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THE EFFECT OF VENTRICULECTOMY, PROSTHETIC LARYNGOPLASTY, AND EXERCISE, ON UPPER AIRWAY FUNCTION IN HORSES WITH LEFT LARYNGEAL HEMIPLEGIA

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By

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ABSTRACT

THE EFFECT OF VENTRICULECTOMY, PROSTHETIC LARYNGOPLASTY AND EXCERCISE ON UPPER AIRWAY FUNCTION IN HORSES WITH LEFT LARYNGEAL HEMIPLEGIA

BY

Kristie Karol Shappell

The effect of ventriculectomy and prosthetic laryngoplasty on upper airway flow mechanics and blood gas tensions in exercising horses with left laryngeal hemiplegia was assessed. Five adult horses were trained to stand, trot (4.5 m/s), and gallop (7.2 m/s) on a treadmill (6.38° incline). Inspiratory and expiratory airflows ($\dot{V}_{Imax}$, $\dot{V}_{Emax}$) were measured using a 14 cm diameter pneumotachograph in a facemask. Inspiratory and expiratory transupper airway pressures (Pu_I, Pu_E) were determined as pressure differences between barometric and lateral tracheal pressures. Upper airway impedances (Z_I, Z_E) were defined as the ratio of peak $Pu/\dot{V}$ on inspiration or expiration. Blood collected from exteriorized carotid arteries was analyzed for oxygen and carbon dioxide tensions (Pa_{O_2}, Pa_{CO_2}), pH, hemoglobin content (Hb), and bicarbonate concentration (HCO_3^-). Heart rate (HR) was determined with a heart rate monitor. Measurements were made with horses standing, trotting, and galloping before left recurrent laryngeal neurectomy (LRLN) (baseline), 14 days after LRLN, 30 days after ventriculectomy, and 14 days following prosthetic laryngoplasty. Results were analyzed using a two-way analysis of variance with means compared using Tukey's ω procedure ($p < 0.05$). Exercise before LRLN increased HR, respiratory frequency, $\dot{V}_{Imax}$, $\dot{V}_{Emax}$, Pu_I, Pu_E, Pa_{CO_2}, and Hb, decreased Pa_{O_2}, HCO_3^- and pH, and did not change Z_I and Z_E. After LRLN, Pu_I and Z_I during exercise were greater than baseline measurements. Ventriculectomy failed to improve upper airway flow mechanics induced by LRLN, while prosthetic laryngoplasty was successful in restoring upper airway flow mechanics to baseline values.

DEDICATION

To my Mom and Dad, June L. and Harry W. Shappell, and to my main squeeze Randy J. Krainock for their belief in my abilities, support of my goals, and their marvelous sense of humor and perspective.

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I. Introduction

Abnormal inspiratory noise has been described in exercising horses since the late 17th century.[1] In the 19th century, it was shown that laryngeal hemiplegia is one of the causes of abnormal inspiratory noise production in exercising horses and that this condition is caused by recurrent laryngeal nerve injury.[2]

Most modern surgical procedures used to correct left laryngeal hemiplegia in horses (ventriculectomy, arytenoidectomy, and vocal cordectomy) are modifications of techniques used in the 1800s.[3] Williams reintroduced the technique in 1905 and the procedure was popularized by Hobday in 1936.[4] Surgical therapy remained unchanged until Marks (1970) described the use of a suture prosthesis (prosthetic laryngoplasty) to treat laryngeal hemiplegia.[5] Ventriculectomy has been performed alone or in conjunction with the previously mentioned procedures.[5,6,7]

Until recently, the efficacy of surgical procedures used to treat left laryngeal hemiplegia was evaluated using subjective criteria such as reduction of inspiratory noise during exercise and improved athletic performance.[3,8,9] A technique to objectively evaluate upper airway flow mechanics in exercising horses has been developed at the Pulmonary Laboratory at Michigan State University.[10] Using this technique, prosthetic laryngoplasty was shown to reverse upper airway obstruction induced by left laryngeal hemiplegia. The objectives of this study were twofold. First, to evaluate the effect of ventriculectomy on upper airway flow mechanics in exercising horses following left recurrent laryngeal neurectomy. Second, to determine if prosthetic laryngoplasty was an effective procedure for alleviating mechanical impairments of upper airway flow measured following left recurrent laryngeal neurectomy in horses exercising at greater speeds than previously measured with this technique.

II. General Review of Laryngeal Hemiplegia

A. Historical Perspective

In the late seventeenth century, Solleysel described inspiratory stridor in exercising horses.[1] The lay term "roaring" was popularized in the nineteenth century to describe this condition.[2] The anatomic origin of this noise production in horses was unknown until Bouley (1825) recognized left recurrent laryngeal nerve damage at necropsy in a horse which "roared" while alive. This prompted investigations by Dupuy (1825) and Gunther (1834).[2] Independently, these investigators sectioned the left recurrent laryngeal nerve and reported abnormal noise production in exercising horses concomitant with "wasting" of left laryngeal musculature in the same animals at necropsy. The importance of differentiating between the causes of abnormal respiratory noise was emphasized by Fleming, and he reserved the term "laryngismus paralytica" for animals exhibiting inspiratory dyspnea during exercise.[2] "Laryngismus paralytica" described both unilateral and, the less common, bilateral laryngeal paralysis. The term "hemiplegia laryngis" or laryngeal hemiplegia appeared in later literature to describe the unilateral condition.[3] Several diseases (e.g. strangles, bronchitis, influenza, enlarged bronchial glands, etc.) have been purported to cause left laryngeal hemiplegia, as these diseases preceded the development of "roaring" in some individuals.

Diagnosis of laryngeal hemiplegia remained difficult until rigid- and flexible-fiberoptic endoscopy became available in veterinary medicine.[11] Using endoscopy, differentiation of laryngeal hemiplegia from other causes of inspiratory stridor became possible.

In the late 19th century oral iodine, iron, mercury, and arsenic were recommended medical therapy for laryngeal hemiplegia; alone, or in combination with percutaneous strychine or electricity applied over the cricoarytenoideus dor-

salis muscle.[12] Surgical therapy at that time included chemical cautery or injection of counter irritants over the larynx, unilateral or bilateral vocal cordectomy, ventriculectomy, arytenoidectomy, and combinations of those procedures.[12] Surgical therapy remained unchanged until Marks (1970) described use of a suture prosthesis (prosthetic laryngoplasty) to treat laryngeal hemiplegia.[5]

The effects of medical and/or surgical therapy for left laryngeal hemiplegia were only evaluated subjectively[8,13,14] and reported "success rates" varied depending on the criteria chosen for determining success (e.g. noise reduction, improved racing times, etc.). Additionally, before the advent of the endoscope, it was difficult to assess the effect of treatment because laryngeal hemiplegia was likely misdiagnosed being confused with other diseases causing abnormal upper respiratory noise during exercise. In 1986, a method for measuring upper airway resistance in exercising horses was reported.[10] Following recurrent laryngeal neurectomy, upper airway resistance was increased during inspiration when compared with baseline values. Prosthetic laryngoplasty decreased inspiratory resistance towards baseline values. In the present study, I evaluated ventriculectomy alone and then prosthetic laryngoplasty at greater treadmill speeds than in the previous study by measuring upper airway flow mechanics in exercising horses with left laryngeal hemiplegia.

B. Anatomy, Etiology, and Pathology

The intrinsic laryngeal musculature is symmetrically innervated at the level of the larynx without evidence of nerve fiber decussation to the contralateral side.[15] Adductor muscles (cricoarytenoideus lateralis, arytenoideus transversus, vestibularis, and vocalis muscles) and abductor muscles (cricoarytenoideus dorsalis muscle) are innervated by the recurrent laryngeal nerve. The cricothyroideus muscle which tenses the vocal fold receives innervation from the cranial laryngeal nerve.[16] Innervation is symmetrical at the level of the larynx,

but the right and left recurrent laryngeal nerves have different anatomic pathways prior to innervating the larynx.[15] The right and left vagi arise in the medulla oblongata and exit the cranium through the jugular foramen. The nerves descend, passing along the dorsal aspect of the guttural pouches, and subsequently course along their respective jugular furrows into the thorax. There the left recurrent laryngeal nerve (LRLN) branches from the vagus at the base of the heart, dividing into two branches that eventually reanastomase, and pass across the axial surface of the aorta and ligamentum arteriosum. The LRLN then ascends passing along the dorsolateral aspect of the trachea to the level of the larynx. In contrast, the right recurrent laryngeal nerve (RRLN) branches from the vagus 25-30 cm cranial to the LRLN at the level of the second rib and passes medial to either the right subclavian or costocervical arteries before ascending dorsolateral to the trachea until reaching the larynx.[15] The average length of the RRLN & LRLN are 76.0 cm and 97.6 cm, respectively.[17]

Neural pathology associated with laryngeal hemiplegia (LH) is characterized by progressive loss of myelinated nerve fibers, most obvious in the distal part of the recurrent laryngeal nerve.[18] In addition, segmental demyelination and remyelination have been observed. In chronic cases, increased endoneurial connective tissue and nuclei with sporadic Wallerian or secondary degeneration have been described.[19] This neuropathology results in neurogenic atrophy of the intrinsic laryngeal musculature. Endoscopically[20], failure to dilate the rima glottis by abducting the arytenoid cartilages appears to be the major problem in laryngeal hemiplegia, but histologically, both abductor and adductor muscles are affected.[21] Histologically, myofiber type grouping (resulting from interruption of innervation) myofiber atrophy with fatty replacement of fibers, and fiber hypertrophy in some areas (though atrophy is more pronounced) characterizes changes in the laryngeal musculature.[19,22,23] However, these changes must

be interpreted with caution because some clinically normal horses show histologic and gross changes compatible with the neuropathology and neurogenic atrophy of LH. In one sample, 30% of clinically normal horses had histologic abnormalities of the laryngeal musculature.[19] Changes in adductor muscles appeared more severe than those in abductor muscles.[21] In a sample of 75 horses, the left intrinsic laryngeal musculature, excluding the cricothyroideus muscle, weighed less than the musculature of the right side suggesting that a degree of left-sided atrophy may be present in many clinically normal horses. When compared to normal horses, the difference between the weights of the right and left intrinsic laryngeal musculature was significantly greater in one horse with laryngeal hemiplegia.[24] It has been suggested that atrophy of 50% of the left cricoarytenoideus dorsalis muscle is necessary before clinical signs of inspiratory stridor are evident.[17]

Several causes have been proposed for laryngeal hemiplegia and these are summarized as follows:

1. Congenital
2. Acquired
    a. Toxic damage to the LRLN by chemical or bacterial toxins
    b. Nutritional deficiencies
    c. Nerve damage induced by viral infection
    d. Mechanical damage to the LRLN by compression, stretching, or trauma.

Cook has suggested that LH is a congenital disease.[25] In a single fetal larynx, histochemical studies have shown muscle fiber grouping similar to that present in animals with LH.[21] The presence of this muscle fiber grouping suggests that LH may have a congenital etiology. But, additional fetal larynxes should be examined. Attempts to show that LH is an inherited condition has not provided consistent results. A long-term study in South Africa was unable to

show that LH is inherited while another study suggested inheritance occurred as a simple recessive.[3,25]

Laryngeal hemiplegia may occur concomitant with other diseases. Those diseases that precede, or may be present concurrent with LH, have been proposed as etiologies of the disease. Laryngeal paralysis has occurred in conjunction with paralaryngeal abscess, infection with Staphlococcus aureus[26], unilateral rupture of the rectus capitis ventralis major and minor muscles leading to guttural pouch mycosis[27], other bacterial infections which lead to lymph node enlargement[28], plant poisoning, lead poisoning[29], organophosphate intoxication[30,31], perivascular or perineural injections[32], and lacerations involving the jugular furrow.[33] Additionally, plasma thiamin deficiency recognized in some horses with laryngeal hemiplegia, is postulated to cause a peripheral neuropathy similar to that observed in humans with beriberi (thiamin deficiency).[34] Neuropathy in other long peripheral nerves, as observed in humans with beriberi, has been documented in horses with LH though this was not correlated with thiamin deficiency in these horses. Additionally, thiamin deficiencies in other species, like the cow, do not cause atrophy of intrinsic laryngeal musculature.[35] A "dying back" phenomena of distal degeneration of peripheral nerves with few changes in central nuclei (anterior horn cells)[36], were similar to changes seen with thiamin deficiency. But, the changes were not specific for thiamin deficiency as similar signs of degeneration occurred with other neurotoxins. Bilateral laryngeal hemiplegia in an adult human male was related to increased herpes simplex virus-complement fixation antibody titers during the initial phase of the illness.[37] Though herpes viruses play a role in some equine disease, viral replication within peripheral nerves and resulting damage does not explain the unilateral expression of the disease present in most cases of equine laryngeal paralysis. In addition, most infectious disease

etiologies fail to explain the predominence of LH in large (16-17 hand) mature male horses.[38]

In horses, the LRLN is longer than the right recurrent laryngeal nerve,[16] and tension on the nerve resulting from the longer anatomic pathway of the LRLN has been postulated to cause a neuropathy and atrophy of laryngeal musculature. In addition, it has been suggested that anatomic variations of the typical nerve routes might further lengthen the path the nerve travels and cause additional tension along the LRLN.[39] Experimentally, chronic slow stretching of nerves in humans increases nerve length and fails to impair nerve function.[40] Therefore, the above explanation for the occurrence of LH is unlikely. In addition, chronic tension on the LRLN does not explain muscle and nerve histopathology observed bilaterally in clinically normal horses and horses with LH.

