

# **Biomechanical Evaluation of Two Surgical Methods of Stabilization of the Atlantoaxial Joint**

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(Abstract)

Several methods of surgical stabilization of the atlantoaxial joint are described in the veterinary literature. Threaded acrylic pins placed ventrally together with polymethylmethacrylate (PMMA) is a well-established technique that has been widely used in clinical cases. However, Kishigami tension bands are a less technically demanding procedure with potentially fewer complications. The purpose of this study was to biomechanically compare these two techniques in ventral-to-dorsal bending in both mature and immature dogs.

Seventeen normal canine cadavers <15kg were collected and radiographed to determine skeletal maturity. The cervical spines were dissected leaving bony and ligamentous structures intact. Eight mature spines and 9 immature spines were randomly divided into two groups. In one group a Kishigami tension band was applied over the dorsal arch of the atlas and attached to the spinous process of the axis using orthopedic wire. In the second group, six acrylic pins were placed ventrally in the atlas, axis, and transarticularly. The pins were then cut and covered with PMMA. The specimens were potted in custom steel pots and biomechanically analyzed in ventral-to-dorsal four-point bending. Load-displacement curves representing the degree of stiffness were compared between the groups. Stabilization using ventral pins and PMMA had a significantly greater stiffness than a Kishigami tension band when bending in ventral to dorsal bending. Within the stabilized vertebral segment, there was no significant difference between the stiffness of immature vs. mature bone. Further analysis in torsion and analysis in abnormal dogs will be helpful in establishing the clinical significance of these findings.

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## **Abbreviations/symbols**

|      |                            |
|------|----------------------------|
| AA   | Atlantoaxial               |
| CT   | Computed Tomography        |
| MRI  | Magnetic Resonance Imaging |
| N    | Newtons                    |
| PMMA | Polymethylmethacrylate     |

# Chapter 1: Introduction and Literature Review

## Introduction

The atlantoaxial joint is a unique joint in the spine due to the absence of an intervertebral disc and the presence of an odontoid process along with ligamentous attachments between the occipital bone, atlas, and axis. These ligaments provide most of the stability for the atlantoaxial joint. The atlantoaxial joint is capable of many movements including rotation, flexion, extension, and lateral bending.<sup>35</sup> The unique aspects of this joint make it more susceptible to subluxation associated with congenital abnormalities or acquired trauma. Atlantoaxial subluxation typically occurs in small breed dogs, although it has been seen in all sizes of dog and even in other species.<sup>1-4, 25</sup> This condition can be associated with severe neurologic deficits, and even death due to compression on the cranial cervical spinal cord and resulting respiratory depression. Stabilization of the atlas and axis can be accomplished by external support (conservative management) or by surgical stabilization. There are several methods of surgical management described, including both dorsal and ventral approaches to the atlantoaxial joint. The Kishigami tension band, applied dorsally, was initially described in 1984 and has more recently been evaluated in a clinical setting.<sup>16, 18</sup> A ventral approach using pins and polymethylmethacrylate is a common stabilization method used in the atlantoaxial joint.<sup>20, 29, 30,</sup>  
<sup>31</sup> To the author's knowledge, there is no biomechanical study available comparing the stability provided by the Kishigami tension band when compared to other modalities. The primary objective of this study is to evaluate the biomechanical properties of the Kishigami tension band when compared to ventral pins and PMMA in mature and immature dogs. We hypothesize that the ventral pins and PMMA construct will have a significantly greater stiffness than the

Kishigami tension band in ventral to dorsal bending. We anticipate that our results will help guide surgeons' implant choices as well as encourage additional biomechanical studies on other available methods of atlantoaxial stabilization.

## Literature Review

### Anatomy and Embryology of the Atlantoaxial Joint

The first cervical vertebra, or the atlas, articulates with the skull cranially, and the second cervical vertebra, the axis, caudally. These two vertebrae have unique shapes when compared to other vertebrae in the vertebral column. The cranial articulation between the occipital bone and atlas is formed between the occipital condyles and deep concavities on the cranial surface of the atlas (cranial articular fovea). These cranial articular fovea cup the occipital condyles and form a joint whose main movement is flexion and extension, allowing for a free up and down, or “yes”, movement of the calvaria in relation to the rest of the spine.<sup>9</sup> This joint has a range of approximately 90° when fully flexed.<sup>9</sup> The caudal articular surface between the atlas and the axis consists of two shallow glenoid cavities that form an articulation with the cranial articular surface of the axis, which together with a loose joint capsule allows for more rotary movement of the head. For this reason, this joint is often called the “no” joint. The atlantoaxial joint is a diarthrodial articulation.<sup>29</sup> It differs from other joints in the vertebral column due to the lack of an intervertebral disc and the incorporation of a bony prominence (odontoid process) along with ligamentous attachments.

The first cervical vertebra has a flat dorsal arch and differs from other vertebra because a spinous process is not formed. The transverse processes of the atlas are wing-like projections laterally. The body of the atlas is smaller, flatter, and thinner than the bodies of other cervical vertebrae.<sup>5</sup> The atlas contains bilateral alar foramina or notches on the cranial and lateral surface of the dorsal arch. The spinal cord passes through the central vertebral foramen, which is present in all vertebrae.<sup>5</sup> The transverse foramen is a short oblique canal through the transverse process of the atlas. The vertebral vein and artery run through this space.<sup>5</sup> The lateral vertebral foramen

sits at the craniodorsal part of the vertebral arch, and contains the vertebral artery.<sup>5</sup>

Embryologically, the adult atlas develops from three centers of ossification. One center forms the ventral arch, and two additional sections form the lateral masses and fuse at midline to become the dorsal arch.<sup>9</sup> These centers fuse around 4 months of age.<sup>6</sup>

The second cervical vertebra, or the axis, has an elongated dorsal spinous process that is blade-like cranially and expanded caudally. The ventral aspect of this vertebra contains two deep fossae separated by a median crest. The odontoid process is a cranioventral process of the ventral aspect of C2 that lies within the vertebral foramen of the atlas. The transverse foramen of the axis is present near the base of the transverse process (Figure 1.1).<sup>5</sup> Embryologically, the axis is formed from seven bony elements.<sup>6</sup> Centrum 2 forms the main bulk of the vertebral body. There are two lateral centers that form the arch and its processes, which fuse to centrum 2 at around 3 months of age.<sup>6</sup> One section (centrum 1) forms the cranial articular surface of the axis body and the odontoid process. This fuses later at 7-9 months of age.<sup>6</sup> There is a smaller ossification center at the very apex of the odontoid process called the centrum of the proatlas which is not present in all dogs. The proatlas fuses with centrum 1 at 3 to 4 months of age.<sup>6</sup> A small section just caudal and ventral to centrum 1 is intercentrum 2, which fuses with centrum 2 at 4 months.<sup>6</sup> Finally, a narrow caudal epiphyseal ossification completes the body of the axis around 7-9 months.<sup>6</sup>

The ligamentous attachments of the occipital bone, atlas, and axis differ from any other vertebral articulations in the vertebral column. The major ligamentous attachments of the atlanto-occipital joint include the lateral atlanto-occipital ligament, which courses cranioventrolaterally from the lateral part of the dorsal arch of the atlas to the jugular process of the occipital bone, and a small ligament from the inner surface of the ventral arch of the atlas to the lateral part of the foramen magnum.<sup>5</sup> In addition, the dorsal atlanto-occipital membrane is a broad strap-like

membrane that is divided on midline and runs at an oblique angle from the dorsal edge of the foramen magnum caudally to the dorsal arch of the atlas, bilaterally.<sup>5</sup> The ventral atlanto-occipital membrane associates with the synovial joint and forms a thin joint capsule between the ventral aspect of the foramen magnum and the ventral arch of the atlas.<sup>5</sup>

The ligaments of the atlantoaxial joint include the transverse ligament, alar ligaments, and the apical ligament (Figure 1.1).<sup>5</sup> The transverse ligament is a strong ligament that attaches one side of the ventral arch of the atlas to the other. The transverse ligament lies over the odontoid process within the vertebral foramen. This ligament limits ventrodorsal movement at the atlantoaxial joint.<sup>5</sup> The apical ligament is thin and travels from the odontoid process to the ventral aspect of the foramen magnum.<sup>5</sup> The paired alar ligaments travel from the odontoid process to the medial aspect of each occipital condyle, bilaterally.<sup>5</sup> The joint capsule is thin and extends into a fibrous layer that runs left to right between the dorsal arch of the atlas and the arch of the axis. This fibrous layer is called the dorsal atlantoaxial membrane.<sup>5</sup> The nuchal ligament attaches to the caudal aspect of the spinous process of the axis and runs caudally to the spinous process of T1.<sup>5</sup>

The stability of the vertebral column in general is established by the bone, intervertebral disc, ligaments, membranes, and muscular attachments. External forces that act on the spine include bending (dorsoventral and lateral), rotation, shear, and axial loading.<sup>4</sup> The vertebral body acts as a buttress to resist bending and axial loading, and the articular facets resist all external forces.<sup>4</sup> The intervertebral disc is considered to be the single most important stabilizing factor against rotation and lateral bending.<sup>15</sup> The assessments of these specific portions of the spine are based on the thoracolumbar spine. The atlantoaxial joint is unique in that the basic shape of C1 and C2 are different than other vertebrae, and the joint does not contain an

intervertebral disc. The odontoid process and its associated ligaments are believed to provide most of the stability. To the author's knowledge, there have been no published veterinary reports specifically evaluating the biomechanics of the atlantoaxial joint. As previously mentioned, the major motion in the atlantoaxial joint is rotational. The major motion in the atlantooccipital joint is ventral and dorsal flexion. Bending in the ventral direction in dogs with atlantoaxial instability is the most likely movement to cause compression of the spinal cord, especially if the odontoid process is intact or dorsally deviated. Bending in the ventral direction is the force that implants are designed to neutralize in order to prevent subluxation and spinal cord trauma from the odontoid process. For this reason, ventral bending will be the primary force evaluated in this study.

### **Atlantoaxial Subluxation**

Atlantoaxial subluxation is a condition that most commonly occurs in young, small breed dogs, although it can occur in large breed dogs and cats.<sup>1-4, 25</sup> There is no apparent sex predilection, however 56% of the dogs with atlantoaxial subluxation in the reported literature are less than one year of age.<sup>3</sup> Atlantoaxial subluxation can arise secondary to odontoid aplasia or hypoplasia, fracture or separation of the odontoid process, or failure of the ligaments due to rupture or malformation.<sup>25</sup> Ligamentous damage is generally associated with trauma, although a congenital absence of ligaments has been reported.<sup>11</sup> In one report of 46 dogs with atlantoaxial subluxation, odontoid process aplasia was noted in 46% of dogs, abnormal odontoid process conformation in 30%, and a normal odontoid process was noted in 24% of dogs with atlantoaxial subluxation.<sup>25</sup>

