CANINE MANDIBULAR OSTEOTOMY MODEL: THE EFFECTS OF FIXATION ON BONE HEALING AND NERVE REGENERATION

by

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(ABSTRACT)

Osteotomies made between premolar 3 and premolar 4 in the body of the mandible in canine cadaver hemimandibles (n = 48) were stabilized with five interdental fixation apparatuses in a preliminary biomechanical study. Testing in bending determined ultimate strength, stiffness, and yield strength of the interdental fixation apparatuses. Erich arch bar supplemented with acrylic had significantly (P < 0.05) greater ultimate strength, stiffness, and yield strength than Stout loop supplemented with acrylic, Acrylic, Stout loop, and Erich arch bar alone. Due to the combined superior biomechanical strength of Erich arch bar supplemented with acrylic, it was utilized as the interdental fixation apparatus for the in vivo study.

Bilateral osteotomies made between premolar 3 and premolar 4 in the body of the mandible were stabilized with monocortical bone plate (n = 6), interdental (n = 6), and external skeletal fixation (n = 6). None of the dogs showed clinical evidence of pain or discomfort associated with the fixation devices or the development of neuromas. Radiographic signs of bone healing were observed at all osteotomy sites by 16 weeks. Histologic evaluation of bone healing of the mandible with monocortical bone plate, interdental fixation, and external skeletal fixator was not significantly different (P > 0.05) at 8 and 16 weeks postoperatively.

The inferior alveolar nerves were evaluated electrophysiologically pre-operatively and at 4, 8, and 16 weeks postoperatively. Nerves were histologically evaluated at 4, 8, and 16 weeks after injury. Nerve function disappeared immediately postoperatively and returned in 64% (24 of 36) by
4 weeks, in 78% (28 of 36) by 8 weeks, and 83% (30 of 36) by 16 weeks. Neuromas developed in 100% (36 of 36) of the nerves.

Using a transverse osteotomy model, results indicate that the type of bone and nerve healing does not significantly differ between fixation groups tested. Therefore, a simpler and more economical fixation device, Erich arch bar-acrylic, should be suitable to repair selected mandibular fractures in the dog.
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Learning to do,
Doing to learn,
Earning to live,
Living to serve.

FFA motto
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LITERATURE REVIEW

Purpose

The purpose of this project was twofold: first to identify the best method of interdental fixation for mandibular fracture repair in the canine using in vitro stability and strength testing, and second to compare this method with other established methods in vivo with regard to clinical return to function, radiographic and histologic appearance of bone healing, and effects on regeneration of the inferior alveolar nerve.

Significance

Mandibular fractures are common in dogs. In many instances, traditional stabilization techniques are undesirable. Anecdotal reports suggest that interdental fixation is a viable alternative, but no systematic approach has been designed to evaluate 1) relative strengths of different methods of interdental fixation and 2) how well these compare to other, more accepted techniques. In addition, the effects of mandibular fracture on the neurologic structure in the area have been virtually ignored in veterinary medicine.

Determination of optimal interdental fixation techniques via in vitro biomechanical testing

Based on anecdotal evidence of success, availability of materials, and ease of application, the most clinically applicable apparatuses were chosen and developed for testing. Stainless steel wire, stainless steel arch bar, and poly(methyl)methacrylate (acrylic) were used for the interdental fixation apparatuses. Although the biomechanical strength of an apparatus in vitro may not fully characterize its in vivo strength, biomechanical testing remains an important process in the development and acceptance of a new fixation method.
Biomechanics, a sub-specialty of mechanical engineering, evaluates the effects of forces on biological systems and those materials which are used to augment biological structures.\(^1\) The strength and stiffness of a material, when subjected to standardized external forces, characterizes that material and provides information on its use and applications.\(^2\) An understanding of strength and stiffness relative to a biological system requires a basic knowledge of the forces acting on a structure.

By convention, force is anything that causes the acceleration of matter. External forces that act upon a structure are considered loads, while forces from within a structure are termed stresses.\(^1\) Stresses are forces generated in the substance of a material in response to loads and may be subdivided into three types, tension, compression, and shear. The deformation created in an object when a load is placed upon it is termed strain.\(^1\) Strain may be obvious (i.e. the bending of a wire) or hidden (i.e. the strain produced by standing on a metal plate).\(^1\) Strain can also be subdivided into three types, tension, compression, and shear. Therefore, stresses refer to the resistance of a substance to deformation, whereas strain is the actual deformation of a substance subjected to an external force.

Young's modulus, a measure of the stiffness of a material, is the relationship of stress divided by the elastic strain caused by a load on a structure.\(^1\) Stiffness is derived from a stress/strain curve by determining the slope of the elastic phase.\(^1\) Materials with steeper slopes are considered to be more stiff. The elastic phase is the phase in which the material returns to its original shape and size after being deformed. Stiffness and strength of a material are not equal. Chalk and steel are both stiff but are weak and strong respectively.\(^1\) When enough force is placed upon a structure to cause it to be irreversibly deformed, the elastic limit has been reached and exceeded.\(^1\) The point at which irreversible deformation begins is termed the yield point (or yield strength).\(^1\) As the stress/strain graph reaches a plateau, the ultimate strength is
reached.\textsuperscript{1}(Fig 1) This is the point at which material failure and gross deformation occur. A rapid drop in the plot is the end of the plastic phase where catastrophic failure occurs.

To determine the ultimate strength, stiffness, and yield strength of different interdental fixation apparatuses, an accurate model was needed. Wooden dowels are commonly used as the model for biomechanical testing of fixation devices of the long bones since both are "grained" materials and have similar geometric shapes.\textsuperscript{1} This was considered unacceptable since it did not accurately reflect the mandible's unique dental arcade architecture and the innate structure of the tooth. Instead, mandible specimens from cadavers were used.

Since the biomechanical properties of bone change as its hydration status changes, it was recognized that the model had limitations.\textsuperscript{3,4} Wet bone, which simulates \textit{in vivo} strength, is much less resilient than dry bone.\textsuperscript{1} However, all mandibles in this project were intended primarily as an anchor for the fixation apparatus. The bone itself was not being tested. Furthermore, since all mandibles were harvested and stored under identical conditions, differences between groups should accurately reflect fixation strength differences. Changes secondary to autolysis were not considered biomechanically significant at the low storage temperatures and within the short time frame of the study.\textsuperscript{5}

Poly(methyl)methacrylate is a commonly chosen material for interdental fixation apparatuses due to its excellent handling and strength characteristics.\textsuperscript{6} The monomer of poly(methyl)methacrylate is a liquid at room temperature and must be polymerized to form the final solid product.\textsuperscript{2} Formation of a thermoplastic polymer, such as poly(methyl)methacrylate, requires the presence of the monomer (liquid), the polymer (powder), and a free radical. The dry component of the polymer mixture is micronized spherical polymer (10 to 30 \(\mu\text{m}\)) powder. The liquid is methyl methacrylate monomer with an initiator and one or more stabilizers.\textsuperscript{2} Once initiated, the polymerization process is a spontaneous chemical reaction involving chain initiation,
chain propagation, and chain termination.\textsuperscript{2,7,8} Polymerization will continue until a feedback mechanism occurs such as an interaction with another free radical.\textsuperscript{2}

Poly(methyl)methacrylate cures with minimal volume change, shrinking about 0.5 - 1.0 volume percent, then gradually expanding by 1-2 volume percent over the first 30 days due to water and lipid absorption.\textsuperscript{2,8} Cement thickness of less than 5 mm will not exceed a temperature of 39 - 42 °C. Higher temperatures detected with its use may be dependent on thermocouple placement.\textsuperscript{2,9,10} Tissue necrosis secondary to the application of poly(methyl)methacrylate to dental structures has not been documented.

The polymerization process of the thermoplastics has three distinct phases: dough time, working time, and setting time.\textsuperscript{2} The dough time occurs approximately 3 minutes after the initial mixing of the components and has a malleable or 'plastic' quality. The setting time is generally 10 minutes in duration and is associated with a temperature rise due to the chemical energy released during the polymerization process.\textsuperscript{2} The working time is the difference between the dough and setting time, generally around 6 minutes in length. The working time can be extended with the use of syringes.

Although poly(methyl)methacrylate can be modified, it will not readily adhere to itself. If an attempt is made to modify the poly(methyl)methacrylate it must be clear of all debris, including blood.\textsuperscript{2} Development of sensitivity to the monomer of poly(methyl)methacrylate has been documented in humans\textsuperscript{11-13} presumably due to a contact reaction with methylmethacrylate. The coloring agents added to poly(methyl)methacrylate may become a source of local tissue response as well.\textsuperscript{2} Testing the materials in cell cultures prior to manufacturing and distribution helps minimize these problems clinically.\textsuperscript{2} While similar reactions have not been documented in dogs, increased use of poly(methyl)methacrylate in this species may uncover more idiosyncratic reactions.

The strength of thermoplastics can be increased substantially by means of reinforcement.\textsuperscript{14-16} Reinforced acrylic composites most commonly consist of a thermoplastic and a
filler, usually either fiber or particles of glass spheres. Compression forces can be overcome by reinforcing with metal wires. In general, the thermoplastic material transmits the load to the reinforcement material.

Application of prolonged pressure, applied to the tooth, can cause tooth movement. Remodeling and recontouring of the bony alveolus is a constant process in response to the normal forces placed on the structures. It is possible to cause tooth movement with the application of Erich arch bar alone. Since a relatively large sector of the dental arcade is encompassed by the poly(methyl) methacrylate in the interdental fixation apparatus these forces should be neutralized.

Comparison of in vivo fixation techniques

Bone healing following disruption of the continuity of its structure, is quite different than the phenomena of bone deposition-resorption that maintains the bony skeleton. As bone heals, a gradual increase in stiffness and strength occurs due to the maturation of the callus that forms at the fracture site. If the fracture site is not stabilized by any form of fixation or coaptation, the body will produce tissue of adequate elasticity to allow mechanical movement (i.e. fibrous connective tissue), which will gradually become more rigid over time. The spectrum of healing can range from a relatively short process of direct bony union to complete non-union. Non-union, although poorly defined with regard to time, reflects failure to bridge the fracture gap with osteoid after a few months. The type of healing depends primarily on the degree of stability offered by the fixation.

Bone healing is classified into stages to clarify the process of healing. The stages of healing actually overlap. The first stage of healing is induction; and is the least differentiated of the stages. It occurs from the time of trauma to the end of the inflammatory period. The microenvironmental changes in pH, enzyme release, and the presence of bone morphogenic protein are thought to induce the formation of bone. The initial tissue present at the fracture site is the
hematoma.\textsuperscript{19,20,22} The exact role of the hematoma in fracture healing remains controversial.\textsuperscript{19,21} The hematoma may function as a source of leukocytes that transform into fibroblasts and osteoblasts. However, removal of the hematoma during rigid internal fixation has no negative effect on fracture healing.\textsuperscript{19,21} Fracture stabilization begins as the hematoma develops into granulation tissue during the first few days following trauma. Its elastic nature allows it to double its length before failure.\textsuperscript{19}

The granulation tissue quickly changes in the next few days to fibrous tissue. This stage of soft callus is similar to the fibroblastic phase of soft tissue healing.\textsuperscript{21} The presence of maturing collagen fibers increases the stiffness of the fracture area, allowing only about 10% elongation prior to failure.\textsuperscript{19} Osteogenic cells from the periosteum, endosteum and surrounding tissues proliferate at this stage and endosteal and periosteal callus formation begins if movement occurs at the fracture site.\textsuperscript{21,22} Mucopolysaccharide and collagen production peak in about one week, while calcium uptake by the tissues gradually increases and peaks at several weeks post-trauma.\textsuperscript{21}

The next stage, hard callus formation, is characterized by mineralization of cartilage and fibrous tissue.\textsuperscript{20,21} Islands of cartilage in healing fractures is variable, their presence depending upon rapidity of callus formation, movement of fracture site, and species.\textsuperscript{20,22,23} Cartilage in callus is replaced by a process similar to endochondral ossification in the fetus.\textsuperscript{24} The process of woven bone formation in cartilage involves the mineralization of the intercellular substance and the death of the chondrocytes. As cartilage cells mature, they become swollen and produce large amounts of alkaline phosphatase. Active transport of supersaturated solutions of mineral causes mineralization of intracellular substance, which is followed by death of chondrocytes.\textsuperscript{24} The spaces left by the dead chondrocytes are eventually taken over by the ingrowth of capillaries from the surrounding tissues. The quality of this bone is coarse-fibered and will ultimately be replaced by true lamellar (fine-fibered) bone.\textsuperscript{24,25} This process begins at the ends and progresses towards the center of the fracture, taking about 10 to 20 days for the development of coarse bone.\textsuperscript{19,26}
Mineralization occurs within the collagen fibers in fibrous tissue\textsuperscript{19,25}, which further increases the mechanical stiffness of the healing fracture. Radiographic visualization of hard callus is possible due to the mineralization of osteoid or cartilage, but not until about six weeks after the fracture.\textsuperscript{24} As the mineralized callus matures, the radiographic appearance of the callus becomes more uniform. In long bones this time period is associated with the re-establishment of endosteal and periosteal blood supply.\textsuperscript{21} Function to the bone returns in this phase.

