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VOCAL FUNCTION FOLLOWING VERTICAL HEMILARYNGECTOMY: COMPARISON OF FOUR RECONSTRUCTION TECHNIQUES IN THE CANINE

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The goals of laryngeal reconstruction have been prevention of aspiration, production of a functional voice, and maintenance of an adequate airway for decannulation. A number of procedures for partial laryngeal reconstruction have accomplished these objectives. However, few studies have attempted to compare patients' vocal characteristics following different reconstruction procedures. In this study, an in vivo canine model was used to compare acoustic and aerodynamic measures of vocal function for the following vertical hemilaryngectomy reconstruction techniques: 1) a superiorly based sternohyoid muscle flap, 2) a modified epiglottic laryngoplasty, 3) a new procedure using a layered vascularized buccal mucosal flap and a transversely oriented sternohyoid muscle flap, and 4) hemilaryngeal transplantation combined with arytenoid adduction. Hemitransplantation provided the most efficient phonation of the four techniques. The vascularized buccal mucosa flap produced the best phonation of the autologous tissue techniques examined. Both vascularized buccal mucosa flap and hemilaryngeal transplantation subjects demonstrated a mucosal wave on stroboscopy. The results indicate that vocal function will improve as the layered structure of the vocal fold is more accurately replicated in a reconstructed hemilarynx. Endoscopic findings and whole organ sections are presented.

KEY WORDS — laryngeal reconstruction, vertical hemilaryngectomy, vocal function.

INTRODUCTION

Although surgeons have described partial laryngeal reconstruction techniques for over a century, few studies have attempted to compare laryngeal function following reconstruction with different methods. In this study, four different methods for reconstruction of vertical hemilaryngectomy defects were evaluated in an in vivo canine model: 1) a sternohyoid muscle flap, 2) an epiglottic cartilage and mucosa composite flap with a separate sternohyoid muscle flap, 3) a vascularized buccal mucosal flap and underlying sternohyoid muscle flap with laryngeal framework reconstruction, and 4) a hemilaryngeal transplant with arytenoid adduction. We hypothesized that closer replication of the structural properties of the vocal fold would result in corresponding improvements in vocal function.

Reconstruction after partial laryngectomy is intended to prevent aspiration, provide a functional voice, and maintain an airway adequate for decannulation. Thus, an ideal reconstruction technique should restore the sphincteric competence of the glottis; if the arytenoid is resected, it should provide a relatively rigid posterior structure to occlude against the intact arytenoid, producing glottal competence. Closure of the glottis should be firm, so that an adequate subglottic pressure can be produced to drive phonation. Finally, reconstruction should provide a cross-sectional lumen sufficient for respiration. An adequate airway is more likely when one arytenoid can be preserved.

Two types of mucosal flaps have been used in laryngeal reconstruction. Rotational flaps are generally taken from the false vocal fold, aryepiglottic fold, and pyriform sinus. Free mucosal grafts are usually harvested from the oral mucosa. These flaps are intended to replace the excised laryngeal mucosa and lamina propria, which function as a superior glottic interface in the native state. However, such flaps have several disadvantages. First, if used alone, they do not provide enough bulk to replace the excised tissue, and therefore are usually combined with underlying muscle or cartilaginous flaps. Second, rotational flaps often produce distortion of the pyriform sinus anatomy, potentially resulting in aspiration. Third, free mucosal grafts placed in the larynx typically undergo atrophy or necrosis. This atrophy may result in an incompetent glottis. Finally, such

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grafts ultimately do not differ histologically from muscle and myofascial surfaces that gradually mucosalize.[1,2] Therefore, many investigators believe the disadvantages of laryngeal reconstruction with rotational or free mucosal grafts outweigh their benefits.

Pedicled muscle flaps are much more commonly used for reconstruction of partial laryngectomy defects.[1,3-6] Potential donor muscles include the sternohyoid, omohyoid, and sternocleidomastoid. Some methods also include the overlying fascia or thyroid perichondrium. The muscle can be pedicled superiorly or inferiorly, or placed as a bipedicled flap.

Muscle flaps provide excellent bulk to replace the excised hemilarynx and can be modified for various tissue defects. However, they also result in an adynamic glottic interface with a thin mucosal layer that has poor viscoelastic and vibratory properties. Despite the disadvantages related to vocal function, many otolaryngologists contend that muscle flaps are the best option available for partial laryngeal reconstruction because of their versatility and consistent results.[4]

A wide variety of cartilaginous flaps have been described for partial laryngeal reconstruction.[7-10] One approach utilizes a composite epiglottic flap with attached mucosa for reconstruction of near-total or vertical hemilaryngectomy defects.[11-14] In this method, the mucosa provides an intact laryngeal surface, while the epiglottic cartilage contributes structural support.

A few free tissue transfer methods for laryngeal reconstruction have also been described. Cases of human laryngeal reconstruction with iliofemoral, deltopectoral,[15] or radial forearm free flaps[16] have been reported, and reconstruction using a lateral thoracic fascia vascularized flap with free buccal mucosa and cartilage grafts has been described in the rabbit model.[17] To date, free tissue transfers have not been widely used for partial laryngeal reconstruction.

The present hypothesis is that vocal function will improve as the layered structure of the vocal fold is more accurately replicated in a reconstructed hemilarynx. A canine model was used to test the hypothesis. Modified muscle and cartilage flaps were chosen as the first two reconstruction methods for evaluation. The third technique was a pedicled mucosal flap with intact, vascularized submucosa. We hypothesized that this technique would provide more efficient phonation than either the muscle or cartilage flap, because it more closely replicates the native laryngeal lamina propria. A vascularized buccal mucosal flap was chosen because of its reliable blood supply. For replacement of the laryngeal musculature, a transversely oriented, superiorly based sternohyoid muscle flap was placed at the level of the glottis. Finally, a microplate was fixed parallel to the neoglottis to stabilize the laryngeal framework where the thyroid cartilage had been removed.

