladel, the Netherlands) administered at the dose of 0.2 mg/kg or buprenorphine at the dose of 0.03 mg/kg (Temgesic, Schering-Plough S.p.A., Segrate, MI, Italy). Each dog was judged to be no longer in the need of pain relief within five days after surgery.

Follow up. Regular clinical examinations were performed in order to evaluate clinical responses weekly for the first month, then monthly for the first three months. Telephone interviews

were done on a regular basis during the first two years. Computed tomography examinations were performed in all surgically treated dogs at least six months and one year after surgery.

RESULTS

Population. Twelve dogs suffering from AA instability with incongruence were enrolled (Table 1). For the control groups, 120 CT examinations of normal dogs, 10 of each breed or morphological type, examined for non-neurological reasons were retrieved from an archival database (Table 2). Surgical intervention was performed in 6/12 affected patients.

Imaging, qualitative analysis and measurements

MRI. Magnetic resonance imaging showed spinal cord compression at the C1-C2 level in 12/12 affected dogs. The spinal cord compression was due to the impingement of the tip of the odontoid. The mean compression was 28.6% (range 15-50%). The compression was exacerbated by flexion, with a mean value of 41.3% (range 28-67%). The compression was completely reducible after longitudinal traction (extended position) in 3/12 patients, partially reducible in 6/12 (Fig. 4) and non-reducible in 3/12. With regard to the ligaments, MRI did not display breakages, but the apical ligament and the dorsal AA ligament were subjectively found to be elongated in 7/12 dogs (Fig. 5).

Other concurrent malformations observed on MRI in affected dogs were: Chiari-like malformation with syringohydromyelia (4/12), atlanto-occipital overlapping (2/12) (Fig. 5), atlas dysplasia (1/12), maldirection of the lamina of the atlas (1/12), o congenital odontoid process separation (1/12) (Fig. 6), fusion of C2-C3 (1/12) and dural band at the C1-C2 level (1/12).

CT. Affected dogs – neutral position. The mean distance between the odontoid process of the axis and the fovea of the atlas was 3.0 mm (range 1.9 mm-5.1 mm). In 6/12 dogs the distance between the cranial third of the spinous process of the axis and the arch of the atlas was less than 1 mm, whereas in the other six dogs a gap ranging from 2.0 mm to 5.3 mm (mean=3.7 mm) occurred. In two dogs the apex of the dens was located cranial to the Chamberlain line.

Affected dogs – flexed position. The mean distance between the odontoid process of the axis and the fovea of the atlas was 3.9 mm (range 2.8 mm-6.0 mm). In 3/12 affected dogs the distance between the cranial third of the spinous process of the axis and the arch of the atlas was the same as in the neutral position (less than 1 mm), whereas in the other nine dogs an increased gap occurred within a range of 3.2 mm to 8.2 mm (mean=5.3 mm). In five dogs cranio-dorsal rotation of the axis within the atlas was observed, leading to basilar invagination (Fig. 5). In those dogs the apex of the dens was located cranial to the Chamberlain line. Normal dogs - neutral position. The mean distance between the odontoid process of the axis and the fovea of the atlas was 1.5 mm (range 0.8-1.9 mm). The mean distance between the cranial third of the spinous process of the axis and the arch of the atlas was 1.4 mm (range 0.8 mm-2.0 mm). Normal dogs - flexed position. No variations regarding the respective position of the atlas and the axis were detected.

In affected dogs, the mean normalised differences between the dorso-ventral atlas diameter and the dorso-ventral axis diameter was 29.67% with a median of 35.07% and a standard deviation of 25.64%. For the control group, the mean difference was 4.67% with a median of 3.95% and a standard deviation of 5.21% (Table 3A).

In affected dogs, the mean normalised differences between the latero-lateral atlas diameter and the latero-lateral axis diameter was 37.69% with a median of 40.96% and a standard deviation of 19.31%. For the control group, the mean difference was 5.58% with a median of 3.20% and a standard deviation of 6.99% (Table 3B).