Neural ischemia has been proposed as a mechanism for the neuropathy observed in horses with LH[36] because it causes similar neurohistologic changes. However, vascular perfusion abnormalities with either bilateral or unilateral vessel pathology have not been described as a feature of the disease. Peripheral nerves have an extensive anastomotic blood supply which is seldom occluded except by compression. Experiments to determine if ischemia of the LRLN would result in LH, are needed.

Since neural degeneration and laryngeal muscle atrophy have been observed bilaterally, it has been suggested that another factor must be present to explain the more commonly observed unilateral paralysis. Baker proposed that failure of neural regeneration following degeneration of the LRLN could be the reason.[8]

In a New Zealand population of horses with LH, the cause of the disease was undetermined (idiopathic) in 89% of the cases. Thus, although there is a general consensus on the muscle and nerve pathology characterizing LH, the etiology of the neural damage remains controversial in most cases.[32]

C. Diagnosis of Laryngeal Hemiplegia

Animals with laryngeal hemiplegia are usually presented for inspiratory dyspnea during exercise and in some cases exercise intolerance.[32] Similar clinical signs are observed in horses with other diseases that cause upper respiratory obstruction (e.g. laryngo-palatal dislocation or soft palate paresis[41], epiglottic entrapment or subepiglottic cysts[42], rostral displacement of the palatopharyngeal arch[43], arytenoid chondritis[44], nasal obstruction[45], and severe pharyngitis[46]). Clinical signs of lower respiratory tract inflammation and obstruction[47] may also mimic those of LH. These conditions can occur alone or in conjunction with LH making a definitive diagnosis difficult. Diagnosis of LH requires a thorough history to determine onset of clinical signs and a description of conditions under which inspiratory stridor or exercise intolerance are present. Physical and lameness examinations and clinicopathologic evaluation (complete blood count and blood chemistry profile) can be used to determine the presence of systemic disease that may be causing exercise intolerance.

Three procedures for external palpation of the larynx have been suggested to aid the diagnosis of LH.[48] First, a prominent muscular process may be palpable on the left side of the patient's larynx in chronic cases of LH in which the left cricoarytenoideus dorsalis is atrophied. Secondly, inspiratory stridor may be elicited by depressing the muscular process on the affected side and reducing the diameter of the laryngeal lumen (arytenoid depression test). Horses with LH have abnormal muscular function and do not resist this manual depression. Lastly, dorsal pressure on the cricotracheal ligament will cause obstruction and inspiratory stridor when there is laxity of the cricotracheal ligament (cricotracheal ligament intrusion test). Laxity of the cricotracheal ligament has been observed in some animals with LH.

The laryngeal abductor (or slap) test should be included as a diagnostic test for LH.[49] Slapping of one side of the withers of a normal horse results in

contraction of laryngeal muscles and adduction of the contralateral arytenoid. Failure of the contralateral arytenoid to adduct suggests it may be paralyzed and supports a diagnosis of LH.

Following a physical examination at rest, the horse should be exercised when feasible, to evaluate the severity of inspiratory stridor at different speeds. Also, nasopharyngeal endoscopy should be done in unsedated animals before and following exercise because endoscopy is important in differentiating between the many causes of upper airway obstruction. Medial displacement of the affected arytenoid cartilage relative to the normal resting position, shortening of the vocal fold on the affected side[48], and reduction of the cross sectional area of the rima glottis[50] have been described in horses with laryngeal hemiplegia.

D. Treatment

Modern surgical procedures (ventriculectomy, vocal cordectomy and arytenoidectomy) used to treat laryngeal hemiplegia are modifications of nineteenth century surgical techniques.[2,4] General anesthesia, allowing long surgical procedures, enabled refinement of techniques and development of new approaches. Ventriculectomy, or removal of the laryngeal ventricle, is thought to lateralize the vocal fold, increasing the cross sectional area of the laryngeal lumen.[14] This technique was developed in the 1800's by Gunther, but it was soon replaced by other procedures. Ventriculectomy was reintroduced by Williams in 1905 and popularized by Hobday in 1936.[4] The larynx is approached through the cricothyroid ligament. The laryngeal ventricle on the side of the affected arytenoid is everted, excised and the wound allowed to heal by second intention. Skin, subcutaneous tissues, and the cricothyroid ligament also heal by second intention. Recommendations for postoperative rest vary from 4-8 weeks or until the skin incision is healed.[4]

In the past, only subjective criteria were used to evaluate the benefit of ventriculectomy for treating LH. Noise reduction following ventriculectomy has been reported in 20%[4] to 30%[8] of patients treated. Fifty to 95%[4,8] of animals are said to show improved athletic performance postoperatively. Suturing of the ventricular orifice after ventrical removal is proposed to further improve performance.[7] Excision of the vocal ligament in conjunction with ventriculectomy is practiced but the efficacy of vocal cordectomy has not been reported.[6]

Although ventriculectomy lateralizes the vocal folds, it may not prevent laryngeal lumen obstruction by the affected arytenoid cartilage during inspiration. Placement of a suture prosthesis to fix the arytenoid cartilage in an abducted position has been described.[5] Briefly, an approach is made between the lingual facial and jugular veins and the omohyoideus muscle. The cricopharyngeal and thyropharyngeal muscles overlying the larynx are exposed. A nonabsorbable suture is inserted in the cricoid cartilage, lateral and parallel to its dorsal midline. Suture material is drawn beneath the cricopharyngeus muscle, advanced cranial, and inserted through the muscular process of the arytenoid cartilage in a medial to lateral direction. Tension placed on the suture pulls the corniculate process of the arytenoid cartilage caudal and lateral, enlarging the laryngeal lumen. The surgical wound is closed in a routine manner. Many surgeons perform a ventriculectomy in conjunction with the laryngoplasty.[5,8,51,52] Restoration of normal anatomic relationships, by lateralization of the affected arytenoid, is one of the criteria used to evaluate the procedure, and Marks reported that in 88% of the cases prosthetic laryngoplasty combined with ventriculectomy reestablished normal anatomic relationships within the larynx.

Classification of the affected arytenoid as fully abducted with normal movement, in an intermediate position with abnormal abduction, or in a paramedian position with no active abduction or adduction, is suggested for

selecting appropriate surgical therapy.[48] Ventriculectomy alone has been suggested to be appropriate for treating animals with an arytenoid in an intermediate position while combined ventriculectomy and prosthetic laryngoplasty have been suggested for treatment when the arytenoid is paralyzed in the paramedian position.[48] The significance of the intermediate position is controversial. Horses with arytenoids which move at different times (asychronous movements) have been diagnosed as being affected with LH.[53] Baker reported that asynchrony or fluttering of the arytenoids, without paralysis, is not an early indication of LH as progression to paralysis does not appear to occur. Thus, asynchronous arytenoid movement may be normal in the horse.

Modifications of the prosthetic laryngoplasty procedure have been reported. They include different surgical approaches (e.g. dorsal to the lingual facial and jugular veins)[54], various materials for the prosthesis or multiple prostheses[55], and laryngoplasty alone or in conjunction with ventriculectomy.[56] Until recently, the efficacy of prosthetic laryngoplasty had been evaluated by subjective criteria, including respiratory noise reduction, endoscopically determined arytenoid position, and athletic performance. Measuring the amplitude of respiratory noise or determining the position of the arytenoid endoscopically are fraught with inter-observer error. Racing performances pre- and postoperatively have been analyzed in an attempt to quantitate improvement in athletic performance.[52,53] Spiers assessed the racing performances of horses receiving one of four procedures involving modifications of prosthetic laryngoplasty.[57] An abductor muscle prosthesis without ventriculectomy, a prosthesis with ventriculectomy, a prosthesis using a horizontal suture pattern in the cricoid with ventriculectomy, and two prostheses with ventriculectomy were compared. There was no statistically significant difference in the success rate with these procedures, but horses receiving laryngoplasty without ventriculectomy appeared to outperform all other animals except those in which two

abductor muscle prostheses had been placed. Animals which received a prosthetic laryngoplasty with two prostheses had better racing performances than animals in which only one prosthesis had been used. Combining ventriculectomy with prosthetic laryngoplasty did not improve racing performance relative to prosthetic laryngoplasty alone.

Postoperative complications after prosthetic laryngoplasty include coughing (especially during feeding), formation of infected suture sinus tracts, laryngeal luminal penetration by the prosthesis[54], nasal discharge of food or water, laryngeal swelling, and dysphagia or choking.[56] Coughing is the most common problem and may result from excessive abduction of the arytenoid, distorting the palatopharyngeal arches, and blocking the lateral food channel.[58]

Arytenoidectomy is usually performed as a salvage procedure following unsuccessful laryngoplasty or used to treat laryngeal obstructions including arytenoid chondritis[9] and ossification of laryngeal cartilages.[59] The surgical approach for this procedure is through the cricothyroid ligament and has been described above. Insufficient exposure of the laryngeal lumen requires extension of the incision through either or both the thyroid and cricoid cartilages.[8] Different portions of the affected arytenoid cartilage may be removed. In a total arytenoidectomy, the entire cartilage is removed while, in a partial arytenoidectomy, the muscular process is left in situ. When the subtotal arytenoidectomy is performed, the corniculate and muscular processes remain. Submucosal dissection of the cartilage is extended laterally and dorsally until the cartilage is removed. The laryngeal mucosa is sutured and the laryngotomy incision is left to heal by second intention.[8] Ventriculectomy and/or vocal cordectomy are sometimes performed in conjunction with the arytenoidectomy.[59] The success rates of partial and subtotal arytenoidectomy procedures have only been subjectively assessed. Pasture soundness and return to athletic function

have been reported.[9,59,60] Complications of total arytenoidectomies include dysphagia and inhalation pneumonia. Those problems may have been partially alleviated by the subtotal and partial arytenoidectomy procedures as they may reduce foreign body aspiration. Although subtotal arytenoidectomy increases laryngeal luminal diameter and exercise tolerance, 36% of the animals in one study[60] exhibited nasal discharge of food or water. Thus, arytenoidectomy appears to improve performance but postoperative complications warrant using it only in cases of upper airway obstruction where prosthetic laryngoplasty is ineffective in enlarging the laryngeal lumen.

Several additional procedures have been advocated for treating laryngeal hemiplegia in other species. Nerve-muscle pedicle transfers for reinnervation of the cricoarytenoideus dorsalis muscle have been successful in humans[61] and dogs,[62] but not in horses.[63] Laryngeal pacemakers, or units providing electrical impulses to abductor muscles of the larynx through nerve-muscle pedicles, have also been investigated. An implantable instrument for muscle stimulation is not available in the horse but it has been shown that lengthening of the trachea during inspiration (as signaled by a strain gauge sutured across tracheal rings) can trigger electrical stimulation of the cricoarytenoideous dorsalis muscle via a nerve-muscle pedicle. This device would maintain upper respiratory function until reinnervation of the nerve-muscle pedicle had occurred.[64]

Laryngeal pacemaker models have been developed to stimulate the cricoarytenoideus dorsalis without relying on nerve-muscle pedicle regeneration in dogs. One type of electrical pacemaker stimulates the cricoarytenoideus dorsalis through electrodes placed within the muscle. The pacemaker is attached to a receiver coil implanted beneath the animals skin. Thoracic movements during inspiration trigger a portable transmitter which signals the implanted receiver coil causing an electrical impulse which stimulates the cricoarytenoideus dorsalis muscle.[65]

Laryngeal pacemakers are not available for clinical use but are attempts to provide a more physiologic means of maintaining respiration during LH.

Until recently, surgical correction of LH has only been evaluated using subjective criteria. Our laboratory has developed a technique for objectively measuring upper airway flow mechanics in normal animals and those with LH. This allows comparison of the efficacy of surgical procedures in reducing airway resistance resulting from laryngeal hemiplegia. Objective evaluation of prosthetic laryngoplasty has been accomplished[10] and it has been shown to be an effective procedure for reducing upper airway resistance caused by laryngeal hemiplegia. In this study, I describe the evaluation of ventriculectomy as a technique for treating left laryngeal hemiplegia in horses and the success of prosthetic laryngoplasty to reduce airway obstruction when animals with LH exercise at high speeds. In the next section of this literature review, I will discuss flow mechanics principles underlying the measurement technique used in the study.