The stage of remodeling is the longest and may take years to complete\textsuperscript{21} even though functional utility of the bone was restored in the stage of hard callus. The haversion systems are arranged parallel to lines of stress, excess bone is removed, and the ultimate shape of the bone is conformed to match functional usage.\textsuperscript{26} Non-lamellar bone is also referred to as coarse fibered or woven bone. Although the exact mechanism is unknown, immature animals have a much greater capacity to remodel bone than the adult. This effect is believed to be mediated through the epiphyseal plate\textsuperscript{24} and to be a function of the increased metabolic rate of the immature individual.\textsuperscript{27}

Bone healing may be further divided into primary (gap) healing and secondary (callus) healing.\textsuperscript{19,21,24,28-30} The most striking difference is the callus formation with secondary bone healing and the complete lack or minimal production of callus with primary bone healing.\textsuperscript{31} Secondary bone healing is fundamentally similar to second intention soft tissue wound healing.\textsuperscript{20,23} Depending on its location and function, a callus may be divided into an anchoring callus, sealing callus, or bridging callus.\textsuperscript{26} An anchoring callus develops along the periosteum on the outer surface of the bone a fair distance (centimeters) from the fracture site. Sealing callus develops across the fracture gap and is formed from endosteal proliferation. Bridging callus is formed between the anchoring callus on both sides of the fracture ends.\textsuperscript{26} The thickness of the callus formed is directly proportional to the amount of fracture fragment movement during healing.\textsuperscript{20,32}

Primary bone healing, fracture union with bone being the first and only connective tissue to form at the fracture site, occurs with rigid internal fixation.\textsuperscript{19,21,24,26,28-31,33} The bony union that
results has minimal to no periosteal or endosteal callus and requires months to return to normal bone strength. Secondary osteons traverse the fracture line where original cortical bone is in contact, proceeding at 70 to 100 μm/day. In areas where the bones are not in direct contact, gap healing, another type of primary bone healing occurs. Gaps less than 800 μm will be filled in with woven bone, which is replaced later by lamellar bone. When rigid fixation and anatomic alignment are not achieved, bone will progress through the phases of bony union with the development of external callus formation. Secondary bone healing results in a rapid restoration of mechanical strength and integrity, allowing bone to withstand physiologic forces more quickly. Many fractures in man are allowed to heal by secondary intention if the fracture fragments are aligned relatively well, and some form of immobilization is employed during the healing process. If the ultimate strength of the healing tissue is exceeded, differentiation into bone may be delayed or lead to a nonunion. The term primary bone healing should not be misunderstood to mean that it is superior to secondary callus formation. In actuality, secondary bone healing results in a more rapid bony union. The major disadvantage of secondary bone healing is that the bone requires some form of external coaptation to limit the movement of the fracture fragments until clinical and functional union can be achieved. The result is a decreased range of motion due to joint stiffness and increased morbidity secondary to muscle atrophy. More proliferative callus formation is apparent within 3 weeks in less-rigidly fixed fracture repairs.

Mandibular fractures, while easily diagnosed, are rarely life threatening. Facial asymmetry, jaw droop, excessive salivation, malocclusion of the dental arcades, pain and blood on the hair coat are generally evident. The mandible is one of the most unusual and functional bones of the body; representing a challenge for repair because of its comparatively short bone characteristics and a relatively extensive muscular attachment. The mandibular musculature is comprised of the masseter, temporal, lateral pterygoid, medial pterygoid, and the digastricus.
muscles. Functionally, the mandible in the dog has a relatively simple mechanical action. Its hinge-like movement imparts a scissor action, reflected in its chewing patterns, its shape, and the anatomy of the temporomandibular joint.44

Fractures of the jaw in man occur most often because of domestic violence or trauma secondary to vehicular accidents.26,45,46 They comprise over 20 - 40% of all facial trauma cases46,47 and affect young males predominantly.47,48 Mandibular fractures in the dog occur secondary to vehicular trauma, falls, kicks, guashots, and fights with other animals.38 Mandibular fractures represent 3-6% of all fractures seen in the dog38,49-51 and affect young males predominantly.49 Location of mandibular fractures in the dog can be quite variable; the most common site being the body of the mandible from the premolars to the molars.49,52

The vertical forces (biting) acting upon the mandible are approximately 10 times those in the horizontal plane.53 The forces required to produce mandibular fractures are not documented in the dog. In man it is believed that a minimum of 1890 Newtons (425 pounds) of force is necessary to produce a single subcondylar fracture.54 The area of force application has a direct bearing on the type of fracture created.55 The concept of advantageous (favorable) and disadvantageous (unfavorable) fractures relates to the orientation of the fracture line. A disadvantageous fracture line is oriented such that muscular contraction distracts the fracture ends and, due to their inherent instability, are more likely to require some form of fixation to neutralize distracting forces.26,55 Mandible fractures are unique in that they will proceed to bony union despite non-rigid stability and the presence of gaps.50

The main objective of fracture fixation is to provide rigid alignment of fracture ends while allowing rapid return to function. In long bone fractures open reduction and internal fixation with bone plates satisfies these criteria. Any method used in the treatment of mandibular fractures which allows earlier return to normal jaw function and better nutrition is clinically more successful than methods that immobilize the maxillomandibular unit.56
Nerve injury/Regeneration

The peripheral nervous system is comprised of sensory, motor and autonomic neurons.\textsuperscript{57} Peripheral nerves consist of nerve fibers, endoneurium, perineurium, and epineurium.\textsuperscript{58} (Fig 2) Each fiber within the endoneurium contains an axon, surrounded by Schwann cells.\textsuperscript{58} (Fig 2) Myelin is specialized fused Schwann cell surface membrane and its thickness is directly proportional the diameter of its associated axon.\textsuperscript{57} Nutrient arteries, derived from regional arteries, are the major blood supply to peripheral nerves and divide into ascending and descending branches upon their arrival to the nerve.\textsuperscript{58} These vessels travel longitudinally along the epineurium and communicate with each other through a series of anastomoses.\textsuperscript{58} At certain points, some of the vessels penetrate into the interior of the nerve.\textsuperscript{58} Debate still exists as to the relative importance of this vascular supply.\textsuperscript{58} (Fig 2)

Nerve injuries are classified into three categories based on the severity of trauma. Neuropraxia, is functional injury without morphologic damage. The connective tissue sheaths and nerve axons remain intact and conduction spontaneously recovers in days to weeks.\textsuperscript{59,60} Axonotmesis, is transection of the axon followed by Wallerian degeneration of the distal segment. Axonotmesis is associated with more severe trauma such as crushing or stretching. The endoneural sheath structure remains intact and the severed axons may regrow resulting in functional recovery in 2-6 months.\textsuperscript{59,60} Neurotmesis involves the complete separation of the entire nerve trunk, recovery being possible only with surgical anastomoses.\textsuperscript{59,60}

Nerve degeneration and regeneration have been extensively studied\textsuperscript{61} but the elements of nerve healing are still not well understood.\textsuperscript{62} Waller's initial studies, performed in 1850, showed that degenerative changes occur in the distal stump after nerve severance, prompting the suggestion that the cell body provides trophic and nutritional factors necessary to maintain the distal segment.\textsuperscript{62} However, under appropriate conditions the proximal axon can regenerate.
Regenerating fibers are smaller in diameter and have thinner myelin sheaths with short internodes. Together these factors contribute to reduce the conduction velocity of action potentials in these fibers.

Once cut, the part proximal to the site of injury initially seals off, forming a clot of blood cells, serum, and mucopolysaccharides. This swelling persists for about one week. The part distal to the site of injury undergoes Wallerian degeneration. Disintegration of peripheral axons and myelin sheaths are evident histologically within the first 48 hours after injury. Two-5 days following injury, Schwann cells devoid of their axons proliferate distal to the site of transection and line up longitudinally (bands of Büngner). Neuronal cell bodies also undergo a predictable series of changes following axonal injury termed axon reaction. Eccentric displacement of the nucleus, cytoplasmic swelling, and dissolution of Nissl substance are characteristics of this axon reaction, and have been considered to be either degenerative changes in the neuronal cell body or evidence of metabolic activation in preparation for regeneration.

While less well characterized, changes also occur in the ganglion and central sensory nuclei following peripheral nerve trauma. The severity of this process, termed deafferentation, is affected by the maturity of the animal, proximity of the peripheral nerve lesion to the ganglion, and the type of lesion as well as the type of neuron.

Regeneration begins within 24 hours after a traumatic event. The proximal nerve stump sends out unmyelinated fiber sprouts (diameters less than 0.5 μm) known as the growth cone. If the growth cone fibers reach the distal Schwann cell tubes they randomly enter and grow distally at a rate of 1 to 3 mm/day. Regenerating axons develop thin myelin sheaths at 3 weeks post trauma. Axon regeneration continues during the fourth and fifth weeks, and the regenerating units are surrounded by fibroblasts and Schwann cell processes. After 5 weeks, the myelinated axons increase in size and the myelin sheaths become thicker. However, regenerating fibers never achieve their original diameters. Excess sprouts are culled.
Success of regeneration depends primarily on the proper guidance of the nerve sprouts into the intact Schwann cell tubes. Surgical techniques to reanastomose nerves primarily attempt to align the ends. If regenerating axons are not able to cross the severance gap, the distal portion of the nerve will gradually shrink in size and endoneurial, epineurial, and perineurial fibrosis will progress over the next 12 to 18 months. Although axonal regeneration is not prevented, fibrosis inhibits progression of axonal growth cones. In the distal tip, the rate of axonal advancement slows, and the ameboid tip of the regenerating fibers project into surrounding tissue. New nerve bundles occur in association with blood vessels, connective tissue fibers, and other nerve fibers.

If the regenerating sprouts are blocked, a tangled mass of axons, Schwann cells, and connective tissue forms a neuroma. Neuromas are non-neoplastic swellings or enlargements occurring at the end of the proximal segment. They occur whenever a peripheral nerve is transected. While functionally similar, neuromas may be subclassified as fusiform, bulbous, lateral and dumbbell based on gross appearance. The histologic appearance of neuromas can be variable with regard to the appearance of connective tissue, inflammatory infiltrate, vascularity, Schwann cell and axoplasmic and myelin tissue orientation and abundance. Unmyelinated nerve fiber numbers increase from proximal to distal in a neuroma.

The activity of neuromas differs markedly from normal neurological structures. Painful syndromes occur in man following the development of neuromas and depend on which nerve is traumatized, the degree of regeneration, and the time period from trauma. Dysaesthesias, abnormal sensations that are generally painful, arise from damaged, regenerating peripheral nerve axons. Spontaneous electrical activity, chemosensitivity, mechanosensitivity and ephaptic transmission have been implicated in their genesis.
In veterinary patients, neuromas are most commonly reported in horses following surgical neurectomy. The actual incidence of neuroma formation is unknown but painful sequellae have been reported in 25% of the equine patients undergoing this surgical procedure. Neuromas in chickens secondary to de-beaking procedure are documented, and there is a single report of tail amputation neuroma secondary to tail docking procedures in dogs. Experimentally, severe self-mutilation, a syndrome referred to as autotomy, has been reported in rats following peripheral nerve injury.