Clinical signs associated with atlantoaxial subluxation are consistent with compression of the cranial cervical spinal cord. A review of the literature revealed gait deficits in 84% of patients with atlantoaxial subluxation, and cervical hyperesthesia is noted in 61% .<sup>3</sup> Gait deficits vary from mild ataxia to tetraplegia and are dependent on the severity of spinal cord compression and damage. Severe spinal cord compression can result in hypoventilation and sudden death.<sup>3</sup> Diagnosis can be accomplished using survey radiography, CT, or MRI scan of the cervical spine.<sup>3</sup> Lateral cervical radiographs will demonstrate an increased distance between the dorsal arch of C1 and the most cranial aspect of the spinous process of C2, as well as dorsal displacement of the axis.<sup>3</sup> Gentle ventroflexion in the lateral view radiographically or fluoroscopically may be helpful to assess mild instability, however extreme caution is necessary because spinal cord compression is more likely in this view.<sup>3</sup> The odontoid process should also be assessed on survey films in the ventrodorsal view or an open-mouth rostrocaudal view, although the presence of an abnormal odontoid process alone is not sufficient evidence for atlantoaxial instability (Figure 1.2).<sup>3, 10, 12, 13</sup> Computed tomography (CT) may also be implemented to visualize the presence of the odontoid process and assess ossification of the bone. Past research has shown that dogs with incomplete ossification of the atlas are 35 times more likely to develop atlantoaxial subluxation than dogs with complete ossification of the atlas.<sup>7</sup> Magnetic Resonance Imaging (MRI) can also be used to assess bony malformation in addition to ligamentous structures.<sup>39</sup> MRI can also elucidate spinal cord compression and secondary changes such as intramedullary hyperintensity on T2-weighted images, syringohydromyelia, or other concurrent congenital abnormalities (Figure 1.3).<sup>4</sup> The presence of suspected extensive spinal cord malacia or syringohydromyelia on MRI may provide prognostic information for patients with atlantoaxial subluxation.<sup>14</sup>

## Nonsurgical Management

Nonsurgical management of atlantoaxial subluxation includes immobilization with a cervical splint, exercise restriction, the use of analgesics, and sometimes the administration of anti-inflammatory medications.<sup>4, 35</sup> The goals of treatment include decompression of the spinal cord by reduction of the subluxation and stabilization of the atlantoaxial joint.<sup>35</sup> Stability with this method depends on the formation of fibrous scar tissue around the atlantoaxial joint.<sup>3</sup> Historically, nonsurgical treatment has been reserved for dogs with clinical signs of cervical pain only, dogs with mild neurologic deficits and minimal anatomic displacement, dogs with radiographically normal odontoid processes, and due to client or patient constraints.<sup>3, 35</sup>

There have been four reports totaling 31 cases of atlantoaxial subluxation managed nonsurgically in the literature.<sup>25, 34-36</sup> A majority of the dogs were young at the time of presentation, with a median age of 2 in one study<sup>35</sup>, and 20/24 dogs under a year of age in another report.<sup>34</sup> One report found that dogs older than 2 years of age at admission had a significantly worse final outcome<sup>25</sup>, while another study found no significant association between age and outcome of cases.<sup>35</sup> Twenty of the 30 cases reported had minor or major trauma associated with the onset of clinical signs.<sup>34, 35</sup> One study reported no difference in outcome between dogs that did and did not have a normal odontoid process.<sup>35</sup> The duration of clinical signs ranged from 1 day to 3 years.<sup>35</sup> Havig et al. reported that the rate of onset affected final outcome. Dogs with greater than 30 days of clinical signs prior to presentation were more likely to have a poorer outcome than dogs with less than 30 days duration of clinical signs.<sup>35</sup> Nonsurgical treatment in all reports involved the application of a splint around the cervical spine and cage rest.<sup>25, 34-36</sup> Corticosteroids were also administered prior to presentation in 12/19 cases in one report.<sup>35</sup> The material used and length of the splint were variable. Havig et. al. used

fiberglass cast material and soft padding extending from the rostral extent of the mandible caudally to the xiphoid process in most dogs (Figure 1.4). In 4 dogs the bandage was extended caudally to the last thoracic vertebra. Lorinson et. al. constructed a neck wrap consisting of a well-padded bandage placed from the caudal edge of the mandible to the shoulders or, in very small dogs, a padded Styrofoam cup. Post-application radiographs in one report revealed improved alignment in 5 of the 10 cases radiographed.<sup>35</sup> Duration of immobilization varied from 4 weeks to 15 weeks. At the time of splint removal, the outcome was considered good in 26/31 reported cases (83%).<sup>35, 34, 36</sup> The definition of a good outcome involved voluntary ambulation in all dogs, and included a normal neurologic exam in 16 dogs. Long-term outcome after one year involved euthanasia related to atlantoaxial subluxation in 8/31 dogs.<sup>34, 35</sup> A concern with nonsurgical management of atlantoaxial subluxation is the recurrence of clinical signs following removal of the neck brace.<sup>4</sup> Havig et. al. suggested that surgical stabilization may have provided improved stability in the 6 cases that were euthanized or died in that study, and surgical stabilization should be recommended in cases of relapse.<sup>35</sup> Complications associated with splint application include corneal ulcers, moist dermatitis, decubital ulcers, otitis externa, and respiratory distress.<sup>35</sup> Havig et. al. suggests that nonsurgical management should be considered in cases with an acute onset of neurologic signs, immature bone incapable of firmly holding implants, and where there are financial constraints. Surgical stabilization should be recommended in cases with a chronic history of clinical signs, patients with mature bone, and when a relapse of clinical signs or failure of nonsurgical management occurs.<sup>35</sup>

## **Surgical Management**

The goals of surgical management are similar to nonsurgical management: decompression of the spinal cord by reduction and stabilization of the atlantoaxial joint. Surgery

in the craniocervical region is complicated by the unique anatomy of the cranial cervical vertebrae and by the substantial spinal movement allowed in this region.<sup>37</sup> There are few points for instrument fixation and bony fusion attachment.

### **Surgical Management - Dorsal Surgical Approaches**

Surgical stabilization of the atlantoaxial joint using a dorsal approach has been described using multiple methods including dorsal wiring, dorsal suture, nuchal ligament fixation, Kishigami tension band, and dorsal cross-pinning.<sup>9, 16-18, 23, 22, 26</sup> The dorsal wiring procedure was described in the initial paper defining atlantoaxial subluxation in 1967,<sup>9</sup> and later modified.<sup>23</sup> The procedure involves a dorsal approach to the atlantoaxial space. Two holes are then drilled in the spinous process of the axis, and the dorsal atlanto-occipital membrane is incised over the dorsal arch of the atlas. A loop of orthopedic wire is passed ventral to the dorsal arch of the atlas in a caudal-to-cranial direction through the vertebral canal and retrieved from the atlanto-occipital space. The free end of wire is passed through the previously-drilled caudal hole in the axis and the two ends are twisted together. The cranial loop of the wire is folded caudally and cut. An end is passed through the cranial hole in the spinous process of the axis, and the two free ends are twisted together.<sup>10</sup> Alternate techniques include using a single strand of wire beneath the dorsal arch of the atlas, or passing wire through predrilled holes in the arch of the atlas.<sup>9, 19, 23</sup> Modifications of this procedure include the use of nonmetallic suture or the nuchal ligament to pass under the dorsal arch of the atlas.<sup>22, 21</sup> When using suture in place of orthopedic wire, the approach and procedure are similar to the dorsal wiring procedure.<sup>21</sup> Orthopedic wire is used to pass under the dorsal arch of the atlas and non-metallic suture is threaded through this loop, which is then drawn back under the arch of the atlas. The strand is cut, and the suture is threaded through two holes created in the spinous process of the axis, the same as in the dorsal wiring

procedure.<sup>21</sup> When using the nuchal ligament, the approach is the same as for dorsal wiring.<sup>22</sup> The cranial attachment of the nuchal ligament is maintained, and the ligament is split longitudinally and transected at its caudal attachment to T1. Both free ends are then passed ventral to the dorsal arch of the atlas using a looped wire in the same fashion as the dorsal wiring procedure. The ends of the ligament are then tied to each other over a notch that is created in the dorsal aspect of the spinous process of the axis.<sup>22</sup>

The dorsal wiring technique has been reported in 27 dogs, with an overall success rate of 52%.<sup>10, 20, 19</sup> Major complications encountered include fracture of the dorsal arch of the atlas and wire breakage.<sup>9, 19</sup> Surgical management of atlantoaxial subluxation using the dorsal suture technique has been reported in 10 dogs, with a successful outcome in 5 of the 8 dogs available for follow-up.<sup>21, 22</sup> Complications included suture failure and inappropriate suture placement, both of which resulted in destabilization and the need for a second surgery.<sup>10, 21</sup> The use of the nuchal ligament has been reported in four dogs, with successful outcomes in three of those patients.<sup>22</sup> Complications included breakage of the nuchal ligament in the area of the notch in the spinous process of the axis. A second procedure was performed in this dog using suture instead of the nuchal ligament, and failure occurred a second time where the suture passed through the notch in the spinous process of the axis.<sup>22</sup>

Dorsal cross pinning is another procedure that has been reported for stabilization of the atlantoaxial joint.<sup>26</sup> This procedure involves the placement of 1.25mm Kirschner wires through the spinous process of the axis in a ventrolateral direction to engage and penetrate the caudal half of the wing of the atlas. Correct orientation of the implant can be facilitated by pre-drilling holes in the wings of the atlas and using a guide for the wire.<sup>26</sup> This procedure was reported in one case with significant neurologic improvement six months postoperatively. Disadvantages of this

technique include difficult pin placement due to sliding off the edge of the wing of the atlas, and the presence of a large amount of exposed implant which may contribute to implant weakness and tissue reaction.<sup>26</sup>

The Kishigami tension band was described by Kishigami in 1984 as a modification of the dorsal wiring technique.<sup>16</sup> The dorsal arch of C1 tends to be very thin in small dogs, and the surgically placed wire was pulling through the dorsal arch post-operatively with the dorsal wiring method. To avoid this complication, a stainless steel retractor with a broader hook for the dorsal arch of C1 was developed.<sup>16</sup> The retractor bands were custom-made according to specific dimensions with two main legs that form a U, a shorter center leg, and a wide hook to be placed over the dorsal arch of C1 (Figure 1.5).<sup>16</sup> The wide hook over the dorsal arch of C1 was meant to provide a wider surface area of bone-implant contact, thereby spreading the force placed on the dorsal arch over a larger area, and decreasing the chance of fracture of the dorsal arch. The tension band is designed to oppose tension between the laminae of the atlas and the axis, created by ventroflexion of the head.<sup>17</sup> The fulcrum point of ventroflexion is at the floor of the vertebral canal.<sup>17</sup> Dorsally placed implants are further from the center of motion, subjecting the implant to less stress with motion.<sup>17</sup>

The procedure to place the Kishigami tension band involves a dorsal approach to the atlas and the axis, with removal of associated muscular attachments. Three small holes are drilled in the dorsal spine of the axis.<sup>16</sup> Teflon thread is threaded through the cranial hole and the center ring of the Kishigami A/A Tension Band. The two follow-up case series omitted this step in the surgical procedure.<sup>17, 18</sup> Malleable stainless steel orthopedic wire is threaded through the caudal hole in the spinous process of the axis, and both ends are bent forward and directed through the center hole intersecting each other.<sup>16</sup> The dorsal atlanto-occipital membrane is incised along the

frontal edge of the dorsal arch of the atlas using a custom-made blade for this purpose. The wide hook of the Kishigami Tension Band was then placed over the dorsal arch of the atlas. This is the most delicate step of the procedure.<sup>18</sup> The U-shape of this hook is narrowed or widened using forceps to accommodate the thickness of the dorsal arch.<sup>16</sup> Once the retractor is in place, the Teflon thread is slowly pulled, bringing the atlantoaxial joint into reduction. The two ends of the wire are brought forward and threaded outward through the hooks of the side legs of the Kishigami Tension Band, and bent backward. Excess wire is cut and the hooks of the side legs are closed. In the Kishigami study, post-operative radiographs were used to verify anatomical reduction and proper placement of the Kishigami Tension Band. The patients were placed in a neck brace and cage rest was recommended for two weeks after the surgery.<sup>16</sup>

A series of 5 cases; one cat and four dogs; were evaluated in the initial 1984 study by Kishigami.<sup>16</sup> Neurologic improvement was noted in all cases, and all cases were eventually ambulatory. The selected cases were variable in species, size, and severity, and one case had a suspected fracture of the spinous process of the axis. A case report evaluating two failures of the Kishigami tension band was published in 1989 by van Ee.<sup>17</sup> One case had a confirmed fracture of the dorsal arch of the atlas secondary to implant tension, and the other suffered from acute death several days post-operatively, without a follow-up necropsy. Implant failure was attributed to excess motion at the implant-bone interface resulting in bone erosion and reabsorption adjacent to the implant along the thin lamina of the dorsal arch. A follow up case series was presented in 2010 by Pujol et. al.<sup>18</sup> This case series evaluated both the original Kishigami Tension Band design, and a modified band without a center hook. No difference was noted between the two implant types. No complications were noted intra-operatively associated with the placement of the Kishigami Tension Band. Following surgical stabilization of the

atlantoaxial joint in 8 dogs, 6 experienced a good or excellent outcome with no signs of recurrence after 12 months. One dog remained neurologically unchanged and was considered to have a good outcome. Two dogs were euthanized within one month of surgery due to lack of improvement or deterioration neurologically.