III. Principles of Upper Airway Flow Mechanics

The upper respiratory tract is a dynamic system in which changes in respiratory tract geometry can be evaluated by measuring resistance to gas flow. Poiseuille developed an equation describing laminar flow ($\dot{V}$) in systems of cylindrical tubes as a function of driving pressure (P). Driving pressure is the pressure drop measured across a system. Poiseulle's equation,

$$P = 8\,\mu l / \pi r^4\,\dot{V}$$

incorporates the variables, rate of airflow ($\dot{V}$), gas viscosity within a tube (μ), tube length (l), and tube radius (r).[66] The most commonly described patterns of airflow are laminar, transitional, and turbulent. Laminar flow occurs at low flow rates when air streams are parallel to the sides of straight tubes. Turbulent flow develops at higher flow rates, both within a straight cylinder and at branch points which disrupt the parallel air streams. Transitional flow is a combination of both flow types with laminar flow occuring in straight portions of a system and turbulent flow at branch points. Since the pattern of flow is not constant within the respiratory system, the Reynolds number (Re) should be calculated to determine if flow is laminar, transitional, or turbulent.[67,68] Reynolds number is a dimensionless unit that incorporates gas density (ρ), tube radius (r), gas viscocity (μ), and flow rate ($\dot{V}$) in the following equation

$$Re = \frac{2\rho}{\mu\pi r}\,\dot{V}$$

If Reynolds number is greater than 3,000, turbulent flow will develop in the system. If Reynolds number is less than 2,300, flow is primarily laminar. When the Reynolds number is between 2300 and 3000, transitional flow is present. In systems of laminar flow, Poiseulle's equation will describe the relationship

between pressure and flow. For a particular system, the variables in Poiseulle's equation

$$8ul/\pi r^4$$

can be considered equal to a constant K_1. K_1 represents the mechanical energy loss within the system from laminar flow allowing a simplified equation

$$P = K_1\dot{V}$$

It has been suggested that in bronchioles, flow is probably laminar and that turbulent flow occurs in the central airways especially during exercise when airflows are high.[69]

When flow becomes turbulent, the pressure-flow relationship is dependent on the density of the gas within the system examined and can be described by the equation

$$P = K_2\mu^{0.25} \quad \rho^{0.75} \quad \dot{V}^{1.75}$$

The equation describes the driving pressure for turbulent flow. The effects of incorporating both laminar and turbulent flow on driving pressure can be described by Rohrer's equation

$$P = k_3\mu\dot{V} + k_4\rho\dot{V}^2$$

where k_3 is a constant representing the mechanical energy loss due to laminar flow, μ is the viscosity of the gas, k_4 is the mechanical energy loss due to turbulent flow, and ρ is the denisty of the gas. Changes in k_3 and k_4 reflect changes in respiratory system geometry.[67]

Resistance (R) has been defined as the ratio of the change in pressure over the change in flow ($\Delta P/\Delta\dot{V}$). Resistance is the slope of the tangent to a pressure-flow curve for a particular system measured at a specific $\dot{V}$. Whenever pressure and flow can be measured, resistance can be calculated.

The respiratory system is not composed simply of rigid tubes. Potential energy is stored within the walls of compliant airways. Kinetic energy is present in moving air masses, and frictional energy loss occurs as air streams contact the walls of the airways. Therefore, R is inadequate to describe changes in respiratory system geometry as it only includes resistive or frictional forces and does not describe the combination of resistive, elastic, and/or inertial elements that are present in the respiratory system.[70] Impedance (Z) is a complex parameter that incorporates all three elements (resistive, elastic, and inertial).[70] Impedance represents the magnitude of obstruction to oscillatory flow within the portion of the respiratory system examined. The greater the impedance, the greater the oscillatory pressure difference required to maintain a given flow. Impedance is calculated from the ratio $\Delta P/\Delta \dot{V}$ at a specific frequency of respiration.

During inhalation, a reduction in intraluminal pressure occurs so that intraluminal pressures are negative relative to barometric and extraluminal soft tissue pressures. The effect on the upper respiratory tract is primarily evident at the larynx and nasal ali as these areas are supported by cartilage and muscular contraction is required to abduct cartilage structures and maintain luminal diameter. In addition, the cross-sectional area of the larynx is small relative to the pharynx and trachea.

If the cross sectional area of the larynx decreases, the velocity of flow through that part of the upper respiratory tract increases. Consequently, the intraluminal pressure decreases to allow conservation of energy within the system (Bernoulli's principle) (Figure 1).

Failure of muscular contraction to abduct the arytenoid cartilages, could result in dynamic collapse of the larynx, obstructing airflow. Slight collapse of a portion of the airway will further reduce the cross-sectional area of the respiratory tract causing increased airflow velocity at that point

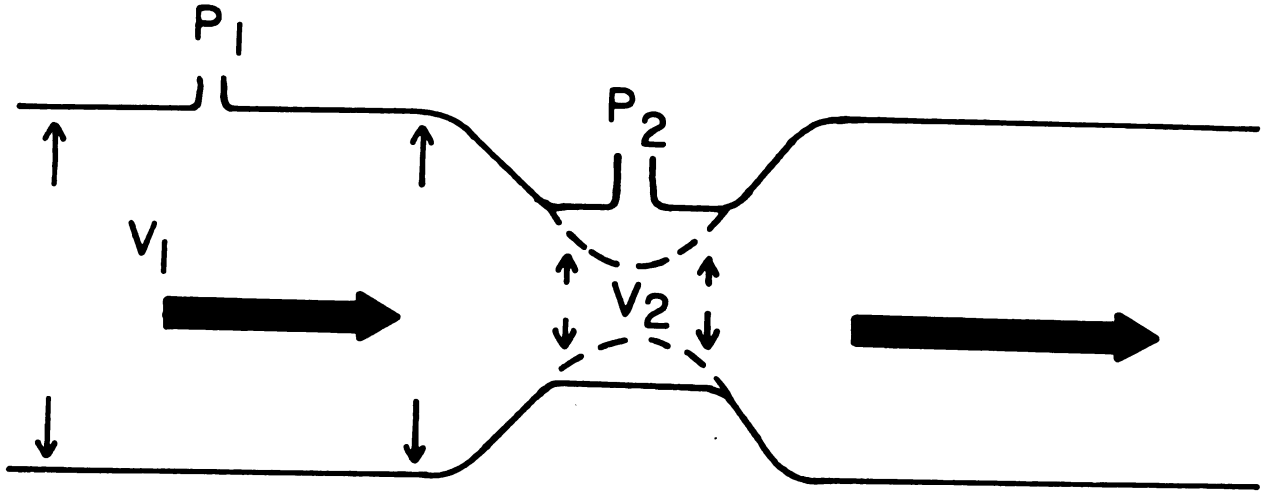

Figure 1. Schematic representation of Bernoulli's effect creating dynamic collapse of a narrowed airway. Velocity of airflow, V_1, increases to V_2 in the narrowed portion of the airway. Concurrently, the intraluminal pressure, P_1, decreases to P_2 in the narrowed part of the airway.

and a further reduction in intraluminal pressure resulting in collapse of the airway. On exhalation, airways do not collapse because the intraluminal pressure is positive relative to barometric pressure and pressure in the extraluminal soft tissues.

In normal animals, the arytenoid cartilages of the larynx can abduct and the nostrils can dilate preventing dynamic collapse of the airways. Animals with LH are unable to dilate the affected arytenoid and dynamic collapse occurs. Increases in upper airway resistance, caused by laryngeal hemiplegia, are alle viated by prosthetic laryngoplasty.[10] The effect of other procedures for treating laryngeal hemiplegia on airway resistance remains to be determined.

When evaluating the efficacy of ventriculectomy and prosthetic laryngoplasty in horses with left laryngeal hemiplegia, I also measured arterial blood gas tensions. The rationale for the use of these measurements in this study is described in the next section of this literature review.

IV. Review of Arterial Blood Gas Tensions in Exercising Horses

Hypoxemia and concomitant normocapnia or hypocapnia have been observed in horses competing in endurance rides.[71] Hypercapnia and hypoxemia have also been measured in horses exercising at high speeds on both a racetrack and treadmill (8.5 m/s).[72,73]

The causes of hypoxemia are

1. reduced concentration of oxygen in inspired air,
2. unevenly matched ventilation and perfusion within the pulmonary system,
3. shunting of blood with low oxygen tension past unventilated regions of the lung,
4. impairment of gas diffusion across the capillary endothelium and alveolar walls, and
5. hypoventilation.[69]

In exercising horses, without pulmonary disease, breathing room air, it is unlikely that the first reason contributes to hypoxemia. Exercise improves matching of ventilation and perfusion in humans, reducing ventilation-perfusion mismatch and shunting.[74] In addition, membrane-diffusing capacity increases as the blood volume of the pulmonary capillary bed increases.[74] Diffusion impairment or unmatched ventilation and perfusion are unlikely causes of the hypoxemia associated with exercise. But, hypoventilation may be a factor. In humans exercising strenuously, respiratory frequency increases and tidal volume decreases.[74] Possibly similar events are occurring in horses. If low oxygen tension results from hypoventilation, then a rise in P_{ACO_2} should be observed. The increase in P_{ACO_2} and concomitant reduction in P_{AO_2} can be predicted from the alveolar gas equation[69]

$$P_{AO_2} = P_{IO_2} - \frac{P_{ACO_2}}{R} + \left[P_{ACO_2} \cdot F_{IO_2} \cdot \frac{1-R}{R} \right]$$

P_{AO_2} is the partial pressure of oxygen in the alveolus, P_{IO_2} is the oxygen ten-

sion of the inspired gas, $P_{A_{CO_2}}$ is the alveolar carbon dioxide tension, and R is the respiratory quotient. The variables in parentheses provide a correction factor (F) when air is breathed. $F_{I_{O_2}}$ is the fractional concentration of the inspired gas and R is the ratio of CO_2 production to oxygen consumption. A simplification of the equation is:

$$P_{A_{O_2}} = P_{I_{O_2}} - \frac{P_{A_{CO_2}}}{R} + F$$

The equation provides a useful estimate for $P_{A_{O_2}}$. Alveolar carbon dioxide tension is assumed to be equivalent to arterial carbon dioxide tension and the latter is more easily measured.[69,74] From the equation

$$P_{I_{O_2}} = (P_B - P_{H_2O}) F_{I_{O_2}}$$

where barometric pressure (P_B), water vapor pressure (P_{H_2O}), and $F_{I_{O_2}}$ are known, $P_{I_{O_2}}$ can be calculated.

If $P_{I_{O_2}}$ was 147 mmHg and Pa_{CO_2} was measured as 45.0 Torr, the alveolar gas equation would predict a P_{AO_2} of 90.7 Torr. If Pa_{CO_2} was measured as 50 Torr, the predicted P_{AO_2} would be 85.4 Torr. Hypoxemia in horses exercising near maximal velocity has been reported to be as low as 61.5 Torr.[72] Therefore, additional mechanisms have been suggested to explain the severe hypoxemia of exercise. It is possible that increased cardiac output during exercise causes decreased transit time of red blood cells through the pulmonary capillary vasculature so the cells do not become fully saturated with oxygen.[75] Reduced alveolar oxygen tension may also result from a process called stratification whereby the distance that oxygen must diffuse is increased because of the large dead space in large species relative to smaller species.[75]

One study attempted to determine if pharyngeal lymphoid hyperplasia (PLH) impaired athletic performance by causing airway obstruction.[76] Blood gas tensions were measured in exercising horses and no significant differences were

observed before and following chemical induction of pharyngitis. It was suggested that upper airway obstruction was not a cause of exercise intolerance in lymphoid hyperplasia because oxygen tensions were unchanged. But, a controlled study correlating airway obstruction from pharyngeal lymphoid hyperplasia and changes in blood gas tensions has not been reported. Arterial blood gas tensions and acid-base balance were measured in one horse with laryngeal hemiplegia.[77] Hypercapnea and severe hypoxemia (Pa_{O_2} - 53.2 Torr, Pa_{CO_2} 58.1 Torr) were measured during exercise, before any surgical intervention. The oxygen and carbon dioxide tensions improved following prosthetic laryngoplasty without ventriculectomy (Pa_{O_2}-83.6 Torr, Pa_{CO_2}-39 Torr). The study suggested that hypoxemia occurring in normal exercising horses may worsen when upper airway obstruction is present and that some surgical procedures may be effective in improving blood gas tensions.