The fourth technique, hemilaryngeal transplantation, is the most anatomically accurate method of hemilaryngeal reconstruction, and thus represents a theoretic ideal. In addition, it provides an opportunity to investigate the feasibility of partial organ transplantation. Reinnervation of the thyroarytenoid muscle and an arytenoid adduction were included in this method.

MATERIALS AND METHODS

OVERVIEW OF EXPERIMENTAL DESIGN

Twelve adult male mongrel dogs were selected for the experiment. Three animals were assigned at random to each of three autologous reconstruction conditions; the remaining three subjects were retained as replacements for animals developing serious postoperative complications. Each animal was approximately 1 year old and weighed 20 to 25 kg. All had normal-appearing vocal folds on direct laryngoscopy; dogs with an unusually large posterior glottic gap on laryngeal closure were excluded.

Two additional animals (male littermate beagles, approximately 1 year old and weighing 12 to 15 kg) were assigned to the hemilaryngeal transplantation condition. Mixed leukocyte cultures and genetic sequencing were performed to assess the major histocompatibility reactivity at the DLA-D region and verify a haplo-identical match.

Prior to laryngeal reconstruction, phonation was produced with transtracheal stimulation to accumulate baseline acoustic, aerodynamic, and videolaryngoscopic data. A stimulating electrode endotracheal tube was inserted through a tracheotomy. Following the procedure, the tracheotomy was closed and allowed to heal for 4 to 6 weeks prior to hemilaryngectomy and reconstruction.

When recovery was complete, a surgical intervention (hemilaryngectomy with autologous reconstruction, or hemilaryngeal transplantation) was performed. Two months following surgery, phonation was again evaluated with transtracheal stimulation. Laryngeal specimens were harvested after the second evaluation.

BASELINE ACOUSTIC, AERODYNAMIC, AND ENDOSCOPIC DATA

Preparation for Phonation. Each dog received acepromazine maleate (0.2 mg/kg) intramuscularly

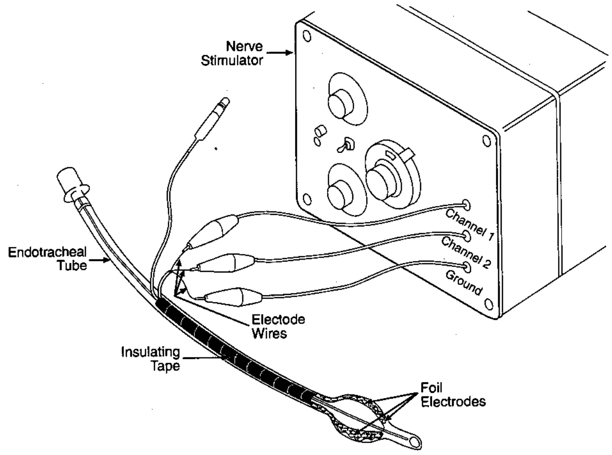

Fig 1. Custom endotracheal tube and nerve stimulator for transtracheal recurrent laryngeal nerve (RLN) stimulation.

as a preoperative sedative. Pentobarbital sodium was administered intravenously to the level of corneal anesthesia. Additional pentobarbital was given to maintain this level of anesthesia throughout the procedure.

The subject was placed supine on the operating table and direct laryngoscopy was performed. The dog was intubated with a cuffed endotracheal tube for ventilator-assisted respiration. Cefazolin sodium (1.0 g) was administered intravenously for antimicrobial prophylaxis and continued for 7 days postoperatively. Dexamethasone sodium phosphate (8 mg intravenously) was administered to reduce laryngeal edema during phonation.

Following sterile skin preparation, a midline vertical incision was made from the sternal notch to just below the cricoid cartilage. Dissection was carried out in the midline and the strap muscles were retracted laterally. A low tracheotomy was made at the level of the sternal notch, through which a cuffed endotracheal tube was passed for assisted ventilation. The oral endotracheal tube was then removed.

A second tracheotomy was placed three tracheal rings superior to the first, and a recurrent laryngeal nerve (RLN)–stimulating endotracheal tube was inserted and directed superiorly so that its tip was located approximately 10 cm below the glottis. This tube (Fig 1) had foil electrodes attached to the cuff so that the RLN could be stimulated through the tracheal cartilage.[18,19] The tube was positioned so that the electrodes on the cuff were oriented with the stimulating electrodes adjacent to the tracheal-esophageal groove. A ground electrode was positioned at the anterior tracheal wall.

Recurrent Laryngeal Nerve Stimulation. With transtracheal stimulation of the RLN, phonation could be produced in each dog without risk of injury to the RLN. (Superior laryngeal nerve stimulation would have required an open dissection and was not performed.) Stimulation was provided via a nerve stimulator (WR Medical Electronics Co, model 2SLH, St

