

Flexed radiographic angles for determination of atlantoaxial instability in dogs

by

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Abstract

Atlantoaxial instability (AAI) is primarily a congenital neurologic disorder of young, toy breed dogs. AAI which was first reported in 1967, is now included in a subset of craniocervical malformations recognized in young small and toy breed dogs as craniocervical junction abnormalities. With AAI, instability can be secondary to bony malformations between the first two cervical vertebrae or ligamentous instability, resulting in spinal cord compression that manifests in varying degrees of neurologic dysfunction and pain.

Atlantoaxial instability is also recognized as a congenital condition in people, and objective measures have been proposed in the diagnosis of AAI in humans. The atlantodental interval, used in humans for diagnosis of AAI, is not applicable for veterinary patients, due to the large number of dens abnormalities identified in dogs with AAI.

Throughout the years there have been a number of studies trying to improve our ability to diagnosis atlantoaxial instability safely and reliably in dogs; however, there remains no standard protocol for diagnosis based on flexed lateral radiographs. Without the aid of advanced imaging, the diagnosis of AAI in veterinary medicine is largely subjective, based on interpretation of lateral cervical radiographs with a non-standardized degree of flexion.

A retrospective case series of dogs diagnosed with AAI was reviewed and compared with prospective case controls to investigate an objective method of diagnosis based on flexed lateral cervical radiographs. Medical records of dogs diagnosed with AAI from three veterinary teaching institutions were reviewed. Flexed lateral cervical radiographs were evaluated to obtain specific measurements based on anatomic landmarks. Means of these measurements were used to determine the position at which normal toy breed dogs (prospective case controls) were radiographed.

Flexed lateral radiographs of thirty-one affected cases were positioned at a mean of 51° flexion. When flexed lateral radiographs were evaluated, 90.3% of affected cases could be diagnosed based on evaluation of an atlas to axis angle (AAA) $>10^{\circ}$. When Yorkshire terriers, Chihuahuas, and associated mixed populations were evaluated, 22/24 of the affected dogs met a cutoff value for AAA $>10^{\circ}$. Flexed lateral radiographs in the control population were positioned at $51 \pm 10^{\circ}$, and only two of the control dogs were within the AAA cutoff value. There was no difference between the measurements obtained for the flexed lateral radiographs when compared to the exaggerated flexed lateral views in the control population. These findings support the use of mild cervical flexion during positioning to obtain objective measurements for a radiographic diagnosis of AAI in toy breed dogs.

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Chapter 1 - Review of Atlantoaxial Instability in Dogs

Atlantoaxial instability (AAI) is predominantly a congenital neurologic disorder of young, toy breed dogs that results in varying degrees of neurologic deficits secondary to spinal cord compression.^{1,2} AAI is encompassed in craniocervical malformations recognized in young small and toy breed dogs known as craniocervical junction abnormalities.^{3,4}

Congenital bony abnormalities involving the first two cervical vertebrae and insufficient ligamentous stability can result in the development of the condition. Published radiographic measurements for diagnosis of AAI in veterinary medicine are limited,^{5,6} and there remains no diagnostic protocol for flexed lateral cervical radiographs. While the diagnosis remains largely subjective, there are a number of surgical options reported for stabilization of the atlantoaxial joint.^{1,2,7,8}

Anatomy

The anatomy of the first two cervical vertebrae is complex, and these vertebrae have distinct anatomic differences from the other cervical vertebrae.⁹

The atlas, the first cervical vertebra, articulates cranially with the occipital condyles of the skull and caudally with the axis, the second cervical vertebrae. The atlas lacks a spinal process and has a smooth dorsal arch. Additional distinguishing features of the atlas are its large lateral “winged” processes and its cupped cranial surface, the cranial articular foveae, that allow for articulation with the occipital condyles.^{9,10} The vertebral artery and vein course through the transverse foramina, which are short oblique canals extending through the transverse processes of the atlas. The vertebral artery then enters the vertebral foramen after coursing through the lateral vertebral foramina located on the craniodorsal aspect of the dorsal arch.¹⁰

The axis, the second cervical vertebra, articulates with the atlas via glenoid cavities that primarily results in rotational movement. The axis' discernible features include a prominent dorsal spinous process as well as a dens, a forward-projecting process also referred to as the odontoid process. The odontoid process is a bony projection on the cranioventral surface of the axis that articulates with the atlas within the vertebral canal.^{9,10}

The atlas and axis are composed of multiple centers of ossification; therefore, the development and fusion of these bones can result in various anomalies.⁹ The atlas develops from the fusion of three bony elements. Paired neural arches become the dorsal arch and corresponding transverse process, while the ventral arch derives from the intercentrum 1. The development of the axis is more elaborate as it is composed of seven bony elements. The components of the developing axis consist of paired neural arches, centrum I which becomes the dens, centrum of proatlas, intercentrum II, centrum II, and an epiphysis.⁹

A number of ligamentous structures contribute to the stability of the atlantoaxial joint. The transverse ligament, which overlies the dens, secures the dens to the ventral aspect of the vertebral canal, preventing dorsal deviation. Paired alar ligaments extend from the craniolateral border of the dens and attach to the corresponding occipital condyle, while a single apical ligament extends from the cranial aspect of the dens and attaches to the basioccipital bone. Additionally, the dorsal atlantoaxial ligament connects the atlas' dorsal arch to the cranial aspect of the dorsal spinous process of the atlas.^{1,10,11}

Pathophysiology

Atlantoaxial instability is most frequently observed in young, toy breed dogs. While trauma has been associated with AAI, most clinical cases are the result of congenital

abnormalities of the ligamentous or bony components of the atlantoaxial joint.^{1,2} The congenital form of this disorder has also been reported in humans, equids, and bovine.¹¹

Aplasia or hypoplasia of the dens, is frequently observed in dogs with congenital AAI.¹² Additionally, separation of the dens has also been reported to result in AAI.^{12,13} The first case series of AAI in toy breed dogs, reported a non-visible dens radiographically in 4/10 cases and a separation of the dens in 5/10 cases.¹³ Beaver et al., reported 46% odontoid aplasia and 30% conformational dens abnormalities in dogs managed surgically for AAI.¹⁴

The number of bony elements that contribute to the development of the atlas and axis can contribute to congenital abnormalities in the area. Recently, Warren-Smith reported five dogs with cervical signs diagnosed with incomplete ossification of the atlas via computed tomography (CT) or magnetic resonance imaging (MRI). While none of these dogs were toy breeds, four of the five dogs had concurrent AAI.¹⁵ A retrospective review, by Parry et al., of 120 dogs undergoing cervical CT, revealed incomplete ossification of the atlas in 10%, including the four dogs which were previously reported by Warren-Smith.¹⁶ In this large retrospective review, 8/120 dogs were diagnosed with atlantoaxial instability.¹⁵ Three of the eight dogs diagnosed with AAI were toy breed dogs; however, none of these dogs were found to have incomplete ossification of the atlas¹⁶. Therefore, while incomplete ossification of the atlas can be observed concurrently with AAI, there is insufficient evidence to associate this atlas abnormality with the congenital form of instability seen in toy breed dogs.