The advantages of a dorsal surgical approach include simplicity of the procedure, and lack of requirement for any special instrumentation. The approach is direct and presents few potential hazards when compared to the ventral approach.<sup>26</sup> A dorsal approach does not allow an odontoidectomy if there is any dorsal deviation or a fracture of the odontoid process.<sup>18</sup> A dorsal approach will allow additional decompression with a hemilaminectomy, although many surgeons feel that once stability is obtained, decompression is unnecessary.<sup>19, 34</sup> The main complications of dorsal fixation are death or failure of fixation. Death is due to cardiac or respiratory arrest, which may occur during placement or tightening of the wires.<sup>24</sup> About 30% of dogs will require a second procedure after a standard dorsal fixation due to implant failure.<sup>4</sup> Advantages of the Kishigami tension band are noted when compared to other dorsal approaches. The flat cranial hook which pulls the dorsal arch of the atlas toward the axis is more effective at repartitioning forces along the dorsal arch which leads to less of a chance of fracture of this thin lamina when compared to dorsal wiring or dorsal suture.<sup>16, 18</sup> The retractor is more stable in immobilizing the joint and has greater durability than wire or thread.<sup>16</sup> The installation of the Kishigami Tension Band carries less risk to the medulla oblongata or cranial cervical spinal cord when compared to the dorsal wiring or dorsal suture techniques.<sup>16</sup> The passage of the wire or suture under the dorsal arch of the atlas can result in contusion to important central nervous system structures. The pre-formed hook of the Kishigami Tension Band eliminates the need to pass implants through the spinal canal, minimizing the risk of injury to the medulla or cervical spinal cord.

The Kishigami tension band is also made of thicker and more stable material than a thin orthopedic wire, suture, or body tissue, which may reduce the risk of implant failure.<sup>18</sup> Stabilization of the atlantoaxial joint using a dorsal approach relies on fibrous scar formation across the atlantoaxial joint, whereas ventral surgical techniques strive to form a permanent fusion or arthrodesis for long-term stabilization.<sup>18</sup> It is theorized that stabilization using the Kishigami Tension Band may preserve normal physiology of atlantoaxial motion (i.e., rotation) and carries less risk of adjacent segment disease than ventral rigid arthrodesis.<sup>18</sup> Potential complications associated with the Kishigami Tension Band are also noted. The stabilization of the atlantoaxial joint using this device depends on the integrity of the dorsal arch of the atlas and the spinous process of the axis. These two areas can have very thin bone structure, especially in the small breed dogs typically affected with atlantoaxial instability.<sup>17</sup> Excessive motion at the atlantoaxial joint prior to fibrous scar formation may result in a fracture of the dorsal arch of the atlas, and thus implant pull-out.<sup>17</sup> Insufficient tightening of the wire may lead to Kishigami Tension Band instability and subluxation of the atlantoaxial joint.<sup>18</sup> The selection of wire size which is too thin may result in widening of the holes in the spinal process with movement.<sup>16</sup>

### **Surgical Management - Ventral Surgical Approaches**

Surgical stabilization of the atlantoaxial joint may also be accomplished using a ventral approach. The ventral approach to the neck is routine, involving dissection of the superficial musculature along midline or just off of midline (paramedian approach), taking care to avoid important structures such as the recurrent laryngeal nerve and the vascular supply to the thyroid gland.<sup>4</sup> The visceral cervical structures are gently retracted laterally allowing access to the deep midline longus colli muscle group, which sits ventral to the cervical spine. Care must be taken to avoid excessive retraction of the trachea or esophagus.<sup>20</sup> The longus colli musculature is

dissected away exposing the ventral vertebral bodies of the cervical spine. There are three main methods of ventral fixation: transarticular pin placement, pin or screw placement with bone cement, the use of lag screws, or ventral plating.

Several authors have described the use of pins applied ventrally for stabilization of the atlantoaxial joint.<sup>20, 28-30</sup> Sorjonen and Shires described a ventral technique in 18 dogs in 1981. The technique involves an odontoidectomy and scarification of the articular cartilage between the facets of C1 and C2. Autogenous cancellous bone is placed in this space to promote bony fusion. Non-threaded Kirschner wires are placed bilaterally from the body of the axis through the atlantoaxial joint and into the atlas. Placement of the pin starts at midline on the caudoventral body of the axis and is directed medial to the alar notch on the cranial edge of the atlas, with the point of the pin angled ventrally as far as possible. The ideal angle for pin placement is 29° between a line drawn at midline and a line drawn from the medial border of the alar notch through the atlantoaxial joint. Another study by Thomas et. al. described a similar surgical technique as the Sorjonen and Shires study. The Sorjonen and Shires study evaluated 18 normal dogs. Six dogs had ventral transarticular pins placed through the atlantoaxial joint, six had ventral pins placed in addition to sharp separation of the dorsal atlantoaxial ligament, and six had only separation of the dorsal atlantoaxial ligament. Only one dog in each group exhibited neurologic signs aside from pain after the procedure. All dogs exhibited cervical pain. The Thomas et. al. report looked at a large cohort of dogs with clinical atlantoaxial subluxation, 17 of which were treated surgically using transarticular pins. Both reports evaluated a majority of young small breed dogs. Post-operative complications included pin migration 7/35, respiratory distress in 2/35, and sudden death in 2/35 with tracheal stenosis and focal tracheal necrosis noted on necropsy. Long-term follow up was not available in one study, since all dogs were

euthanized 6 weeks post-operatively for histopathologic analysis of bony fusion.<sup>29</sup> Atlantoaxial joint fusion was present in 3/12 dogs in the stabilization group, and 0/6 dogs in the control group.<sup>29</sup> All of the control dogs were found to be unstable, whereas 10/12 in the stabilized group were considered stable based on amount of movement of the atlantoaxial joint at necropsy, despite the lack of bony fusion.<sup>29</sup> In the study evaluating clinical cases, 47% of the cases were normal or ambulatory with ataxia 3 months to 10 years post-operatively.<sup>20</sup>

Several studies have been published that use a modification of the original transarticular pin technique described above.<sup>28,30</sup> Four pins are added in addition to the transarticular pins described above for atlantoaxial stabilization in a publication by Schulz et. al. in 1997 in an attempt to provide greater stability and a greater chance of arthrodesis than transarticular pins alone. The use of polymethylmethacrylate may also lessen the incidence of pin migration and fixation failure which has been described with transarticular pins alone.<sup>30</sup> Two Kirschner wires or acrylic fixation pins are directed perpendicular to the median plane and transverse plane into each of the pedicles of the atlas. The transarticular pins are then placed after atlantoaxial reduction. Two pins are then placed into the caudal body of the axis at an approximate 30° angle to the transverse plane.<sup>30</sup> The pins are cut to 1-2 cm and the tips are bent perpendicular to the pin placement angle. The pins are then secured with polymethylmethacrylate infused with Cefazolin. The main intraoperative complication with this procedure in this study was hemorrhage from the vertebral sinuses.<sup>30</sup> Nine dogs were included in this study, and five dogs experienced postoperative complications. One dog had migration of the pin through the oral cavity and it was removed. One dog experienced hypothermia. One dog experienced dyspnea that resolved after surgery. One dog suffered from apnea immediately post-operatively and required mechanical ventilation for 48 hours after surgery, but eventually recovered. One dog developed progressive

pulmonary edema and died 2 days postoperatively. Overall long-term outcome after surgery was deemed good or excellent according to owners in 8 dogs. This particular technique may provide greater stability and therefore a greater chance of arthrodesis than with transarticular pins alone.<sup>30</sup>

A modified technique was described by Platt et. al. in 2004 using cortical screws, Kirschner wires, and polymethylmethacrylate. The Kirschner wires are used as transarticular pins and the screws are placed in the pedicle of the atlas and in the body of C2 to allow for reduction of the atlantoaxial joint. Once reduction was achieved, the implants are covered with polymethylmethacrylate. Nineteen dogs were admitted in the study.<sup>28</sup> Two dogs died within 48 hours of surgery secondary to aspiration pneumonia. Of the 17 remaining dogs, 16 showed neurologic improvement, and 3 were considered neurologically normal 2 days to 2 months after surgery. One dog was euthanized two months after surgery due to a transarticular pin fracture and subsequent cervical pain. Of the sixteen dogs that remained greater than 2 months after surgery, all dogs were considered to be the same or better than they were 1 month after surgery. One dog developed a draining tract associated with a loosened screw in C2. One dog experienced a broken transarticular pin and pin migration 10 months postoperatively after presenting for recurrent cervical pain. Overall, 13/19 dogs were considered to have a successful outcome (68.4%).<sup>28</sup> If the dogs with implant migration and removal and the one dog with no neurologic improvement but no cervical pain were considered successful, it would have been an 84.2% success rate. A noted disadvantage of multi-implant fixation is an increased volume of polymethylmethacrylate required, resulting in increased possibility of upper respiratory and esophageal complications.<sup>28</sup> Two advantages of this particular technique were listed. The combination of screws and polymethylmethacrylate provided better holding power when

compared to pins and polymethylmethacrylate.<sup>28</sup> They also noted an improved method of attaining and maintaining reduction without inserting an instrument into the intervertebral space.<sup>28</sup>

The application of lag screws involves a ventral surgical approach and placement of lag screws across each of the ventral articular facets between the axis and the atlas.<sup>24</sup> The screws are placed in a pre-drilled pilot hole that has been tapped. Surgical stabilization using lag screws has been reported in 11 dogs, with an overall success rate of 91%.<sup>3,10,20,24</sup> A review of 10 cases of atlantoaxial instability in which lag screws were used to stabilize was published in 1987.<sup>24</sup> Nine of the ten dogs made uneventful recoveries over a two month period. One dog died suddenly ten days after the procedure from an unknown cause. This particular study did not define neurologic improvement in each case, making it difficult to compare to other more well-defined studies. A modified procedure has been described using cannulated screws in place of lag screws.<sup>32</sup> The dog in that report was normal neurologically after 12 weeks. Advantages of cannulated screws included the ability to reposition the guide wire if appropriate placement was not achieved, and stabilization of the joint while the screw is inserted.<sup>32</sup> The cannulated screw is also self-drilling and self-tapping, minimizing technical maneuvers when compared to lag screws placement.<sup>32</sup> A comparison study by McCarthy et. al. in 1995 found that ventral lag screws were significantly more successful than dorsal wires or ventral pins, based on the published literature. They also noted that lag screws resulted in significantly fewer complications than pins, but not double wire loops.<sup>3</sup> When using a screw inserted in lag fashion, however, there is a small volume of axis bone available for screw engagement. The target area for screw positioning does not permit any error.<sup>28</sup> The presence of only two implants may also increase the risk of failure rates.<sup>4</sup>

Ventral plating has been described for the stabilization of atlantoaxial subluxation, using a variety of plate types.<sup>3,20,33</sup> The procedure in one report involves a Straumann ASIF mini H plate for 2mm screws that is found to be a suitable size to bridge the atlantoaxial articulation and allow for two screws to be placed in each vertebral body, either side of midline.<sup>33</sup> The screws are placed in pre-drilled and pre-tapped holes. The screws in the atlas are inserted just medial to the alar notch by angling the drill bit 20° laterally. The axial screws are positioned so that their points just entered the vertebral canal as far laterally as possible. The case report of four cases by Stead et. al. showed good neurologic improvement in 3 of the 4 described cases. The fourth case died within one hour of surgery. The death was thought to be due to underlying cardiac disease rather than an association with the procedure. This procedure carries a high degree of difficulty as correct angulation of the screw holes at 10° to 20° laterally is essential to avoid damage to the spinal cord, leaving little margin for error.<sup>33</sup> Thomas et. al. also reported the use of plates applied ventrally in 1991. It was attempted on two dogs with good outcome in one in which a T-plate was used, although a small amount of screw migration was noted 5 days after surgery. The other dog had a straight plate applied and suffered from progressive respiratory distress and was euthanized 7 days post-operatively.