The trigeminal nerve (cranial nerve V) supplies the majority of sensation to the face, oral and nasal cavities. Since the branches are minimally protected by soft tissue, facial trauma frequently results in injury to one of its branches. Although many orofacial neuromas are incidentally discovered during surgical assessment of other lesions, people frequently develop unrelenting pain referred to as causalgia. Four posttraumatic pain variants are recognized in man exhibiting orofacial pain in the distribution of a nerve (neuralgia); anesthesia dolorosa, sympathetic mediated pain, hyperpathia, and allodynia (hyperalgesia). Allodynia is a quick-response pain to low intensity stimuli that are normally non-painful. Hyperpathia is a delayed pain response to mechanical pressure that possesses "after-image" qualities. Sympathetic mediated pain, also known as causalgia, is pain aggravated by emotional stimuli, cold, or increased sympathetic tone. Anesthesia dolorosa is pain present in an area of numbness where the reflex response to noxious stimuli is absent or depressed. The incidence of causalgia may be greater with injury to peripheral nerve injuries of the extremities than the orofacial region, perhaps due to a greater population of sympathetic fibers in limb nerves and the greater likelihood of ephaptic transmission.

Nerve injury in the orofacial region may occur subsequent to a variety of facial injuries, including dental procedures. Greater than 90% of the cases of mandibular body fractures in man result in trigeminal nerve injury. The inferior alveolar nerve, a branch of the trigeminal
nerve, is associated with a 1-5% incidence of injury secondary to tooth extraction, and 50% to 90% of people undergoing mandibular osteotomies develop neuropathies 6 months or more following surgery.\textsuperscript{60,95} This orofacial neuralgia results in constant pain in approximately 81% of these patients, while 19% experience intermittent pain.\textsuperscript{94}

Similar syndromes have not been documented in the dog. Histologic, physiologic, or clinical evidence documenting the formation of neuromas in the maxillofacial region of the dog does not exist. If neuromas develop in the dog without clinical manifestations of pain, then identifying differences between man and dog may provide insight into the mechanism of neuroma pain.
References


Figure 1 - Diagramatic Stress ($\sigma$) - Strain ($\varepsilon$) curve for steel (---) and rubber (----). Steel is more stiff than rubber, but rubber is more elastic. The yield point (elastic limit) for rubber is not reached within the units of this graph.
Figure 2 - Diagramatic representation of the mandibular branch of the trigeminal nerve. The inferior alveolar nerve that arises from the mandibular branch of the trigeminal nerve enters the mandibular canal medially and exits at the mental foramen rostrally (mesially).
Evaluation of bending strength of 5 interdental fixation apparatuses applied to canine mandibles

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aIsomet diamond wafer sectioning blade, Beuhler-Isomet, Lake Bluff, IL.
bSigmaScan, Jandel Scientific, Corte Madera, CA.
cSumma sketch plus, Summagraphics, Fairfield, CA.
dTechnovit, Jorgensen Labs, Loveland, CO.
eErich arch bar, W. Lorenz Surgical Instruments Inc, Jacksonville, FL.
fKirschner orthopedic wire, Kirschner Medical, Timonium, MD.
gJet repair acrylic, Lang Dental Manufacturing Co. Inc, Wheeling, IL.
hEtch gel, Henry Schein Inc, Port Washington, NY.
iInstron testing machine, Instron Corp, Canton, MA.

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SUMMARY

Strength in bending was determined for interdental fixation apparatuses applied to hemimandibles obtained from 24 canine cadavers. Hemimandibles were osteotomized perpendicular to the long axis between the third and fourth premolars, and segments were stabilized with 1 of 5 interdental fixation apparatuses: 1) Erich arch bar (EAB, n=6); 2) Stout loop (SL, n=6); 3) Acrylic (A, n=6); 4) Stout loop and acrylic (SLA, n=24); and 5) Erich arch bar and acrylic (EABA, n=6). Ultimate strengths (mean ± SEM) to failure for EAB, SL, A, SLA, and EABA were 395 ± 48, 523 ± 57, 1106 ± 102, 1306 ± 156, and 2707 ± 504 N·m, respectively. Stiffnesses (mean ± SEM) of EAB, SL, A, SLA and EABA were 2944 ± 357, 6322 ± 2201, 16010 ± 5017, 15777 ± 1026, and 27079 ± 5576 N·m/radian, respectively. Yield strengths (mean ± SEM) of EAB, SL, A, SLA and EABA were 66 ± 6, 264 ± 19, 911 ± 126, 1114 ± 159, and 1855 ± 401 N·m, respectively. There were no significant differences in acrylic weight, cross-sectional area of the acrylic, or area moment of inertia of acrylic at the osteotomy site among A, SLA, and EABA; and there were no significant differences in osteotomy surface area and area moment of inertia at the osteotomy site among all apparatuses (P > 0.05). The EABA apparatus had significantly higher mean ultimate strength, mean stiffness, and mean yield strength compared to other interdental fixation apparatuses. There were no significant differences in mean ultimate strength, mean stiffness or mean yield strength between EAB and SL (P > 0.05). Apparatuses that combine acrylic with metal reinforcement (SLA, EABA) were significantly stronger and stiffer than those that used metal alone (EAB, SL) or acrylic alone (A).
Mandibular fractures in dogs will heal even in the presence of fracture gaps and small amounts of movement between fragments as long as the mandibular canal vascularity is protected, revascularization is encouraged, and infection is prevented.\textsuperscript{1} The ideal device for fracture fixation would be rigid enough to relieve apparent pain and enhance bony union, provide occlusive alignment, prevent soft tissue entrapment by implants and minimize damage to neurovascular structures, tooth roots, and tooth buds.\textsuperscript{1,2} In addition, it should allow for immediate restoration of function, be light and not cumbersome, economical and readily available, and require only a reasonable amount of time, expertise and ancillary equipment to apply.\textsuperscript{1,2} Damage to tooth roots and neurovascular structures by trauma and by implants may not cause clinical signs; however, endodontic and periodontal complications including alveolar bone resorption, pulpitis and tooth loss may develop.\textsuperscript{3,4} The inferior alveolar artery and its branches provide the sole blood supply to alveolar bone, periodontal ligament, and teeth.\textsuperscript{5}

The most common method for mandibular fracture repair in dogs is external coaptation using a tape muzzle.\textsuperscript{6} This fixation method is inexpensive and does not affect vascular supply of fracture fragments or tooth roots and does not interfere with neurovascular structures of the mandibular canal.\textsuperscript{7} Potential complications include permanent malocclusion, moist dermatitis under the muzzle, and delayed return to function.\textsuperscript{2,7,8} External fixation methods using intrafragmentary pins and acrylic connecting bars may adequately stabilize mandibular fractures\textsuperscript{2}; however, because of the anatomy of the mandible,\textsuperscript{9} iatrogenic trauma to structures in the mandibular canal is possible.\textsuperscript{8,10} Pin loosening and pin-tract infection are the 2 most frequent problems associated with use of external skeletal fixation pins.\textsuperscript{11} In addition, dogs and their owners may not tolerate the appliance, or the fixator bar may catch on household furnishings.\textsuperscript{12} Internal fixation methods such as intramedullary pinning and plate fixation may also cause iatrogenic trauma to tooth roots and neurovascular structures. Disruption of fracture fragment vascular supply during implant application may complicate healing.\textsuperscript{7,13,14} Other drawbacks to
plate fixation are the expense of the equipment and the substantial time investment required to learn technical principles of application.\textsuperscript{1,15-17}

Interdental fixation methods are used for temporary or definitive mandibular fracture stabilization in human beings.\textsuperscript{18-21} Clinical reports have recommended interdental fixation for stabilization of mandibular fractures in dogs.\textsuperscript{5,22,23} Advantages of interdental fixation for stabilization of mandibular fractures include preservation of tooth roots and neurovascular structures of the mandibular canal, minimal disruption of fracture fragment vascular supply, restoration of occlusion, and early return to function.\textsuperscript{13} The purpose of the study reported here was to determine the ultimate strength, stiffness, and yield strength in bending of 5 interdental fixation apparatuses applied to canine mandibles that had been subjected to osteotomies.

Materials and Methods

Mandibles were obtained from 24 adult dogs (body weight $\pm$ SEM = 18.8 $\pm$ 2.0 kg) after death. All mandibles were of similar size and had normal tooth eruption patterns, and all tooth crowns were morphologically normal. All soft tissues, except gingival mucosa, were removed from the mandible using sharp dissection and periosteal elevation. Mandibles were stored in plastic containers at -15 C until prepared and analyzed.

Mandibles were divided at the symphysis to provide paired hemimandibles. A lateromedial radiographic view of each hemimandible was obtained, and teeth were cleaned using hand and ultrasonic scalers. Hemimandibles were cut\textsuperscript{a} perpendicular to their long axis between the third and fourth premolars. Area of mesial and distal osteotomy surfaces was measured, using a computerized digitizer\textsuperscript{b} and measurement software.\textsuperscript{c} The mesial and distal hemimandibular segments were embedded in self-curing acrylic\textsuperscript{d} to provide a 9-cm length centered at the osteotomy site for fixation application. Hemimandible segments were stabilized with 1 of 5 interdental fixation apparatuses: 1) Stout loop (SL, n=6); 2) Erich arch bar (EAB, n=6); 3) Acrylic (A, n=6);
4) Stout loop and acrylic (SLA, n=24); and 5) Erich arch bar6 and acrylic (EABA, n=6). Stout loop fixation, using 24-gauge stainless steel wire6 (SL) and Erich arch bar (EAB) fixation, and direct application of acrylic to crown surfaces (A) have been described previously.16,18 Acrylic material used was poly(methyl)methacrylate8. For composite interdental fixation apparatuses (SLA and EABA), the metallic component was applied before the acrylic. All interdental fixation apparatuses were applied between premolar 2 and molar 1 (Fig 1). For interdental fixation apparatuses using acrylic, buccal and lingual crown surfaces of premolars 2, 3, and 4, and lingual crown surface of molar 1 were etched with phosphoric acid gel10 (40%) prior to acrylic application.24 The etching substance was removed after 1 minute, and crown surfaces were rinsed with distilled water and dried with nitrogen gas. Ratio of acrylic monomer to polymer was 2:1. Acrylic was applied to crown surfaces, and to metal surfaces for SLA and EABA, by syringe during the doughy stage of polymerization, and the weight of acrylic was recorded. Consistency of acrylic and application technique prevented acrylic from contacting gingiva. All fixation apparatuses were applied by a single investigator (DAK).

After interdental fixation, specimens were placed in a modified, 4-point bending device (Fig 2) similar to one previously described.25 Vertical and horizontal alignment of the specimen in the mounting jig was carefully monitored during mounting to ensure reproducibility of alignment and to minimize variations caused by mounting misalignment. Testing was performed on a hydraulic material test system4 at crosshead speed of 2.5 mm/min. Specimens were oriented so that the fixation material was loaded in tension and bending and were tested to failure (Fig 3). Ultimate strength (N·m), stiffness (N·m/radian) and yield strength (N·m) were determined for each specimen from graphs generated directly from the test system load cell. Failure was defined as loosening of implants, or catastrophic failure (A, SLA, EABA). For comparison intact hemimandibles (n=7) were mounted as described and loaded to failure. Cross-sectional surface area of the acrylic was measured, and area moment of inertia was estimated.
Four experimental trials were performed, and 6 mandibles were tested in each trial. For trial 1, 1 hemimandible was randomly assigned to be stabilized with SL, and the contralateral hemimandible was stabilized with SLA. For trial 2, 1 hemimandible was randomly assigned to be stabilized with A, and the contralateral hemimandible was stabilized with SLA. For trial 3, 1 hemimandible was randomly assigned to be stabilized with EAB and the contralateral hemimandible was stabilized with SLA. For trial 4, 1 hemimandible was randomly assigned to be stabilized with EABA and the contralateral hemimandible was stabilized with SLA. Interdental fixation apparatuses from each trial were analyzed using a paired t-test (P < 0.05). Data from all groups was analyzed using the general linear model (GLM) for one-way analysis of variance (ANOVA), Scheffe's and Duncan's method of multiple comparisons, with P < 0.05 considered to be significant.