Intervertebral discs are present in every intervertebral space with the exception of C1-C2, and they allow for transmission of stress and strain during movement of the spine. Ligaments associated with the intervertebral disc and vertebral column, aid in stability of the vertebral bodies.¹⁰ The atlantoaxial ligaments provide the primary means of stability between C1-C2 in the

absence of an intervertebral disc.¹⁷ While the absence of one or more of the ligaments can contribute to AAI, ligamentous abnormalities can be found separately or in conjunction with bony abnormalities.^{13,18} In 1966, Baker, was the first to report a disorder of the atlantoaxial joint secondary to tearing or stretching of the transverse ligament.¹³ Watson also confirmed ligamentous abnormalities with AAI in an immature toy breed, when necropsy revealed the absence of a transverse ligament in conjunction with malformations of the atlas and dens.¹⁸ A cadaveric study involving the transection of the various ligaments within the complex demonstrated that the paired alar ligaments provide the most stabilization to the atlantoaxial joint under ventrodorsal shear load.¹⁷ This is in contrast to findings in humans with AAI, as the transverse ligament contributes a greater portion of stability compared to the paired alar ligaments. It is believed that the atlantoaxial joint in people relies solely on the competency of the transverse ligament to prevent posterior (dorsal) deviation of the dens.¹⁹

Atlantoaxial instability is also recognized as a congenital condition in people, frequently affecting those with Down syndrome and Morquio syndrome. The congenital form of AAI associated with these syndromes, is a result of hypermobility and instability secondary to ligamentous laxity and osseous abnormalities.¹⁹

Diagnosis

The diagnosis of AAI in veterinary medicine is largely subjective, and for many years has been based on the interpretation of lateral cervical radiographs with a non-standardized degree of flexion. While there are several surgical methods of repair reported for AAI in dogs;^{1,2,7,8} there remains no set standard diagnostic protocol for flexed lateral cervical radiographs.

Advanced imaging such as myelography, computed tomography, and magnetic resonance imaging provides further information regarding spinal cord compression secondary to AAI; however, few objective measurements to confirm the diagnosis have been identified even with the use of advanced imaging.^{6,20} Assessment of the dens-to-axis length ratio and dens angle have been assessed via computed tomography in an attempt to evaluate characteristics of toy breed dogs that are likely to develop or be affected with AAI.²⁰ However, the use of these techniques has not been applied to clinical diagnosis. The evaluation of the dens-to-axis length ratio has also been assessed on neutral lateral radiographs; however, the use of CT provided a greater sensitivity for diagnosis.⁶

In 2000, McLear compared the degree of movement between the atlas and axis in dogs presented with thoracic or lumbar myelopathy to dogs with known AAI. This abstract evaluated radiographs of 8 dogs with a diagnosis of AAI and revealed an average angle of 146° between the dorsal arch of the atlas and the dorsal spinous process of the axis. Additionally, McLear measured the overlap between the dorsal spinous process of the atlas and the axis and found this measure to be significantly less in the affected population compare to the control population. A major limitation of the abstract was the small affected population, as there were only 8 affected cases included in the radiographic review. Additionally, this abstract included giant breed dogs in the case selection, which are not known to develop the congenital form of AAI.⁵

More recently, Cummings evaluated the C1-C2 angle in neutral lateral radiographs for 10 toy breed dogs affected with AAI and 92 control toy breed dogs. A cutoff value of the C1-C2 angle of $\leq 158.1^{\circ}$ revealed a sensitivity of 60.0% and a specificity of 98.9% for diagnosis of the 10 affected cases.⁶ Another measurement evaluated in this study included the C1-C2 overlap, which assessed the overhang of the spinous process of the axis to the dorsal arch of the atlas.

This measure was recorded as a positive value in 95% of control dogs and negative in 80% of the affected population. When the overlap was evaluated at $\leq +1.55\text{mm}$ this proved to be the most sensitive (100%) and specific (94.5%) neutral lateral radiographic measurement for the diagnosis of AAI in the 10 affected cases.⁶

Atlantoaxial subluxation in people, can be diagnosed using the atlantodental interval (ADI). The ADI is a repeatable measurement for which established normal measurements in adults and children have been determined based on radiographic and CT images. The magnitude of the measurement dictates the need for surgical intervention.^{21,22} Unfortunately this measurement is unreliable for the diagnosis of AAI in veterinary patients, due to the high incidence of anatomic dens abnormalities in dogs.¹⁴ Published radiographic measurements for diagnosis of AAI in veterinary medicine are limited,^{6,20} and there remains no diagnostic protocol for flexed lateral cervical radiographs. Without the aid of advanced imaging, the clinician must rely largely on a subjective evaluation of images in concert with signalment and physical exam findings to achieve a diagnosis.

Treatments, Risks, and Complications

Treatment of AAI can vary from medical management to any of a number of surgical procedures. Medical management, or non-surgical treatment, typically involves strict cage rest, the application of a cervical splint, and the use of analgesics. A non-surgical option can be pursued in very young patients, with immature bones, in order to provide support until they have grown to an adequate size to undergo surgical treatment. Non-surgical treatment options are often chosen in patients with minimal neurologic deficits; however, a number of cases have been reported to be successfully treated with medical management despite being non-ambulatory.^{1,2,12}

To date, there remains no cases series comparing non-surgical and surgical management of AAI in dogs.

As the goal with non-surgical treatment is the development of fibrous tissue to stabilize the atlantoaxial joint, a major concern with this treatment is that any improvement may regress after removal of the cervical splint.^{1,2,12} While medical management of AAI avoids the risks of general anesthesia and implant-associated complications, a number of other complications from the use of cervical splints have been reported. In a retrospective study of 19 patients undergoing non-surgical treatment for AAI, 7 dogs developed complications associated with cervical splinting.²³ Complications reported include inadequate stabilization, dermatitis, otitis externa, skin ulceration, corneal ulceration, and decubital ulcers.^{1,2,23} Since cervical splints are often left in place for a minimum of 6 weeks,¹ adequate padding during application and routine follow ups are imperative to reduce splint associated complications. Medical management has been reported to result in death or euthanasia in up to 37.5% of cases.²

The goal of surgical treatment of AAI is reduction of the instability and stabilization of the atlantoaxial joint.² The procedures can be classified into two groups based upon the approach used. Initial surgical techniques involved the use of a dorsal approach, while more recent techniques use a ventral approach.²

Geary reported the first techniques attempted for treatment of AAI in dogs. In his case series, all patients underwent a dorsal approach for placement of an orthopedic wire. Initially the wire was passed from the dorsal spinous process of the axis to the wings of the atlas; however, this technique was found to be unsuccessful, as there was lack of improvement or wire breakage in 2 of the 4 cases.¹³ Wire placement was then attempted by passing a looped wire through the epidural space, around the dorsal arch of the atlas, and then through holes in the dorsal spinous

process of the axis prior to tightening. Despite the revised technique, there remained a high risk of peri-operative death, as when this technique was used in 13 dogs, 4 suffered from respiratory problems and cardiac arrest in the post-operative period.¹

Complications associated with Geary's early atlantoaxial wiring techniques involved breakage of the wire and perioperative death. Patients undergoing placement of wire through the vertebral canal of the atlas were at risk of cardiopulmonary arrest secondary to iatrogenic spinal cord trauma. These early complications prompted the use of alternative materials and techniques to reduce the risks associated with dorsal procedures.^{1,13}