There are several advantages of ventral stabilization in atlantoaxial instability. The ventral approach allows for an odontoidectomy if indicated, and may result in better reduction of the atlantoaxial joint since the surgeon is able to visualize the ventral aspect of the vertebral canal.<sup>29</sup> A ventral approach also allows for disruption of articular cartilage and subsequent placement of an autogenous cancellous bone graft.<sup>20</sup> The ventral approach also provides more immediate rigid joint stabilization rather than relying on the formation of a fibrous scar over time as with a dorsal procedure.<sup>3,29</sup> This rigid arthrodesis may predispose patients with ventral

stabilization to future adjacent segment disease, although this has not been specifically evaluated in relation to atlantoaxial subluxation. Ventral stabilization procedures require specialized equipment and the placement of implants can be technically demanding with a small margin of error.<sup>3,29</sup> The most common complications of ventral procedures are death and implant failure that necessitates a second surgery.<sup>4</sup> The primary causes of death include respiratory or cardiac arrest and pulmonary edema.<sup>4,20,25,30</sup> Aspiration pneumonia was seen in multiple cases.<sup>20,28</sup> Sudden death or respiratory dysfunction may be secondary to excessive manipulation or contusion of the spinal cord and caudal brainstem associated with the procedure, resulting in impaired respiratory drive or motor dysfunction.<sup>4,20,30</sup> Esophageal damage and tracheal necrosis may have occurred secondary to implant migration or implant interaction with esophageal and tracheal tissue, as was confirmed histologically in a few cases.<sup>20</sup> The use of multiple implants may result in larger quantities of polymethylmethacrylate being used, and further damage to the trachea, as was previously discussed.<sup>3</sup> However, implant failure is more likely with the use of transarticular pins alone than after the use of multiple implants and polymethylmethacrylate.<sup>3,4</sup> The exothermic reaction of polymethylmethacrylate may reach temperatures over 100° C.<sup>27</sup> This may result in thermal necrosis of adjacent bone and soft tissues.<sup>27</sup> However, it has been shown that the center of the polymerizing mass will reach higher temperatures than the bone/methacrylate interface.<sup>27</sup> Post-operative infection can also increase with the use of polymethylmethacrylate, and some surgeons add an antibiotic to the polymer prior to settling.<sup>30</sup> The main causes of implant failure are Kirschner wire migration or a loss of reduction, which tend to occur in the first 3 weeks postoperatively.<sup>4,20,25,30</sup> Threaded pins are preferred over Kirschner wire since they are much less likely to migrate and have greater pullout strength.<sup>4</sup> It has been shown that when complete reduction and stabilization is not achieved, fusion of the

joint may be delayed.<sup>20, 25, 29</sup> If complete failure of the fixation does occur, a second surgery is recommended to regain stabilization.<sup>20, 25</sup> In a literature comparison study by McCarthy et. al., there was no significant difference in the outcome or number of complications when comparing dorsal techniques (dorsal atlantoaxial wiring, dorsal atlantoaxial suture, nuchal ligament technique, atlantoaxial Kishigami retractor) and ventral techniques (atlantoaxial pinning, ventral atlantoaxial lag screws, ventral plating).<sup>3</sup>

### **Spine Biomechanics**

Normal canine spines are subjected to torsion, compression, shear, and bending forces in all planes of movement.<sup>8</sup> The ventral, dorsal, and lateral bending forces are prominent in normal range of motion of the neck. The spine is designed to neutralize some forces, but does a poor job managing others. The vertebral body resists axial loading, and the vertebral body size is correlated with strength.<sup>37</sup> The facet joint does not support much axial load.<sup>37</sup> The facet is an apophyseal joint with a loose capsule and synovial lining.<sup>5</sup> In humans, cervical vertebrae 3-7 do not restrict gliding movements within the facet.<sup>37</sup> For this reason, they have a decreased ability to resist flexion, extension, lateral bending, and rotation. The lumbar spine facets have a better ability to resist rotation due to their orientation in a sagittal plane.<sup>37</sup> The intervertebral disc resists axial loading, but this resistance decreases with age.<sup>37</sup> Forces such as flexion, extension, and lateral bending increase intervertebral disc bulging and herniation.<sup>37</sup> The atlantoaxial joint does not contain an intervertebral disc.<sup>5</sup> There is also a continuous influence of spinal musculature on spinal stability.<sup>37</sup> Benzel et. al. states that biomechanical studies involving cadavers are uniformly complicated by the inability to accurately mimic the stabilizing contributions of continuous muscle influences.

In humans, the cranial cervical spine has a wedge-like configuration, resulting in lateral transmission of force vectors from axial loading. Important contributors include the transverse ligament, which provides containment of the odontoid process, and the cranial ring of the atlas which is composed of dense cortical bone.<sup>5</sup> A circumferentially intact ring of the atlas is not necessary for spinal stability.<sup>37</sup> The axis is attached to the occipital bone by apical and alar ligaments and a tectorial membrane.<sup>5</sup> The atlas tends to act as a fulcrum that regulates movement between the occiput and the axis. The atlantoaxial joint mainly allows flexion and extension.<sup>29</sup> Minimal lateral flexion and rotation is allowed. Most of the rotation that occurs will occur at the odontoid process.<sup>37</sup> The sum of the movement from occiput to the axis is greater than that seen in any other region of the spine.<sup>37</sup>

Bending in the ventral direction in dogs with atlantoaxial subluxation is the most likely to cause compression of the spinal cord, especially if the odontoid process is intact. Bending in the ventral direction is the force that implants are designed to neutralize in order to prevent subluxation and spinal cord trauma from the odontoid process, and therefore improve the neurologic status of the patient. Therefore, bending in ventroflexion is the primary force we chose to evaluate in this study.

Bending forces are often referred to as moments. A moment is defined as a tendency for a force to twist or rotate an object, and can be calculated by multiplying an applied force by a perpendicular distance from force vector to the instantaneous axis of rotation.<sup>37</sup> Moments are expressed in units of torque. Pure bending refers to the application of equal and opposite bending moment at each side of a specimen, creating a uniform bending moment across the bone.<sup>38</sup> Pure bending rarely occurs clinically.<sup>37</sup> Four point bending refers to the application of load at each end of a specimen, and two opposite loads applied between the ends.<sup>38</sup> The bending moment

increases from one end to the first inner load, is constant to the next inner load, and decreases to the other end load (Figure 1.6).<sup>38</sup>

A load/displacement curve can be generated when evaluating a structure biomechanically. Load is defined as a local force and is expressed in Newtons (N).<sup>37</sup> Load is positioned on the Y axis. Displacement is defined as local deformation and is expressed in units of length such as meters (m) or millimeters (mm).<sup>37</sup> Displacement sits on the X axis. The load/displacement curve is also sometimes called the stress/strain curve. The slope of the ascending linear portion of the curve represents stiffness, or elasticity. Stiffness is defined as the rate at which a material deforms when a load is applied.<sup>38</sup> The steeper the slope of the curve, the stiffer the material.<sup>38</sup> The point “Y” corresponds to the yield point, which is the point at which the curve becomes non-linear. At point “Y” the strain exceeds the material’s ability to recover.<sup>38</sup> Prior to point “Y”, once the load is removed the material should return to its resting state.<sup>38</sup> This is referred to as elastic deformation.<sup>38</sup> The point “U” is the ultimate failure point, at which the material can withstand no more strain and will not return to its resting state if the load is removed.<sup>38</sup> Permanent deformation is referred to as plastic deformation.<sup>38</sup> The area under the load/displacement curve corresponds to toughness, or the total energy absorbed during the loading process (Figure 1.7).<sup>37</sup> Bone is viscoelastic, meaning the force-deformation characteristics are dependent on the rate of loading. Rapidly loaded bone stores more energy.<sup>38</sup>

### **Cadaver Preparation**

The methods used in this study are similar to what has been described in other veterinary spine biomechanical studies.<sup>41, 42</sup> These methods include storage of specimens in air-tight containers wrapped in saline-soaked towels. A recent study by Kaye et al. indicates that there is

no statistically significant change in the mechanical properties of bone over 3 freeze-thaw cycles when specimens were stored at  $-20^{\circ}\text{C}$ .<sup>40</sup> When degradation did occur, the effect of freezing on the mechanical properties was smaller than the normal variation of those properties across a sample prior to freezing (Kaye).

Multiple clinical case studies have been published regarding the atlantoaxial joint and surgical stabilization procedures.<sup>1, 2, 9, 11, 14, 16-18, 20-34</sup> To the author's knowledge, there are no veterinary in vitro biomechanical studies available evaluating the atlantoaxial joint. More specifically, there are no studies comparing the stability provided by the Kishigami tension band when compared to other stabilization modalities. The purpose of this study is to biomechanically compare the Kishigami tension band and ventral stabilization with pins and polymethylmethacrylate in ventral-to-dorsal bending in both mature and immature dogs. The major variable evaluated will be stiffness.

## **Chapter 2: Materials and Methods**

### **Part 1: Specimen Collection and Preparation**

Seventeen canine cadavers were collected to be used in this study. The dogs were euthanized for reasons other than related to this study. All cadavers weighed less than 15 kg. Both immature and mature specimens were collected. No breed restrictions were placed on cadavers. Cadavers were received either fresh (<12 hours after euthanasia) or frozen.

Lateral and ventrodorsal cervical spinal radiographs were obtained on all cadavers prior to dissection. Radiographs were used to confirm normal skeletal anatomy and assess skeletal maturity. Cadavers with open vertebral body endplate physes or incomplete ossification of C2 were considered skeletally immature (Figure 2.1).

The cervical spine specimens were collected immediately after radiographic confirmation of anatomy by removing the caudal 1/3 of the calvarium and the cervical spine to the level of C4 en bloc after thawing specimens that were previously frozen. All muscle and other soft tissues were removed from the cervical spine and occipital bone via sharp manual dissection. The supporting ligaments and fascia remained intact. The specimens were then wrapped 0.9% NaCl-soaked paper towels and placed in airtight plastic bags to prevent dehydration. Specimens were then frozen at -20 °Celsius until subsequent use in the study. Specimens were thawed at 4° C for 24 hours prior to use. Specimens underwent either 2 or 3 freeze-thaw cycles. During preparation and testing, specimens were kept moist using routine spraying of 0.9% NaCl.<sup>a</sup>

Vertebral segments were randomly allocated into two groups based on the type of

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<sup>a</sup> Veterinary 0.9% Sodium Chloride Injection USP ®, Abbott Laboratories, North Chicago, IL

surgical stabilization to be used. Of the 17 specimens, 8 had stabilization of the atlantoaxial joint using a Kishigami tension band (Group K), and 9 had stabilization of the atlantoaxial joint using ventrally placed pins and polymethylmethacrylate (PMMA). These are referred to as Group V. There were a similar number of immature (Group I) and mature (Group M) specimens in each group. The groups were allocated as shown in Table 2.1.