In this thesis, I propose to correlate changes in blood gas tensions and acid-base balance with measurements of upper airway flow mechanics parameters before any surgical intervention, in horses with laryngeal hemiplegia induced by recurrent laryngeal neurectomy, and following corrective surgical procedures (ventriculectomy and prosthetic laryngoplasty). If a correlation between upper airway obstruction and blood gas tensions was found, measurement of blood gas tensions could be helpful in diagnosing upper respiratory obstructive disease and monitoring responses to procedures for treating the obstruction.

V. Effect of Ventriculectomy, Prosthetic Laryngoplasty and Exercise on Upper Airway Function in Horses with Left Laryngeal Hemiplegia

A. Materials and Methods

Subjects -- Five adult horses (4.6 ± 0.8 years of age, weighing 464 ± 23 kg [$\bar{X}$ ± SEM]) were used in the experiments. Horses were immunized against the common respiratory virus infections (equine influenza and rhinopneumonitis) and were pastured for one month prior to training. On endoscopic examination of the upper airway, no abnormalities were found in any horse prior to the experiments. Horses were trained to wear a face mask while walking, trotting, and galloping over a 30 day period on a treadmill.[a] Animals were induced for all surgical procedures with glycerol guiacolate[b] (500 ml of a 10% solution) and thiamylal[c] (2 grams) given intravenously to effect, followed by endotracheal intubation and maintenance on halothane and oxygen in a semiclosed circle anesthetic system.

Measurement Techniques--To measure inspiratory and expiratory airflow rates, a fiberglass facemask was placed over the horse's nose and sealed to the face with a rubber shroud. The mask allowed unimpeded dilation of the nostrils. A 14 cm diameter pneumotachograph[d] was mounted on the face mask (Figure 2). To reduce mask pressure inhomogeneity, a flow straightener element[e] was interposed between the external nares and the pneumotachograph. The combined resistance of the mask-pneumotachograph assembly was 0.04 cm H_2O/L/sec up to a flow rate of 70 L/sec. Pressure changes across the pneumotachograph were measured using a differential pressure transducer.[f] After each experiment, the pneumotachograph-

[a] Jetline, DeSales Inc, Sand Lake, Mich.

[b] Glycerol guiacolate, Guaiacol Glyceryl Ether USP, Aceto Chemical Co., Flushing, NY.

[c] Biotal, Biocentic Division, Boehringer Ingelheim Animal Health Inc., St. Joseph, MO.

[d] Marian 6" Laminar Flow Straightener Element, Meriam Instruments, Grand Rapids, Mich.

[e] Mesh SS screen, McMaster-Carr, Chicago, Ill.

[f] Model DP 45-22, Validyne Sales, Northridge, Calif.

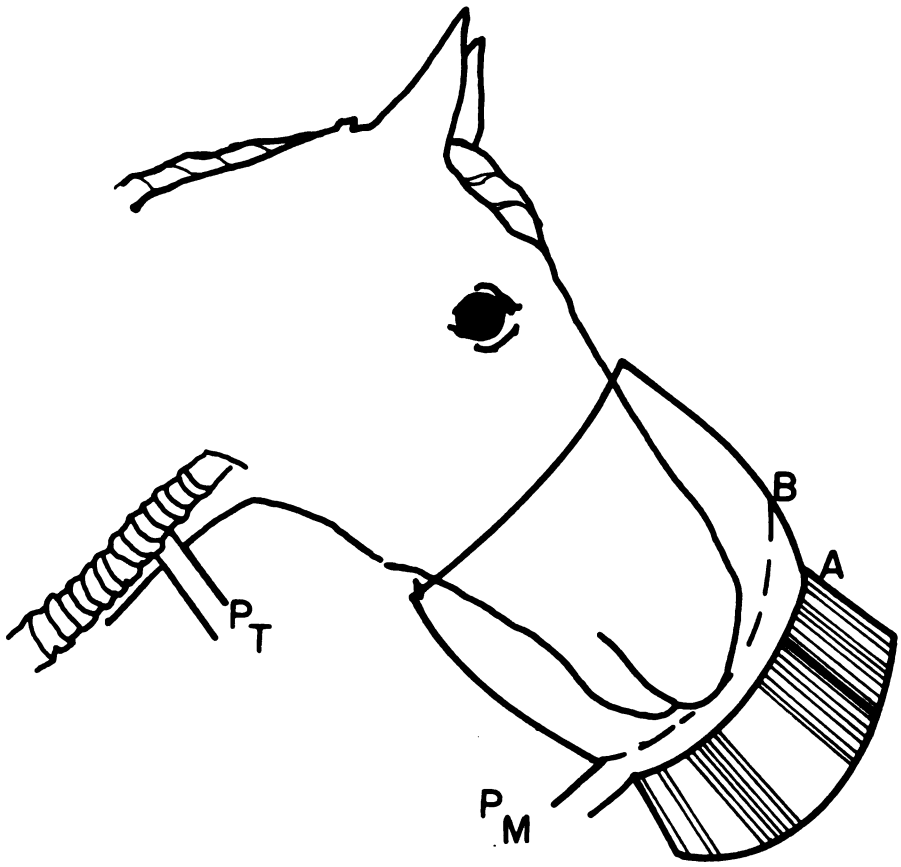

Figure 2. Schematic representation of the face mask with the 14 cm diameter pneumotachograph (A) and flow straightener element (B). Sites for measurement of lateral tracheal pressure (P_T) and mask pressure (P_m).

transducer system was calibrated, using a rotameter flow meter[g] capable of measuring flow rates up to 90 L/sec.

Transupper airway pressure (Pu) was defined as the pressure difference between a side hole catheter in the trachea[10] and barometric pressure (P_B). The Pu was measured using a differential pressure transducer.[h] To avoid phase differences between flow and pressure signals caused by equipment, signals were synchronized up to 10 Hz.[78] All signals were recorded on a physiograph.[i]

Because inertia and airway deformation result in complex upper airway pressure and flow relationships at high respiratory flow rates,[70] pressure and flow signals generated during exercise were not in phase. Therefore, peak Pu on inspiration and expiration (Pu_I and Pu_E, respectively) as well as peak airflow rates on inspiration and expiration ($\dot{V}_I max$ and $\dot{V}_E max$) were measured for a given breath.[10,70] Both inspiratory and expiratory impedance (Z_I and Z_E) were calculated[70] from the ratio of peak pressure and flow measurements which were averaged for at least 10 breaths. Respiratory frequency (f) was determined from the physiograph tracing. Heart rate (HR) was measured using a base apex lead system and a heart rate computer.[j]

Arterial oxygen and carbon dioxide tensions (Pa_{O_2} and Pa_{CO_2}) hemoglobin content (Hb), bicarbonate concentration (HCO_3^-), and pH, were measured in samples taken from an exteriorized right carotid artery. Analyses were performed using a blood gas analyzer.[k] Gas tensions were corrected for rectal blood temperatures using standard equations.[79]

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[g] Model FP-2-37-P-10/77, Fisher and Porter Co, Warminster, Pa.

[h] Model DP 45-34, Validyne Sales, Northridge, Calif.

[i] Model 8188, Gould Inc, Madison Hts, Mich.

[j] Equistat, Equine Biomechanics and Exercise, Unionville, Pa.

[k] Model AB21, Radiometer, Copenhagen, Denmark.

Experimental Design--Measurements were made with horses on a treadmill (incline 6.38°) while standing, trotting at 4.3 m/s, and galloping at 7.2 m/s. While trotting and galloping, horses were exercised for 2 minutes and data was obtained during the last minute of each exercise period. Horses were allowed to rest for two minutes between exercise periods or until their heart rate was below 80/min.

Experiments were performed in healthy horses before surgical intervention (baseline), 14 days following left recurrent laryngeal neurectomy[10], 30 days after left ventriculectomy as described by Hobday[4] and 14 days following a modification of the prosthetic laryngoplasty procedure as described by Marks et al.[5] A silicone treated polyester fiber[l] suture material was substituted for the elastic suture material used by Marks et al. In addition, surgical needles were used to insert the prosthesis through the cricoid cartilage and muscular process of the arytenoid cartilage (Martin's uterine, 1/2 circle, cutting edge 1860-3D and 1860-6D[m], respectively).

Statistical Analysis--A two-way analysis of variance was used to evaluate the effects of exercise and the surgical procedures on upper airway flow mechanics, blood gas tensions and heart rate. When F values were significant at $P < 0.05$, treatment means were compared using Tukey's ω procedure.[14]

B. Results

Prior to surgical intervention (baseline), increasing treadmill speed from standing to the trot and gallop progressively increased HR, f, $\dot{V}_{I}max$, $\dot{V}_{E}max$, Pu_{I}, Pu_{E}, Hb, and Pa_{CO_2}, and decreased Pa_{O_2}, pH, and HCO_3^-, while Z_I and Z_E were unchanged (Table 1).

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[l] 5 Ticron, American Cyanamid Co, Pearl River, New York.

[m] Martins Uterine Needles, Anchor Products Co., Addison, IL.

Table 1 Effects of exercise on upper airway flow mechanics values, blood gas tensions, and acid base parameters in five horses before surgical intervention.

	Exercise		
Value	Standing	Trotting	Galloping
HR(min^{-1})($\bar{X}\pm SE$)	41.2±4.2	143.6±18.5[a]	192.0±8.4[a]
f (min^{-1})	15.6±3.1	67.2±3.5[a]	88.8±7.5[a]
$\dot{V}_{Imax}$ (L/s)	4.3±.5	38.0±4.7[a]	56.3±3.2[a,b]
$\dot{V}_{Emax}$ (L/s)	4.9±1.0	40.7±5.4[a]	59.0±3.6[a,b]
Pu_I (cm of H_2O)	2.7±.4	20.9±3.8[a]	29.7±4.0[a,b]
Pu_E (cm of H_2O)	1.8±.4	9.5±2.0	11.9±1.5[a]
Z_I (cm of H_2O/L/s)	.63±.08	.53±.06	.52±.06
Z_E (cm of H_2O/L/s)	.43±.11	.22±.02	.21±.03
Pa_{O_2} (Torr)	94.6±3.6	67.6±1.7[a]	55.6±2.9[a,b]
Pa_{CO_2} (Torr)	37.8±.9	41.2±.3	43.7±1.4[a]
pH	7.414±.007	7.357±.016	7.279±.012[a,b]
HCO_3^- (mEq/L)	23.8±.5	22.7±.9	20.0±1.0[a]
Hb (gm/dl)	12.6±.9	16.5±.3[a]	17.2±.3[a,b]

a Data significantly different from same measurement made while standing.

b Data significantly different from same measurement made while trotting.

Following recurrent laryngeal neurectomy, Z_I and Pu_I (Figure 3a and 4a) were significantly increased at the trot and gallop compared to baseline. These increases were unattenuated by ventriculectomy but were reversed after prosthetic laryngoplasty. No significant differences in Z_E and Pu_E (Figure 3b and 4b) were observed between baseline measurements and those made following any surgical manipulation while animals were standing or moving at any treadmill speed.

When compared with baseline measurements at the gallop, $\dot{V}_I max$ (Fig 5a) was significantly decreased following recurrent laryngeal neurectomy. $\dot{V}_I max$ measured following ventriculectomy or prosthetic laryngoplasty was not significantly different from baseline measurements. Following recurrent laryngeal neurectomy, $\dot{V}_E max$ at the gallop (Fig 5b) was unchanged compared to baseline measurements. A significant reduction in $\dot{V}_E max$ measured following ventriculectomy was reversed by prosthetic laryngoplasty.

Following recurrent laryngeal neurectomy, f at the gallop (Fig 6) decreased concomitant with an increase in Pa_{CO_2} (Fig 7a) when compared with baseline measurements. Pa_{CO_2} and f were not statistically different from baseline measurements following ventriculectomy or prosthetic laryngoplasty.

When compared with baseline measurements, left recurrent laryngeal neurectomy, ventriculectomy, and prosthetic laryngoplasty had no effect on Pa_{O_2} (Fig 7b), HR (Fig 8), pH (Fig 9), or Hb (Fig 10). However, in standing horses following ventriculectomy, there was a slight but statistically significant increase in Pa_{CO_2} (Fig 7a) and HCO_3^- (Fig 11).