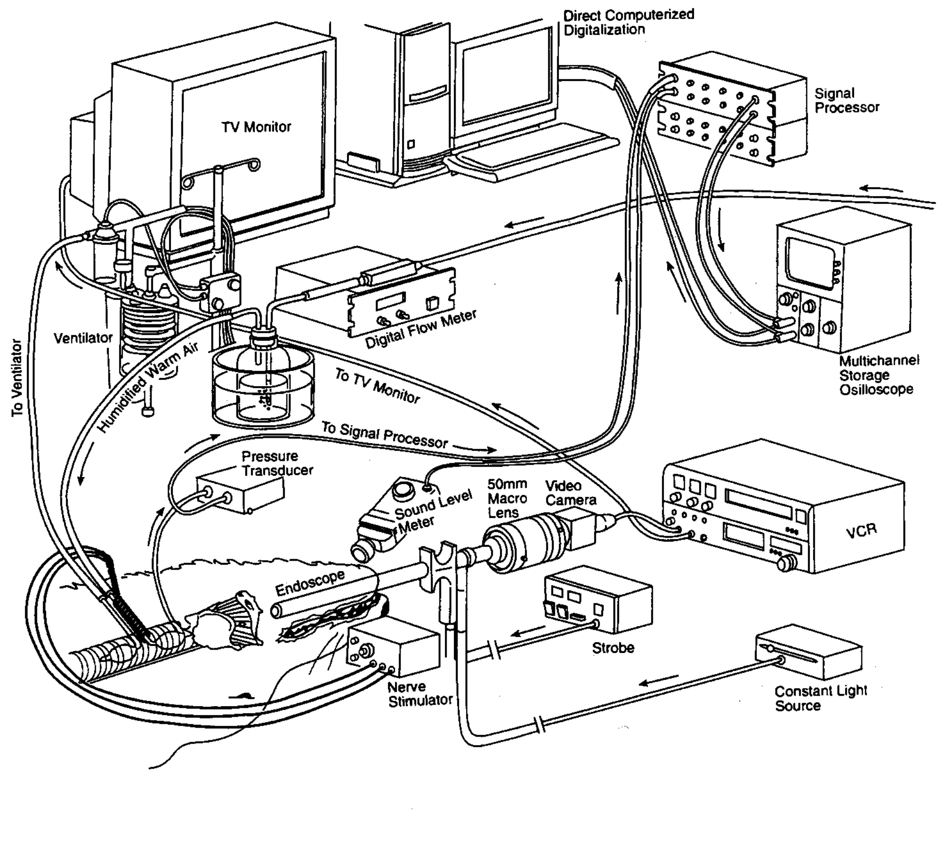

Fig 2. Schematic diagram of equipment used for collection of transtracheal phonation data.

Paul, Minn) connected to the tracheal electrodes. The stimulus frequency was 80 Hz, with a 1.5-millisecond pulse duration and current of 3 to 5 mA. The stimulator and other equipment used in the in vivo model of phonation are depicted in Fig 2.

Subglottic Pressure, Flow, and Acoustic Signal. Subglottic pressure was measured with a catheter-tipped pressure transducer (Millar Instruments, model SPC 340, Houston, Tex) placed 2.0 cm below the glottis. The instrument was calibrated with a manometer prior to each experiment. The pressure-regulating system exit port was connected to a flowmeter (Edwards High Vacuum International, model 825 Series B, Wilmington, Mass). Air was bubbled through 5 cm of heated water for humidification and warming to 37°C when measured at the glottic outlet. This flow was directed through the glottis to drive phonation during transtracheal stimulation of the RLN.

Sound level measurements were made in decibels sound pressure level with an acoustic meter (Quest Electronics, model 211A, Oconomowoc, Wis) that was suspended at the entrance to the oral cavity.

Subglottic pressure, flow, and acoustic signals were digitized simultaneously with a 12-bit analog-to-digital converter (SA Instrumentation, model SA-414, San Diego, Calif) and C-Speech signal processing software (Paul Milenkovic, University of Wisconsin, Madison, Wis). The signals were low-pass-filtered at 3 kHz and sampled at 20 kHz for 2.8 seconds in each trial.

The acoustic power and aerodynamic power were calculated with the following formulae.

(1) Acoustic power = $2r^2Pe^2/Po^c$

where: r = sound meter distance to the glottis in cm

Pe = acoustic intensity in dynes/cm^2

dB = (20log10)Pe/0.0002 dynes/cm^2

Po^c = 41.4 dynes/cm^3

(2) Aerodynamic power = Fm Sm

where: Fm = flow in cm^3/s

Sm = subglottic pressure in dynes/cm^2

1 mm Hg = 1.3332×10^{-3} dynes/cm^2

Videolaryngoscopy and Videostroboscopy. All subjects underwent an endoscopic evaluation during phonation. Videolaryngoscopy was performed with a 0° endoscope (Karl Storz Endoscopy-America Inc, Culver City, Calif) connected to a halogen light source via a fluid-filled light cable. For videostroboscopy, a laryngostrobe (Storz, model 8000) was connected to the endoscope. Images were recorded with a charge-coupled device video camera (Toshiba, model IK-C30A, Buffalo Grove, Ill) and a 3/4-in videotape recorder (Sony, model VO-9850, Park Ridge, NJ). Recorded images were viewed on a video monitor (Sony, model PVM-1341) for frame-by-frame analysis.

Test-Retest Reliability. To ensure that preoperative measures of phonation were truly representative, baseline measures were replicated for one subject prior to hemilaryngectomy. In this subject, phonation was produced with transtracheal stimulation, as described above; after an interval of 1 month for recovery, the in vivo model was reapplied and a second set of baseline data were gathered. No significant differences were found between the two pretests for any measure of phonation.

HEMILARYNGEAL RESECTION TECHNIQUE

The subjects received acepromazine maleate (0.2 mg/kg) intramuscularly as a preoperative sedative. Pentobarbital sodium was administered intravenously to the level of corneal anesthesia. The subject was placed supine on the operating table and a mixture of 0.5% to 2.0% halothane and oxygen was administered to maintain anesthesia throughout the procedure. Ampicillin and gentamicin were administered intravenously as antimicrobial prophylaxis and continued for 7 days postoperatively. Intraoperative monitoring included a continuous electrocardiogram and a rectal thermometer.