All specimens were thawed at 4° C prior to stabilization. The occipital bone was removed from C1 by sharp dissection. The apical and alar ligaments were incised from the odontoid process, but the transverse ligament remained intact. All surgical procedures were performed by the same surgeon.

## **Part 2: Surgical Technique**

Kishigami tension band: Eight specimens were stabilized at the atlantoaxial joint using a Kishigami tension band, as described by Kishigami et al. and Pujol et al. The Kishigami tension bands were custom made of surgical grade stainless steel according to the specifications in the original 1984 publication.<sup>b</sup> Three sizes were constructed; small, medium, and large to accommodate the variability of weights of dogs in the study. The custom made large bands were 5mm longer and 2.5mm wider than the original band (Figure 1.5).

The specimens were placed in ventral recumbency, and all soft tissue was cleared from the spinous process of C2. Two small holes were drilled in the spinous process of C2 using a round burr and power drill. The holes were placed on midline in the transverse plane and in the cranial 1/3<sup>rd</sup> of the spinous process of C2. These holes were placed in line with the Kishigami

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<sup>b</sup> Tension Band, Mountain Precision Tool, Blacksburg, VA

tension band. Malleable stainless steel orthopedic wire<sup>c</sup> was passed through the caudal hole, and the ends were directed through the cranial hole intersecting each other. An appropriate Kishigami device was then selected for each patient based on body weight. Specimens with a body weight of less than 13.5kg had a medium Kishigami device, and specimens >13.5kg and <15 kg had a large Kishigami device placed. Of the specimens collected, none were small enough to warrant use of the small Kishigami device. When a large Kishigami band was used, 20G stainless steel wire was also used. When a medium Kishigami band was used, 22G stainless steel wire was selected. The cranial hook of the Kishigami band was placed over the dorsal arch of C1. The wire was threaded through the caudal eyelets from medial to lateral on both sides of the Kishigami band. The wire was then looped caudally and the atlantoaxial joint was reduced. Excess wire was cut using wire cutters. The eyelets on either side of the Kishigami band were then crushed to secure the wire (Figure 2.2). Appropriate implant placement was confirmed visually and radiographically prior to biomechanical testing.

Ventral pins and PMMA: The specimens were placed in dorsal recumbency. Residual soft tissue was cleared from the ventral aspect of C1 and C2 using periosteal elevators. Pointed reduction forceps were used to hold the atlantoaxial joint in reduction for placement of pins. Two 0.045cm positive profile threaded interface acrylic pins<sup>d</sup> were placed as transarticular pins from medial to lateral. These pins were angled laterally and proximally toward the medial aspect of the alar process of C1 as described by Sorjonen and Shires 1981. Two 0.045cm threaded interface acrylic pins were placed in the pedicle of the atlas of C1, just medial to the alar notch directed perpendicular to the median plane and transverse plane as described by Schulz et. al.

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<sup>c</sup> Orthopedic Wire 20 Ga, 22 Ga, IMEX® Veterinary Inc., Longview, TX

<sup>d</sup> Mini INTERFACE® Half-pin 0.045”, IMEX® Veterinary Inc., Longview, TX

Two additional pins were placed in the body of C2 starting just lateral to midline and angling from medial to lateral at approximately a 30° angle to the transverse plane. The pins were cut about 0.5 cm from the exit point in the bony cortex. Polymethylmethacrylate<sup>e</sup> (PMMA) was molded over each of the 6 exposed pin tips from the medial aspect of the wings of C1 bilaterally to the body of C2. The amount of PMMA used varied depending on the size of the specimen; however, enough was used to cover the exposed pins without applying in excess. (Figure 2.3). Appropriate implant placement was confirmed visually and radiographically.

### **Part 3: Biomechanical Analysis**

Potting procedure: After stabilization, the spines were potted in preparation for biomechanical testing. Prior to potting, molding clay was used to cover and protect the implant from any involvement with methacrylate acrylic. Wood screws were placed in the dorsal aspect of C2 extending ventrally and caudally into C3 for additional reinforcement and isolation of the atlantoaxial joint. The caudal end of the vertebra was potted in a square steel tube using non-surgical grade bone acrylic (Technovit®).<sup>f</sup> Two separate square steel tubes were available for potting depending on the size of the vertebrae. If a specimen was too long to fit into one of the pots, a band saw was used to remove a portion of the caudal end, although C3 remained intact in every specimen. The caudal pot was allowed to harden for 15-20 minutes. A custom-made steel pot involving a flat base, a vertical support, a steel ring, and a flat steel support on the top surface was used to pot the cranial portion of the specimen. Four pointed cortical screws were positioned in the steel ring coming to a point near the center of the ring. The specimen was placed in the ring with the spinous process facing the base of the custom pot. The pointed screws were

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<sup>e</sup> Bone Cement, Zimmer® Inc., Warsaw, IN

<sup>f</sup> Technovit®, Jorgensen Laboratories, Loveland, CO

advanced toward the center until they gained adequate purchase in the cortical bone of the pedicle of C1 at four points; two dorsal, and two ventral. The cranial articular surface of C1 (including the spinal canal) was packed with molding clay<sup>g</sup> to prevent interaction of the odontoid process, transverse ligament, and implant with Technovit ®. The cranial portion was then potted with enough Technovit ® to cover the cranial 1/3 of C1 (Figure 2.4).

The cranial aspect of the potted specimen had a consistent distance between the surface where the load was applied (ventral) and the surface that rested on the machine (dorsal) due to the custom steel pot. The caudal aspect of the potted specimen was attached to an infinitely adjustable flat steel construct using screws and nuts. The adjustable steel support was raised or lowered to match the height of the cranial pot, creating an even surface for the application of force across the cranial and caudal pots. The potted specimens were then placed in a servohydraulic test system consisting of an MTS 858 Bionix test system and Test Resources 235-2S-L Series Controller.<sup>i</sup> This servohydraulic testing system is capable of 5000 Newtons (N) of load. The specimens were placed with the ventral spine facing the ceiling, and the load was applied to the ventral aspect of the atlantoaxial joint. The inner supports on the ventral side were spaced at 63mm, and the outer supports on the dorsal side were spaced at 130mm. This created a four-point bending scheme (Figure 2.5). The order of testing was completely random and was independent of testing group.

Once the specimen was securely placed the machine, the inner supports were lowered to the level of the pots without registering any force (zero Newtons). Force was then applied at a

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<sup>g</sup> Play-Doh®, Hasbro®, Pawtucket, RI

<sup>h</sup> 858 Bionix Test System, MTS®, Eden Prairie, MN

<sup>i</sup> Test Resources 235-2S-L Series Controller, Test Resources Inc., Shakopee, MN

<sup>j</sup> MTL-Windows Software (MTL7-1.001), Test Resources Inc, Shakopee, MN

speed of 5mm/min and data was captured at a speed of 100Hz using MTL-Windows software (MTL-1.001).<sup>j</sup> Specimens were loaded to failure. Failure was defined as increased displacement without increased load. Testing was discontinued when the implant had visible or audible breakage, when the pots contacted the machine and displacement was limited, or when the applied force reached a machine maximum of 5000 N. Data for load and displacement were generated and analyzed.

#### **Part 4: Data Analysis**

Data points were collected and graphed to create a load/displacement curve for each specimen tested. The generated load/displacement curves for many specimens contained an initial slope which became suddenly very steep as the servohydraulic unit reached the maximum 5000 N of load. The initial slope of the curve was calculated based on the first 2.5 mm of displacement. The final portion of the curve was not representative of the implant, rather it was an evaluation of the extreme limits of the atlantoaxial joint as it was tested beyond physiologic loads. A final slope was calculated based on subjective evaluation of the linear region near the end of the slope. However, this data was not analyzed since it was not representative of the stiffness of the implant. The initial slope for each specimen was recorded and the mean and median for each Group (K, V, I, M) was generated.

Statistical analysis was performed using statistical software.<sup>k</sup> Linear models on the logarithmic scale were used. The mean, median, and geometric least squares mean were generated and analyzed using the GLIMMIX procedure. Two-way ANOVA models were used to compare implant type (Group K vs. Group V) and bone maturity (Group I and Group M).

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<sup>k</sup>SAS version 9.3, SAS®, Cary, NC

## Chapter 3: Results

Seventeen canine spines were collected, stabilized, and analyzed biomechanically. Load-displacement curves were generated. Load-displacement curves have a typical curve shape (Figure 1.7). The load-displacement curves generated in this study initially followed a typical curve shape in which the slope gradually increased to an increasing linear portion, followed by a sudden small drop of the curve where the implant began to fail. After this point, the physiologic limit of the atlantoaxial joint was reached as it became completely engaged and locked. The hydraulic loading machine would reach maximum N force (5000) with no change or minimal change in displacement. This would result in a very steep curve at the end of the study (Figure 3.1). The influence of creep was minimized by selecting the initial linear slope of the line once the implant was engaged and the load increased over the baseline load. The line was discontinued when the load increased substantially without any increase in displacement, or when there was a small drop in load correlating to implant failure. This occurred when a portion of the pot engaged the inner or outer supports, or when the physiologic limit of the atlantoaxial joint was reached, and the implant was no longer engaged.

The median initial slope (stiffness) in for Group K was 101.422 N/mm. The median stiffness in Group V was 135.272 N/mm. (Table 3.1) A 2-way ANOVA comparison of the least squares means between Group K and Group V found this difference to be statistically significant ( $p = 0.0129$ ). (Table – 3.2) (Figure 3.2 and Figure 3.3)

The median stiffness of Group I was 126.748 N/mm. The median stiffness of Group M was 140.613 N/mm. A 2-way ANOVA comparison of the least squares means between Group I

and Group M was not statistically significant ( $p = 0.6292$ ). (Table 3.2) (Figure 3.4 and Figure 3.5)

When both implant type and maturity level are considered together in a full 2-way ANOVA, there is no significant difference in stiffness ( $p = 0.5923$ ). (Table 3.3)

We can further isolate why no difference was found when both implant type and maturity level are considered using a simple effect comparison of least squares means and a Holm-Tukey adjustment for multiple comparisons. (Table 3.4 and Table 3.5). There is a significant difference between Group K and Group V within the Group I ( $p = 0.038$ ), but there is no significant difference between implant type within the Group M. When Group I and Group M were compared within Group K and Group V, there was no significant difference.

Of the 8 specimens stabilized with the Kishigami tension band, all 8 exhibited failure. As load was increased, the orthopedic wire through the eyelet of the Kishigami tension would straighten, resulting in loosening of the implant at the wire-implant interface. Two specimens also had the Kishigami tension band slide off the dorsal arch of C1, however this occurred after significant wire loosening, allowing a subjectively increased range of motion for the Kishigami tension band compared to directly after application.

The pin and PMMA construct failed in two ways; fracture of the PMMA and separation of the PMMA from the cortical bone. Fracture of the PMMA occurred in 3/9 of the specimens, and separation of the PMMA from the cortical bone occurred in one specimen. One of the specimens with fracture of the PMMA also had visible pin bending at the bone-implant interface after testing.

## Chapter 4: Discussion

The ventral pins and PMMA construct was found to be significantly stiffer in bending than the Kishigami tension band. Also, no significant difference in stiffness was noted between immature and mature bone regardless of implant type. When all factors are considered, implant type and bone maturity, there is no significant difference between the stiffness in any of the groups.

Basic biomechanical principles imply that when a bone is placed in bending load, the fracture will occur on the tension side rather than the compression side, because bone's compressive strength is greater than its tensile strength.<sup>37</sup> In addition, the tension band principle states that active distracting forces are counteracted and converted into compressive forces.<sup>44</sup> Thus, placement of an implant on the tension side of a long bone leads to compressive forces on the bone.<sup>44</sup> This may help compress the long bone fracture, providing a more rigid internal fixation and resist bending.<sup>44</sup> The Kishigami tension band is placed on the tension side of the atlantoaxial joint when bending in the ventral direction. The ventral pins and PMMA construct is placed on the compression side. Although this biomedical principle applies to fractures, it would theoretically suggest that the Kishigami tension band is better at neutralizing tension force than the ventral pins and PMMA construct based on the placement of the implant dorsally.