The use of nylon suture and a portion of the nuchal ligament was evaluated to attach the dorsal arch of the atlas to the dorsal spinous processes of the axis, to try to reduce complications associated with breakage of materials.^{1,2} The development of the Kishigami Atlantoaxial Tension Band (AATB) was focused on reducing the risk associated with passing suture or wire through the vertebral canal of the atlas.^{2,24} Use of the Kishigami AATB, involves the placement of a cranial metallic hook over the dorsal arch of the atlas which is then secured to the dorsal spine of the axis with wires. This technique was used for stabilization of congenital AAI in 6 toy breed dogs, of which none experienced intra-operative complications and 4 had an improvement in their neurologic status with no evidence of recurrence.²⁴ Jeffery devised and reported success with the use of Kirschner wires for dorsal cross-pinning for atlantoaxial joint stabilization.²⁵ This surgical technique involves reduction of the joint, placement of Kirschner wires from the dorsal spinous process of the axis in a ventrolateral direction into the wings of the atlas, and application of polymethylmethacrylate (PMMA) over the wires for stabilization.^{10,25}

Dorsal fixation procedures have been reported to have complications rates as high as 71%¹⁰, and result in death or euthanasia in 10.1% of cases.²

A disadvantage of the previously discussed dorsal techniques involves the lack of permanent fusion of the atlantoaxial joint. While, an advantage of the dorsal approach over the ventral approach is the reported ease of access to the atlantoaxial joint, the ventral procedures are advocated by most authors, as they allow for permanent fusion of the joint.¹² The ventral exposure allows for removal of cartilage from the articular surfaces and the application of bone graft, to aid in healing.^{1,10} Sorjonen evaluated the success of arthrodesis both radiographically and on necropsy in 12 dogs that had underwent transarticular pinning 6 weeks prior. At necropsy, 10/12 patients had some form of fusion with the technique²; as 3/10 had a fibrous union, 8/10 had a cartilaginous union, and 4/10 had a bony union.

The first reported ventral stabilization technique involved the placement of transarticular Kirschner wires through the ventral articular surfaces.¹ The use of transarticular wires prompted the use of transarticular lag screws in a similar fashion with the screw angled toward the medial boarder of the ipsilateral alar notch.^{1,10} To aid in rigid stabilization of the transarticular pin technique, Schulz described the placement of additional pins perpendicular to the transverse plane in the pedicles of the axis and atlas, which were then covered in PMMA.^{1,26} Aikawa described a modified version of Schulz's ventral stabilization technique using threaded pins placed in a similar angle to that of the transarticular pins. Of the 49 dogs that underwent this modified technique, 47 left the hospital, and of those 94% improved neurologically. Pin breakage was observed in 30% of placed pins with the majority of the broken pins being placed in a transarticular fashion.⁷

A modification of the transarticular screw technique involves the placement of cortical screws in the wings of the atlas, at the insertion point of the longus colli muscles, and the level of the transverse process of the axis, and the placement of a Kirschner wire bridging the distance

between the screws. Following application of the implants, the apparatus is encased in PMMA. This technique was developed to target patients with poor bone quality or those that had anatomical variations that excluded them from other reported techniques. Results in the case series for this technique performed in 12 dogs revealed 4 complications, one of which was implant failure. The recovery of ten dogs was reported to be excellent while two were reported to be good.²⁷

Riedinger reported that ventral techniques including transarticular screws and ventral plating provided increased stability of the atlantoaxial joint under shear load compared to a dorsal clamp fixation. However, a limitation of this study was that the dorsal clamp and ventral plate implants used, have never been evaluated in clinical cases of AAI.⁸ More recently, a biomechanical study evaluating three ventral fixation techniques, two of which have been reported for the use of stabilization of AAI in toy breed dogs, revealed that multiple metal implants with PMMA fixation had a higher resistance to flexion compared to plate fixation and transarticular fixation.²⁸

Complications associated with ventral fixation techniques have been reported to be as high as 53%.²⁹ An inherent risk with the various ventral techniques is the approach to the atlantoaxial joint, as this approach involves manipulation and retraction of the trachea, esophagus, recurrent laryngeal nerve, and carotid sheath.¹⁰ Disruption of vital structures can result in hemorrhage, laryngeal paralysis, and aspiration pneumonia.² A modified parasagittal approach, which involves dissection between the right sternocephalicus and sternothyroideus muscles, has been reported in dogs undergoing ventral surgical techniques for AAI. The goals with this approach were to minimize the amount of dissection, improve surgical exposure, and provide protection of vital structures throughout the procedure. This modified approach was used

successfully in 5 patients undergoing surgery for AAI, none of which experienced complications associated with the approach.³⁰ While there have been a few comparisons of the various techniques for stabilizing the atlantoaxial joint,^{1,2} there have been no reports for comparison between the approaches.

Reduction of the atlantoaxial joint is necessary prior to application of ventral fixation techniques; however, failure to maintain alignment while implants are inserted can result in repeated concussions to the spinal cord, resulting in worsening of neurologic signs and death.¹⁰ Platt reported the use of cortical screws placed in the caudal portion of the ventral axis to serve as an attachment for orthopedic wire allowing reduction of the axis ventrally, thus reducing the risk of iatrogenic damage to the spinal cord during implant placement.^{1,10} The use of Gelpi retractors placed between the atlanto-occipital junction and a fenestration in the C2-C3 intervertebral disc space has been reported to aid in successful removal of articular cartilage and reduction of the atlantoaxial joint.³¹

The application of ventral implants also carries the risks of breaching the spinal canal, implant migration, implant failure, and hemorrhage secondary to laceration of the vertebral arteries. Improper implant placement resulting in inadequate bone purchase has been reported to be the primary cause of implant migration.²⁹ Death or euthanasia in patients undergoing ventral procedures has been reported in up to 12.8% of cases.² Given the size of the patients undergoing surgery for AAI, the use of computed tomography to determine the bone corridors for implant placement has been recommended.² A retrospective evaluation of CT images from cervical scans of toy breed dogs, revealed a mean bone-corridor length of 7mm and a width ranging from 3-5mm. Additionally, the optimal transarticular implant angle was determined to be $40 \pm 1^\circ$ in the medial to lateral direction and $20 \pm 1^\circ$ in the ventral to dorsal direction.³² Given the narrow corridors for

implant placement, various techniques involving three dimensional (3D) reconstructed images have been evaluated in the hopes of easing the degree of difficulty with transarticular implant placement. Leblond reported the use of a pre-surgical planning method to simulate optimal implant positioning; however, this technique while providing information on the corridors and landmarks for placement continues to rely on the surgeon's ability to estimate the optimal angle for placement intra-operatively.³³ A follow up study-evaluated the use of a 3D model, to determine individual patient's bone corridors and associated safety margins based on anatomic landmarks.³⁴ In a biomechanical study looking at ventral fixation techniques, Leblond reported the use of a 3D drill guide prototype set to the previously determined projected angles for transarticular implant placement. It was determined with this prototype that 86.8% of screws were placed appropriately, while 4.4% were placed dangerously. An appropriate screw position was defined as a screw placed within the previously established intended safe implantation corridors, while a dangerous screw was defined as one with a clinically significant vertebral canal violation.³⁴ However, limitations to the use of the drill guide prototype included the required visual adjustment to ensure proper aiming toward the alar notch and the use of Beagle cadavers which have larger bone corridors.³⁵ With the repeatable use of CT and 3D reconstruction to determine optimal bone corridors in toy breeds, the next step to improve safety with implant placement may be the design and use of a 3D printed guide specific to the individual patient that could be placed intra-operatively on the ventral surface of the atlas and axis to aid in implant placement.