C. Discussion

Inspiratory and expiratory impedance remained unchanged with exercise while significant increases in heart rate, respiratory frequency, inspiratory and expiratory flow, inspiratory and expiratory pressure, arterial carbon dioxide

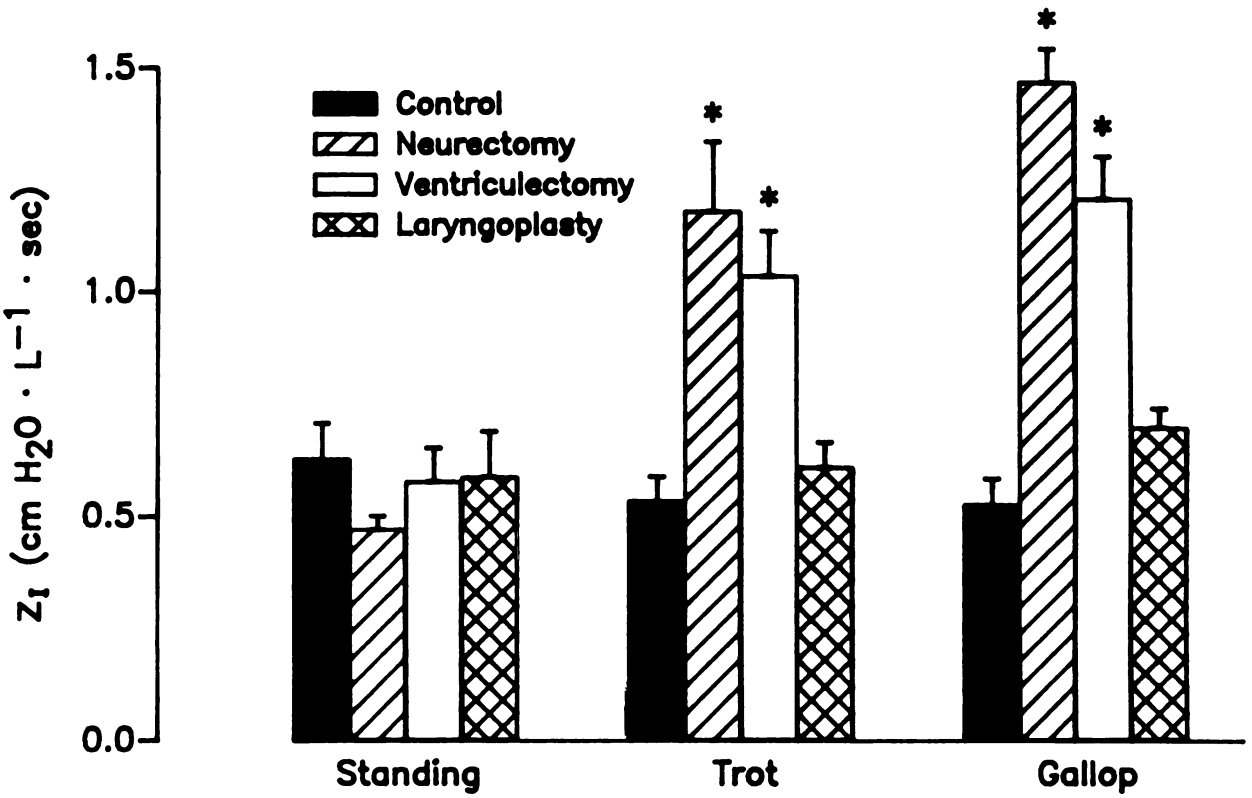


Figure 3a. Inspiratory impedance at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention)

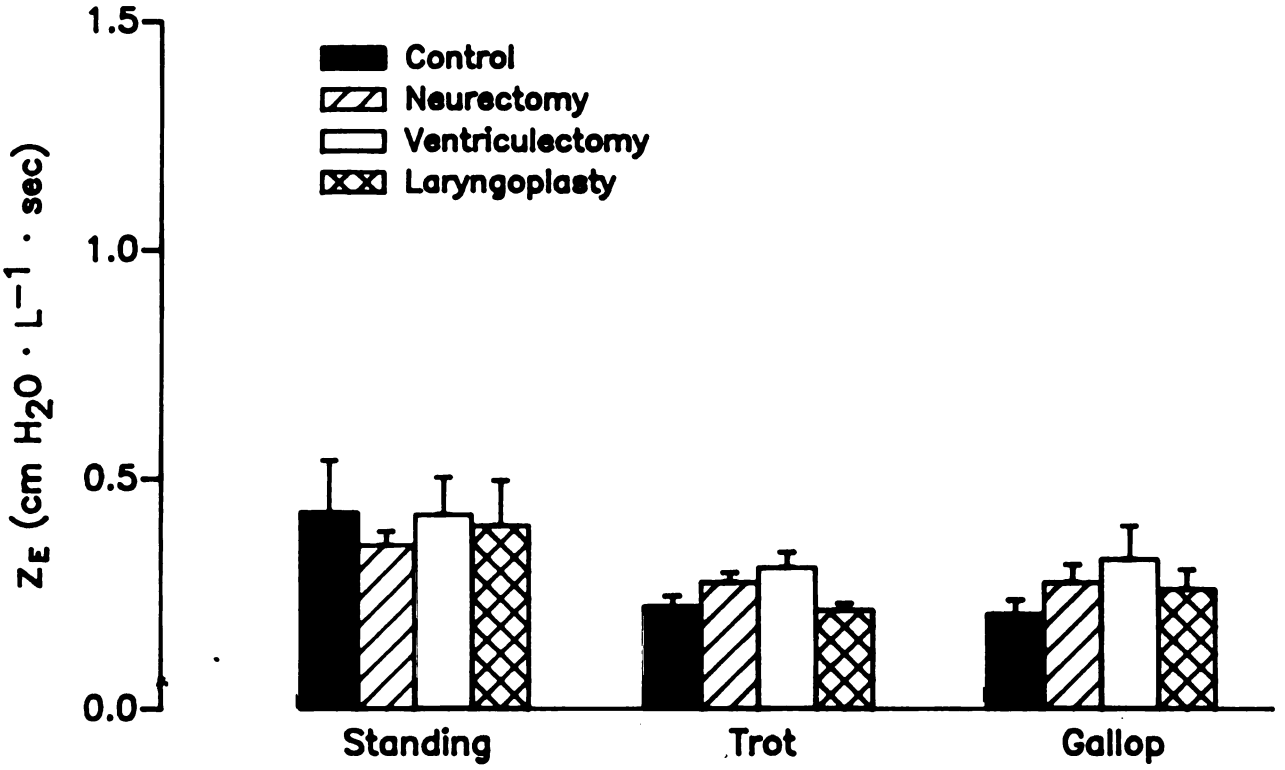


Figure 3b. Expiratory impedance at three levels of exercise before and after surgical intervention.

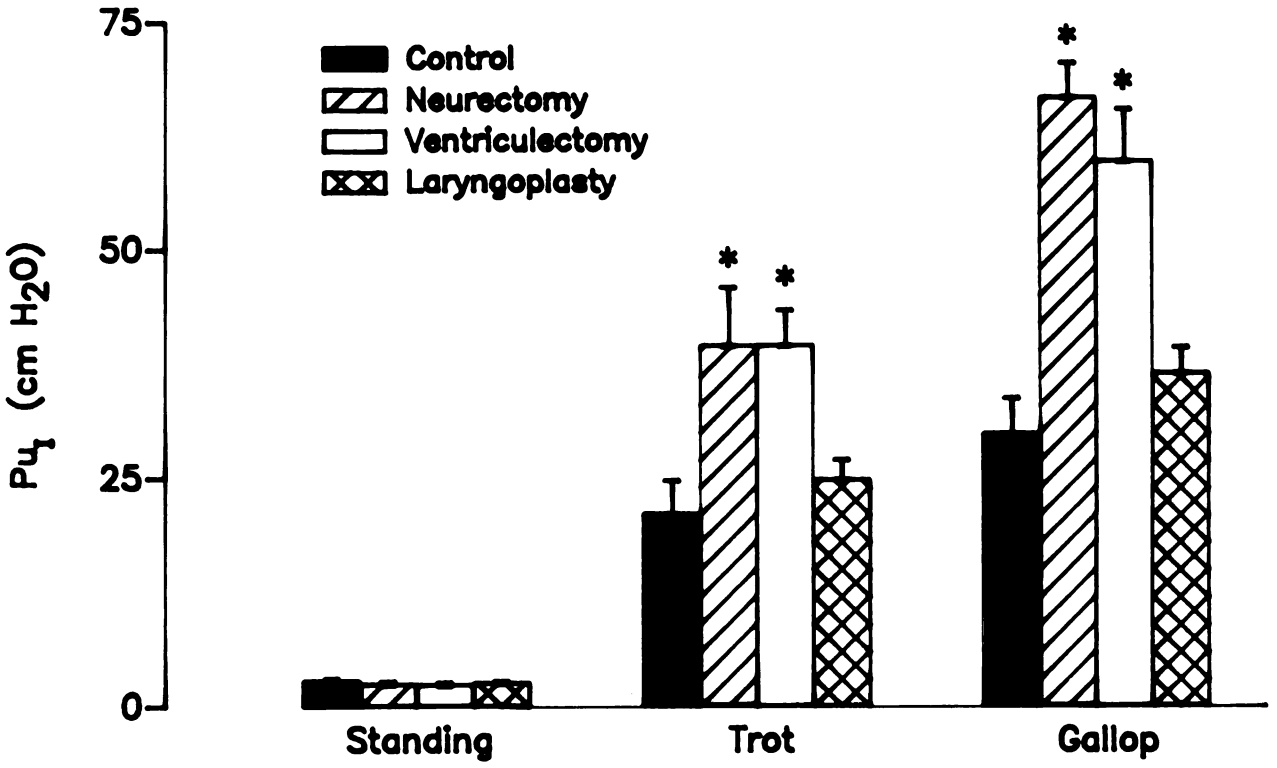


Figure 4a. Peak transupper airway inspiratory pressure at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).

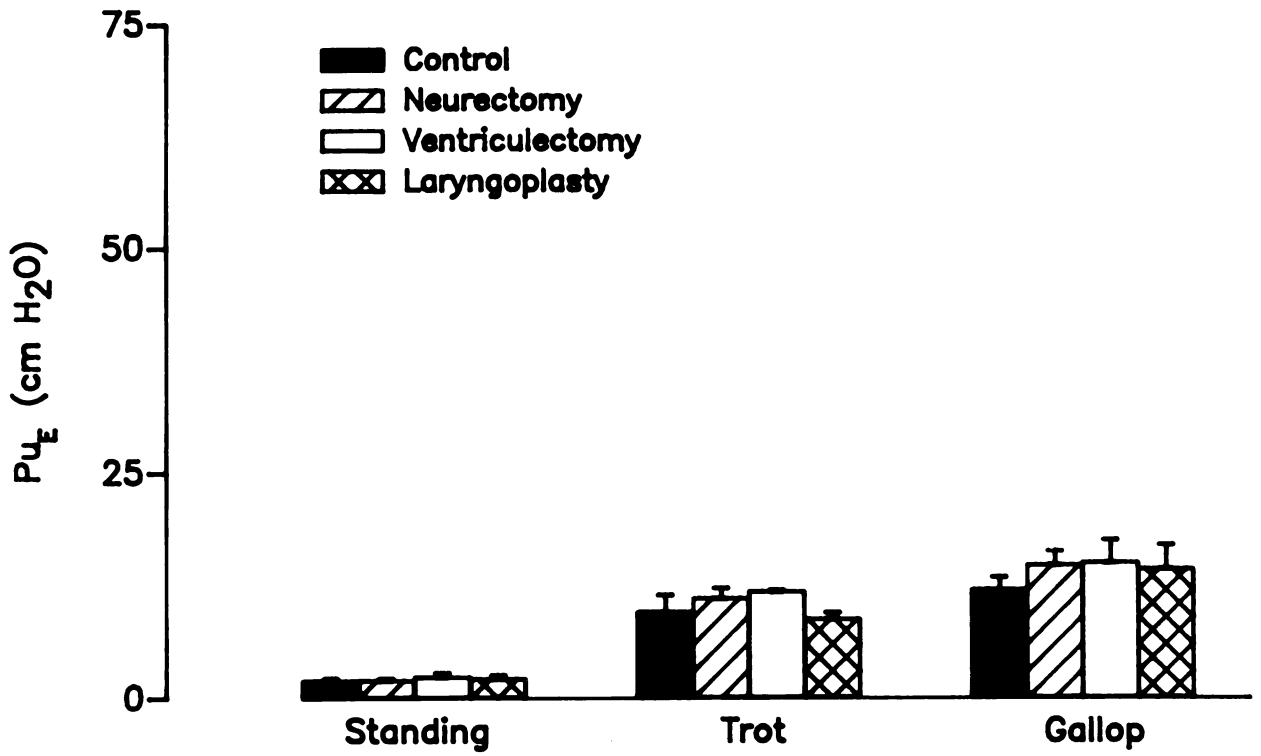


Figure 4b. Peak transupper airway expiratory pressure at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).