The lack of significant difference in stiffness between stabilized mature and immature bone in this study was unexpected. It was hypothesized that stabilized mature spines would have increased stiffness when compared to immature spines due to differences in bone strength. Some of the immature cadavers were medium to large breed dogs (Boxer, German Shepherd Dog) that

fit within the weight specifications of this study, which may have resulted in some bias since these specimens had larger bone structure, despite the immaturity.

A previous study evaluating the Kishigami atlantoaxial tension band identified fracture or a defect over the dorsal arch where the implant was placed as a potential problem.<sup>17</sup> The major point of failure in this study was the wire-implant interface. In the current study, the orthopedic wire would eventually straighten and pull out of the Kishigami tension band in all of the specimens as the load was increased.

The lack of evidence of fracture of the dorsal arch of C1 may be due to the size of the specimens included in this study. The dog in VanEe's study evaluating failure of the Kishigami tension band was a Yorkshire terrier weighing 1.4kg, whereas the mean weight of cadavers in this study was 10.3kg. The smallest cadaver was a Pomeranian weighing 5.4kg. The point of failure in this specimen was fatigue of the wire where it contacted the Kishigami tension band.

The methods of failure in this study were either fracture of the PMMA or separation of the PMMA from the cortical bone on the vertebral body of the axis. The most common methods of failure of a PMMA/pin construct in the literature are pin migration, pin loosening, and pin pull-out.<sup>43</sup> These methods of failure may be more likely to occur with cyclic loading rather than loading to failure. We did not evaluate cyclic loading in this study.

After continued load application, 3/9 Group V specimens and 1/8 Group K specimens had no evidence of failure up to 5000 N of load. The specimen in Group K had to be re-potted due to a lack of adequate space around the atlantoaxial joint for testing. Testing of this specimen resulted in contact between the pot and the servohydraulic loading machine. All of the specimens tested eventually reached maximum load (5000 N) due to compression of the atlantoaxial facets

and increased contact and axial loading of the vertebral bodies. This was considered the physiologic limit for the atlantoaxial joint. For most specimens, this occurred after failure of the implant. The terminal portion of the load/displacement curve had a steep linear portion, which was not analyzed in order to prevent the data from being skewed. This steep linear portion occurred as the physiologic limit of the atlantoaxial joint was reached.

Stiffness refers to the rate of deformation a material undergoes when a load is applied. An increased stiffness is beneficial when discussing implants because it can correlate to toughness, or area under the load/displacement curve. The stiffer the implant; the more rigid the fixation. The atlantoaxial joint is unique because of the increased range of motion in that segment. The goals of surgical management in cases of atlantoaxial subluxation are to reduce the luxation and decompress the spinal cord.<sup>4</sup> Successful correction of atlantoaxial subluxation does not necessarily require rigid fixation. Some surgeons will approach the atlantoaxial joint ventrally and apply autogenous bone graft or scarify the cartilage between C1 and C2 with a goal to achieve rigid fixation.<sup>29</sup> Even with this strategy, only 3/12 achieved rigid fixation in the study by Sorjonen and Shires. The control cases in that study had compromised dorsal atlantoaxial ligaments, and only one control case showed neurologic signs aside from pain after this procedure. Atlantoaxial subluxation and subsequent compression of the cranial cervical spinal cord results in clinical signs. This brings the question as to whether rigid fixation is necessarily better when dealing with the atlantoaxial joint. Many of the dorsal approach procedures do not aim for rigid fixation, but rather prevent subluxation while a fibrous scar is formed around the joint. The same is true for conservative management of atlantoaxial subluxation. Rigid fixation may also theoretically result in excessive loading at adjacent segments, increasing the chances of adjacent segment disease.<sup>43</sup>

It may be tempting to evaluate the angle of displacement of the atlantoaxial joint at failure of the implant to attempt to make some clinical correlation. It is difficult to make any clinical correlations from the information obtained in this study, since indications for surgery of the atlantoaxial joint are based on clinical signs attributable to spinal cord compression. The maximum joint angle without causing spinal cord compression has not been evaluated in dogs. Therefore, determining the angle of displacement in this study would offer no additional clinical information because there would be no point of reference.

There are a set of inherent limitations involved in a study using cadavers and bony specimens. The muscle and other structures surrounding the spinal column provide a substantial amount of stability in an intact specimen, and removal of those structures for testing *in vitro* may not mimic the specimen *in vivo*.<sup>37</sup> Soft tissue structures are also prone to desiccation during storage and testing, which may affect their biomechanical properties.<sup>37</sup> The specimens in this study were kept moist during testing using saline solution and paper towels. The small sample size in this study is also a potential limitation.

The dogs included in this study had normal anatomy and the ligamentous structures (transverse ligament and occipitoatlantoaxial ligament) were left intact. These specimens had normal odontoid structure and normal bone density. Small or toy breed dogs with abnormal odontoid process structure and/or abnormal ligamentous structures make up a substantial portion of the population of dogs that develop atlantoaxial subluxation clinically.<sup>1, 3, 4, 20, 25</sup> The atlantoaxial joint is capable of a wide range of motions. This study only evaluated the specimens bending in the ventral direction, which is not necessarily representative of atlantoaxial movement *in vivo*. Additional forces placed on the implants including lateral bending, torsion, and shear forces may have mimicked the atlantoaxial segment *in vivo*. Cyclic loading will provide

information about fatigue failure. Fracture and luxation implants *in vivo* often fail secondary to fatigue failure rather than load failure.<sup>37</sup>

## Chapter 5: Future Directions

Further analysis regarding the biomechanics of the atlantoaxial spine in dogs is indicated. The cervical spine, and especially the atlantoaxial joint, is subjected to many other forces besides bending during everyday movement. Bending in ventroflexion was chosen specifically due to the increased risk of damage to the cranial cervical spinal cord in that movement when an intact odontoid process is present. Evaluation of the stabilized atlantoaxial spine in lateral bending, torsion, and shear forces would provide more information regarding implant performance during movement *in vivo*.

It would also be interesting to evaluate the two implant types used here in abnormal dogs. The presence of an intact transverse ligament and normal odontoid process in the dogs used in this study may not be applicable to the population of dogs that typically develop atlantoaxial subluxation. Since the transverse ligament and odontoid process were intact in the specimens in this study, we are unsure what role they play in adding to the perceived stiffness of the implants.

It is difficult to draw any clinical conclusions from this study for many reasons. One reason is that the maximum allowable angle of deformation of the atlantoaxial joint prior to the development of clinical signs due to spinal cord compression is not known in dogs. While we were able to evaluate the stiffness of the implants, it was difficult to determine whether the amount of implant failure seen with increased load application would have resulted in a relapse of atlantoaxial subluxation, and therefore, clinical signs. A study is needed to identify the maximum allowable angle of deformation of the atlantoaxial joint prior to the development of clinical signs.

To help with clinical application, a study evaluating the use of both implant types in clinical cases of atlantoaxial subluxation would also be indicated. The goal of the ventral fixation with pins and PMMA is to rigidly stabilize the atlantoaxial joint, whereas the Kishigami tension band allows for some lateral and rotational movement, but aims to prevent ventral bending. A prospective clinical case study with a large number of dogs, long-term follow-up and, ideally, histopathological information after death would be needed to obtain more information about these two implant types *in vivo*.

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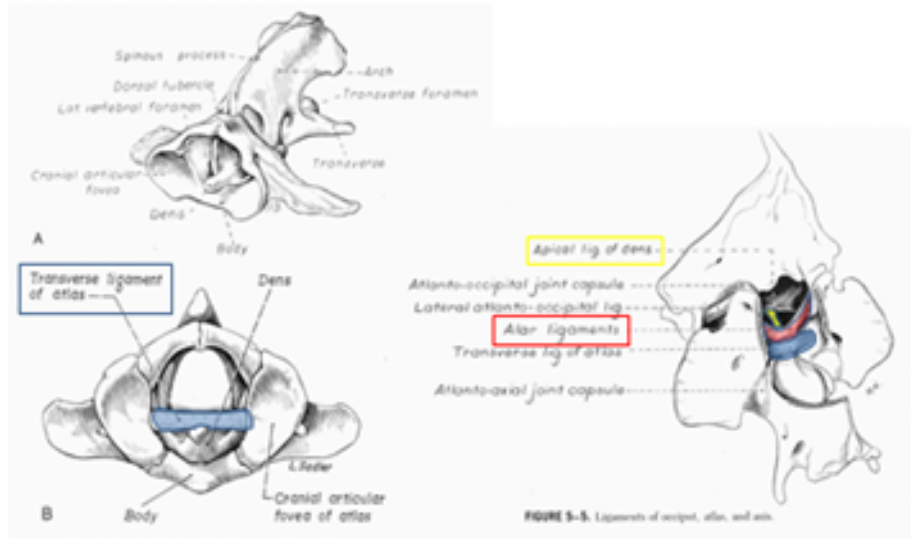
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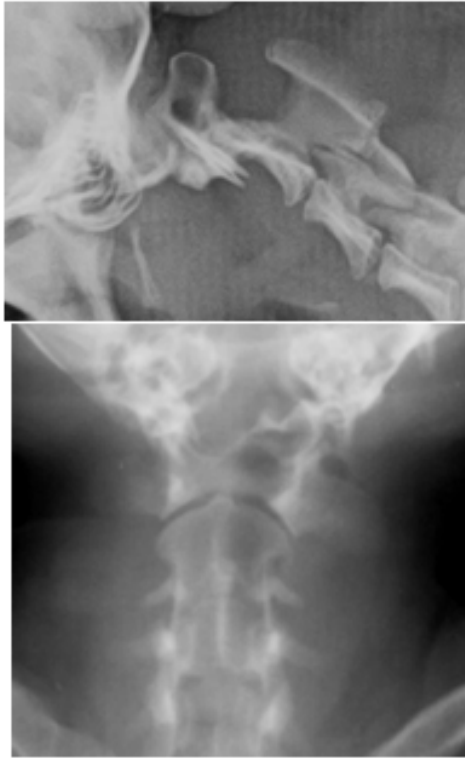
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# Figures



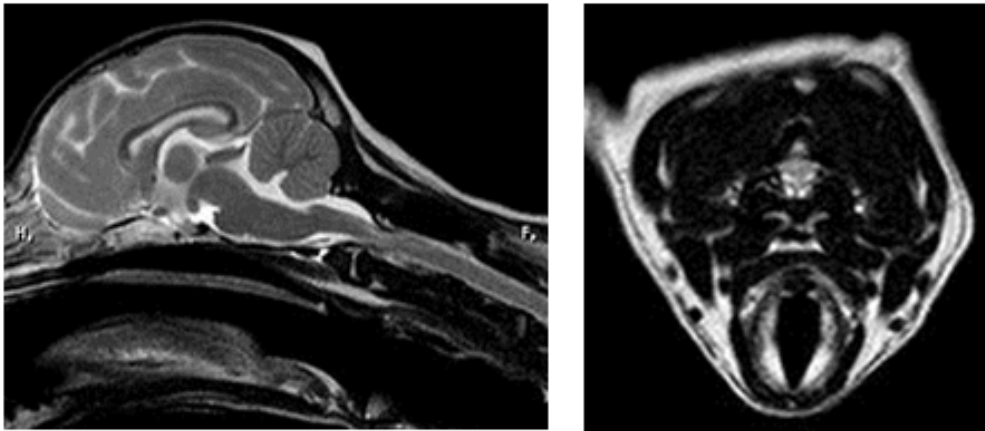
**Figure 1.1: Anatomy of the Atlantoaxial Joint.**  
From Evans HE. 1993

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**Figure 1.2: Survey Radiographs of Atlantoaxial Subluxation (A) and Odontoid Aplasia (B)**

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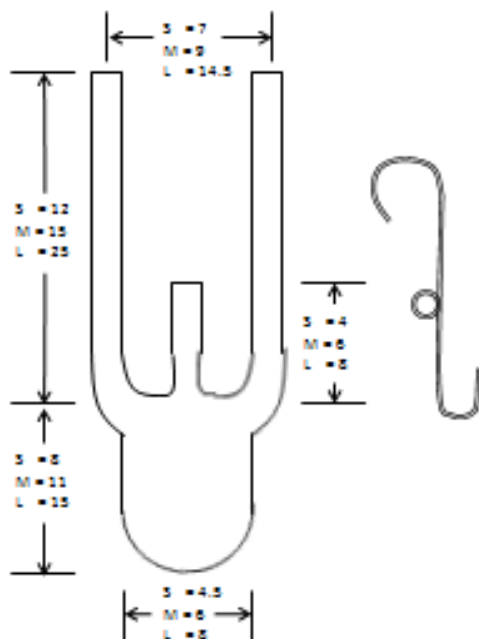
**Figure 1.3: MRI of atlantoaxial subluxation**  
Dorsal and ventral spinal cord compression noted at C1-2.  
Intraparenchymal T2 hyperintensity at C1-2.