Results

Hemimandibles did not have any radiographic signs of previous fracture, osteoporotic disease, or pathologic changes of tooth roots. Cross-sectional area of the osteotomy surfaces and area moment of inertia were identical between hemimandible pairs and were not significantly different between groups. Acrylic weight was not significantly different among A, SLA, and EABA. Intact hemimandibles failed within the bony substance in all specimens. For those apparatuses that used acrylic, 94.4% (34 of 36) of specimens failed by fracture through the acrylic. The remaining 2 specimens failed by loosening of the acrylic from the tooth crown. For those specimens stabilized with metal alone (SL, EAB), all failed by the wire breaking. Examination of the fracture surfaces of the acrylic after testing to failure confirmed that the cross-sectional area of each specimen and area moments of inertia were not significantly different. This indicated repeatable loading and failure of the acrylic in the testing effort.
Bending moment-angular displacement curves were affected by the structural and material properties of the fixation apparatus material/bone composite. Fixation apparatuses using metal alone (SL and EAB) yielded curves with low slopes, indicating low stiffness (Fig 4A). Specimens stabilized with acrylic alone (A) behaved similar to other brittle thermoplastic materials²⁷ and had high stiffness and minimal yielding prior to failure (Fig 4B). Fixation apparatuses incorporating acrylic and metal (SLA and EABA) were also characterized by high stiffness and high yield strength (Fig 4C). But, after failure of the acrylic component, the metal continued to yield.

The EABA apparatus had significantly higher mean ultimate strength, mean stiffness, and mean yield strength compared with mandibles stabilized with other interdental fixation apparatuses (Table 1). Mean ultimate strength, mean stiffness, and mean yield strength were not significantly different between the EAB and the SL apparatus. Composite interdental fixation apparatuses incorporating acrylic and metal reinforcement (SLA, EABA) had significantly higher mean ultimate and yield strengths than other apparatuses. All interdental fixation apparatuses that used acrylic (A, SLA, EABA) had significantly higher mean ultimate strength, mean stiffness, and mean yield strength than apparatuses that did not employ acrylic (EAB, SL). Intact hemimandibles had significantly higher mean ultimate strength, mean yield strength and mean stiffness compared with all interdental fixation apparatuses.

Discussion

The most common location for mandibular fractures in dogs is between premolar 1 and molar 2.⁶ Because of this, we elected to study the biomechanical strengths of interdental fixation apparatuses using a standard osteotomy between premolars 3 and 4. At this location, muscles of mastication and skeletal conformation of the mandible and maxilla tend to confine mandibular movement to a predominantly ventrodorsal direction.⁹₂⁶ During mastication, most of the forces acting on the mandible would result in bending, with tension on the alveolar border. Shear loads
would result from grinding of food in the molar region. In this study, specimens were subjected to bending but not to shearing loads.

Kinematic analysis of the modified 4-point bending apparatus revealed that deviations from conventional 4-point bending were negligible over the range of angular deflections measured in this study. Force analysis and testing of beams with known properties indicated that longitudinal forces and couples introduced by the interlocking rigid links were also negligible over the range of angular deflections and loads measured. This agreed with a previous study that used a similar jig. Because intact hemimandibles failed by fracturing and did not dislodge from the acrylic potting compound used to hold them in the test jig, it was assumed that instability of the junction between specimen and jig was negligible.

The strength of thermoplastics can be increased by reinforcement. In the present study, stainless steel wire and Erich arch bars were used to reinforce acrylic, and the ultimate strength of composite interdental fixation apparatuses (EABA, SLA) was greater than the summation of the mean ultimate strengths of their individual parts. This would suggest a synergistic effect. The acrylic-metal composite interdental fixation apparatuses provided a contiguous material along the tension band surface of the mandibular fracture model between enamel, acrylic, and metal. Interfacing a compression plate to bone, a method known as plate luting, has been shown to augment fracture healing in the equine. Plate luting involves insertion of a space filling substance (poly(methyl)methacrylate) between the bone and plate fixation device to increase the contact area between them and transfer load to the poly(methyl)methacrylate-plate composite. In this study, acrylic was applied similarly to provide a contiguous area of contact between teeth and the reinforcing interdental wire fixation method. The design and orientation of the reinforcement had an effect on strength of the composite. There was a significant difference in mean ultimate strength between composite interdental fixation apparatuses although there was no significant difference between apparatuses when the reinforcement components (EAB, SL) were
used alone. Acrylic does not adhere well to metal\textsuperscript{31}, but conforms to crown shape and interdigitates with gross metal architecture (metal cleats of the arch bar and wire twist). The orientation and design of EAB reinforcement likely contributed to a better mechanical connection than the mechanical connection of SL and acrylic. This may explain the greater mean ultimate strength of the EABA composite interdental fixation apparatus when compared to the SLA apparatus.

Etching teeth with phosphoric acid gel results in the formation of microporosities within enamel prism cores or around rod peripheries on the tooth surface.\textsuperscript{24} Microporosity depth has been reported to range from 20 to 50 \textmu m.\textsuperscript{32,33} Dental acrylic materials have been shown to penetrate these microporosities, forming finger-like projections resulting in a strong bond between acrylic material and enamel.\textsuperscript{24} Although the enamel/acrylic interface was not specifically studied, only 2 of 36 specimens failed by loosening of the acrylic from the tooth.

Deformation and/or fracture of interdental fixation apparatuses occurred within 3 mm of the osteotomy site in 91.7\% (44 of 48) of the fixation specimens analyzed. The location of failure was probably related to the stress concentrating effect of the osteotomy in bending. The shearing occlusal action of the fourth maxillary premolar and first mandibular molar required acrylic application to only the lingual surface of the first molar. This transition zone of acrylic application from bilateral (buccal and lingual) to unilateral (lingual) occurred at the fourth premolar and first molar interproximal space. Analyses were performed sequentially on hemimandibles from the same dog to eliminate the variation between dogs and its potential effect on interdental fixation application and ultimate strength, stiffness, and yield strength. Following sequential analysis, justification for comparison between groups was based on similar acrylic fixation material cross-sectional areas in the region of the osteotomy, similar acrylic fixation attachment in all specimens, the high stiffness of the hemimandible specimen except at the osteotomy or test site, the similarities
in the acrylic weight for various specimen testing, hemimandibles with equivalent cross-sectional areas, and consistency of interdental fixation application based on a single operator.

It remains unknown how rigidly canine mandibular fractures must be fixed to support primary healing of bone. Early in the fracture healing process it is generally agreed that the more rigid the fixation, the more conducive it is to bone healing.\textsuperscript{34-36}

This study used a transverse osteotomy as a fracture model. Interdental fixation devices may have different biomechanical properties when applied to oblique or comminuted fractures of the mandible. Moreover, the loading of the specimens in this study was in noncyclical bending and tension only, and interdental fixation apparatuses may behave differently under conditions of fatigue testing.
References


Table 1 - Mechanical properties of intact hemimandibles and of interdental fixation apparatuses applied to hemimandibles subjected to osteotomy.

<table>
<thead>
<tr>
<th>Group</th>
<th>Ultimate strength N·m</th>
<th>Percentage of control</th>
<th>Yield strength N·m</th>
<th>Percentage of control</th>
<th>Stiffness N·m/rad</th>
<th>Percentage of control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact (n=7)</td>
<td>6661±515</td>
<td>100</td>
<td>6171±515</td>
<td>100</td>
<td>657400±226500</td>
<td>100</td>
</tr>
<tr>
<td>EABA (n=6)</td>
<td>2707±504*†</td>
<td>41</td>
<td>1855±401*†</td>
<td>30</td>
<td>27079±5576*†</td>
<td>4</td>
</tr>
<tr>
<td>SLA (n=24)</td>
<td>1306±156*</td>
<td>20</td>
<td>1114±159*</td>
<td>18</td>
<td>15777±1026*</td>
<td>2</td>
</tr>
<tr>
<td>A (n=6)</td>
<td>1106±102*</td>
<td>17</td>
<td>911±126*</td>
<td>15</td>
<td>16010±5017*</td>
<td>2</td>
</tr>
<tr>
<td>SL (n=6)</td>
<td>523±57*</td>
<td>8</td>
<td>264±19*</td>
<td>4</td>
<td>6322±2201*</td>
<td>1</td>
</tr>
<tr>
<td>EAB (n=6)</td>
<td>395±48*</td>
<td>6</td>
<td>66±6*</td>
<td>1</td>
<td>2944±357*</td>
<td>0.5</td>
</tr>
</tbody>
</table>

EABA = Erich arch bar and acrylic, SLA = Stout loop and acrylic, A = Acrylic, SL = Stout loop, EAB = Erich arch bar. N·m = Newton meter, N·m/rad = Newton meter/radian. Control = intact hemimandible.

* Significantly (P < 0.05) different from intact hemimandible value. † Significantly (P < 0.05) different from all other interdental fixation methods.

Values are expressed as mean ± SEM.
Fig 1A - Photograph of interdental fixation apparatuses applied to hemimandibles from coronal view: Erich arch bar (a); Stout loop (b); Stout loop and acrylic and Erich arch bar and acrylic composite methods (c); Acrylic (d).
Fig 1B - Photograph of interdental fixation apparatuses applied to hemimandibles from lingual view: Enich arch bar (a), Stout loop (b), Stout loop and acrylic and Enich arch bar and acrylic composite methods (c and d).
Fig 2 - Schematic of the modified 4-point bending test apparatus. S=specimen; black arrows=points of rotation (interlocking rigid links); open arrows=direction of movement of specimen when load is applied to the jig.
Fig 3 - Photograph of test specimen and modified 4-point bending test apparatus, showing a mandibular interdental fixation apparatus after failure.
Fig 4 - Diagram of representative bending moment-angular displacement curves for metal (A), acrylic (B), and acrylic-metal composite (C) interdental fixation methods.
Bone healing of mandibular body osteotomies after plate, interdental, and external skeletal fixation in dogs

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aEriech arch bar, W. Lorenz Surgical Instruments Inc, Jacksonville, FL.
bJet repair acrylic, Lang Dental Manufacturing Co, Inc, Wheeling, IL.
cPromAce, Fort Dodge Lab Inc, Fort Dodge, IA.
dMorphine sulfate, Schein Pharmaceutical, Inc, Port Washington, NY.
eBio-tal, Bio-CEutic Labs, St. Joseph, MO.
fHalocarbon Lab, North Augusta, SC.
gKefzol, Eli Lilly and Co, Indianapolis, IN.
hZimmer Gigli wire, Zimmer Inc, Warsaw, IN.
iPDS, Ethicon Ltd, Somerville, NJ.
jTorbutrol, Fort Dodge Lab Inc, Fort Dodge, IA.
kSynthes (USA), Paoli, PA.
lOsteo-Technology International, Timonium, MD.
mBlue Ridge Anesthesia, Lynchburg, VA.
nTechnovit, Jorgensen Labs, Loveland, CO.
oManostat, SPI, Precision caliper, Switzerland.
pSumma sketch plus, SummaGraphics, Fairfield, CA.
qSigma Chemical Company, St. Louis, MO.
rLiquamycin, LA-200, Pfizer Inc, New York, NY.
sBeuthanasia-D, Schering Corporation, Omaha, NE.
tDiamond wafering blade No. 11-4247, Beuhler Ltd, Lake Bluff, IL.
uMetadi diamond suspension, Beuhler Ltd, Lake Bluff, IL.
vAssociation for the Study of Internal Fixation, Synthes Ltd (USA), Paoli, PA.

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SUMMARY

Bilateral mid-body mandibular osteotomies were created between mandibular premolar 3 and premolar 4 in 18 adult dogs. The osteotomies were repaired with either monocortically applied bone plates (n=6), Erich arch bar supplemented with acrylic interdental fixation (n=6), or type I external skeletal fixation with acrylic connecting bar (n=6). Functional assessment (pain, temporomandibular joint range of motion, stability, and ability to eat) was completed before surgery and on a daily basis postoperatively. Radiographic assessment (osteotomy gap distance, fracture alignment, osteotomy healing, and periosteal callus surface area) was completed at postoperative weeks 4, 8, and 16. Histologic assessment (bone healing characterization), using fluorochrome bone labeling and toluidine blue stain, was completed at postoperative weeks 4, 8, and 16.