In affected dogs, the mean normalised differences in diameter between the caudal opening of the atlas and the cranial opening of the axis was 55.81% with a median of 55.59% and a standard deviation of 14.10%. For the control group, the mean difference was 9.49% with a median of 9.05% and a standard deviation of 5.35% (Table 3C).

The latero-lateral atlas and axis diameters were significantly different between the affected and control-group dogs (p-value=0.0007). The dorso-ventral atlas and axis diameters were significantly different between the two categories (p-value=0.03). The caudal opening of the atlas

diameter and cranial opening of the axis diameter were significantly different between the two categories (p-value=0.00004).

Treatment. Six of twelve dogs were surgically treated. The remaining dogs were conservatively managed with rest, corticosteroids, analgesics or application of a customised head and neck brace. Of the surgical interventions performed, three dogs had a completely reducible spinal cord compression, and three had a partially reducible spinal cord compression due to axial invagination into the atlas. Four dogs presented with ambulatory, ataxic tetraparesis and two dogs were non-ambulatory. Intraoperative and immediate post-operative complications within the first week were not observed.

Follow up. The mean follow up was three years (range: 1-6 years) (Table 1). In the 6/12 surgically treated dogs, a substantial amelioration of the presenting complaints was observed within the first few days following the surgical intervention. The two non-ambulatory dogs regained the ability to ambulate within two weeks. For those two dogs, at three months following surgery and at subsequent examinations, mild tetraparesis was evident in one whereas the other was normal. Regarding the four tetraparetic dogs, they were normal at the two-month follow up examination. A substantial reduction of the range of motion with regard to rotation of the head on the neck was evident clinically in these four dogs, but this finding did not impair the dog's quality of life in the owner's opinion. On MDCT follow-up examination, the implants were correctly positioned, the AA joints were stable and the pre-operative compressive myelopathy was absent (3/6) or reduced (3/6). Among the conservatively treated dogs, neural deficits were stable in two dogs, whereas a mild progressive deterioration was observed in four dogs.

DISCUSSION

To the authors' knowledge, this is the first prospective study regarding AA instability with incongruence in dogs. Taking into consideration the CT, MRI and surgical findings obtained, it

could be assumed that this pathological condition represents the canine analogue of human basilar invagination.

No data regarding the differences in diameter of the atlas and axis in normal dogs are available in the literature, and for this reason a control group was considered. The latero-lateral (p-value=0.00007) and dorso-ventral (p-value=0.03) atlas and axis diameters were found to be significantly different between the affected and control-group dogs.

To better describe the anatomical setting of the pathology, new terms never used by standard anatomical nomenclature were introduced. The cranial and caudal canal openings of the vertebra were defined as the vertebral foramen enclosed by the most caudal part of the atlas and the most cranial part of the axis, measured in the reformatted sagittal image plane. The diameters of the caudal opening of the atlas and cranial opening of the axis were significantly different between the normal and affected dogs (p-value=0.00004).

Considering that a relevant difference in canal diameter of the atlas and the axis is not reported in classical AA instability of toy breeds, this study highlights that dogs suffering from AA incongruence represent a sub-group within dogs affected from AA instability, requiring a dedicated diagnostic CT/MRI based protocol and a different surgical approach. In previous studies, this condition was named “dorsal constriction of the axis” [11]. However, considering the results of this study, the term AA incongruence could be preferred because it is more comprehensive and includes the different aspects of this disorder. In fact, the so-called dorsal constriction of the axis is one aspect of this disease, and due to a reduction of dorso-ventral diameter of the second vertebra, it is easily detectable on plain latero-lateral radiography. As demonstrated in this CT/MRI based study, a significant reduction of the latero-lateral diameter of the atlas is also present, leading to articular incongruence and, finally, instability. The ligament integrity observed in many cases suggests that articular incongruence could be the primary cause of instability in this sub-group of dogs suffering from AA instability, which is different from classical AA instability of toy breeds.

In normal dogs, the relationship between the occipital bone, the atlas and the axis should be stable when the head and neck are in the neutral, flexed and extended positions. The physiological movements of this joint do not cause any spinal compression. The main characteristic of incongruence is represented by the disruption of this relationship, which was assessed in this study in CT multiplanar images of all affected patients.