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**Figure 1.4: External Coaptation for Conservative Management of Atlantoaxial Subluxation.**

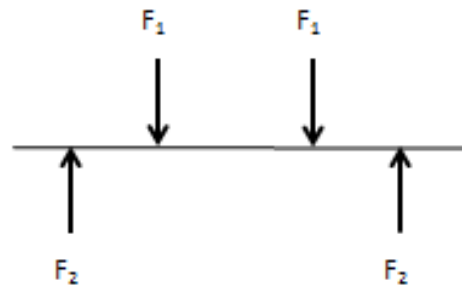
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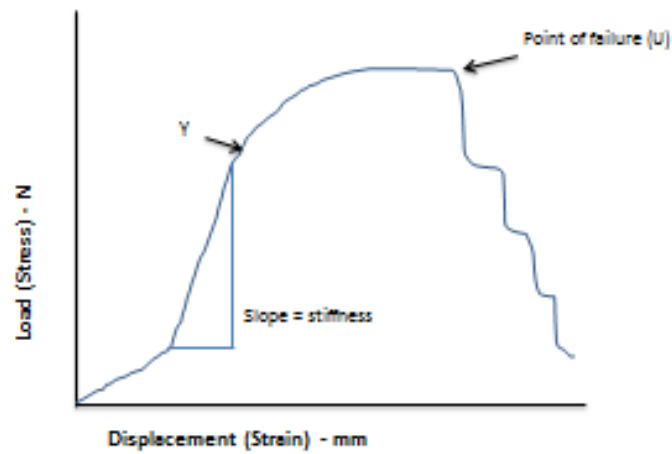
**Figure 1.5: Design of Original Kishigami Tension Band**

Numbers correspond to millimeters.  
Adapted from Kishigami, 1984

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**Figure 1.6: Four Point Bending**  
 Two equal loads applied at each end and two additional loads applied between them from the opposite direction.  
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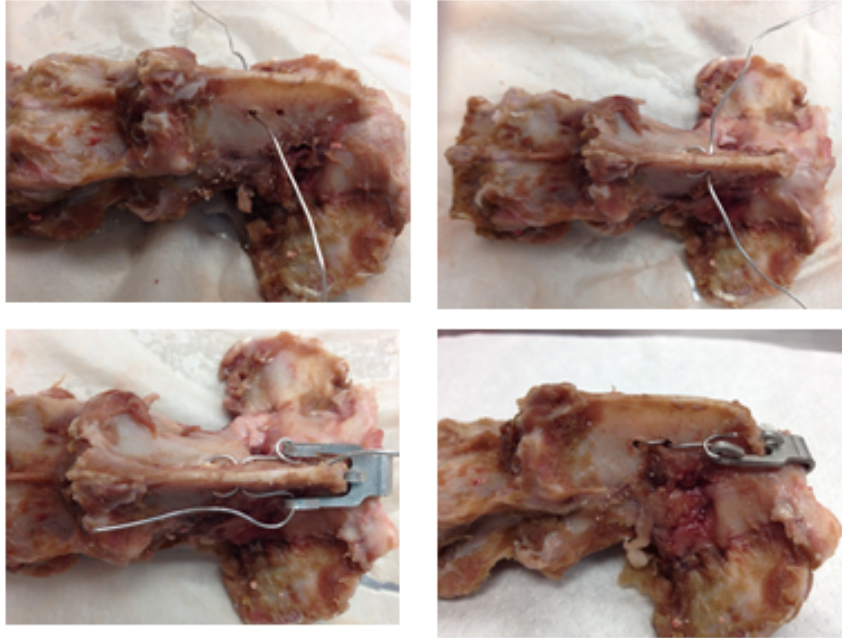
**Figure 1.7: Load/Displacement Curve**  
 Point Y represents the yield point  
 Point U represents the point of failure  
 Page 24, 32



**Figure 2.1: Immature Specimen**

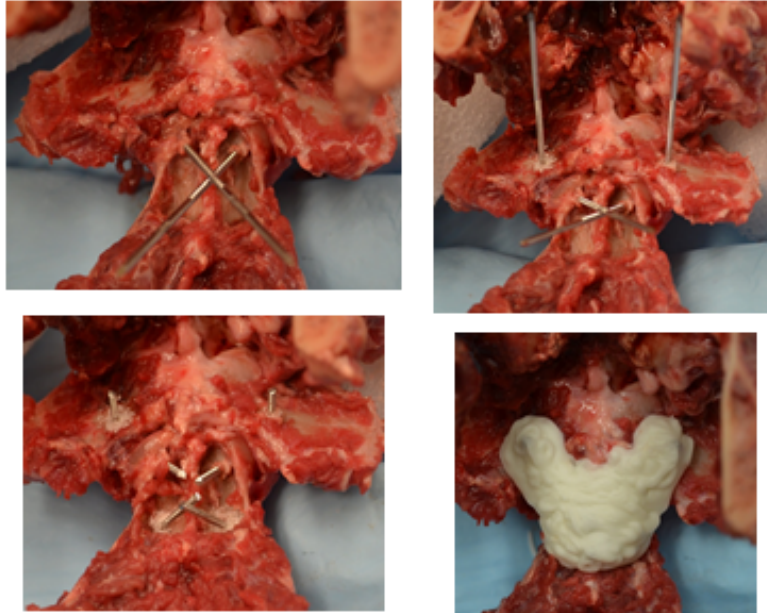
Radiograph of an immature specimen demonstrating open physes in the vertebral body, and incomplete ossification of the spinous process of C2.

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**Figure 2.2: Application of the Kishigami Tension Band**

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**Figure 2.3: Application of Pins and PMMA ventrally at the atlantoaxial joint.**

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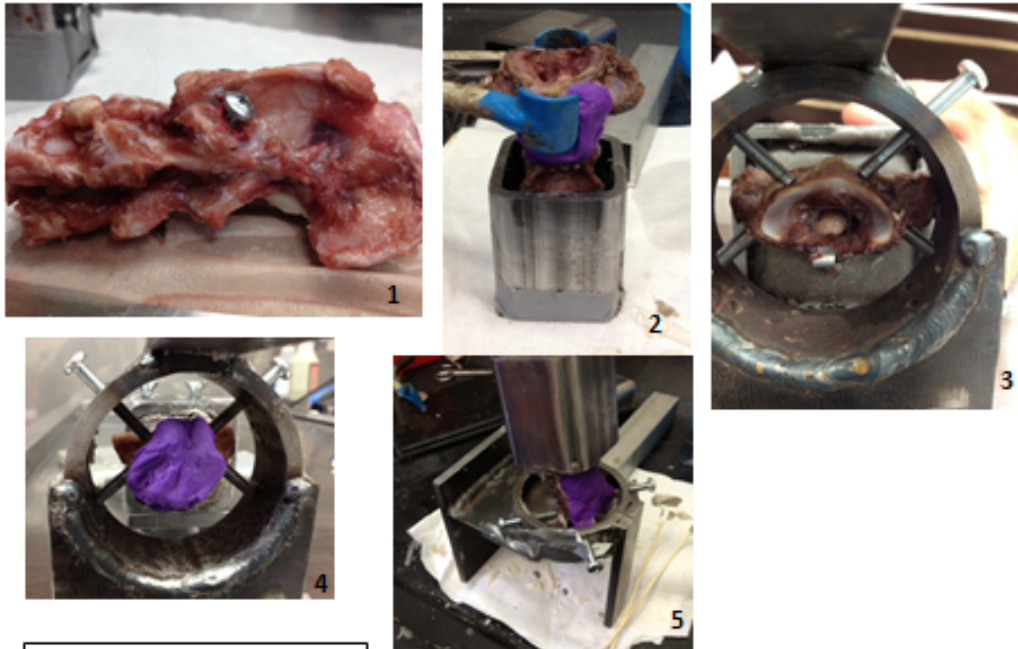


Figure 2.4: Potting procedure for biomechanical testing

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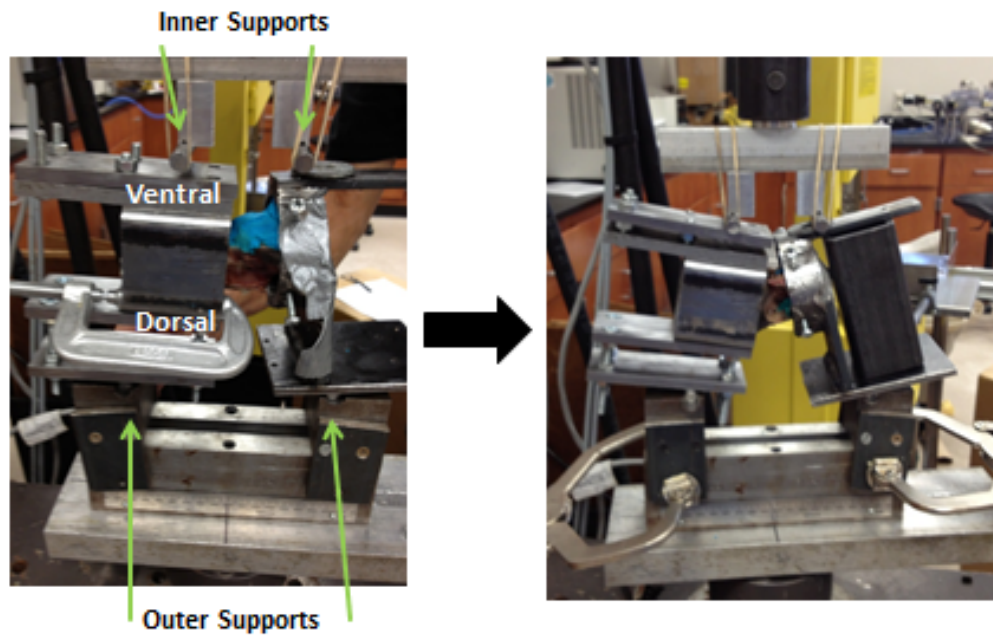


Figure 2.5: Biomechanical Analysis  
An example of a specimen being analyzed in four-point bending.