The use of PMMA to increase rigid fixation with the ventral techniques and reduce implant migration can result in serious complications including tracheal or esophageal necrosis, thermal injury due to the exothermic reaction while the product sets, and infection. To reduce

tissue trauma secondary to the use of PMMA, it is important to have the appropriate angulation of the implants to ensure the use of a compact mass of PMMA. Additionally the application of sterile saline to PMMA while it is curing can reduce thermal damage to local soft tissues.^{1,2} The addition of an antibiotic to PMMA is often used to reduce the risk of infection.^{7,26,27}

Additional complications associated with surgical fixation of AAI include fractures, which can be the result of implant failure, instability, or immature bone.¹⁰ Fractures of the dorsal spine of the axis have been reported with dorsal fixation techniques,²⁹ while fractures of the atlas and axis have been reported with ventral transarticular techniques.³⁶

The treatment options for AAI in people also include conservative management and surgical procedures. Non-surgical techniques involve the use of cervical halter traction and immobilization, while surgical procedures include a wide array of anterior and posterior procedures. The various treatment options carry their own indications, contraindications, and associated risks.¹⁹

Prognosis

Patients undergoing treatment of AAI can have varying degrees of recovery, based on the technique chosen, the success of stabilization, as well as the presenting neurologic signs. With spinal cord injuries, there is a risk for pathologic changes to the cord that can result in lack of improvement of neurologic status following surgical treatment.² Additionally, the risk of inadequate decompression of the cord or concurrent instability can result in lack of improvement or recurrent pain. Recurrent pain has been documented for months following surgical treatment and often results in euthanasia.²⁶

Various risk factors for dogs undergoing surgical repair of AAI have been evaluated. In a retrospective review of dogs undergoing both dorsal and ventral repair techniques, age at onset of clinical signs, duration of clinical signs, and pre-operative neurological status were factors associated with success of surgical management. If a patient's neurologic signs were observed at less than 2 years of age, they were more likely to have a successful first surgical procedure and a lower post-operative neurological grade. Likewise, if patients were observed to have clinical signs for 10 months or less prior to undergoing surgery, they were found to have similar outcomes. While the number of cases undergoing dorsal versus ventral techniques varied, neither the surgical approach nor technique were found to be a potential risk factor for outcome.¹⁴

Reported perioperative mortality rates with surgical fixation range from 10-30%.^{14,29} In an metanalysis review of 336 published cases of AAI, 84.5% of cases were reported to undergo surgery, while 70.8% of those cases had ventral procedures performed. Ultimately 82.6% of ventral procedures, 65.1% of dorsal procedures, and 11.6% of medically managed cases were found to have a successful outcome.²

Abbreviations

3D- Three Dimensional

AAI- Atlantoaxial instability

AATB- Atlantoaxial tension band

ADI- Atlantodental interval

CT- Computed tomography

PMMA- polymethylmethacrylate

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Chapter 2 - Flexed Radiographic Angles for Determination of Atlantoaxial Instability in Dogs

Introduction

Atlantoaxial instability (AAI) is primarily a congenital neurologic disorder of young, toy breed dogs. AAI which was first documented in 1967,¹³ is now included in a subset of craniocervical malformations recognized in young small and toy breed dogs as craniocervical junction abnormalities (CCJA). These junctional abnormalities often result in neck pain and cervical myelopathies and most require the use of advanced imaging for diagnosis. AAI can occur as a sole condition or in conjunction with other CCJAs.^{3,4} Atlantoaxial instability can be associated with bony malformations between the first two cervical vertebrae, such as an aplastic or hypoplastic dens, abnormalities with ossification of the atlas, or insufficient ligamentous stability; all of which can contribute to varying degrees of neurologic deficits secondary to spinal cord compression.^{1,2,16,17} AAI is most likely to affect Chihuahuas, Yorkshire terriers, Maltese, toy or miniature Poodles, Pekingese, and Pomeranians.^{2,17}

Atlantoaxial instability is also recognized as a congenital condition in people, frequently affecting those with Down syndrome. Atlantoaxial subluxation in people can be diagnosed using the atlantodental interval (ADI). The ADI is a repeatable measurement for which established normal distances for adults and children have been determined and the magnitude of the measurement can then determine the need for surgical intervention.^{21,22} This measurement is unreliable for the diagnosis of AAI in veterinary patients, due to the high incidence of anatomic

dens abnormalities in dogs.¹⁴ However, Cummings recently reported measurements for a dorsal atlantodental interval and ventral atlantodental interval in 10 dogs affected with AAI.⁶

In 2000, McLear compared the degree of movement between the atlas and axis in dogs with thoracic or lumbar myelopathy to dogs with known AAI. That study included giant breed dogs in the case selection, which are not known to develop the congenital form of this condition.⁵ More recently Cummings reported cutoff values for a C1-C2 angle and C1-C2 overlap for toy breed dogs affected with AAI; however, these cutoffs were established on neutral lateral radiographs resulting in a low sensitivity.⁶

Published radiographic measurements for diagnosis of AAI in veterinary medicine are limited,^{5,6} and there remains no set standard diagnostic protocol for flexed lateral cervical radiographs. Advanced imaging such as myelography, computed tomography (CT), and magnetic resonance imaging (MRI) may provide further information regarding underlying pathology and resultant spinal cord compression.^{1,2} Objective measurements to confirm the diagnosis have been proposed, with the use of advanced imaging;²⁰ however, the intent with our study was to provide an objective method for positioning and diagnosis, without the aid of advanced imaging.

The objectives of this study were to determine a flexed position for radiographic diagnosis of atlantoaxial instability (AAI) and identify radiographic measurement cutoffs to differentiate affected dogs from normal toy breeds.

Materials and Methods

Data Collection Protocol

The medical records of dogs admitted to the Kansas State University Veterinary Health Center, University of Missouri Veterinary Health Center, and Oklahoma State Center of Veterinary Health Sciences from March 2005 through March 2017 were reviewed to identify dogs diagnosed with atlantoaxial instability.

To qualify for inclusion in the confirmed AAI group, all dogs were required to be breeds with a high reported prevalence for AAI, have at least one flexed lateral cervical radiograph available for review, be clinically affected, and have a final diagnosis of AAI. At the time of presentation, the diagnosis of AAI was subjectively assigned to dogs with radiographic displacement of the dens into the vertebral canal or with an increased distance between the dorsal arch of the atlas and the dorsal spinous process of the axis. The final diagnosis was subjectively assessed by the clinicians on the case or confirmed with advanced imaging or intra-operative findings.