Following sterile skin preparation, a tracheotomy was performed at the fifth tracheal ring with an inferiorly based flap sutured to the skin edge. The oral endotracheal tube was removed and a sterile cuffed endotracheal tube was placed in the stoma for assisted ventilation. A midline vertical skin incision was made that extended from the level of the hyoid bone to the cricoid cartilage.

A pedicled external thyroid perichondrium flap was made. The perichondrium was incised vertically a few millimeters lateral to the midline on the contralateral side of the specimen and horizontally along the superior and inferior borders of the thyroid cartilage from the vertical incision to 5 mm anterior to the posterior edge of the ipsilateral thyroid cartilage. An elevator was used to raise the perichondrial flap off the underlying cartilage. A No. 15 blade was used to make the thyroid cartilage cuts in the midline and at the border of the posterior third and anterior two thirds on the ipsilateral side of resection. A midline thyrotomy was made and superior and inferior cuts were completed through the thyrohyoid and cricothyroid membranes. A mucosal incision was made in the midline of the posterior commissure. The specimen was excised, including the true vocal fold, ventricle, false vocal fold, thyroarytenoid muscle, arytenoid, and anterior two thirds of the ipsilateral thyroid cartilage.

RECONSTRUCTION TECHNIQUES

Superiorly Based Muscle Flap. This procedure has been described in detail by Calcaterra.[4] Briefly, the sternohyoid muscle flap, including the outer layer of fascia, was made larger than the dimensions of the laryngeal defect in anticipation of muscle atrophy. The flap was raised superiorly to the hyoid bone with preservation of the vascular and nerve supply. The flap was rotated with the external fascial layer directed toward the laryngeal lumen. The fascia was sutured to the laryngeal mucosa posteriorly and inferiorly along the cricoid with interrupted absorbable sutures. The perichondrium was then approximated as described, with the anterior remnant of the muscle flap used to reconstruct the anterior commissure.

Epiglottic Cartilage and Mucosa Composite Flap. The epiglottis was mobilized as described by Tucker et al.[11] The preepiglottic contents were dissected in a plane immediately anterior to the cartilage. The hyoepiglottic and glossoepiglottic ligaments were cut. The superior mucosal attachments of the epiglottis were carefully preserved to provide a pedicled vascular supply to the cartilage and mucosa on its laryngeal surface. The composite flap was then brought into the larynx and the inferior and lateral edges were trimmed to fit in the defect. The flap was sutured to the cricoid and free mucosal edge posteriorly and to the cricothyroid membrane inferiorly as described by Olson and Sullivan.[14]

A superiorly based sternohyoid muscle flap was mobilized, placed lateral to the epiglottic composite flap, and sutured to the cricoid inferiorly. The muscle flap provided bulk for medialization of the epiglottic flap. For anterior closure, the mucosa and inner perichondrium of the epiglottic flap and thyroid cartilage were approximated with interrupted 5-0 absorbable sutures. The external thyroid perichondrium was then approximated over both flaps.

Vascularized Buccal Mucosa Flap. A third group of dogs was reconstructed with a vascularized buccal mucosa flap. The details of this technique will be published separately. Briefly, a 2 × 3-cm pedicled flap was elevated, based on the facial artery and vein. This was sutured into position in the hemilarynx. A transversely oriented, superiorly based sternohyoid muscle flap, as described by Hirano,[1] was positioned deep to the mucosal flap to provide adequate bulk for the neoglottis. A microplate fixed to the thyroid cartilage served both to stabilize the laryngeal framework and as lateral support for the mucosal and muscle flaps at the level of the glottis.

Hemilaryngeal Transplantation With Arytenoid Adduction. Many aspects of the hemilaryngeal transplant protocol, including canine selection, immunosuppression, surgical preparation, and postoperative care, were identical to those used for orthotopic canine laryngeal transplantation.[20] Briefly, the vascular supply of the hemitransplant was based on the cranial thyroid artery and hyoid venous arch. The anterior branch of the recipient RLN was dissected and tagged for anastomosis to the thyroarytenoid branch in the donor prior to removal of the specimen. The intralaryngeal defect and donor specimen were otherwise identical to those of the subjects who underwent autologous reconstructions. The donor arytenoid was fixed to the recipient cricoid with nonabsorbable suture and an arytenoid adduction was performed. The mucosa was closed in layers and miniplates were used to stabilize the laryngeal framework at the anterior commissure and posterior third of the thyroid cartilage.

POSTOPERATIVE CARE

Autologous Reconstructions. Each dog was given water on the first postoperative day, and soft food on the third postoperative day. All of the subjects were decannulated between the second and third postoperative weeks. The dogs were decannulated if they tolerated a sustained period of exercise with the tracheotomy tubes removed and their stomas occluded with surgical tape. After decannulation, the stomas closed spontaneously.

Hemilaryngeal Transplant. The postoperative care was as described by Berke et al,[20] except that an esophagostomy tube was utilized to provide nutrition as soon as bowel function returned. This was removed on postoperative day 7 and the animal was given water and soft food the following morning. The dog was not decannulated, so that the transplant hemilarynx could be evaluated with a flexible endoscope placed through the tracheotomy stoma. In this manner, the hemilarynx was monitored without sedation for gross signs of organ rejection.

POST-HEMILARYNGECTOMY ASSESSMENT

The dogs were assessed 2 months after hemilaryngeal reconstruction. Acoustic, aerodynamic, and endoscopic data were collected by the methods described above. After data collection, a laryngectomy was performed and the subjects were painlessly euthanized.