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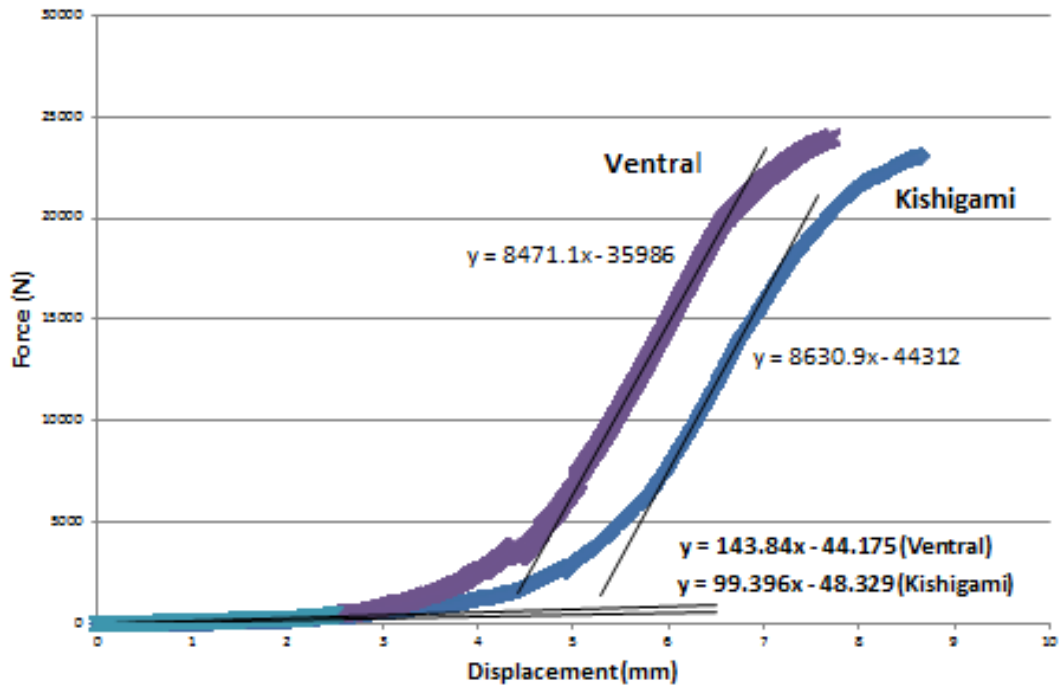


Figure 3.1: Generated Load/Displacement Curve of Ventral Implants and Kishigami Tension Band

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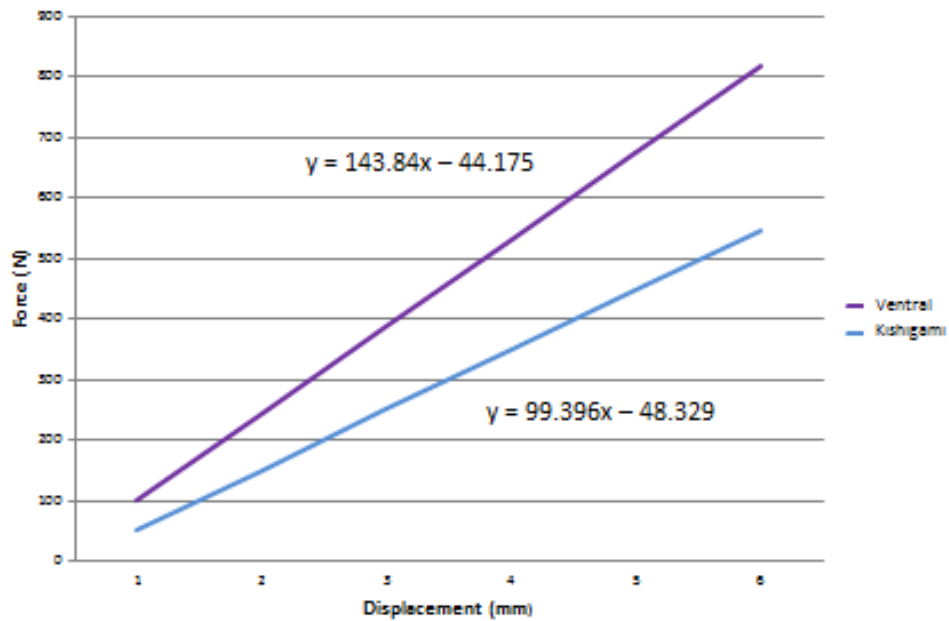


Figure 3.2: Initial Slope of Load/Displacement curve for Group K vs. Group V

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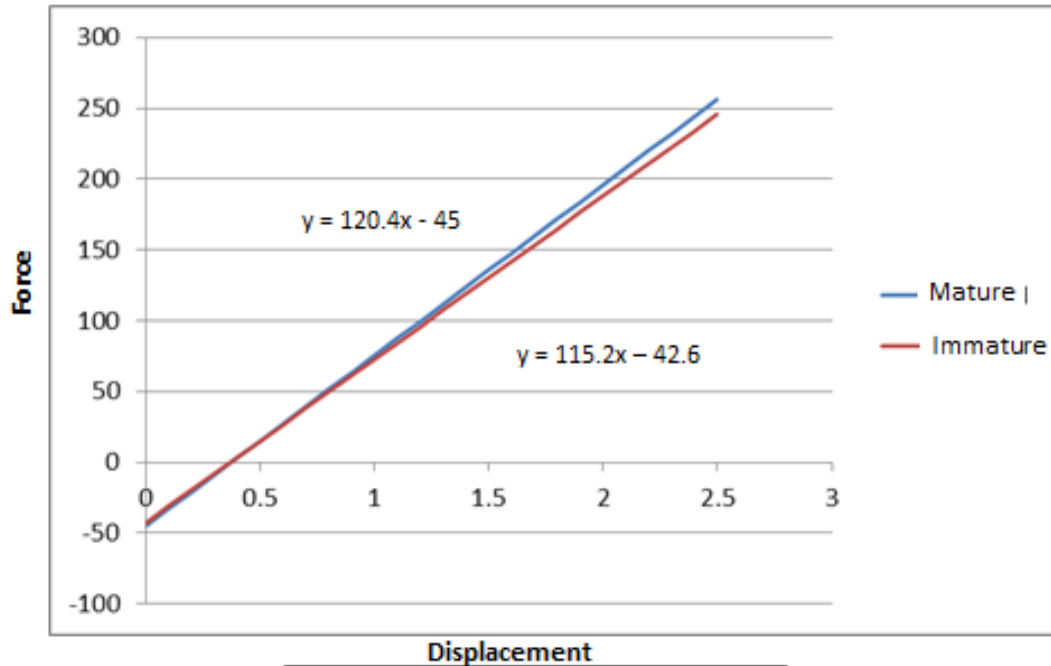
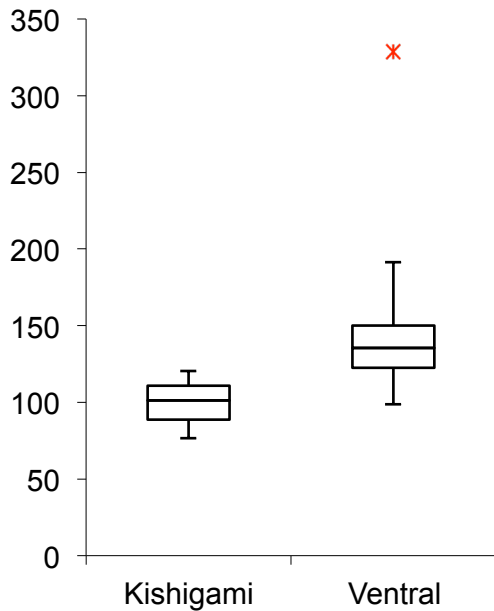


Figure 3.4: Initial Slope of Load/Displacement curve for Group I vs. Group M

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\* Min

Figure 3.3: Box Plot of Stiffness for Group K and Group V

\* = outlier

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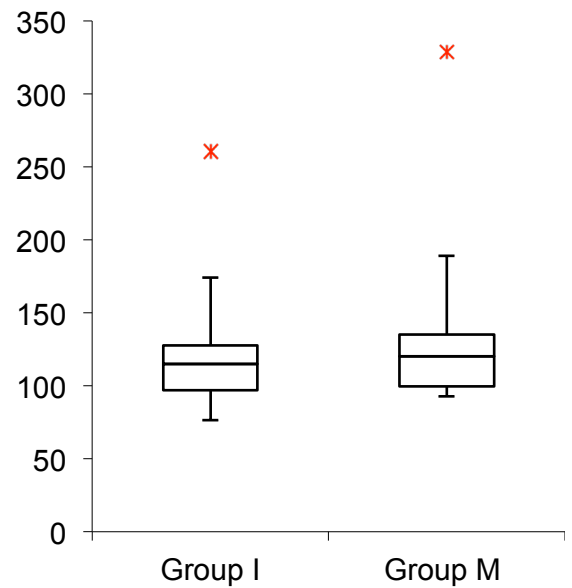


Figure 3.5: Box Plot of Stiffness for Group I and Group M

\* = outlier

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## Tables

| Table 2.1: Number of Specimens per Group |                            |                     | Page 27 |
|--|----------------------------|---------------------|---------|
| Skeletal Maturity                        | Method of Stabilization    | Number of specimens | Group   |
| Mature (M)                               | Kishigami tension band (K) | 4                   | KM      |
| Mature (M)                               | Ventral pins and PMMA (V)  | 4                   | VM      |
| Immature (I)                             | Kishigami tension band (K) | 4                   | KI      |
| Immature (I)                             | Ventral pins and PMMA (V)  | 5                   | VI      |

| Table 3.1: Descriptive Statistics for Groups |             |        |        |                    | Page 32 |
|--|-------------|--------|--------|--------------------|---------|
| Group  | Sample Size | Mean   | Median | Standard Deviation |         |
| K  | 8           | 99.32  | 101.42 | 16.43              |         |
| V  | 9           | 164.99 | 135.27 | 76.78              |         |
| M  | 9           | 140.61 | 120.40 | 72.85              |         |
| I  | 8           | 126.75 | 115.17 | 58.61              |         |

| Table 3.2: Differences of Group Least Squares Means |       |          |                |    |         |               | Page 32, 33 |
|---|-------|----------|----------------|----|---------|---------------|-------------|
| Group   | Group | Estimate | Standard Error | DF | t Value | Pr >  t       | Alpha       |
| K   | V     | -0.4397  | 0.1543         | 14 | -2.85   | <i>0.0129</i> | 0.05        |
| I   | M     | -0.07382 | 0.1543         | 14 | -0.48   | <i>0.6398</i> | 0.05        |

| Table 3.3: Type III Tests of Fixed Effects |        |        |         |               | Page 33 |
|--|--------|--------|---------|---------------|---------|
| Effect                                     | Num DF | Den DF | F Value | Pr > F        |         |
| Implant                                    | 1      | 13     | 7.85    | <i>0.0150</i> |         |
| MI Group                                   | 1      | 13     | 0.24    | <i>0.6292</i> |         |
| Implant*MI Group                           | 1      | 13     | 0.30    | <i>0.5923</i> |         |

| Table 3.4: Simple Effect Comparisons Implant*MI Group Least Squares Means by MI Group Adjustment for Multiple Comparisons: Holm-Tukey |         |         |         |               |       | Page 33 |
|---|---------|---------|---------|---------------|-------|---------|
| Simple Effect Level   | Implant | Implant | Pr >  t | Adj P         | Alpha |         |
| MI Group I  | K       | V       | 0.0380  | <i>0.0380</i> | 0.05  |         |
| MI Group M  | K       | V       | 0.1256  | <i>0.1256</i> | 0.05  |         |

Table 3.5: Simple Effect Comparisons Implant\*MI Group Least Squares Means by Implant  
 Adjustment for Multiple Comparisons: Holm-Tukey Page 33

| Simple Effect Level | MI Group | MI Group | Pr >  t | Adj P         | Alpha |
|---------------------|----------|----------|---------|---------------|-------|
| Implant K           | I        | M        | 0.4848  | <i>0.4848</i> | 0.05  |
| Implant V           | I        | M        | 0.9690  | <i>0.9690</i> | 0.05  |