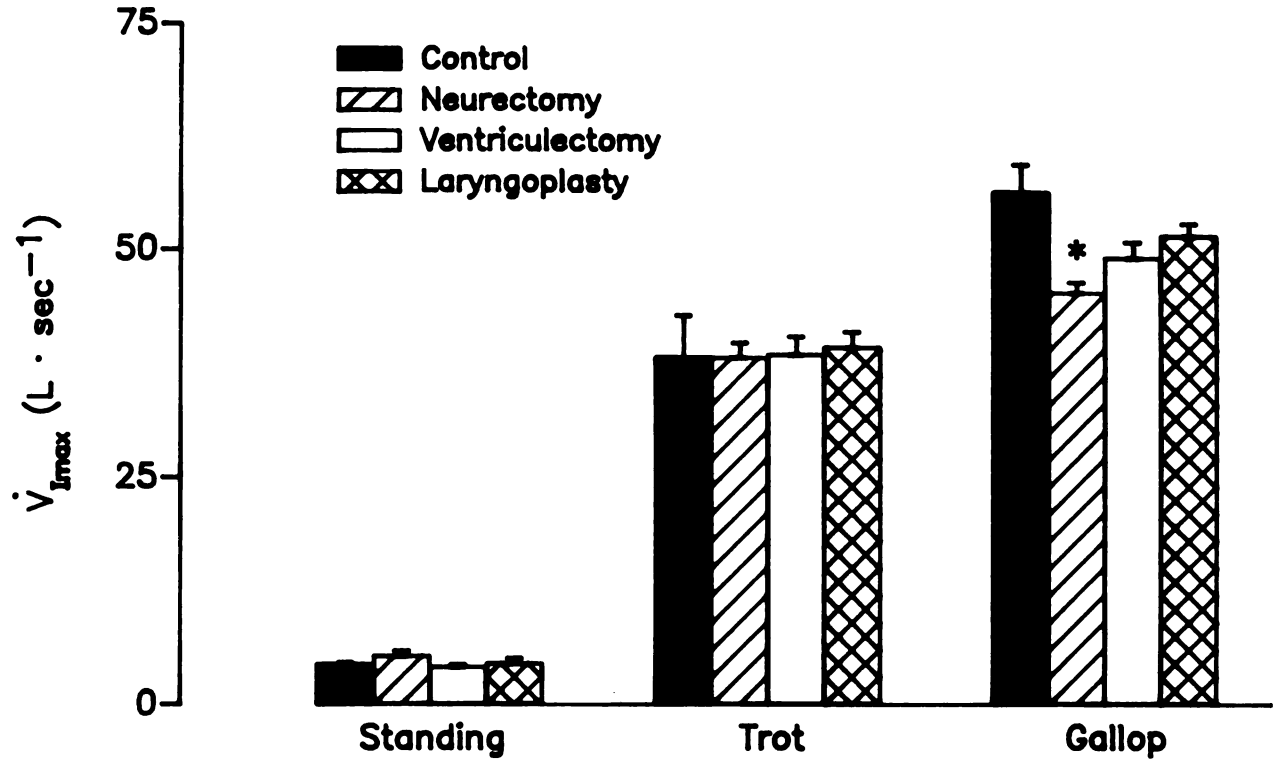


Figure 5a. Maximal inspiratory flow at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).

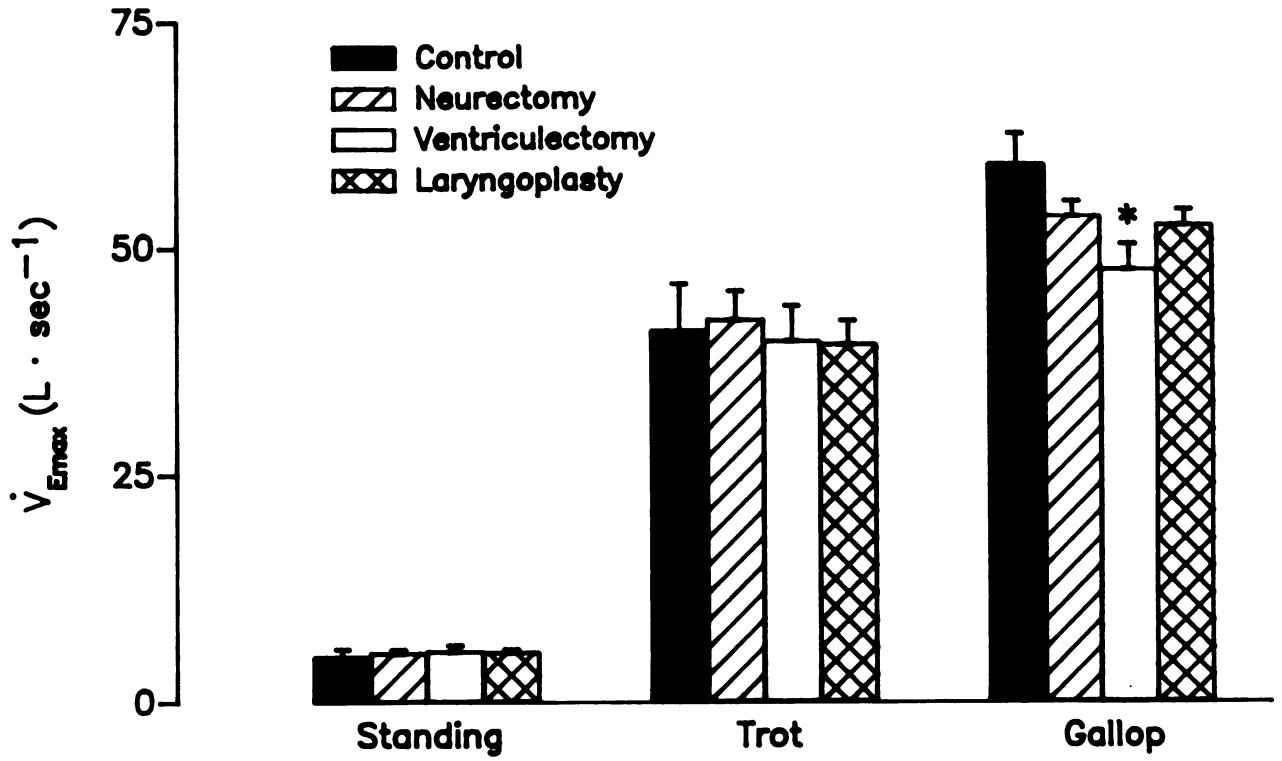


Figure 5b. Maximal expiratory flow at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention)

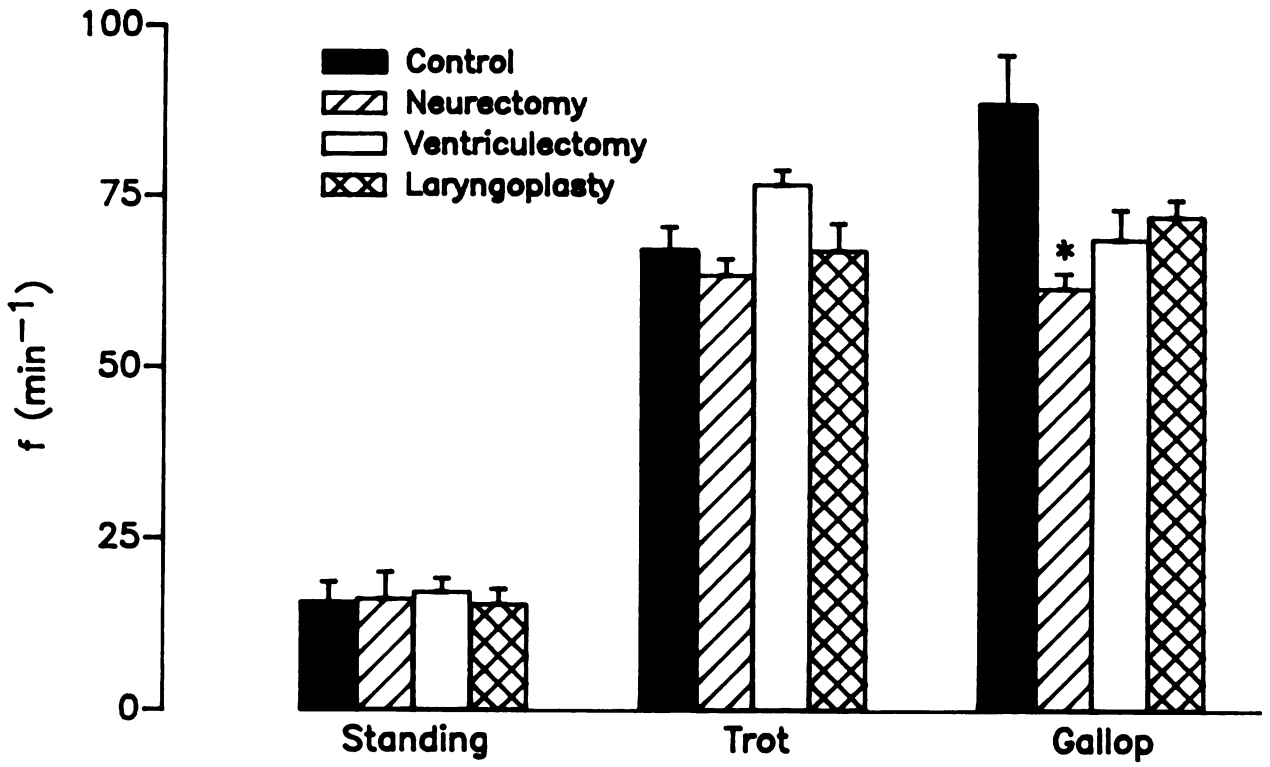


Figure 6. Respiratory frequency at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).