Twenty healthy toy breed dogs presenting to the Kansas State Veterinary Health Center for reasons other than neurologic dysfunction were prospectively enrolled in the study. Age, sex, and body weight were recorded. All dogs underwent a complete physical examination prior to enrollment. Criteria for inclusion included being neurologically normal, toy breeds predisposed to AAI, and no history of cervical pain. Dogs were excluded from the study if cervical hyperesthesia or neurologic deficits were noted during the physical examination. Additionally, dogs were excluded from the study if radiographic abnormalities of the atlas axis junction were noted. Informed client consent was obtained for all dogs, and all procedures in this study were

approved by the Institutional Animal Care and Use Committee at the Kansas State University Veterinary Health Center.

Digital radiographic images were retrospectively collected and evaluated, for dogs that met the inclusion criteria for AAI. The presence or absence of dens abnormalities was recorded, based on evaluation of the ventrodorsal projection. Flexed lateral radiographs were determined to be radiographs with some degree of flexion when compared to a neutral lateral projection of the same dog. The flexed lateral radiographs for affected dogs that included all necessary anatomic landmarks to complete the measurements outlined in Table 1 were evaluated. The angle between the skull and the long axis of C2 (skull to axis angle, SAA) was measured from the flexed lateral radiographic images, to determine what degree of flexion had been obtained by the positioner at the time of acquisition (Figure 2-3). The mean angle, for all dogs with flexed lateral radiographs, 51°, was then used for positioning of the control dogs for their flexed lateral projection.

The control dogs had radiographic images obtained using sedation or general anesthesia, as follows. Dogs presenting for wellness exams were sedated for image obtainment. Sedated dogs received dexmedetomidine (5mcg/kg intravenously [IV] once) and butorphanol (0.2mg/kg IV once) prior to obtaining the images and the dexmedetomidine was reversed with atipamezole (0.01mg/kg intramuscularly [IM] once) after completion of the radiographs. Dogs presenting for dental prophylaxis or elective orthopedic and soft tissue surgeries had images obtained under general anesthesia. Dogs under general anesthesia were premedicated as determined by the attending board-certified veterinary anesthesiologist. All anesthetized dogs were maintained with inhalant isoflurane for radiographs. The control group had a ventrodorsal projection, lateral projection, flexed lateral projection, and an exaggerated flexed lateral projection obtained in that order. The ventrodorsal projection was obtained to confirm the presence of a dens prior to

completion of the remaining views. Positioning of the skull was determined to be lateral when the tympanic bullae and mandibles were superimposed. Positioning of the vertebrae were determined to be lateral when the transverse processes were superimposed. Following completion of a neutral lateral view, control dogs were positioned for flexed lateral cervical radiographs at a skull to axis angle (SAA) of $51 \pm 10^\circ$. This value was chosen because the mean flexed lateral angle at which affected dogs were retrospectively measured was an SAA of 51° . Slight cervical flexion was applied to the dog to obtain an image, and the SAA was then measured. The SAA of $51 \pm 10^\circ$ was verified with use of a transparent protractor placed up to the DR projection screen. If the measured angle was not $51 \pm 10^\circ$, the image was rejected, the dog was repositioned, and the image was repeated. To maintain positioning during image acquisition, the degree of cervical flexion was maintained with sandbags. The exaggerated flexed lateral view was achieved by gently flexing the dog's neck past the previously obtained flexed lateral position ($51 \pm 10^\circ$). The degree of flexion for the exaggerated view was less than that performed on initial physical exam when each control dog was able to have their neck flexed in a manner that allowed the lower jaw to contact the area of the thoracic inlet. Therefore, the exaggerated flexed lateral view was still within a physiologic range of motion. Images were obtained with digital radiography centered over the mid-cervical spine with cranial collimation to include the external occipital protuberance and tympanic bullae, as this positioning was similar to that of the affected population.

All flexed lateral projections available for affected dogs, and all lateral, flexed lateral, and exaggerated flexed lateral projections for control dogs were evaluated and measured once by a single investigator (DW). Four measurements were defined and obtained per lateral projection (Figure 2-1 and 2-2). Table 1 identifies the measurement, the acronym, and the bony landmarks

used to obtain the measure. Additionally, 2 measured angles were defined and obtained (Figure 2-3, 2-4, 2-5 and 2-6). Table 1 also identifies the measured angles, the acronyms, and the bony landmarks used to obtain the angles. All measurements were obtained with the use of calibration features in a PACS system.¹

Statistics

Variables of age, weight, flexed lateral overlap of the dorsal arch of the atlas (ODA), length of the dorsal canal of the axis (LDCA), rock back measure (RBM), axis canal height (ACH), SAA, and AAA were compared between affected and control dogs by independent group T-test. Flexed lateral AAA was compared between affected and control Yorkshire terrier and Chihuahua dogs only by independent group T-test. For the control group dogs, flexed lateral AAA was compared to exaggerated flexed lateral AAA by paired T-test. Within the control group dogs, variables of flexed lateral ODA, LDCA, RBM, ACH, SAA, AAA, and exaggerated flexed lateral AAA were compared in sedated dogs versus dogs under general anesthesia by independent group T-test. Pearson's correlation coefficient was used to evaluate the ODA between the flexed lateral and exaggerated flexed lateral for the control population. A 95% confidence interval was calculated to predict affected Yorkshire terrier and Chihuahua dogs for the flexed lateral AAA. A $p \leq 0.05$ was considered significant for all comparisons.²

Results

The medical records of 73 dogs diagnosed with AAI were reviewed and 39 dogs met the inclusion criteria. Twenty-three dogs were excluded as lateral radiographs were not available for

¹ Carestream

² Winks 7.0.9 Professional Edition

review. Eight dogs were excluded as they were not toy breeds known to have the congenital form of AAI. Three dogs were excluded when AAI was secondary to trauma. Of the 39 included cases, 14 (41.2%) were spayed females, 8 (23.5%) were intact females, 7 (20.6%) were castrated males, and 5 (14.7%) were intact males. Sex was not listed in the medical records available for review for 5 (14.7%). Mean + SD age of affected dogs at the time of diagnosis was 3.1 + 2.4 years (range, 0.33 to 10 years), and mean body weight was 2.1 + 0.9 kg (range, 0.78 to 4.5 kg). Breeds included Yorkshire terriers (n= 21 [53.8%]), Chihuahuas (9 [23.1%]), Maltese (2 [5.1%]), miniature poodles (2 [5.1%]), Pomeranians (2 [5.1%]), and one dog of each Brussels Griffon, Chihuahua mix (2.47kg), and a Yorkshire terrier mix (4.53kg) (2.6%). All affected dogs presented for clinical signs consistent with AAI, ranging from cervical pain to tetraplegia. Advanced imaging was performed in 6/39 dogs; 2 underwent myelography, 2 had CT, one had MRI, and one had both myelography and CT. Information about treatment was recorded in 31/39 cases, as twenty-three underwent surgical treatment and eight had conservative management. None of the affected dogs had exaggerated flexed lateral views available for review.