All dogs were willing and able to eat a softened diet within 24 hours of surgery. No dogs had complications during or after the surgical procedure. No dog appeared painful based on mentation status, willingness to eat, and direct palpation of the surgical sites. All osteotomies were radiographically healed by 16 weeks. There was no significant difference (P > 0.05) in the histologic healing of bone, between groups, at 8 and 16 weeks postoperatively.
Mandible fractures in the dog occur secondary to vehicular trauma, falls, kicks, gunshots, and fights with other animals. Mandibular fractures represent 3-6% of all fractures seen in the dog and affect young male dogs predominantly. Location of mandibular fractures in the dog can be quite variable; the most common site being the body of the mandible.

Mandible fractures, while easily diagnosed, are rarely life threatening. Facial asymmetry, jaw droop, excessive salivation, malocclusion of the dental arcades, pain and blood on the hair coat are generally evident. The mandible is one of the most unusual and functional bones of the body, representing a challenge for repair because of its comparatively short bone characteristics and a relatively extensive muscular attachment.

The main objective for repair of mandibular fractures in dogs is return to normal function. A malalignment of 2 to 3 mm caudally can prevent the closing of the rostral portion of the mouth by a full centimeter. Therefore, it is necessary to maintain occlusive alignment while providing adequate stability for bony union to occur. The ideal fixation should provide stability without damaging soft tissue and dental structures while allowing for immediate return to function.

A variety of techniques have been employed for mandibular body fracture stabilization including tape muzzles, plates, pins, external fixators, interdental wiring, acrylic splints, wires, implanted acrylic and combinations of these techniques. Each of these techniques have advantages and disadvantages.

While tape muzzles are used most commonly, their major disadvantages include delayed return to function, risk of inhalation pneumonia, heat prostration (decreased ventilatory capacity), increased morbidity and fracture disease. Their only advantage is their economy and the ease of application. Bone plates provide rigid fixation and early return to function but they can be cost prohibitive and interfere with the fracture fragment vascular supply, normal dental tissue, and neurovascular structures of the mandible. Like bone plates, intramedullary pins and external
skeletal fixation devices allow normal jaw movement but may be associated with malalignment, tooth root damage, delayed healing due to excessive motion, and osteomyelitis.\textsuperscript{1,19,20,21}

The development of an alternative technique that decreases the morbidity associated with mandibular fracture repair, is economically advantageous, and is easily applied would be an important addition to the clinical treatment of mandibular fractures in the dog. The purpose of the study was to determine and compare the pattern of bone healing of bilateral mandibular osteotomies stabilized with monocortical bone plate, interdental, and external skeletal fixation.

Materials and methods

\textit{Animals} - Bilateral osteotomies of the mandibular body were created in 18 adult dogs (mean ± SEM, 16.8 ± 1.3 kg) randomly assigned to 3 treatment groups. Group A (n=6) dogs were stabilized with a bone plate; group B (n=6) dogs were stabilized with Erich arch bar\textsuperscript{a} supplemented with acrylic\textsuperscript{b} interdental fixation; and group C (n=6) dogs were stabilized with an external skeletal fixator with acrylic connecting bar. All dogs were considered normal prior to inclusion in the study based on complete blood count, serum biochemistry profile, neurologic and physical examinations, and mandibular radiographs; all dogs were housed and maintained according to standards set by humane animal care committee.

Mandibular radiographs were taken 14 days prior to the osteotomy to be certain all dogs were normal. Anesthetic regime for this and all subsequent evaluations was acepromazine\textsuperscript{c} (0.05mg/kg IM) and morphine\textsuperscript{d} (0.5 mg/kg IM) premedicants, followed by 4% thiopental\textsuperscript{e} IV. Dogs were maintained with a halothane\textsuperscript{f} and oxygen mixture (1-2 %) delivered via a cuffed endotracheal tube connected to a semi-closed circle system. During the surgical procedure a balanced electrolyte solution was administered (15 ml/kg/hour, IV) through a cephalic catheter. Dogs were maintained at stage 3, plane 2 of anesthesia for all procedures.\textsuperscript{22,23}
Surgical technique - Mandibles were routinely prepared for surgery with the dog in dorsal recumbancy. A fenestrated sterile operating room barrier drape allowed exposure to the entire mandible. Preoperative prophylactic antibiotics (cefazolin\(^8\) 25 mg/kg IV) were given to all dogs. A ventral approach\(^{24}\) to the right and left hemimandible was used in all dogs to create the osteotomy. The periosteum was elevated along the ventro-buccal aspect of the ramus with a Freer periosteal elevator after incision of the periosteum with a scalpel blade. Using curved forceps and a scalpel blade two fenestrations were made buccally and lingually in the gingiva mesial to premolar 4. The mandible was cut transversely using a Gigli wire\(^{3}\) which entered the mouth at the buccal gingival opening, was positioned between the third and fourth premolar, and exited at the lingual gingival opening. Mosquitoe hemostatic forceps were used to occlude the inferior alveolar artery. The inferior alveolar nerve and mandibular vein retracted into the mandibular canal mesially and distally. Ventral fascia was closed with 3-0 polydioxonone\(^{1}\) in a simple continuous pattern. The skin was closed with 3-0 polydioxonone in a continuous horizontal mattress pattern placed subdermally. Electrocautery was not used. Post-operative analgesics (butorphanol\(^{11}\) 0.4 mg/kg, IM, q 6-8 hours) were administered for a minimum of 12 hours.

A 6 hole, 2.7 mm dynamic compression plate\(^{k}\) was placed onto the ventro-buccal aspect of the hemimandible in dogs assigned to group A. Monocortical screw application (6mm screws) stabilized the osteotomy in a neutral position. All cortices were pre-threaded with a tap, and cortical screws were used in all instances.

Dogs in Group B received Erich arch bar supplemented with acrylic interdental fixation\(^{25}\) spanning the lingual surface dental arcade from the second premolar to the first molar. The interdental fixation apparatus was applied as previously described (appendix A).\(^{25}\) Final reduction was maintained manually until the acrylic was fully polymerized.

The external skeletal fixator, in group C dogs, spanned the interdental arcade from the second premolar to the first molar. Two 2.0 mm (5/64 inch) Steinman pins\(^{1}\) (trocar point) were
placed in each hemimandible fragment. Stab incisions of the skin, using a scalpel blade, were made at the appropriate sites for pin placement. The pins engaged both mandibular cortices, as previously described\textsuperscript{26,27}, using a low speed drill (150 rpm). The most mesial and distal pins were placed perpendicular to the mandibular ramus. The pins adjacent to the osteotomy site were divergently placed 35° to 40° from perpendicular. The pin ends were cut 3 centimeters from the skin surface and notched to engage the acrylic connecting bar. Thirteen millimeter (½ inch) tubing\textsuperscript{m} was placed over the pins connecting both hemimandible segments.

Poly(methyl)methacrylate\textsuperscript{m} was placed in the tube during the doughy stage of polymerization and final reduction was maintained manually until the acrylic hardened.

\textit{Methods of evaluation} - Three separate parameters were used to evaluate the success of each treatment, clinical, radiographic, and histologic appearance.

\textit{Clinical appearance} - The weights of dogs were monitored weekly during the course of the study. Animals were assessed daily for evidence of discomfort while being exercised, eating, or resting, gross evidence of loosening of interdental fixation apparatuses and external skeletal fixators, pain at the osteotomy or fixation site, and temporomandibular range of motion.

\textit{Radiographic appearance} - Postoperative intra-oral (coronal-ventral) and lateral oblique radiographs were taken to assess osteotomy gap distance, osteotomy alignment, and implant placement. Serial lateral oblique and intra-oral and closed mouth ventrodorsal postoperative radiographs were taken at 4, 8, and 16 week intervals to assess callous formation, osteotomy gap healing, osteotomy alignment, implant loosening and evidence of osteomyelitis. (Figures 1, 2, and 3) Gross evidence of implant loosening was assessed at the time of euthanasia. Two independent observers (DAK, MLM) evaluated the radiographs without knowledge of the others qualitative interpretations (osteotomy healing, osteotomy alignment, evidence of osteomyelitis, implant loosening) or quantitative measurements (osteotomy gap distance, osteotomy healing/callous formation, osteotomy alignment). Qualitative osteotomy alignment scores were based on
ventrodorsal, intra-oral, and lateral oblique views and subjective categorization of the reduction as being inadequate, fair, good, or anatomic. (Table 1) Quantitative osteotomy alignments and osteotomy gap distances were measured from the lateral oblique view using a precision caliper\(^0\) (0.1 mm increments). Periosteal callous formation was measured from a tracing of the intra-oral or ventrodorsal view using a computerized digitizer\(^0\).

*Histologic appearance* - All dogs (n=18) were administered sequential intravenous fluorochrome labels to document mineralization of osteoid at 2 week intervals, beginning on the second post-operative week, according to the following schedule. Xylenol orange\(^4\) (80 mg/kg) on days 14 and 28; calcein\(^4\) (20 mg/kg) on days 42 and 56; tetracycline\(^6\) (30 mg/kg) on day 70; alizarin complexone\(^9\) (30 mg/kg) on days 84 and 98; and xylenol orange (80 mg/kg) on day 112.

Two dogs from each group were humanely euthanized at 4, 8, and 16 weeks post-operatively using a barbiturato\(^5\) overdose (10 mg/kg IV). Interdental fixation apparatuses were removed by cutting the arch bar ligatures with a wire cutter and scoring the poly(methyl)methacrylate with a high speed bur. The hemimandible was dissected from its soft tissue attachments and periosteotomy 3 cm mandibular body bone segments (1.5 cm mesially and distally from osteotomy midline) were removed and fixed in chilled 40% ethanol (4°C) to optimize penetration and fixation. Final specimen preparation was as previously reported (appendix B).\(^{28}\) Sagittal sections were cut using a diamond wafering blade mounted on a precision saw\(^4\). Six 300 µm thick sections were cut from each specimen, 2 each from the buccal, middle and lingual sections of the osteotomy. The sections were numbered 1 through 6, from buccal to lingual, mounted on opaque Plexiglas slides using a cyanoacrylate adhesive, ground to a final thickness of 100 µm with caborundum paper, and then polished with diamond paste\(^b\). After polishing, the slides were processed as follows: slides 1, 3, 5 were prepared for light microscopy by surface staining with toluidine blue; slides 2, 4, 6 were processed for fluorescent microscopy. Qualitative analysis of bone was performed using nonparametric scores based on bone healing characterization.
parameters. (Table 2) Periosteal new bone thickness (callous) compared to original cortical bone thickness, fibrous callous without osteoid formation, and endochondral ossification were cumulative parameters allowing scoring and ranking of bone healing (Figures 4, 5 and 6). Independent observers (GKS, DAK) randomly evaluated the specimens without knowledge of the treatment groups or duration of fixation.

Data were analyzed using analysis of variance, Kruskal Wallis, and Students t-tests where appropriate. The level of significance for all tests was $P < 0.05$.

Results

The randomly chosen treatment groups contained equally sized and gendered dogs with no radiographic signs of previous fracture or disease of the mandible. All dogs were healthy, adult mix-breeds with normal dentition, levels of activity, and mentation.

Clinical - The weights of dogs between treatment groups were not significantly different at any time during the study ($P > 0.05$, Students t-test). No complications were identified during or after the surgical procedure. One hundred percent (18 of 18) of the dogs were willing and able to eat a softened (moistened kibble and canned) food within 24 hours of the osteotomy. Clinical function of the dogs did not appear to be affected by the type of fixation. Analgesics were considered unnecessary based on the dogs' normal activity and mentation.

Radiographic - Implant placement was considered adequate and not significantly different ($P < 0.05$, Kruskal Wallis) in all fixation groups based on postoperative ventrodorsal intra-oral and lateral oblique radiographic assessments. Radiographic evidence of osteomyelitis was not detected in any dog during the period of the study.