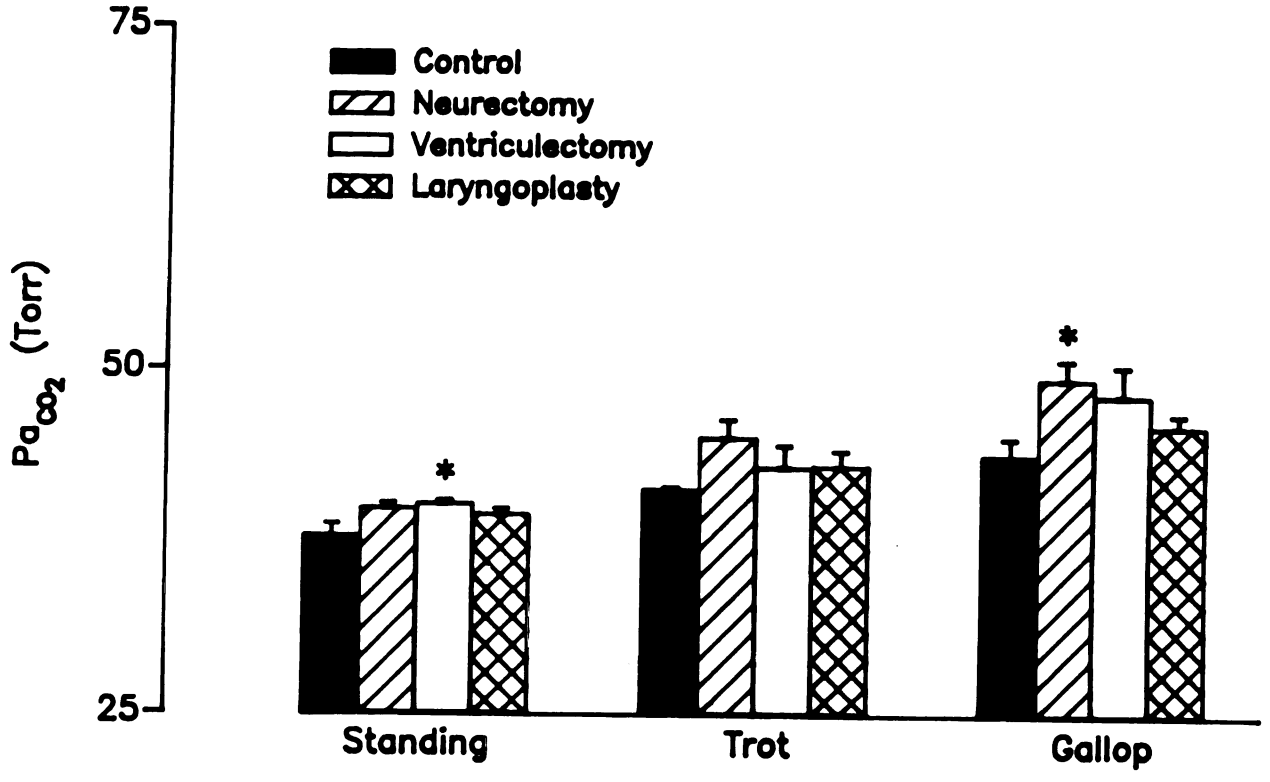
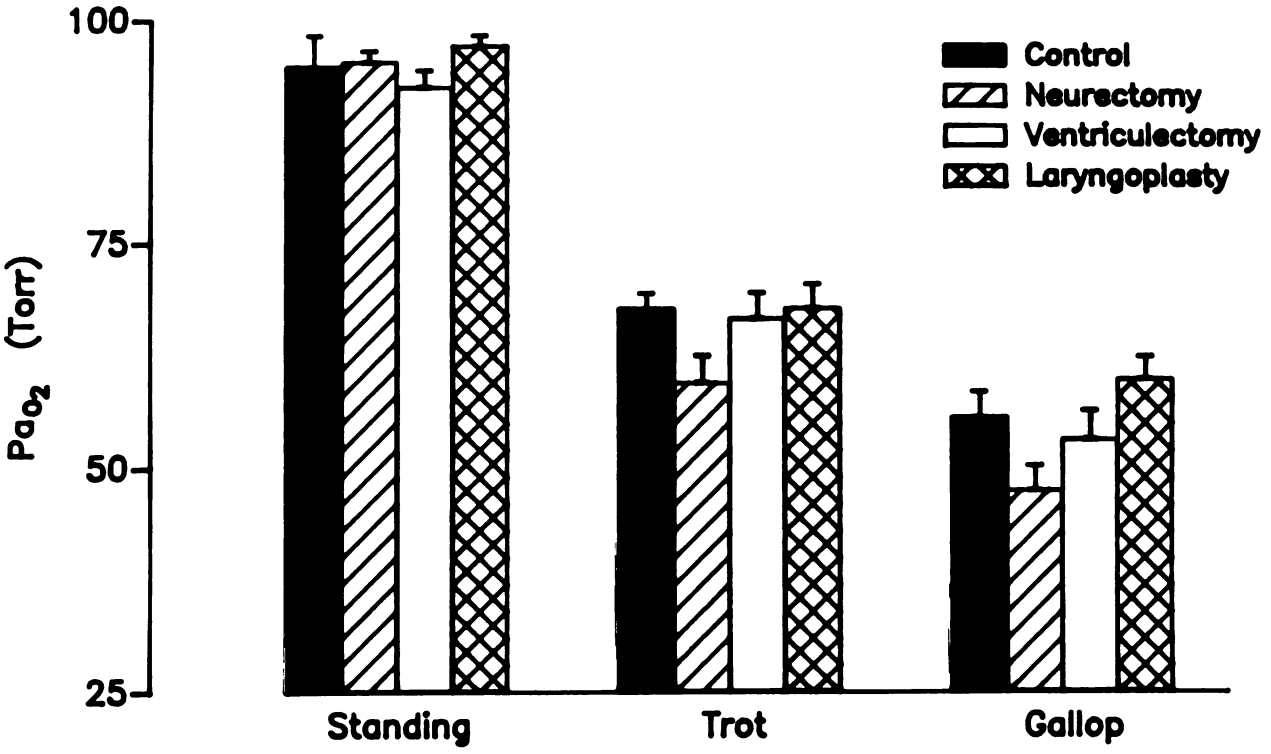


Figure 7a. Arterial carbon dioxide tension at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).



7b. Arterial oxygen tension at three levels of exercise before and after surgical intervention.

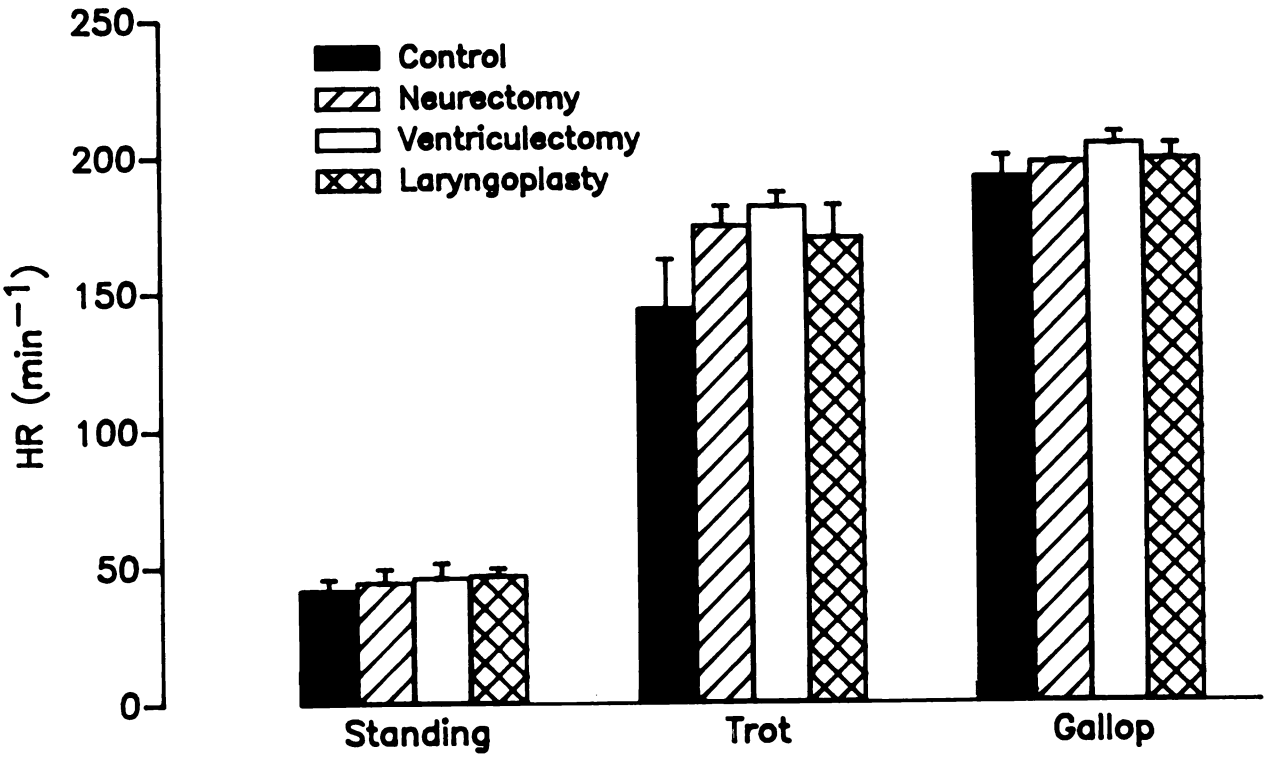


Figure 8. Heart rate at three levels of exercise before and after surgical intervention.

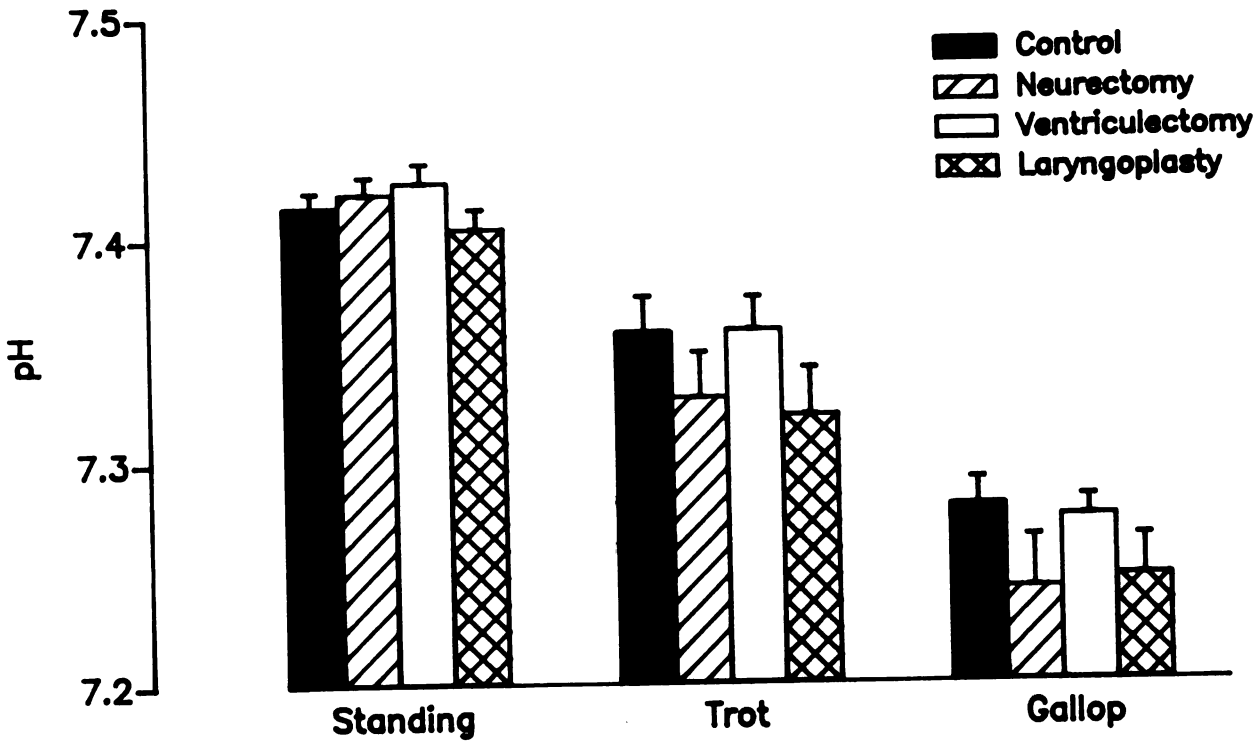


Figure 9. pH at three levels of exercise before and after surgical intervention.

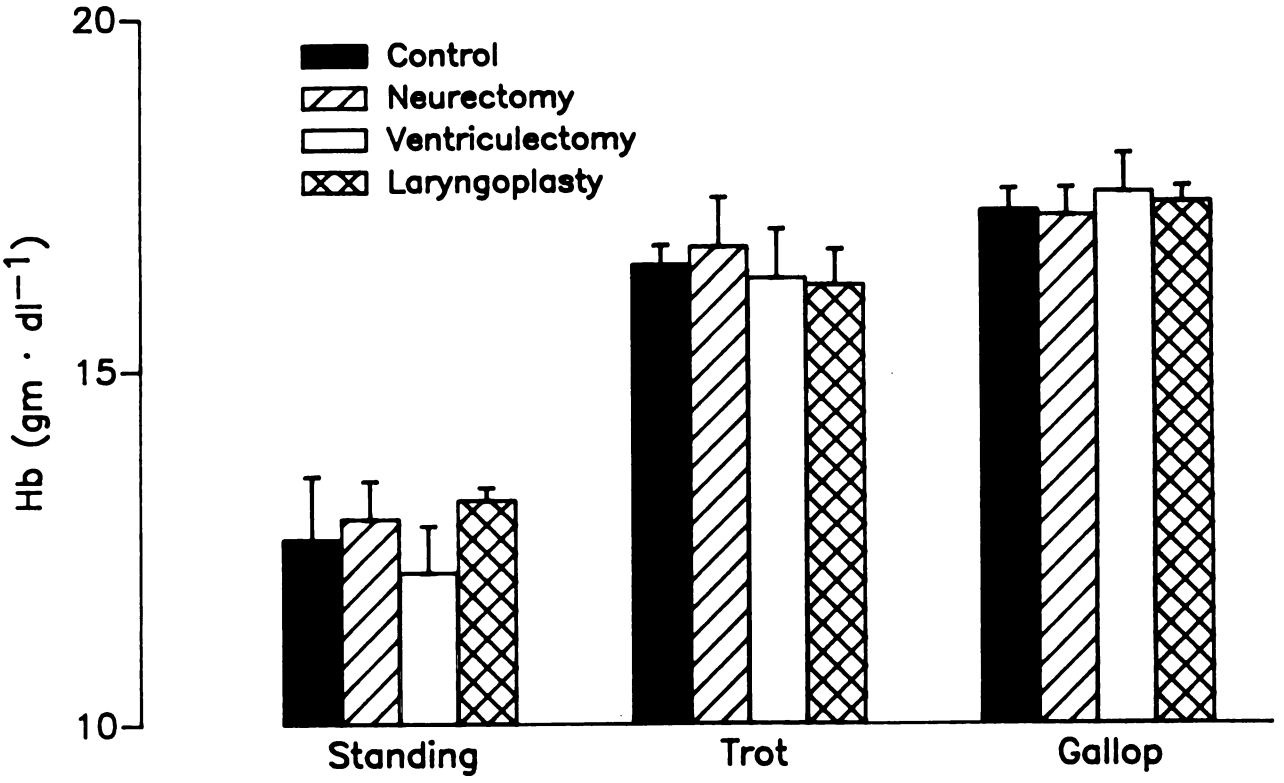


Figure 10. Hemoglobin eoncentration at three levels of exercise before and after surgical intervention.