The combined diagnostic approach described herein, which included both CT and MRI, is consistent with the described approach recently described in veterinary research and used in human medicine for complete evaluation of the cranio-spinal junction [8, 14, 16, 25].

The results of surgical intervention were good in all treated dogs despite a mild degree of persistent, variable compressive myelopathy in 3/6 cases. No dogs required a second intervention and no major complications occurred. In the authors' opinion, the absence of surgical instruments within the spinal canal or directed towards the spinal cord makes this technique easy and safe. Although the sample was limited, the results lead to believe that this surgical approach is effective in solving the clinical signs.

Due to the particular conformation of the AA joint in the considered dogs, standard surgical techniques described for the correction of AA instability are not useful. In fact, considering literature data regarding the treatment of AA instability in toy breeds, conservative options and several surgical stabilisation techniques are described [1, 2, 10, 12, 13, 15, 19, 26]. Standard surgical treatment consists of ventral arthrodesis with cross pinning, transarticular lag screw fixation or vertebral plating [1, 12, 19, 21, 24]. This technique requires AA joint congruence, otherwise the means of synthesis can injure the spinal cord [27]. Moreover, in cases of incomplete ossification of the atlas, standard ventral fixation techniques can be difficult or impossible to perform [27]. Dorsal stabilisation techniques such as sublaminar wiring and non-absorbable sutures within the dorsal muscles or Kishigami AA tension bands are not appropriate for the treatment of AA incongruence mainly because these tension bands strictly require that the joint be congruent [20, 23]. The rationale behind tension bands is that traction exerted on one side will cause

compression on the other side. Thus, in cases where the AA articulation is incongruent, such compression can lead to an exacerbation of basilar invagination, or the displacement of the atlas and the axis toward the foramen magnum. Moreover, each described technique is prone to possible complications such as post-operative dyspnoea, permanent respiratory signs, laryngeal paralysis, recurrence of cervical pain, ataxia, Horner's syndrome, and/or migration of the transarticular pins [24].

The main advantage of the internal surgical approach we report herein to address AA instability with incongruence is that this technique accomplishes a rigid fixation that is able to counteract flexion and/or compressive forces exerted by the head on the neck.

In the authors' opinion, this technique could also be useful for the correction of classical AA instability, but further studies must be performed. In this work, only dogs suffering from partially or totally reducible spinal cord compression were operated on. In the future, the combination of dorsal fixation with a decompressive ventral procedure could be investigated.

In conclusion, in this work we described and redefined a relatively new pathological entity, highlighting CT and MRI features of incongruence and instability of the AA joint. Moreover, we described a novel dorsal rigid surgical fixation technique that is feasible, safe and has a good success rate. The greatest limitation of this study is represented by the small number of dogs that underwent the procedure. Results obtained in this case series should be confirmed by further studies of larger canine populations.

REFERENCES

1. Aikawa, T., Shibata, M. and Fujita, H. 2013. Modified ventral stabilization using positively threaded profile pins and polymethylmethacrylate for atlantoaxial instability in 49 dogs. *Vet. Surg.* **42**: 683–692.
2. Beaver, D. P., Ellison, G. W., Lewis, D. D., Goring, R. L., Kubilis, P. S. and Barchard, C. 2000. Risk factors affecting the outcome of surgery for atlantoaxial subluxation in dogs: 46 cases (1978-1998). *J. Am. Vet. Med. Assoc.* **216**: 1104–1109.
3. Burk, R. L. and Ackerman, N. 1986. *Small Animal Radiology: A Diagnostic Atlas and Text*, Churchill Livingstone, New York.
4. Bynevelt, M., Rusbridge, C., Britton, J. 2000. Dorsal dens angulation and a Chiari type malformation in a Cavalier King Charles Spaniel. *Vet. Radiol. Ultrasound.* **41**: 521–524
5. Cerda-Gonzalez, S. and Dewey, C. W. 2010. Congenital diseases of the craniocervical junction in the dog. *Vet. Clin. North. Am.* **40**: 121–141.
6. Cerda-Gonzalez, S., Dewey, C., Scrivani, P. and Kline K. L. 2009. Imaging features of atlanto-occipital overlapping in dogs. *Vet. Radiol. Ultrasound.* **50**: 264–268.
7. Chamberlain, W. E. 1939. Basilar impression (Platybasia): a bizarre developmental anomaly of the occipital bone and upper cervical spine with striking and misleading neurologic manifestations. *Yale. J. Biol. Med.* **11**: 487–496.
8. Chandra, P. S., Kumar, A., Chauhan, A., Ansari, A., Mishra, N. K. and Sharma, B. S. 2013. Distraction, compression and extension reduction of basilar invagination and atlanto-axial dislocation: a novel pilot technique. *Neurosurgery.* **72**: 1040–1053.
9. DeLahunta, A. and Glass, E. 2009. Small animal spinal cord disease. pp. 243–284. In: *Veterinary Neuroanatomy and Clinical Neurology*, 3rd ed. Saunders Elsevier, St. Louis.