Quantitative assessments - There was no significant difference in quantitative measurements between investigators at any time period ($P > 0.05$, analysis of variance). Periosteal callous was radiographically evident in 61% (11 of 18) of the dogs at 4 and 8 weeks only. There
was no radiographic evidence of periosteal callous at 16 weeks in any fixation group. Periosteal callous surface areas were not significantly different between groups at any time period (P < 0.05, analysis of variance). Osteotomy alignment measurements were not significantly different between groups at any given time period (P > 0.05, analysis of variance). Osteotomy gap distances of mandibles stabilized with interdental fixation were significantly greater than osteotomy gap distances of mandibles stabilized with external skeletal fixators at the immediate postoperative evaluation (P < 0.05, analysis of variance). Osteotomy gap distances of mandibles stabilized with external skeletal fixator were significantly greater than osteotomy gap distances of mandibles stabilized with bone plate at the 4 and 8 week evaluation (P < 0.05, analysis of variance). There was no significant difference in osteotomy gap distances between stabilization methods at the 16 week evaluation (P > 0.05, analysis of variance). (Table 3) Osteotomy alignment scores (Table 4) and osteotomy alignment disparities were not significantly different between evaluators or fixation methods at any time period (P > 0.05, analysis of variance).

Qualitative assessments - Radiographic evidence of bone healing was significantly different between evaluators at 8 and 16 weeks, but not at 4 weeks (P < 0.05, Kruskal Wallis). Interpretation by one investigator (DAK) resulted in consistently higher scores (better healing) than interpretation by the other investigator (MLM). However, there was no difference among investigators as to the interpretation of bone healing relative to time or fixation type (i.e. same statistical results when comparing radiographic bone healing as a function of time and fixation type). Radiographic evidence of bone healing in mandibles stabilized with external skeletal fixator was significantly less than bone healing in mandibles stabilized with bone plate at 4 and 8 weeks (P < 0.05, Kruskal Wallis). Radiographic evidence of bone healing was not significantly different between fixation groups at 16 weeks (P > 0.05, Kruskal Wallis). (Table 5) External fixator devices remained on all dogs for the entire healing period since radiographic evidence of complete healing was not apparent at 4 or 8 weeks. Radiographic evidence of implant loosening was seen in 8% (1
of 12) of the dogs receiving bone plates, in 8% (1 of 12) of the dogs receiving interdental fixations, and in 33% (4 of 12) of the dogs receiving external skeletal fixators. Screw loosening was grossly evident at the time of bone recovery in 8% (1 of 12). Sixteen percent (2 of 12) had bilateral bony sequestra (3mm) at the osteotomy site, located directly beneath the plate. Ninety-two percent (11 of 12) of the interdental fixations were grossly stable and rigidly adherent to the teeth and arch bar. Complications associated with fixation removal occurred in one apparatus. The third premolar was avulsed with the removal of an interdental fixation apparatus.

Histologic - All mandibles stabilized with a bone plate (6 of 6) healed by gap healing as evidenced by minimal periosteal callus formation (Fig 4). Sixty-seven percent (4 of 6) of the mandibles stabilized with interdental fixation healed by gap healing or endochondral ossification. Fibrous callous was present at 4 weeks in 33% (2 of 6) of the mandibles stabilized with interdental fixation. (Fig 5) Sixty-seven percent (4 of 6) of the mandibles stabilized with external skeletal fixator healed by gap healing and endochondral ossification. Thirty-three percent (2 of 6) of the mandibles stabilized with external skeletal fixator healed with a fibrous callous (1 of 6 at 4 weeks and 1 of 6 at 16 weeks). Bone healing characterization scores of mandibles stabilized with bone plate were significantly lower (greater ridigity) (P < 0.05, Kruskal Wallis) than bone healing characterization scores of mandibles stabilized with interdental fixation at 4 weeks. There was no significant difference in bone healing characterization scores between stabilization methods at 8 or 16 weeks (P > 0.05, Kruskal Wallis). (Table 6) Tooth roots were involved in 27.8% (5 of 18; 0 of 6 bone plate group, 2 of 6 interdental fixation group, and 3 of 6 external fixator group) of the osteotomies examined histologically. Fluorochrome bone labeling confirmed areas of osteoid mineralization. (Figures 7 and 8)
Discussion

Immobilization of the jaw, required with maxillomandibular fixation and muzzling significantly reduces the ability to open the mouth.\textsuperscript{17} The result is a decreased range of motion due to joint stiffness and increased morbidity secondary to muscle atrophy.\textsuperscript{33} Significant weight loss has been documented in human beings who have had mandibular fractures stabilized with maxillomandibular fixation.\textsuperscript{34} No doubt similar complications occur in dogs.

The use of rigid internal fixation for the treatment of mandibular fracture in the dog is a well accepted technique in veterinary medicine.\textsuperscript{13,35-38} and promotes primary bone healing without the need for maxillomandibular immobilization.\textsuperscript{39-41} The primary disadvantages to bone plating are increased expense, increased surgical time, increased instrumentation necessary for bone plate application, and specialized training.\textsuperscript{3,13,42} Bone resorption secondary to stress protection, increased infection rates, and malocclusion are reported complications associated with the application of bone plates.\textsuperscript{43-45} Bone plate application was achieved, in this study, using the ASIF\textsuperscript{v} system and engaged the buccal cortex only. The screws were placed monocortically to provide the least invasive means of stabilization, thereby preserving as much of the blood and neurologic supply to the mandible.\textsuperscript{46-47}

Use of interdental wiring, acrylic splints, wires and combinations have been sporadically reported in the literature.\textsuperscript{12,13,15,26,48-50} However, the type of bone healing achieved with these apparatuses has not been reported. Due to the complicated morphology of the dog's dental arcade\textsuperscript{51}, interdental fixation alone has found little use in veterinary medicine. The addition of a polymer such as poly(methyl)methacrylate provides a 'stop' to prevent premature loosening of the arch bar, as well as offering increased strength and rigidity.\textsuperscript{26} Even with failure of the poly(methyl)methacrylate, the reinforcing metal can carry a significant load. This is in sharp contrast to unreinforced poly(methyl)methacrylate which will fail catastrophically.\textsuperscript{25,52}
The arch bar was placed lingually in the dogs to avoid occlusal problems with the maxillary arcade.\textsuperscript{1,25} Morbidity associated with the use of interdental fixation in man include periodontal damage, and loosening and extrusion of supporting teeth.\textsuperscript{53} Tooth extraction in the one mandible with interdental fixation may have been due to its proximity to the osteotomy site. Periodontal damage was not appreciated in any of the specimens.

Radiographic appearance of different groups did reflect minor differences. There was a statistically significant difference in osteotomy gap distance during the latter stages of healing in the external skeletal fixator group. This is probably reflected by the fact that this is a less rigid fixation than bone plating. Similarly, the gap distances were initially greater in group B. This can most likely be attributed to the inability to compress the osteotomy segments with interdental fixation as opposed to bone plates or external skeletal fixation. Despite these differences, healing appeared adequate in all groups based on radiographic and histologic assessments. Evaluator interpretation differences of radiographic bone healing is most likely a function of radiograph interpretation experience. The consistency of interpretations between time periods remained the same and provides support for the lack of differences between groups.

The results of this study indicate that the histologic or radiographic evidence of bone healing of the mandibular body with monocortical bone plate, interdental fixation, and external skeletal fixator is not significantly different at 16 weeks. The degree of stability offered by interdental fixation is believed to be less rigid than bone plate fixation since a more elastic tissue (cartilage) was evident at some of the osteotomy sites. However, based on the type of bone healing, early return to function, avoidance of iatrogenic trauma, and ease of application and economy, a combination of Erich arch bar supplemented with acrylic interdental fixation appears suitable for clinical use in selected cases. The availability and economical cost of materials, together with ease of application make interdental fixation a viable alternative to previously established techniques.
References


36 Sumner-Smith G, Dingwall JG. The plating of mandibular fractures in the dog. Vet Rec 1971;88:595-598.


50 Shulak FS. Complicated fracture of the mandible repaired with a simple wiring technique. VM/SAC 1977;72:174-175.


Table 1 - Radiographic assessment parameters for fixation of mandibles subjected to osteotomy

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Subjective scores</th>
<th>Objective measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Osteotomy alignment</td>
<td>1 - Inadequate</td>
<td>Millimeters of disparity</td>
</tr>
<tr>
<td></td>
<td>2 - Fair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 - Good</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 - Anatomic</td>
<td></td>
</tr>
<tr>
<td>Osteotomy gap</td>
<td>---</td>
<td>Millimeters</td>
</tr>
<tr>
<td>Osteotomy healing</td>
<td>1 - None</td>
<td>Callous formation (cm²)</td>
</tr>
<tr>
<td></td>
<td>2 - Mild</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 - Moderate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 - Marked</td>
<td></td>
</tr>
<tr>
<td>Implant loosening</td>
<td>(+) - Present</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>(-) - Absent</td>
<td></td>
</tr>
<tr>
<td>Osteomyelitis</td>
<td>(+) - Present</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>(-) - Absent</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 - Bone healing characterization parameters of mandibles subjected to osteotomy

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bony periosteal callus</td>
<td>0 - thickness &lt; 50% of cortical thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 - thickness &gt; 50% of cortical thickness</td>
</tr>
<tr>
<td>2</td>
<td>Fibrous periosteal callus</td>
<td>0 - thickness &lt; 50% of cortical thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 - thickness &gt; 50% of cortical thickness</td>
</tr>
<tr>
<td>1</td>
<td>Bony gap (endosteal) callus</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fibrous gap callus</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Endochondral ossification</td>
<td></td>
</tr>
</tbody>
</table>

Larger final scores are considered to be more unstable.
Table - 3 Osteotomy gap distances (millimeters) of mandibles stabilized with bone plate, interdental fixation, and external skeletal fixator subjected to osteotomy

<table>
<thead>
<tr>
<th>Time</th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>post-operative</td>
<td>1.4</td>
<td>1.6*</td>
<td>1.2</td>
</tr>
<tr>
<td>4 weeks</td>
<td>1.1†</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>8 weeks</td>
<td>0.8†</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>16 weeks</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Values are expressed as the mean (analysis of variance, Duncan's multiple range test).  
* significantly (P < 0.05) different from external skeletal fixator at immediate post-operative evaluation.  † significantly (P < 0.05) different from external skeletal fixator at 4 and 8 week evaluation.
Table - 4  Osteotomy alignment scores of mandibles stabilized with bone plate, interdental fixation, and external fixator subjected to osteotomy

<table>
<thead>
<tr>
<th>Time</th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immediate post-op</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
</tr>
<tr>
<td>4 weeks</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
</tr>
<tr>
<td>8 weeks</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
</tr>
<tr>
<td>16 weeks</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
</tr>
</tbody>
</table>
Table 5: Healing scores (based on radiographic evaluation) of mandibles stabilized with bone plate, interdental fixation, and external fixator subjected to osteotomy

<table>
<thead>
<tr>
<th>Time</th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 weeks</td>
<td>2.5 ± 1.1</td>
<td>2.5 ± 0.9</td>
<td>2.0 ± 0.6*</td>
</tr>
<tr>
<td>8 weeks</td>
<td>3.4 ± 0.8</td>
<td>2.8 ± 1.0</td>
<td>2.6 ± 0.9*</td>
</tr>
<tr>
<td>16 weeks</td>
<td>3.6 ± 0.5</td>
<td>3.1 ± 0.8</td>
<td>3.8 ± 0.5</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SD.
* significantly (P < 0.05) different from bone plate at 4 and 8 weeks.
Table 6: Bone healing characterization of mandibles stabilized with bone plate, interdental fixation, and external skeletal fixator subjected to osteotomy