Twenty control dogs were enrolled that met the inclusion criteria and no control dog was excluded from the study. Eleven (55%) dogs were spayed females, 8 (40%) were castrated males, and 1 (5%) was an intact female. Mean + SD age of control dogs at the time of imaging was 7.7 + 3.9 years (range, 0.8 to 12.1 years), and mean body weight was 5.5 + 1.9 kg (range, 2.9 to 9.8 kg). Breeds included mix breeds (55%), with these 11 dogs weighing 4.04-9.78kg, including 3 Chihuahua mixes, 3 Yorkshire terrier mixes, 2 Pekingese mixes, 2 Pomeranian mixes, and a miniature poodle mix. The remaining breeds were miniature poodles (n=3 [15%]), Yorkshire terriers (3 [15%]), Chihuahuas (2, [10%]), and one dog each of a miniature poodle mix (9.3kg) and a toy poodle (5%). Of the 20 control dogs, 11 (55%) presented for annual

examinations, 7 (35%) presented for orthopedic evaluation, and 2 (10%) presented for soft tissue evaluation.

Control dogs were older than the affected dogs ($p < 0.001$), and the control dogs were heavier than the affected dogs ($p < 0.001$).

Radiographic Measurements:

Sedation vs General Anesthesia:

There was no difference for the mean of any of the obtained measurements or angles between sedated and anesthetized control dogs. All control dogs recovered from the sedation or anesthetic protocol without complication.

Flexed lateral radiographs:

Of the affected dogs 31/39 (79.5%) had flexed lateral radiographs reviewed, which including necessary anatomic landmarks to obtain all measurements and angles. There was no difference between the SAA for the affected dogs and control dogs as shown in Table 2, ($p=0.795$).

The results comparing the measurements and angles between the affected and control populations can be found in Table 2. Notably, for the affected population, 94.8% were observed to have a negative ODA, while 80% of the control population was observed to have a positive ODA. The ODA measurements for the affected Yorkshire terriers, chihuahuas, and mixes for these breeds can be observed in Table 3.

The affected group had a larger AAA [$31.6 + 18.2^\circ$ (range, 1.0 to 80.3°)] than the control group [$5.1 + 4.8^\circ$ (range, 0.1 to 18.4°)], ($p < 0.001$). When the AAA was evaluated for Yorkshire Terriers, chihuahuas, and mixes of these breeds (24 affected dogs and 11 control dogs), the measured angle was larger for the affected group [$33.9 + 18.4^\circ$ (range, 1.0 to 80.3°)] than the

control group [$4.9 \pm 4.3^\circ$ (range, 0.1 to 9.9°)], ($p < 0.001$) (Table 3). When the AAA was greater than 10° , 91.6% (22/24) of our affected Yorkshire terriers, Chihuahuas, and mixes of these breeds were confirmed to have AAI (Table 4). When the AAA measured between 26.72° and 41.17° for these breeds, AAI was diagnosed with a 95% confidence interval. In the control population, 2 dogs had an AAA measuring greater than 10° , one of which was a Yorkshire terrier mix.

Exaggerated flexed lateral radiographs:

This positioning was obtained for control dogs only, and the mean SAA for the exaggerated flexed lateral radiographs was 38.91° . There was no difference between the flexed lateral and exaggerated flexed lateral measurements for AAA ($p = 0.465$). Pearson's correlation coefficient for the ODA of flexed lateral and exaggerated flexed lateral control dogs was 0.99.

Other radiographic findings:

Of all affected dogs, 10 were noted to have dens hypoplasia while two were found to have dens aplasia. Overall 30.7% of the affected cases had dens abnormalities detected on radiographs.

In the control dogs, no dens abnormalities were noted, and other radiographic findings included disc space narrowing, spondylosis deformans, congenital vertebral anomalies (hemivertebrae and spina bifida occulta), and suspected chronic discospondylitis.

Discussion

Throughout the years there have been a number of studies trying to improve our ability to diagnosis atlantoaxial instability safely and reliably in dogs.^{5,11,14} Given concerns that excessive flexion could result in worsening clinical signs, we sought to find a mild degree of cervical

flexion that could aid in diagnosis without the use of advanced imaging. Our results indicate that the average degree of flexion used to position the affected AAI population was 51° . Therefore, we postulate that a diagnosis of AAI can be made by interpreting the atlas to axis angle, with a dog positioned at a skull to axis angle of $51 + 10^{\circ}$. Additionally, the likelihood of an accurate diagnosis can be increased when this positioning and measuring criteria is utilized in Yorkshire terriers, chihuahuas, and mixes of these breeds.

McLear reported an angle of linear range of motion between the atlas and axis in normal toy and giant breed dogs, and compared this value to 8 dogs known to have AAI.¹² The abstract reported a cut-off measurement of less than 162° which accounted for 7/8 (87.5%) of the affected population. This measurement was similar to our findings which revealed that a measurement $>10^{\circ}$ (supplementary angle to 170°) provided a diagnosis in 28/31 (90.3%) of our affected dogs. However, our control population was selected for breeds known to be affected with AAI to limit any breed or size inconsistencies that could alter the established measurement protocol. This was an important distinction from McLear's study design, as established differences in atlantoaxial structures have been found in affected and non-affected AAI toy breed dogs compared to other breeds.^{7,13}

Cummings evaluated the C1-C2 angle in neutral lateral radiographs of control toy breed dogs and dogs affected with AAI. This measured angle was supplementary to our AAA. In their 10 affected AAI cases, a cutoff value of $<158.1^{\circ}$ revealed a sensitivity of 60.0% and a specificity of 98.9% for diagnosis.¹¹ Our study used an AAA of $>10^{\circ}$ for a cutoff diagnosis evaluated on flexed lateral radiographs. Assessing this measure with a mild degree of flexion made it more sensitive, with the present study having a 95.8% sensitivity for Yorkshire terriers, chihuahuas, and associated mixes.

The Cummings study also evaluated measurements using neutral lateral radiographs,¹¹ as excessive cervical flexion can result in worsening neurologic signs.^{1,5,15} Positioning for cervical radiographs is often performed under sedation or general anesthesia to minimize motion artifact and to obtain images in the peri-operative period. However, flexion of dogs that are unable to show a pain response can result in worsening neurologic signs; therefore, minimizing the degree of flexion necessary to obtain a diagnosis is imperative. Our results showed that increasing the degree of flexion past our recommended angle of 51° did not increase the chance of a false positive according to the criteria measured. This finding suggests that mild spinal flexion is necessary to obtain a diagnosis.

Previous studies have evaluated the dens to axis length ratio to try to determine which dogs are likely to develop or be affected with AAI.^{11,13} While the evaluation of this measurement has been assessed on neutral lateral radiographs,¹¹ the use of CT for measurement obtainment provided a greater sensitivity for diagnosis.¹³ As dens abnormalities are frequent reported in cases of AAI,¹⁰ the dens to axis length ratio was not evaluated on our flexed lateral images. Interestingly only 30.7% of the affected cases in our study had observable dens abnormalities, which is less than previously reported.¹⁰ Incomplete ossification of the dorsal neural arch of the atlas as described by Takahashi et al.,¹⁶ in addition to ligamentous failure, may help explain why the majority of our affected dogs had radiographically normal appearing dens but suffered from AAI.