10. Denny, H. R. and Butterworth, S. J. 2000. Atlantoaxial subluxation. pp. 217–222. In: A Guide to Canine and Feline Orthopaedic Surgery, 4th ed. Blackwell Science Ltd, Oxford.
11. Dewey, C. W., Marion, D. J. and Loughin, C. A. 2013. Craniocervical junction abnormalities in dogs. *N. Z. Vet. J.* **61**: 202–211.
12. Forterre, F., Vizcaino, R., Stahl, C., Gendron, K. and Spreng, D. 2012. An indirect reduction technique for ventral stabilization in atlantoaxial instability in miniature breed dogs. *Vet. Comp. Orthop. Traumatol.* **25**: 332–336.
13. Havig, M. E., Cornell, K. K., Hawthorne, J. C., McDonnell, J. J. and Selcer, B. A. 2005. Evaluation of non-surgical treatment of atlantoaxial subluxation in dogs: 19 cases (1992–2001). *J. Am. Vet. Med. Assoc.* **227**: 257–262.
14. Jain, V. K. 2012. Atlantoaxial dislocation. *Neurol. India.* **60**: 9–17.
15. Kent, M., Eagleson, J. S., Neravanda, D., Schatzberg, S. J., Gruenenfelder, F. I. and Platt, S. R. 2010. Intraaxial spinal cord hemorrhage secondary to atlantoaxial subluxation in a dog. *J. Am. Anim. Hosp. Assoc.* **55**: 132–137.
16. Marino, D. J., Loughin, C. A., Dewey, C. W., Marino, L. J., Sackman, J. J., Lesser, M. L. and Akerman, M. B. 2012. Morphometric features of the craniocervical junction region in dogs with suspected Chiari-like malformation determined by combined use of magnetic resonance imaging and computed tomography. *Am. J. Vet. Res.* **73**: 105–111.
17. Middleton, G., Hillmann, D. J., Trichel, J., Bragulla, H. H. and Gaschen, L. 2012. Magnetic resonance imaging of the ligamentous structures of the occipitoatlantoaxial region in the dog. *Vet. Radiol. Ultrasound.* **53**: 545–551.
18. Patton, K. M., Almes, K. M. and DeLahunta, A. 2010. Absence of the dens in a 9.5-year-old rottweiler with non-progressive clinical signs. *Can. Vet. J.* **55**: 1007–1010.