The larynges were fixed in formaldehyde and

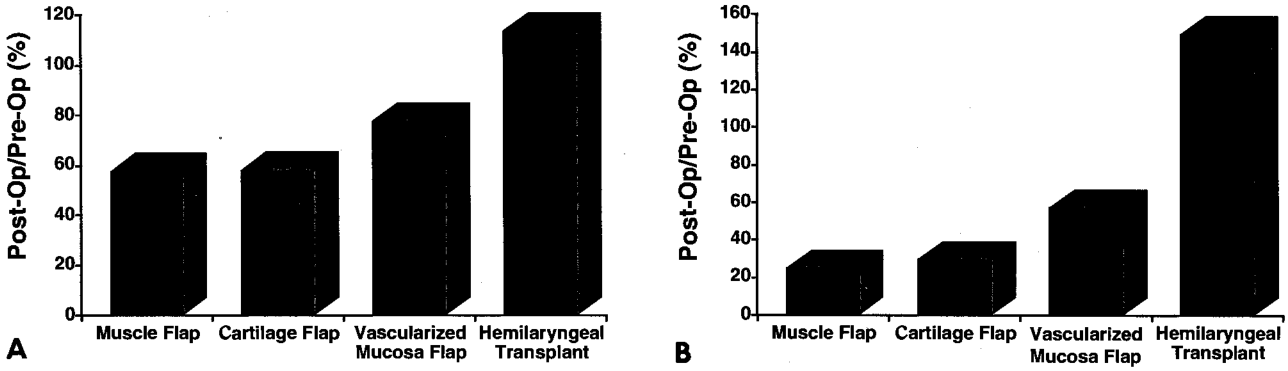

Fig 3. Hemilaryngeal reconstruction technique. A) Average acoustic power. B) Average aerodynamic power.

axially sectioned at the levels of the supraglottis, ventricle, glottis, and subglottis for gross and histologic examination. The specimens were then embedded in paraffin, and hematoxylin and eosin slides were prepared from each axial section.

RESULTS

CLINICAL OUTCOME

The study group included nine mongrel dogs for evaluation of autologous reconstruction techniques and one beagle that underwent hemilaryngeal transplantation. The second beagle was painlessly sacrificed after serving as the transplant organ donor.

Two of the mongrel dogs died in the postoperative period, both of airway obstruction from plugged tracheotomy tubes. The first was in the sternohyoid group and died during the third postoperative day. The other underwent buccal flap reconstruction and died on the eighth postoperative day. An autopsy indicated that neither aspiration, pulmonary infection, nor embolism was the cause of death. Replacement animals were substituted for these dogs, as described above.

The only additional complication was a postoperative seroma that did not respond to repeated aspiration and pressure dressings. The seroma resolved and the wound healed in approximately 10 days after drainage and wound irrigation. None of the subjects developed weight loss or clinical signs of aspiration.

ACOUSTIC AND AERODYNAMIC DATA

Some trial and error was required before consistent transtracheal stimulation of the RLN could be obtained. Therefore, the four preoperative and four postoperative trials with the highest calculated aerodynamic power were selected for each subject for further analysis. Figure 3A shows the average acoustic power for each condition, expressed as a percentage of the average preoperative values. Statistical significance could not be determined, because of the limited numbers of subjects and trials in each condition.

Figure 3B shows the aerodynamic power for each of the techniques, again expressed as a percentage of preoperative values. Aerodynamic power was highest for the hemitransplant dog; however, statistical

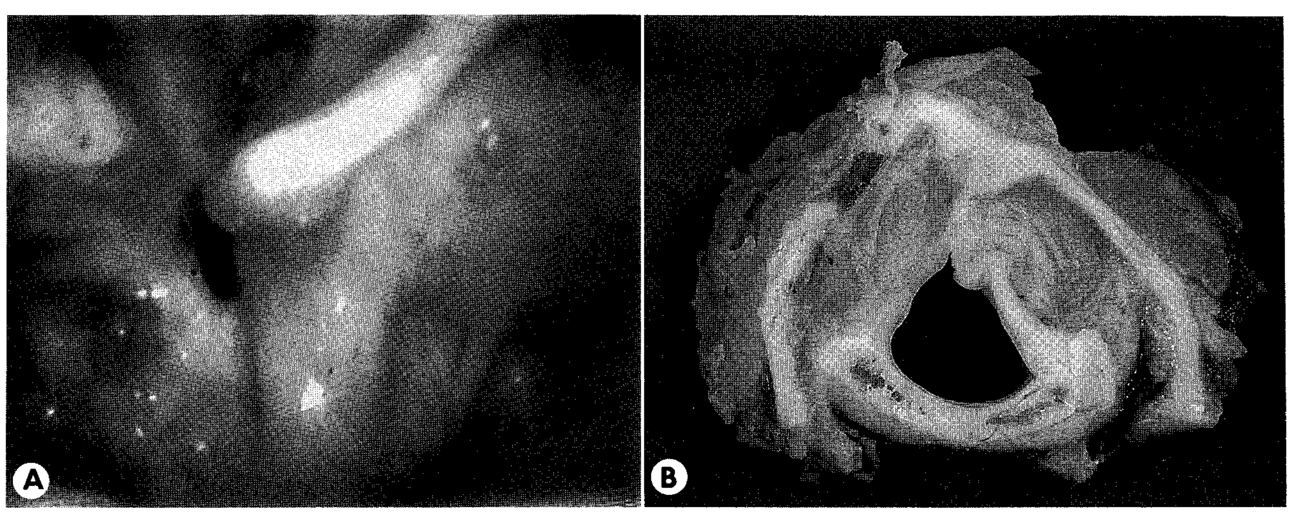

Fig 4. Left sternohyoid muscle flap, 2 months postoperative. A) Endoscopy with right RLN stimulation. B) Whole organ axial section of glottis.