<table>
<thead>
<tr>
<th>Time</th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 weeks</td>
<td>3.0 ± 0*</td>
<td>4.5 ± 0.5</td>
<td>4.0 ± 0</td>
</tr>
<tr>
<td>8 weeks</td>
<td>3.0 ± 0</td>
<td>3.5 ± 0.5</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>16 weeks</td>
<td>2.5 ± 0.5</td>
<td>4.0 ± 1.0</td>
<td>4.0 ± 1.0</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SEM. Statistical analysis: Kruskal-Wallis.
* significantly (P < 0.05) different from interdental fixation at 4 weeks.
Figure 1 - Intra-oral (coronal-ventral) radiographs of canine mandible stabilized with bone plate. (A) immediate postoperative, (B) 8 weeks postoperative, (C) 16 weeks postoperative.
Figure 2 - Intra-oral (coronal-ventral) radiographs of canine mandible stabilized with Enoch arch bar supplemented with acrylic interdental fixation apparatus. (A) immediate postoperative, (B) 8 weeks postoperative, (C) 16 weeks postoperative.
Figure 3 - Intra-oral (coronal-ventral) radiographs of canine mandible stabilized with external skeletal fixator with acrylic connecting bar. (A) immediate postoperative, (B) 8 weeks postoperative, (C) 16 weeks postoperative.
Figure 4 - Light micrograph of gap healing of canine mandible. Original cortical bone (arrow head) and endosteal callus formed at the osteotomy gap (open arrow). (Toluidine blue, X 8)
Figure 5 - Light micrograph of canine mandible. Gap healing with minimal periosteal callus formation is shown. Original cortical bone (arrow head), endosteal callus (open arrow), and periosteal callus (asterisk). (*Toluidine blue, X 8)
Figure 6 - Light micrograph of canine mandible. Fibrous callus formation at the osteotomy site. Original cortical bone (arrow head), fibrous tissue (open arrow), and periosteal callus formation (asterisk). *(Toluidine blue, X 8)*
Figure 7 - Fluorescent light micrograph of canine mandible. Active deposition of osteoid is verified by the presence of fluorescent lines. Original cortical bone (arrow head), endosteal callus (open arrow), and periosteal callus (asterisk). (X 8)
Figure 8 - Fluorescent light micrograph of canine mandible. Absence of osteoid (new bone) formation is evidenced by lack of fluorescence at the osteotomy gap. Original cortical bone (arrow head), fibrous tissue (open arrow), and endosteal new bone formation (asterisk). (X 8)
An evaluation of inferior alveolar nerve healing after mandibular body osteotomy in the dog

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\textsuperscript{a}Erich arch bar, W. Lorenz Surgical Instruments Inc, Jacksonville, FL.
\textsuperscript{b}Jet repair acrylic, Lang Dental Manufacturing Co, Inc, Wheeling, IL.
\textsuperscript{c}PromAce, Fort Dodge Lab Inc, Fort Dodge, IA.
\textsuperscript{d}Morphine sulfate, Schein Pharmaceutical, Inc, Port Washington, NY.
\textsuperscript{e}Bio-tal, Bio-Ceutic Labs, St. Joseph, MO.
\textsuperscript{f}Halocarbon Lab, North Augusta, SC.
\textsuperscript{g}Tytin capsules, 400 mg alloy, Kerr-USA, Romulus, MI.
\textsuperscript{h}Compact 4, Nicolet Instruments, Madison, WI.
\textsuperscript{i}Kefzol, Eli Lilly and Co, Indianapolis, IN.
\textsuperscript{j}Zimmer Gigli wire, Zimmer Inc, Warsaw, IN.
\textsuperscript{k}PDS, Ethicon Ltd, Somerville, NJ.
\textsuperscript{l}Association for the Study of Internal Fixation, Synthes Ltd (USA), Paoli, PA.
\textsuperscript{m}Synthes (USA), Paoli, PA.
\textsuperscript{n}Technovit, Jorgensen Labs, Loveland, CO.
\textsuperscript{o}Blue Ridge Anesthesia, Lynchburg, VA.
\textsuperscript{p}Beuthanasia-D, Schering Corporation, Omaha, NE.
\textsuperscript{q}Craftsman Rotary Tool, Sears Roebuck and Co, USA.

Supported by the Clinical Research Fund of the College of Veterinary Medicine and the Department of Small Animal Clinical Sciences, Virginia Maryland Regional College of Veterinary Medicine, and a donation from Synthes, Inc.
SUMMARY

The effects of three bone fixation apparatuses on healing of the inferior alveolar nerve were determined using 18 adult dogs. Bilateral mid-body mandibular osteotomies were created and stabilized with monocortical bone plate, interdental, and external skeletal fixation. Digastricus muscle evoked potentials were evaluated to determine functional nerve recovery. Digastricus muscle evoked potentials were abolished in all dogs following mandibular body osteotomy. Digastricus muscle potentials returned in 64% (23 of 36) of the hemimandibles by 4 weeks, 78% (28 of 36) of the hemimandibles by 8 weeks, and 83% (30 of 36) of the hemimandibles by 16 weeks. Neuroma formation was present in all groups of dogs regardless of bone fixation apparatus used. However, functional consequences of these neuromas were not readily apparent.
Introduction

Causalgia refers to a syndrome of sustained burning pain that occurs after traumatic nerve injury, frequently in response to a stimulus considered non-painful. The reported incidence of causalgia in humans ranges from 25% to 75%, while the incidence of causalgia induced by experimental nerve injury in laboratory animals varies with species and specific nerve injured. Maxillofacial causalgia secondary to neuroma formation in man is primarily associated with trigeminal nerve injury secondary to mandibular body fractures and orofacial surgery. The inferior alveolar nerve has an extensive course through the mandibular canal in dogs. This anatomical course renders the nerve highly susceptible to injury from mandibular fractures.

The inferior alveolar nerve arises from the mandibular branch of the trigeminal nerve and provides innervation to the periodontal ligament as well as sensation to the lower lip, areas of the oral mucous membrane and the mandibular teeth. In the cat, the inferior alveolar nerve at the mandibular foramen is a single bundle that tapers distally as the nerve courses within the mandibular canal. Anatomical studies of the inferior alveolar nerve in the dog are incomplete.

Loss of the inferior alveolar nerve compromises the animal's ability to sense noxious stimuli and possibly tooth proprioception. Functional abnormalities of the inferior alveolar nerve may be secondary to disease, trauma and iatrogenic injury. In man, inferior alveolar nerve damage is an inherent risk with endodontic therapy and reconstructive surgery of the mandible. Permanent dysfunction is reported in 1% of cases. Only one study has been reported investigating the inferior alveolar nerve regeneration in dogs. This study reported healing without neuroma formation at the light microscope level.

The importance of precise anatomic reduction and rigid fixation on bone healing has been previously investigated. Little attention has been given to the effects of mandibular fracture and subsequent repair techniques on neural structures in the area. The purpose of this study was to
evaluate functional and morphologic changes of the inferior alveolar nerve after mandibular osteotomy and subsequent repair.

Materials and methods

All procedures were reviewed and approved by the university committee for humane treatment of animals. Bilateral osteotomies of the mandibular body were created in 18 adult dogs (kilograms, mean ± SEM, 16.8 ± 1.3 kg) randomly assigned to three treatment groups. Group A (n=6) received monocortical bone plate application; group B (n=6) received Erich arch bar\textsuperscript{a} supplemented with acrylic\textsuperscript{b} interdental fixation; and group C (n=6) received external skeletal fixation with acrylic connecting bar. All dogs were considered normal prior to inclusion in the study based on complete blood count, serum biochemistry profile, neurologic and physical examinations, and mandibular radiographs. Under general anesthesia, radiographs of the mandible were taken and manual and ultrasonic tooth scaling was performed 14 days prior to osteotomy. Anesthetic regime for this and all subsequent evaluations was acepromazine\textsuperscript{c} (0.05 mg/kg IM) and morphine\textsuperscript{d} (0.5 mg/kg IM) premedicants followed by 4% thiamylal\textsuperscript{e} IV and halothane\textsuperscript{f} and oxygen mixture (1-2 %) delivered via auffed endotracheal tube connected to a semi-closed circle system. During the surgical procedure a balanced electrolyte solution was administered (15 ml/kg/hour, IV) through a cephalic catheter. Dogs were maintained at stage three, plane 2 of anesthesia for all procedures.\textsuperscript{11,12} Silver amalgam\textsuperscript{g} inserts were placed into the buccal surface of each mandibular canine and second molar tooth 14 days prior to mandibular osteotomy and inferior alveolar nerve transection. The inserts served as electrode contact sites used to conduct an electrical current stimulating the reflex contraction of the digastricus muscle.

An electrodiagnostic unit\textsuperscript{h} was used to initiate a 0.1 msec duration current at an intensity up to 1.0 mA to the amalgam inserts. Digastricus muscle evoked potentials were recorded following stimulation of the inferior alveolar nerve axons innervating the canine and molar teeth of
each hemimandible using a bipolar recording needle percutaneously placed in the belly of the muscle. Bandpass filters were set at 1 and 10kHz and all responses occurring within 20 msec after the stimulus were recorded.

Mandibles were routinely prepared for a ventral approach. Preoperative prophylactic antibiotics (cefazolin 2.5 mg/kg IV) were given in all dogs. An osteotomy between the third and fourth premolar was created using a Gigli wire saw. The osteotomy transected all structures carried within the mandibular canal; inferior alveolar artery, inferior alveolar nerve and mandibular vein. Mosquito hemostatic forceps were placed on the inferior alveolar artery, but the inferior alveolar nerve and mandibular vein retracted into the mandibular canal proximally and distally. Electrocautery was not used. The ventral fascia was closed with 3-0 polydioxanone in a simple continuous pattern. The skin was closed with 3-0 polydioxanone in a continuous horizontal mattress pattern placed subdermally.

The dogs in group A received fixation via application of an ASIF system, 6 hole 2.7 mm dynamic compression plate onto the buccal and ventral aspect of the hemimandible. Monocortical screw application reduced the osteotomy. The dogs in group B received Erich arch bar-acrylic interdental fixation spanning the mandibular arcade from the second premolar to the first molar. Interdental fixation was applied as previously described. Final reduction was maintained with manual manipulation until the acrylic had fully polymerized. The dogs in group C received application of an external fixator spanning the mandibular arcade from the second premolar to the first molar. Two 2.0 mm (5/64 inch) pins were divergently placed on each side of the osteotomy and stabilized with poly(methyl) methacrylate connecting bars. Thirteen millimeter (½ inch) tubing was placed over the pins stabilizing the hemimandible segments. The poly(methyl) methacrylate was placed in the tube during the doughy stage of polymerization and final reduction was maintained manually until the acrylic hardened.
Inferior alveolar nerve conductance was evaluated in each patient after osteotomy by recording digastricus muscle potentials and observing contraction of the muscles immediately postoperatively and at 4, 8, and 16 week intervals (Fig 1).

Serial postoperative radiographs were taken immediately postoperatively and at 4, 8 and 16 week intervals to assess callous formation, fracture healing, fracture alignment, implant loosening and evidence of osteomyelitis. Two dogs from each group were humanely euthanized at 4, 8, and 16 weeks postoperatively using a barbiturate overdose (10 mg/kg IV).

Nerves were recovered using a high speed bur and fine Lempert rongeurs immediately following euthanasia. The inferior alveolar nerve was removed from the level of the second molar to the caudal mental foramen. Nerves were immersion fixed in chilled 2.5% glutaraldehyde in 0.035 M Sorensens phosphate buffer. The nerves were sectioned immediately proximal, immediately distal and approximately 20 mm distal to the transection site. Sections were post-fixed in 4% osmium tetroxide, dehydrated in alcohols and imbedded in polybed. One micron sections stained with safranin and toluidine blue were examined using light microscopy.

Results

The randomly chosen treatment groups contained equally sized and gendered dogs with no radiographic signs of previous fracture or disease of the mandible. All dogs were healthy, adult mix-breeds with normal dentition, levels of activity, and mentation.

The weights of dogs between treatment groups were not significantly different either at the beginning or conclusion of the study (P > 0.05, Students t-test). No complications were identified during or after the surgical procedure and 100% (18 of 18) of the dogs were willing and able to eat a softened (moistened kibble and canned) food within 24 hours of the procedure. Analgesics were therefore considered unnecessary.
The digastricus reflex was abolished following nerve section, but returned within 4 weeks in 64% (23 of 36), within 8 weeks in 78% (28 of 36), and within 16 weeks in 83% (30 of 36) of the hemimandibles. (Table 1) The functional nerve regeneration rate (millimeters/day) as estimated from the osteotomy site to the canine tooth was not significantly different (P > 0.05, Students t-test) between groups. (Table 2)

The neurovascular bundle in the mandibular canal was continuous in all harvested specimens. Abundant fibrous connective tissue surrounding the neurovascular structures at the site of the osteotomy precluded positive identification of the nerve grossly. However, the nerve was identified in all histologic sections a few centimeters distal to the osteotomy site.