Schneider recently reported a higher incidence of anomalies affecting the C2-C3 vertebrae in dogs affected with AAI compared to those without AAI; with the most commonly reported anomaly involving the intervertebral disc.¹⁷ As radiographs were the only imaging modality assessed in our study, our dogs were not fully evaluated for intervertebral disc

anomalies. Some of our control dogs were noted to have disc space narrowing; however, the area of narrowing was not associated with the C2-C3 intervertebral disc space. The publication by Schneider et al. evaluated 117 affected dogs, and interestingly it was found that our study had a similar case population to theirs as in both studies more than 50% of the affected dogs were Yorkshire terriers and chihuahuas.¹⁷

The anatomic components of the atlantoaxial joint have been well established in the canine model, and the various ligaments that contribute to the alignment and function of the joint play a key role in prevention of AAI.^{6,18} The SAA was used to determine the degree of cervical flexion necessary to obtain measurements for diagnosis. In the present study, there was no difference in the measured SAA between the previously diagnosed and control groups, indicating that the groups were positioned similarly. As there was no difference in the SAA, this finding supports the use of this angle as a repeatable measure of bony landmarks for the positioning of dogs in a mild degree of flexion.

Cummings recently evaluated the C1-C2 overlap, similar to our ODA, in neutral lateral radiographs for affected and control dogs.¹¹ It was found that nearly all the control dogs had a positive C1-C2 overlap while 80% of the affected population had a negative overlap. The results of our study were similar for the control population as 80% of our control dogs had a positive overlap. However, by assessing images with a mild degree of flexion, 95% of our affected population was found to have a negative measure, improving the sensitivity. Cummings also found that the affected dogs had a median overlap of -5.00mm,¹¹ which was similar to that found in our study as the mean ODA for the affected population was -5.50mm. When their reported cutoff of $C1-C2 < +1.55$ was applied to our affected Yorkshire terrier, chihuahua, and mixed population, 95.8% of our affected dogs were below the cutoff.

Limitations of our study include the retrospective nature of case selection. Given that AAI often affects young dogs, case comparison with the control population was difficult. In this study, the control population had a higher weight than the affected population. This finding however, is similar to previous results showing that Yorkshire terriers, chihuahuas, toy poodles, and miniature dachshunds with AAI are almost half the weight of control dogs of the same breeds.¹³ Cummings, too, found a significant difference between the affected cases and the size matched control population, suggesting again that cases affected with AAI are often smaller.¹¹ Additionally, our association with weight could also be attributed to the fact that the affected dogs were younger than the control group, although 30/39 (76.9%) of affected dogs were >12 months at the time of diagnosis. Another limitation pertaining to our retrospective case selection was that not all of the affected dogs had identical diagnostic imaging performed. Therefore, dogs with some marginal degree of instability that would have required advanced imaging to confirm a diagnosis may not have been included. This selection bias may have contributed to our cutoff value and therefore altered the representative sample of our affected dogs. While we acknowledge this limitation, we had to rely on affected cases that were diagnosed within the limitations of the current diagnostic criteria. Another limitation in this study is the lack of palpable anatomic landmarks necessary to obtain the desired degree of flexion for radiographs. Additionally, the measurements obtained require the use of digital radiography with calibration features.

Given that atlantoaxial instability can occur solely or in conjunction with other craniocervical junction abnormalities,^{2,3} the lack of advanced imaging for assessment of other CCJAs in our study could be considered a limitation. Atlantooccipital override (AOO) is a CCJA that results in the atlas being cranially displaced into the foramen magnum, resulting in overlap

between the occipital bone and the atlas. This CCJA is often noted in young toy breed dogs with Yorkshire terriers and chihuahuas reported to develop the condition.³ Typically AOO is diagnosed with CT or MRI; therefore, a diagnosis of this CCJA could not be assessed in our study. If any of the affected AAI cases were also affected with AOO, the degree of force placed in the atlantoaxial joint when achieving a SAA of 51° could differ given abnormal movement at the atlantooccipital joint. It could be postulated that abnormal motion at the atlantooccipital joint could therefore interfere with the evaluation of flexion placed upon the atlantoaxial joint. However, despite this potential for interference with the degree of flexion, a much greater AAA in our affected population was observed compared to control dogs of similar breeds. Therefore, the incidence of other CCJAs did not appear to impact the measurement for the AAA.

Conclusion

The results of the present study, suggest that when lateral radiographs of toy breed dogs suspected to have AAI are positioned with a mild degree of flexion, $51 \pm 10^{\circ}$, and AAA of 10° or greater can be diagnostic. Atlantoaxial instability in dogs, now has an objective measure to aid in the diagnosis when used with mild flexed cervical radiographs.

Abbreviations

AAA- Atlas to axis angle

ACH- Axis canal height

CT- Computed Tomography

LDCA- Length of dorsal canal axis

MRI- Magnetic Resonance Imaging

ODA- Overlap of the dorsal arch of the atlas

RBM- Rock back measure

SAA- Skull to axis angle

Footnotes

1. Carestream
2. Winks 7.0.9 Professional Edition

Figures

Figure 2-1- Measurements of a dog affected with AAI

Image from a 7yr MC Yorkshire terrier affected with atlantoaxial instability, demonstrating the following measurements: overlap of the dorsal arch of the atlas (ODA) measuring -8.3mm, length of dorsal canal axis (LDCA) measuring 11.4mm, rock back measure (RBM) measuring 5.3mm, and the axis canal height (ACH) measuring 7.6mm.



Figure 2-2- Measurements of a control dog

Image from an 8yr MC Yorkshire terrier in the control group, demonstrating the following measurements: overlap of the dorsal arch of the atlas (ODA) measuring +8.00mm, length of dorsal canal axis (LDCA) measuring 19.4mm, rock back measure (RBM) 8.2measuring mm, and the axis canal height (ACH) measuring 7.7mm.



Figure 2-3- SAA of a dog affected with AAI

Image from a 7yr MC Yorkshire terrier affected with atlantoaxial instability demonstrating a skull to axis angle (SAA) of 51.80° . The SAA is the angle obtained by drawing an intersecting line between the length of the dorsal canal of the axis (LDCA) and a line extending from the external occipital protuberance to the caudal aspect of the caudal most tympanic bulla.



Figure 2-4- SAA of a control dog

Image from an 8yr MC Yorkshire terrier in the control group, demonstrating a SAA of 53.24°.



Figure 2-5- AAA of a dog affected with AAI

Image from a 7yr MC Yorkshire terrier affected with atlantoaxial instability demonstrating an atlas to axis angle (AAA) of 38.00° . The AAA is the angle obtained by drawing intersecting lines between the roof of the canal of C1 and the length of the dorsal canal of the axis (LDCA).