19. Pike, F., Kumar, M. and Boudrieau, R. 2012. Reduction and fixation of cranial cervical fracture/luxations using screw and polymethylmethacrylate (PMMA) cement: a distraction technique applied to the base of the skull in thirteen dogs. *Vet. Surg.* **41**: 235–247.
20. Pujol, E., Bouvy, B., Omana, M., Fortuny, M., Riera, L. and Pujol, P. 2010. Use of Kishigami Atlantoaxial Tension Band in eight toy breed dogs with atlantoaxial subluxation. *Vet. Surg.* **39**: 35–42.
21. Rochat, M. C. and Shores, A. 1999. Fixation of an atlantoaxial subluxation by use of cannulated screws. *Vet. Comp. Orthop. Traumatol.* **55**: 43–46.
22. Ryan, T. M., Platt, S. R., Llabres-Diaz, F. J., McConnell, J. F. and Adams, V. J. 2008. Detection of spinal cord compression in dogs with cervical intervertebral disc disease by magnetic resonance imaging. *Vet. Rec.* **163**: 11–15.
23. Sanchez-Masian, D., Lujan-Feliu-Pascual, A., Font, C. and Mascort, J. 2014. Dorsal stabilization of atlantoaxial subluxation using non-absorbable sutures in toy breed dogs. *Vet. Comp. Orthop. Traumatol.* **27**: 62–67.
24. Sanders, S., Bagley, R., Silver, G., Moore, M. and Tucker, R. L. 2004. Outcomes and complications associated with ventral screw, pins, and polymethylmethacrylate for atlantoaxial instability in 12 dogs. *J. Am. Anim. Hosp. Assoc.* **40**: 204–210.
25. Sardhara, J., Behari, S., Jaiswal, A. K., Srivastava, A., Sahu, R. N., Mehrotra, A., Phadke, S. and Singh, U. 2013. Syndromic versus nonsyndromic atlantoaxial dislocation: do clinico-radiological differences have a bearing on management. *Acta. Neurochir. (Wien)* **155**: 1157–1167.
26. Shores, A. and Tepper, L. C. 2007. A modified ventral approach to the atlantoaxial junction in the dog. *Vet. Surg.* **36**: 765–770.

27. Warren-Smith, C. M. R., Kneissl, S., Benigni, L., Kenny, P. J. and Lamb, C. R. 2009.

Incomplete ossification of the atlas in dogs with cervical signs. *Vet. Radiol. Ultrasound*.

55: 635–638.

Table 1. Affected population.

Patient	Breed	Age	Weight (kg)	Sex	Reason for imaging	Type of treatment	Follow-up (months)
1	Pekingese	6 months	5.2	M	Neck pain	conservative	29
2	Cross-breed toy dog	2 years	2.4	F	Neck pain, ambulatory mild tetraparesis	surgery	18
3	Pug	3 years	7.3	F	Ataxia, ambulatory mild tetraparesis	conservative	43
4	Chinese Crested dog	7 months	4.8	F	Neck pain, ambulatory mild tetraparesis	surgery	51
5	Chihuahua	2 years	1.9	M	Non ambulatory tetraparesis	surgery	24
6	Chinese Crested dog	1 year	3.9	M	Neck pain, ambulatory mild tetraparesis	surgery	12
7	Yorkshire terrier	3 years	3.5	F	Neck pain	conservative	72
8	Chihuahua	1 year	3.2	M	Neck pain, non ambulatory tetraparesis	surgery	54
9	Cavalier King Charles	3 years	10.0	M	Ataxia, ambulatory mild tetraparesis	conservative	36
10	Dachshund	3 months	6.8	M	Ataxia, neck pain	conservative	22

11	German Shepherd	4 years	27.6	F	Non ambulatory tetraparesis	conservative	51
12	Yorkshire terrier	7 months	4.2	F	Neck pain, ataxia, ambulatory mild tetraparesis	surgery	20