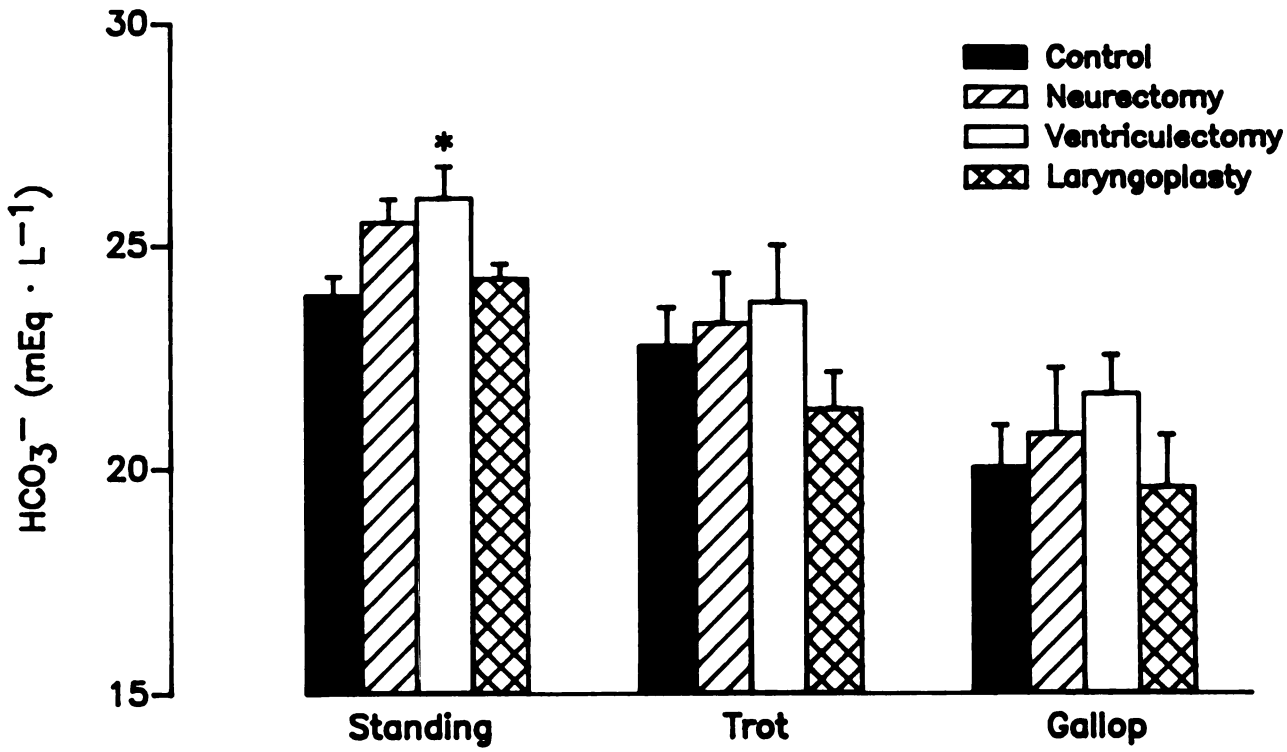


Figure 11. Bicarbonate concentration at three levels of exercise before and after surgical intervention. The asterisk (*) indicates the value is significantly different from baseline (before surgical intervention).

tension and hemoglobin concentration were measured. Concurrently, significant decreases in arterial oxygen tension, bicarbonate concentration, and pH were measured (Table 1). Exercise results in tachypnea as well as progressive hypoxemia, metabolic acidosis, and hemoglobinemia. Other investigators have reported similar results.[73,75,81] During exercise, left recurrent laryngeal neurectomy increases inspiratory impedance in the upper airway requiring larger driving pressures (Pu_I) to generate $\dot{V}_I max$ equivalent to those measured prior to surgical intervention. As the work of breathing increases, the ventilation response to CO_2 is reduced[69] and may in part explain the hypercapnia measured at the gallop following left recurrent laryngeal neurectomy.

The larynx and nostrils are not ridgedly supported by bone or cartilage and require muscular contraction to dilate and maintain a constant upper airway intraluminal diameter during inspiration. Muscle contraction prevents dynamic collapse of the airway and increased inspiratory impedance, especially during exercise. Following left recurrent laryngeal neurectomy inspiratory impedance increases, presumably as a result of altered airway geometry and intraluminal obstruction by the paralyzed arytenoid and vocal ligament. Therefore, when compared with baseline measurements at a given treadmill speed, inspiratory pressure must increase to prevent a decrease in inspiratory flow.[70]

Following ventriculectomy, healing of the everted laryngeal saccule by fibrous scar tissue is thought to enlarge the diameter of the glottis by lateralization of the vocal cords.[14] Some investigators report that retraction of the paralyzed vocal ligament or arytenoid is not evident on endoscopic examination.[6,14] The results of our study show that ventriculectomy failed to alleviate the increased inspiratory impedance and the increased inspiratory transupper airway pressure observed in exercising horses following left

recurrent laryngeal neurectomy. In contrast, prosthetic laryngoplasty effectively improved upper airway flow mechanics returning inspiratory impedance and pressure to baseline values. Therefore, if lateralization of the vocal cords occurs following ventriculectomy, it is insufficient to prevent dynamic collapse of the upper airway during exercise. Instead, it appears that stabilization of the arytenoid cartilage by laryngoplasty is necessary to improve upper airway flow mechanics in exercising horses with left laryngeal hemiplegia.[10]

The effect of ventriculectomy was evaluated 30 days following the surgical procedure when the fibroblastic phase of healing is complete in most tissues.[82] It is therefore unlikely that additional time between ventriculectomy and the measurement periods would have significantly altered the results of this study.

Flow rates obtained in this study ($\bar{X} \pm$ SEM, 59.0 $\pm$ 3.6) were higher than those previously reported by our laboratory[10] and were similar to those attained by racing horses.[83,84] Because the tendency for dynamic collapse of unsupported structures increases as inspiratory flow rate increases[85], our conclusions regarding the effectiveness of ventriculectomy and prosthetic laryngoplasty may be applicable to conditions encountered during racing.

Either procedure, the ventriculectomy or prosthetic laryngoplasty, increases inspiratory flow ($\dot{V}_{I}max$) at the gallop when compared with measurements following recurrent laryngeal neurectomy. This suggests ventriculectomy alone may improve inspiratory flow. This result must be interpreted with caution as the pressure difference across the airway causing the airflow (Pu_I) was still significantly elevated at the gallop when compared with baseline measurements. However, the decrease in expiratory flow ($\dot{V}_{E}max$) at the gallop following ventriculectomy when compared with baseline measurements and those made following ventriculectomy, or prosthetic laryngoplasty, suggest ventriculectomy does reduce expiratory flow as expiratory pressure (Pu_E) is not significantly reduced when compared with base-

line measurements. Possibly, the fibrosed ventricle following ventriculectomy may cause partial obstruction of the airway or reduce airway compliance.

The reduction of respiratory frequency at the gallop following recurrent laryngeal neurectomy probably resulted from the high inspiratory impedance.[86] High inspiratory impedance limited inspiratory flow rates, and therefore necessitated a reduction in respiratory frequency in order to maintain alveolar ventilation. In spite of this change in respiratory pattern, hypoventilation at the gallop still occurred. At the gallop, respiratory frequency is coupled with stride frequency.[87] Although we did not measure stride frequency or stride length, if the coupling persisted in our horses with left laryngeal hemiplegia, stride frequency must also have been reduced from control values. Alternatively, increased stride length, uncoupling of stride, and respiratory frequency or a change in the coupling ratio between stride and respiratory frequencies could have occurred.

As has been previously reported, hypoxemia occurs in galloping horses even without left recurrent laryngeal neurectomy. Blood gas tensions are routinely corrected to rectal temperature. Increases in arterial blood temperature in exercising horses has been previously reported[88], though many studies use rectal temperature to correct for temperature effects on blood gases.[77,89] In a separate experiment, right carotid artery blood temperature and rectal temperature were concurrently measured in two horses using the same exercise protocol described above. Arterial temperatures were measured using a 6 French thermistor-tipped catheter[n] and a thermodilution computer.[o] Rectal temperatures remained unchanged while arterial blood temperatures increased markedly. For each horse evaluated, arterial temperature increased at the trot and gallop,

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[n] American Edwards Lab, Irvine, Calif.

[o] Model 9520A Cardiac Output Computer, American Edwards Lab, Irvine, Calif.

1.6°C and 3.1°C, respectively, from a temperature of 36.6° measured while standing. This suggests that during short periods of exercise as employed in this study, rectal temperature is inappropriate for correcting blood gas tensions as equilibration between core temperature and rectal temperature does not occur. Therefore, for comparison, blood gas tensions were corrected again for estimated changes in arterial blood temperature for each measurement period, and the results are presented in Table 2. Unless otherwise mentioned, Pa_{O_2} and Pa_{CO_2} discussed in the remainder of the paper refer to values obtained after correction for rectal temperature.

Before surgical intervention, mean Pa_{O_2} decreased significantly from 94.6 torr while horses were standing to 55.6 torr at the gallop. Hypoxemia of similar magnitude has been previously reported in exercising horses.[72,73] The mechanism for the decrease in Pa_{O_2} is unknown but hypoventilation is not the sole cause.[69] Because the Pa_{O_2} was unaffected by any of the surgical interventions, exercise intolerance associated with left laryngeal hemiplegia is not due to arterial hypoxemia.

Bisgard has suggested that face masks may change the ventilation pattern during exercise and alter respiratory frequency and arterial blood gas tensions in exercising ponies.[75,86,90] It is possible that the face mask may have caused hypoventilation by increasing dead space and thus altered arterial blood gas tensions.[75] However, the baseline Pa_{CO_2} corrected for arterial temperature (49.2 Torr) was similar to previously reported values for horses[72,73] exercising without a face mask. This suggests the face mask did not alter Pa_{CO_2}.

In conclusion, ventriculectomy was ineffective in correcting upper airway mechanical impairments to flow in exercising horses with left laryngeal hemiplegia. However, even when exercising at high speeds, upper airway obstruction in horses with left laryngeal hemiplegia was successfully corrected using prosthetic laryngoplasty.

Table 2 The effects of exercise on arterial oxygen and carbon dioxide tensions following correction for mean arterial blood temperature (A) or mean rectal temperature (R) in two horses.

	Exercise		
Value	Standing	Trotting	Galloping
Pa_{O_2} Torr (A)	92.3	68.1	66.9
Pa_{O_2} Torr (R)	94.6	67.6	55.6
Pa_{CO_2} Torr (A)	37.2	43.4	49.2
Pa_{CO_2} Torr (R)	37.8	41.2	43.7

VI. Summary and Conclusions

1. A technique was developed to measure upper airway impedance in exercising horses.

2. In normal horses, increasing the intensity of exercise progressively increased HR, f, $\dot{V}_I max$, $\dot{V}_E max$, Pu_I, Pu_E, Hb, and Pa_{CO_2}, decreased Pa_{O_2}, pH, and HCO_3^-, while Z_I and Z_E were unchanged.

3. Left recurrent laryngeal neurectomy increased Z_I, Pu_I, Pa_{CO_2}, concomitant with a reduction in f and $\dot{V}_I max$.

4. Parameters measured following ventriculectomy were unchanged from those measured following LRLN except for a decrease in $\dot{V}_E max$ at the gallop and increases in Pa_{CO_2} and HCO_3- while horses were standing. Therefore, ventriculectomy was ineffective in altering the increase in inspiratory impedence measured after LRLN.

5. Parameters measured after prosthetic laryngoplasty were unchanged from baseline measurements. Therefore, though prosthetic laryngoplasty was ineffective in improving blood gas tension and acid-base impairments, it was effective in reducing inspiratory impedence measured after LRLN.

6. Rectal temperatures may be inappropriate for correcting temperature effects on blood gas tensions. Increased arterial blood temperature can be measured after only two minutes of high intensity exercise.

7. Changes in blood gas tensions in exercising horses may be a poor indicator of airway obstruction. Exercise in normal horses causes large changes in blood-gas tensions that could mask the effects of an obstructive disease or surgical procedure to treat the disease.

8. The effect of the mask on airway flow mechanics parameters, blood gas tensions, and acid-base parameters should be examined.

9. The effect of other upper airway diseases (entrapped epiglottis, rostral displacement of the palatopharyngeal arch, arytenoid chondritis, etc.) on upper airway flow mechanics and blood gas tensions remains to be determined. Additionally, the efficacy of surgical procedures to treat laryngeal hemiplegia and other diseases of the upper airway can be assessed using the technique described in this thesis.

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