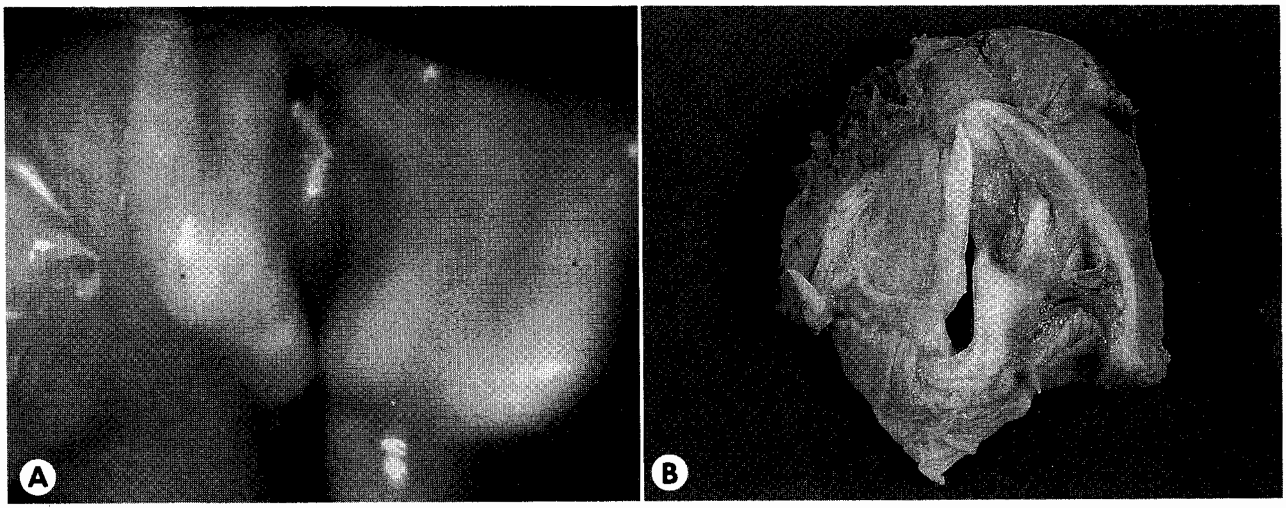

Fig 5. Left epiglottic cartilage and mucosa composite flap, 2 months postoperative. A) Endoscopy with right RLN stimulation. B) Whole organ axial section of glottis.

analysis was again limited by the small numbers of subjects and trials in each condition.

ENDOSCOPY AND WHOLE ORGAN SECTIONS

Sternohyoid Muscle Flap. Videoendoscopy of the superiorly based sternohyoid muscle flap demonstrated an adequate cross-sectional airway at the level of the glottis. A representative endoscopic photograph obtained during RLN stimulation is included as Fig 4A. The flap had mucosalized and the suture lines were well healed. The muscle flap (left) had atrophied posteriorly, resulting in a large posterior glottic gap that could not be closed even with overcompensation by the intact arytenoid. The anterior commissure was rotated to the left of the midline with a shortened anterior-posterior (AP) diameter of the glottis. The native vocal fold (right) was shortened and bowed even when the arytenoid was adducted upon RLN stimulation. This apparently resulted from the loss of support at the anterior commissure after resection of the anterior two thirds of the left thyroid cartilage.

The whole organ section (Fig 4B) confirmed the endoscopic findings of anterior commissure rotation and a shortened glottic AP diameter. The anterior edge of the thyroid cartilage was bent posteriorly, shortening the glottis and preventing the native vocal fold from tensing with adduction. The muscle flap had migrated anteriorly and atrophied posteriorly. There was a small amount of new cartilage and bone formation where the perichondrial flap was positioned external to the muscle flap. There was a thin layer of mucosa overlying the muscle flap on the endolaryngeal surface.

Epiglottic Cartilage Flap. Videoendoscopy of the epiglottic cartilage and mucosa composite flap demonstrated an adequate cross-sectional airway at the

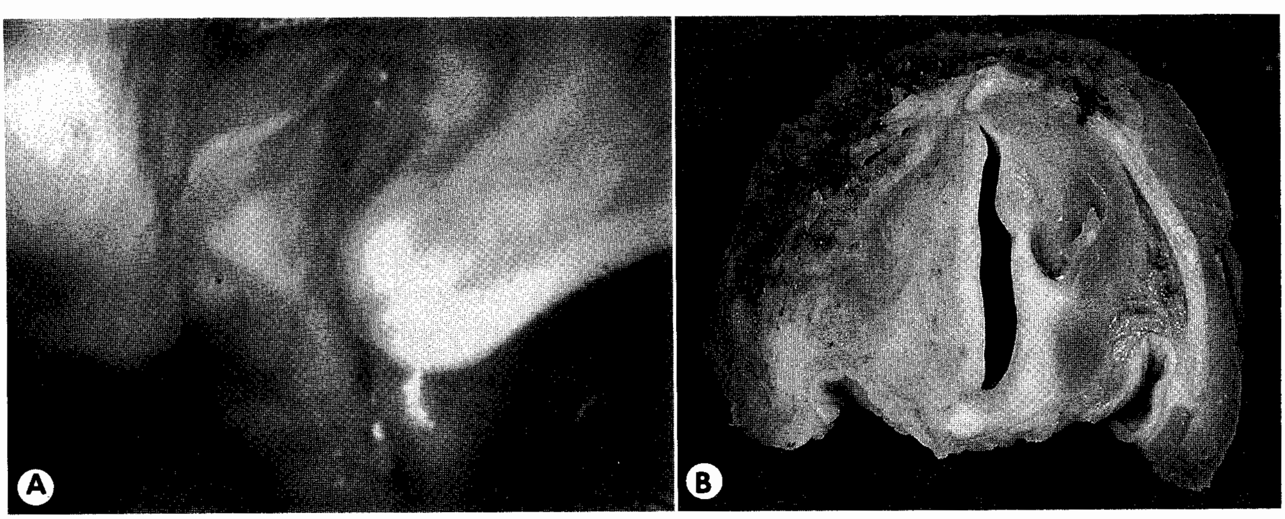

Fig 6. Left vascularized buccal mucosa and sternohyoid muscle flaps with microplate laryngeal framework reconstruction, 2 months postoperative. A) Endoscopy with right RLN stimulation. B) Whole organ axial section of glottis.