Table 2. Control groups

Control Groups	Number and morphological type	List of breeds	Sex	Age range and mean age	weight range and mean weight	Reason for Imaging
1	50 dolicomorphous dolicocephalic	Cross-breed, Cross-breed toy, Greyhound toy, Pomeranian, Chinese,Crested dog, Pinscher toy, Yorkshire Terrier, Chihuahua, Jack Russell Terrier, Australian Silky Terrier, Russkiy Toy Terrier, Toy Poodle, Spitz, Bichon Fries, Toy Dachshund	28 male 22 female	6 months – 5 years mean age 3.1 years	2.3-5.0 kg mean 4.0 kg	11/50 appendicular fractures 10/50 congenital urinary malformations 9/50 portosystemic shunt 7/50 foreign body 4/50 internal otitis media 3/50 canine distemper virus 2/50 hypoadrenocorticism 2/50 rhinosinusitis 1/50 intestinal intussusception 1/50 pyometra
2	10 dolicomorphous dolicocephalic	Dachshund and Cross-breed	5 male 5 female	4 months – 2 year mean age 1.6 years	6.2-9.0 kg mean 7.4 kg	3/10 appendicular and cranioccephalic fractures 3/10 arthritis 2/10 optic neuritis 1/10 hiatal herniation 1/10 hip dysplasia
3	30 mesomorphous brachicephalic	Lhasa Apso, Cross-breed, Boston Terrier, Pekingese, Coton de Tulear, Shih Tzu, Pug, Cavalier King Charles	13 male 17 female	1 year – 3 years mean age 2.2 years	4.0-9.9 kg mean 7.4 kg	11/30 brachycephalic syndrome 5/30 portosystemic shunt 4/20 appendicular fractures 2/20 foreign bodies 4/20 polyradiculoneuritis 1/20 congenital urinary malformations 3/20 staging for neoplasia
4	20 dolicomorphous brachycephalic	Chihuahua, Cross-breed	7 male 13 female	1 year – 3.5 years mean age 2.6 years	2.2-4.3 kg mean 3.1 kg	6/20 appendicular and cranial fractures 4/20 foreign bodies 3/20 ocular/craniofacial injuries 3/20 appendicular fractures 2/20 portosystemic shunt 1/20 hip dysplasia 1/20 toxoplasmosis

5	10 dolichomorphous dolicocephalic	Border Collie, Collie, German Shepherd, Cross-breed	7 male 3 female	2 years – 6 years mean age 4.8 years	22.8- 32.5 kg mean 26.8 kg	5/10 hip or elbow dysplasia 2/10 cranial cruciate ligament rupture 2/10 staging for neoplasia 1/10 polyradiculoneuritis
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Tables 3 (A, B, C). The mean, standard deviation and median values of the measurements.

Table 3A. Normalized differences between the dorso-ventral diameter of the atlas and the one of the axis.

	Mean	Median	Standard deviation
Affected	29.67	35.07	25.64
Control group	4.67	3.95	5.21

Table 3B. Normalized differences between the latero-lateral diameter of the atlas and the one of the axis.

	Mean	Median	Standard deviation
Affected	37.69	40.96	19.31
Control group	5.58	3.20	6.99

Table 3C. Normalized differences between the caudal opening of the atlas and cranial opening of the axis.

	Mean	Median	Standard deviation
Affected	55.81	55.59	14.10

Control group	9.49	9.05	5.35
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Legends

Figure 1. Representation of the measurements performed on CT transverse scans in affected and control dogs: latero-lateral and dorso-ventral diameter of the spinal canal, measured at the middle of the atlas (A) and the axis (B) in a normal dog.

Figure 2. Representation of the measurements performed on CT transverse and reconstructed sagittal scans in affected and control dogs: caudal opening of the atlas (A, blue arrow); cranial opening of the axis (A, yellow arrow); distance between the cranial third of the spinous process of the axis and the arc of the atlas (A, red arrow); distance between the apex of the dens and the corresponding articular surface of the fovea dentis of the atlas (B, orange arrow). The measurements are shown in a normal dog.

Figure 3. Intra operative pictures. (A) The screw is positioned into the center of each wing of the atlas (full arrows) and three additional screws are in the dorsal process of the axis (dashed arrow). (B) Screws were embedded in methyl methacrylate (*).

Figure 4. Patient #11. Sagittal T2-weighted sequences. (A) In neutral position, the spinal cord compression is very remarkable (arrow). (B) After gentle longitudinal traction, reduction of the compression is noticeable (arrow).

Figure 5. Patient #12. Sagittal T2-weighted MRI sequence. Note the atlanto-occipital overlapping (red arrow), the lengthened transverse ligament (*), the maldirection of the lamina of the atlas (full arrow) and the hydrosyringomyelia (dashed arrows), that developed all along the spinal cord.

Figure 6. Patient #3. Multidetector computed tomography reformatted sagittal images, in neutral position (A) and extended position (B). Note the presence of the congenital odontoid process separation (arrows).

↔ Latero-lateral atlas diameter
↔ Dorso-ventral axis diameter

↔ Latero-lateral axis diameter
↔ Dorso-ventral axis diameter