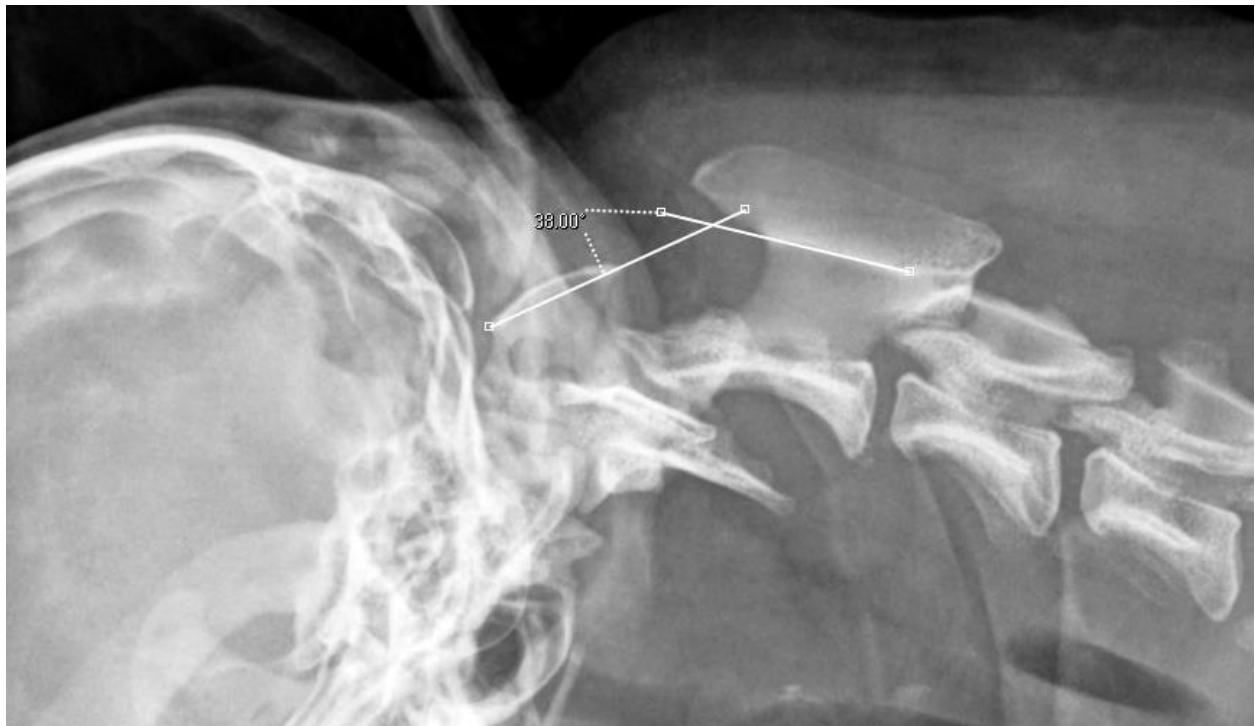


Figure 2-6- AAA of a control dog

Image from an 8yr MC Yorkshire terrier in the control group, demonstrating an AAA of 6.2°.



Tables

Table 2-1- Definitions for the 4 measurements and 2 measured angles obtained on flexed lateral radiographs

Description	Acronym	Landmarks for measurement
Overlap of the dorsal arch of the atlas	ODA	Distance along a line drawn from the caudodorsal aspect of the dorsal arch of C1 to the cranioventral aspect of the dorsal spinous process of C2; the value was positive if the axis was overriding the atlas when measured perpendicular to the C1 spinal canal, and was negative if the axis was not overriding the atlas
Length of dorsal canal axis	LDCA	Length of the roof of the canal of C2 parallel to the floor of the canal
Rock back measure	RBM	Distance along a line drawn from the caudodorsal aspect of the C2 dorsal spinous process to the craniodorsal aspect of C3 dorsal spinous process
Axis canal height	ACH	Height of the vertebral canal of C2 at the narrowest point and perpendicular to the LDCA
Skull to axis angle	SAA	Angle obtained by drawing an intersecting angle between the LDCA and a line extending from external occipital protuberance to the caudal aspect of the caudal most tympanic bullae
Atlas to axis angle	AAA	Angle obtained by drawing an intersecting angle between the roof of the canal of C1 and the LDCA

Table 2-2- Results of the affected versus control population for the 4 measurements, and 2 measured angles

Flexed Lateral Measurements			
	Affected	Control	Adjusted p-value
	N, Mean, SD, Range	N, Mean, SD, Range	
ODA	39, -5.5 ± 3.2 (-12.0-3.6)	20, 2.7 ± 3.6 (-5.2-8.0)	<0.001
LDCA	39, 12.9 ± 2.3 (8.9-17.5)	20, 16.6 ± 2.8 (12.5-23.5)	<0.001
RBM	39, 5.2 ± 1.5 (3.0-9.4)	20, 7.9 ± 2.3 (4.5-12.0)	<0.001
ACH	39, 7.5 ± 0.8 (5.6-9.0)	20, 8.0 ± 0.5 (7.2-9.2)	<0.004
SAA	31, 51.7 ± 14.5 (21.4-88.3)	20, 50.9 ± 5.4 (41.6-60.7)	=0.795
AAA	31, 31.6 ± 18.2 (1.0-80.3)	20, 5.1 ± 4.8 (0.1-18.4)	<0.001

AAA, atlas to axis angle; ACH, axis canal height; LDCA, length of dorsal canal of the axis;

ODA, overlap of the dorsal arch of the atlas; RBM, rock back measure; SAA, skull to axis angle;

N, number of dogs

Table 2-3- Results of the affected versus control Yorkshire terriers, Chihuahuas, and mixes of these breeds for the 4 measurements, and 2 measured angles

Yorkshire terriers/Chihuahuas/Mixes			
	Affected	Controls	Adjusted p-value
Flexed Lateral	N, Mean, SD, Range	N, Mean, SD, Range	
ODA	24, -5.7 ± 2.8 (-12.0-3.1)	11, 3.0 ± 3.85 (-5.2-8.0)	<0.001
LDCA	24, 11.9 ± 1.9 (9.0-14.9)	11, 16.6 ± 3.05 (13.5-23.6)	0.003
RBM	24, 4.8 ± 1.1 (3.0-6.8)	11, 7.9 ± 2.12 (4.5-11.2)	0.004
ACH	24, 7.4 ± 0.8 (5.6-8.8)	11, 7.94 ± 0.58 (7.2-9.2)	0.128
SAA	24, 47.1 ± 15.0 (24.7-72.1)	11, 50.6 ± 11.14 (41.6-60.8)	0.541
AAA	24, 34.9 ± 19.0 (1.0-80.3)	11, 4.9 ± 4.02 (0.1-9.8)	<0.001

AAA, atlas to axis angle; ACH, axis canal height; LDCA, length of dorsal canal of the axis;

ODA, overlap of the dorsal arch of the atlas; RBM, rock back measure; SAA, skull to axis angle;

N, number of dogs

Table 2-4- Measurement and measured angle used for diagnosis of affected Yorkshire terriers, Chihuahuas, and mixes of these breeds

Affected Yorkshire terriers/Chihuahuas/mixes- Flexed Lateral		
	ODA	AAA
Yorkie	-6.70	34.35
Yorkie	-8.30	38.00
Yorkie	-8.00	45.18
Chihuahua	-6.60	23.58
Yorkie	-12.00	80.29
Chihuahua	-7.80	14.15
Yorkie	-5.60	36.63
Chihuahua	-3.20	17.98
Chihuahua	-5.60	26.76
Yorkie	-5.60	43.05
Yorkie	-5.10	41.46
Chihuahua	-6.10	28.66
Chihuahua	3.10	12.00
Yorkie	-2.00	4.00*
Yorkie	-5.40	37.00
Yorkie- Mix	-8.90	57.00
Yorkie	-7.60	52.00
Yorkie	-7.10	27.00
Yorkie	-6.40	54.00
Chihuahua	-3.40	1.00*
Yorkie	-3.40	11.00
Yorkie	-4.80	27.00
Yorkie	-4.00	43.00
Yorkie	-7.00	58.00

* Below cut off value

AAA, atlas to axis angle; ODA, overlap of the dorsal arch of the atlas

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