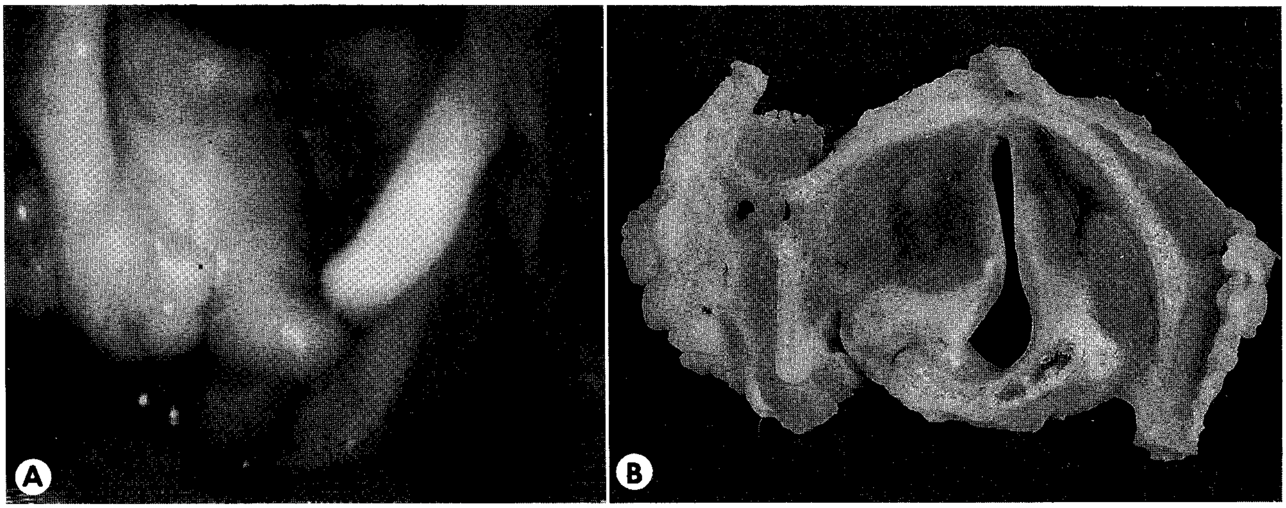

Fig 7. Left hemilaryngeal transplant with arytenoid adduction, 2 months postoperative. A) Endoscopy with right RLN stimulation. B) Whole organ axial section of glottis.

level of the glottis. A representative endoscopic photograph obtained during RLN stimulation is included as Fig 5A. The epiglottic mucosa on the endolaryngeal surface of the flap was intact and well vascularized. The posterior edge of the cartilage flap had pulled away from the cricoid in all three subjects, producing a large glottic gap. The remainder of the epiglottic flap was in the midline and met the contralateral vocal fold during RLN stimulation. There was a sharp anterior commissure where the epiglottic cartilage was sewn to the anterior thyroid cartilage, and a normal AP diameter of the glottis. There appeared to be some tension of the native vocal fold with RLN stimulation, perhaps due to cartilaginous support at the anterior commissure.

Whole organ sections (Fig 5B) confirmed the endoscopic findings of midline flap position, normal AP glottic diameter, and posterior glottic gap. There was little new cartilage or bone growth from the perichondrial flap.

Buccal Mucosa Flap. Videoendoscopy of the buccal mucosa flaps indicated an adequate cross-sectional airway at the level of the glottis. A representative endoscopic photograph obtained during RLN stimulation is included as Fig 6A. The vascularized mucosa flap (left) was fixed to the midline posteriorly. No glottic gap was present upon RLN stimulation. The anterior commissure was sharp and did not deviate from the midline. There was a normal AP diameter of the glottis. The native vocal fold adducted to the midline and tensed with RLN stimulation.

Findings on analysis of the whole organ sections (Fig 6B) were consistent with the endoscopic findings. The airway appeared small because of the position of the opposite vocal fold, but was adequate, with the native vocal fold abducted in the live animal. The miniplate had been incorporated into new cartilage and bone growth, apparently potentiated by the preserved overlying perichondrium.

Hemilaryngeal Transplantation. On endoscopic examination, the transplanted hemilarynx was similar in appearance to the native side (Fig 7A), although the fold was immobile and some edema was present. The native vocal fold abducted normally with respiration; the transplanted fold was fixed by an arytenoid adduction. The mucosa appeared to be healthy, without granulation or scarring. The vascularized mucosa flap (left) was fixed in the midline throughout the glottis and had no glottic gap during RLN stimulation. The anterior commissure was sharp and did not deviate from the midline. There was a normal AP diameter of the glottis. The native vocal fold adducted to the midline and tensed with RLN stimulation. At 2 months posttransplant, the transplanted vocal fold also demonstrated some tension with stimulation of the RLN.

On whole organ section, the airway appeared to be narrow (Fig 7B), but it was adequate clinically when the native vocal fold was abducted. Adduction of the transplant arytenoid was noted, with suture visible in the transverse section.