All nerves examined proximal to the site of injury were normal. No differences were observable between treatment groups and so all groups will be discussed together. Distal segments from nerves harvested 4 weeks after transection still contained abundant myelin debris and bands of Büngner. However, all sections immediately distal to the transection site contained numerous regenerating clusters. Small, thinly myelinated fibers were seen in 60% of the more distal sections. (Fig 2)

By 8 weeks, the regenerating clusters in sections immediately distal to transection were larger and surrounded by thicker myelin sheaths. (Fig 3) In some sections these regenerating axons were widely separated by dense strands of connective tissue. In other sections, the clusters were more closely approximated, but the fibers were not aligned parallel to each other. Intense warping patterns were created by apparently misdirected axons. Sections more distal to the transection site contained fewer regenerating fibers, but all were aligned normally.

Nerves harvested at 16 weeks appeared similar to those harvested at 8 weeks. (Fig 4) Regenerating fibers immediately distal to the site of injury were separated by abundant fibrous connective tissue and were poorly aligned relative to the long axis of the nerve. Fibers in more
distal sections appeared more mature after 16 weeks as evidenced by thicker myelin sheaths and somewhat larger axonal diameters.

Discussion

The digastricus muscle evoked potential is initiated by stimulation of trigeminal sensory axons within the pulp cavities of the canine and molar teeth. These afferent fibers synapse on motor neurons in the mesencephalic nucleus of the pons which innervate the digastricus muscle and complete the reflex arc.\textsuperscript{15,16} Therefore the digastricus reflex provides objective assessments regarding the functional integrity of the inferior alveolar nerve. This reflex was abolished in the more distal canine tooth post injury. However, the reflex remained intact when the nerve was stimulated proximal to the injury (i.e. first molar). This provided an internal control to avoid technical errors.

Previous studies indicate that the inferior alveolar nerve in the cat is histologically normal by 4 to 11 months post trauma.\textsuperscript{17} Similarly, complete regeneration distal to the transection site by 4 months has been reported in the dog.\textsuperscript{10} The light microscope changes in the inferior alveolar nerve in this study appeared similar to those reported in the cat at one to two months after injury and the onset of functional recovery is consistent with previously reported growth rates of 1-2 mm/day.\textsuperscript{17,18} Functional recovery in this study was 25% faster than the 6 weeks reported in the cat.\textsuperscript{19,20} It is possible that collateral innervation from branches of the facial nerve were responsible for the early return of the digastricus muscle reflex. However, inferior alveolar nerve regeneration was supported histologically.

Neuromas were present in all histologic sections near the site of injury. Despite exuberant connective tissue proliferation and no effort to align the nerves, axonal sprouts successfully traversed the severance gap and reinnervated the canine tooth. The rigidity of the fixation apparatuses and associated stability of surrounding structures may have facilitated nerve
regeneration. While not intentional, anatomic alignment of the mandibular canal during osteotomy alignment, together with mechanical support provided by the inferior alveolar artery and the mandibular vein, most likely kept the inferior alveolar nerve in relatively good alignment.

Although pain perception is difficult to assess in dogs, the dogs were observed daily for evidence of discomfort. Attempts made to noxiously stimulate the teeth with either manual manipulation or cold exposure created by feeding crushed ice had no effect. All dogs had a normal range of motion of the temporomandibular joint and were willing to eat softened food within 24 hours of surgery. The absence of weight changes during the course of the study further supported normal food consumption. Therefore, while histologically present, neuromas appear to have minimal functional consequences within the time frame of this study (4 months).

Neither histologic or electrophysiologic differences were discernible between groups of dogs. This was somewhat surprising since the application of both bone plates and external fixators required the placement of screws or pins near the mandibular canal. Plates were intentionally applied monocortically to the ventrobuccal aspect of the mandible to avoid neurovascular structures. The pins used in osteotomies repaired with external skeletal fixator appeared to enter the mandibular canal. Despite this, gross observation during nerve harvesting did not reveal the pins to be compromising the neurovascular structures of the mandibular canal and there was no significant difference in the rate of functional recovery or histologic appearance of the inferior alveolar nerve from dogs in this treatment group. This could be explained by the relative resistance of peripheral nerves to penetrating injuries. The dense epineurial sheath and loose connective tissue attachments may allow displacement rather than penetration of the nerve by penetrating foreign bodies.

Injury to branches of the trigeminal nerve is a frequent sequelae to facial injuries.\textsuperscript{21,22} Fifty to 90\% of people undergoing orofacial surgery develop painful neuromas as a consequence of this injury.\textsuperscript{8,23} Approximately 81\% of these people report constant, unrelenting, burning pain that
is exacerbated by stimuli previously considered non-painful such as light touch or temperature changes.³ A variety of techniques have been tried to alleviate the pain associated with neuromas using neuroma resection, grafting, and decompression.³ This syndrome remains an area of intense research.

Mandibular fractures occur commonly in the dog yet similar signs have not been reported. This study confirms that inferior alveolar nerve injury appears to have minimal consequences. Histologically nerve injury and regeneration appear similar between man and dogs yet there appears to be marked functional differences. While the nature of these differences in not known, dogs do not appear to be a good model to study trigeminal neuralgia.
References


Table 1 Percentage of functional recovery of the inferior alveolar nerve subjected to osteotomy and bone stabilization with bone plate, interdental, and external skeletal fixator fixation

<table>
<thead>
<tr>
<th>Time</th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 weeks</td>
<td>75%</td>
<td>67%</td>
<td>58%</td>
</tr>
<tr>
<td>8 weeks</td>
<td>75%</td>
<td>83%</td>
<td>75%</td>
</tr>
<tr>
<td>16 weeks</td>
<td>83%</td>
<td>92%</td>
<td>75%</td>
</tr>
</tbody>
</table>
Table 2 Functional regeneration rate and functional recovery of the inferior alveolar nerve in dogs subjected to osteotomy and bone stabilization with bone plate, interdental, and external skeletal fixator fixation

<table>
<thead>
<tr>
<th></th>
<th>Bone plate</th>
<th>Interdental fixation</th>
<th>External skeletal fixator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional regeneration rate (mm/day)</td>
<td>1.1 ± 0.3</td>
<td>1.1 ± 0.3</td>
<td>0.9 ± 0.3</td>
</tr>
</tbody>
</table>
Figure 1 - Evoked muscle action potentials of digastricus muscle reflex contraction after stimulation at the canine (1) and molar (2) inserts. (A) immediate pre-operative, (B) immediate postoperative, (C) 4 weeks postoperative in a dog with bone plate fixation.
Figure 2 - Light microscope section of inferior alveolar nerve harvested 4 weeks after transection. (A) proximal to the site of injury, (B) at the site of injury, (C) distal to the site of injury. Regenerating clusters (arrow head) and thinly myelinated fibers (open arrow) are evident. (Toluidine blue and safranin, X 40)
Figure 3 - Light microscope section of inferior alveolar nerve harvested 8 weeks after transection. (A) proximal to the site of injury, (B) at the site of injury, (C) distal to the site of injury. Regenerating clusters (arrow head) and thinly myelinated fibers (open arrow) are evident. (*Toluidine blue and safranin*, X 40)
Figure 4 - Light microscope section of inferior alveolar nerve harvested 16 weeks after transection. (A) proximal to the site of injury, (B) at the site of injury, (C) distal to the site of injury. Fibrous connective tissue (arrow head) and poor alignment (open arrow) are evident. *Toluidine blue and safranin, X 40*
Appendix A

Erich arch bar and acrylic interdental fixation apparatus

The Erich arch bar was applied along the lingual aspect of the mandibular dental arcade from the second premolar to the first molar. Stainless steel orthopedic wire (24 gauge) was used to individually "ligate" the arch bar to each tooth. Buccal and lingual crown surfaces of mandibular premolars 2, 3, and 4, and the lingual crown surface of the first molar were etched with 40% phosphoric acid gel prior to acrylic application. The etching substance was removed after one minute, and crown surfaces were rinsed with distilled water and dried with nitrogen gas. The ratio of acrylic monomer to polymer was 2:1. Acrylic was applied to crown surfaces and the metal surface of the Erich arch bar, by syringe, during the doughy stage of polymerization.
Appendix B

Histologic preparation of bone specimens

Periosteotomy 3 cm mandibular bone segments were removed and fixed in chilled 40% ethanol (4C) to optimize penetration and fixation. Each specimen was maintained in 40% ethanol for 14 days. The specimens were then serially dehydrated in successive solution of 70% ethanol (3 days), 95% ethanol (3 days), and 100% ethanol (2 days and again at 4 days); cleared with xylene (2 changes; 2 and 4 days) and then embedded in clear methyImethacrylate. Dehydration and clearing of the samples was accomplished under a vacuum of 15-21 mm Hg in order to facilitate and accelerate specimen penetration by ethanol and xylene. The embedding in methyImethacrylate proceeded as follows: methyImethacrylate + 20% dibutyl phthalate for 4 days, methyImethacrylate + 20% dibutyl phthalate + 1% benzoyl peroxide for 3 days, and then methyImethacrylate + 20% dibutyl phthalate + 2.5% benzoyl peroxide for 5-7 days. Dibutyl phthalate was added to the methacrylate as a softener, allowing block consistency. Benzoyl peroxide was added to the last two steps as the polymerization catalyst (free radical). The temperature of polymerization was 20C. Once the poly(methyl)methacrylate was formed, a band saw and sander were used to trim the specimen blocks to a size and shape suitable for fastening to the clamp of the sectioning saw.
VITA

Douglas Arthur Kern was born to Ione and Edwin H. Kern on June 8, 1961, at the United States Air Force Academy Hospital in Colorado Springs, Colorado. Doug served as the Rice Lake, Wisconsin chapter president of the FFA, received national recognition for placement in agricultural production, and advanced to the FFA's state parliamentary procedure and public speaking competition for three straight years.

Doug received his American Chemical Society Approved B.S. degree in chemistry from the University of Wisconsin, River Falls in 1983. He received his B.S. in Veterinary Science in 1985 and his D.V.M. in 1987 while attending the College of Veterinary Medicine at the University of Minnesota in St. Paul, Minnesota. He served as the president of the Minnesota Student Chapter of the AVMA and chairman of the SAVMA Educational Symposium in 1986. Doug received the Alpha Zeta Traveling Scholarship and Veterinary Student Council Award for Service to the Veterinary College in 1985. He became a member of the Outstanding Young Men of America and received the Pfizer Veterinary Student Scholarship Award, Certificate of Commendation for Outstanding Contributions to the College of Veterinary Medicine, and the University President's Student Leadership and Service Recognition in 1986. Doug was also awarded the Hill's Pet Products Senior Student Award, Clifton A. Paulson Memorial Award, and AVMA Auxiliary Award in 1987.

After graduating from the University of Minnesota, Doug did a 14 month small animal internship at Rowley Memorial Animal Hospital - Massachusetts Society for the Prevention of Cruelty to Animals in Springfield, Massachusetts and met Lori, who would later become a very important part of his life. He was asked to stay on as Director of Interns and staff clinician and did so until June of 1990. Doug and Lori were married two months prior to starting his combined Master's program and Residency in small animal surgery in July of 1990 in the Departments of Veterinary Medical Sciences and Small Animal Clinical Sciences at the Virginia-Maryland Regional College of Veterinary Medicine at Virginia Polytechnic Institute and State University under the directions of Drs. Karen R. Dyer and Mark M. Smith. Doug and Lori were blessed with a beautiful and healthy daughter, Lindsay Marie, on Friday, September 13, 1991.

Doug successfully defended his Master's thesis on April 9, 1993. He was honored with membership into the National Honor Society of Veterinary Medicine, Phi Zeta, on April 15, 1993 at the completion of his residency/graduate program. The biomechanical portion of his master's research manuscript was accepted by the American Journal of Veterinary Research for publication and had advanced to the National Phi Zeta research paper award competition at the time of this thesis preparation.

Douglas A. Kern, DVM

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