STROBOSCOPY

All dogs in the study underwent stroboscopic endoscopy. A mucosal traveling wave could not be elicited in any of the animals who underwent muscle or epiglottic flap reconstruction. The buccal flap and hemitransplant dogs revealed a traveling mucosal wave that was synchronous with the wave in the native vocal fold. In the buccal flap dogs, there was increased propagation of the mucosal wave superiorly to the supraglottis along the mucosal flap.

DISCUSSION

Previous studies of laryngeal reconstruction methods have emphasized issues of aspiration, voice, and airway. However, few authors have compared different reconstruction techniques by assessing phonation. Blaugrund et al[21] evaluated speech following reconstruction with mucosal and skin flaps. They found that phonation in these patients was primarily supraglottic, and that fundamental frequency was low and restricted in range. Preservation of the arytenoid improved both aerodynamic and acoustic parameters. Hirano et al[22] argued that such comparisons among different reconstruction techniques are problematic because functional results are not predictable, and because of a lack of standardized methods for evaluating vocal function.

This study evaluated four surgical techniques for reconstruction following vertical partial laryngectomy in the canine model. Preoperative and postoperative measures of vocal function were obtained to study the effects of each procedure on each individual subject. Aerodynamic power and acoustic power were measured because they are complementary indicators of vocal function. Aerodynamic power is a function of subglottic pressure, which in turn is a function of both glottic closure and tension. Acoustic power is related to both glottic closure and the periodicity of vibration, and reflects the ability of the larynx to produce acoustic intensity.

The canine larynx has provided insight into the physiology of the human larynx in normal and diseased states. However, several anatomic differences have implications for hemilaryngeal reconstruction. The arytenoid is longer in the dog and occupies about one half of the length of the posterior glottic gap, in comparison to one third in the human. The interarytenoid muscle in the dog is less developed and the posterior commissure closes less tightly during phonation.[23] Animals demonstrating a posterior glottic gap upon transtracheal RLN stimulation during preoperative phonation were excluded from the study. Following hemilaryngeal reconstruction, loss of tissue bulk could prevent the intact arytenoid from closing the posterior glottis, thus creating a glottal gap with a deleterious effect on postoperative phonation. Because the arytenoid is larger in the dog, the consequences of a posterior glottic gap during phonation may be greater than in humans.

Hirano[24] has emphasized the importance of the layered structure of the larynx. He described three anatomic and functional compartments of the larynx: the *cover*, consisting of the epithelium and the superficial layer of the lamina propria; the *transition*, consisting of the intermediate and deep layers of the lamina propria; and the *body*, formed by the vocalis muscle. During speech, the mucosa must move fluidly over the underlying muscle to produce the normal, wavelike motion at the glottis. After severe laryngeal trauma, for example, the mucosa and superficial lamina propria are scarred to the underlying muscle, producing nonvibrating segments of the vocal fold and aperiodic vibration.

For the reconstruction of hemilaryngeal defects, mucosal, muscle, and cartilage flaps have been most commonly used. Mucosal flaps alone do not adequately replace tissue bulk. When used as free grafts over muscle or cartilage, they generally undergo atrophy or necrosis. Muscle or cartilage flaps reconstitute tissue bulk, but when they are allowed to mucosalize, the normal vibratory properties of the glottis are lost, because the submucosa is thin and lacks the unique structural characteristics of the lamina propria. Following muscle or cartilage flap procedures, the hemilarynx usually vibrates poorly, as in the severely traumatized larynx. An ideal alternative for the endolaryngeal submucosa would have the viscoelastic properties of the native lamina propria.

A vascularized full thickness mucosal flap, such as the buccal flap used in this study, offers a theoretically acceptable autologous replacement for the laryngeal mucosa and lamina propria. The data in this study suggest that the viscoelastic properties of the buccal flap submucosa are more similar to those of the native lamina propria than either a mucosalized muscle flap or a cartilage and mucosa composite flap.

On stroboscopy, a mucosal wave occurred in the vascularized mucosal flap and hemilaryngeal transplant subjects. In subjects receiving muscle and cartilage flaps, no wave was identified and phonation was consistently aperiodic and perceptually rough. The lack of a mucosal wave is consistent with the clinical experience of many surgeons performing hemilaryngeal reconstruction in human patients.

The endoscopic data and whole organ axial sections provide anatomic evidence consistent with the phonation data in Fig 3. Both the muscle and cartilage techniques produced a posterior glottal gap. The muscle flap underwent atrophy and migration and the cartilage flap consistently pulled away from the posterior cricoid. This result detrimentally affected glottic closure and subglottic pressure, therefore reducing values for both acoustic and aerodynamic power. The muscle flap lacked framework reconstruction for the resected thyroid cartilage and therefore had no support for the anterior commissure. The results were a shortened glottic AP diameter and a native vocal fold that was unable to tense itself against the reconstructed hemilarynx. The cartilage flap provided some support of the anterior commissure. Unfortunately, in every dog the posterior edge of the epiglottic cartilage detached from the cricoid, producing a posterior glottic gap.

The vascularized buccal mucosa flap, combined with a muscle flap and laryngeal framework reconstruction, provided the best autologous repair of the excised tissue defect. This method replaced the thyroid cartilage support and the bulk of the intrinsic laryngeal musculature, resulting in both a normal AP glottic diameter and medialization of the entire neoglottis.

Hemilaryngeal transplantation was studied to investigate the results of an idealized autologous reconstruction. Although technically feasible, this is not an option for human partial laryngeal reconstruction at this time. Nonetheless, the dog that underwent hemilaryngeal transplantation achieved the best results in this study. Postoperative acoustic and aerodynamic power values were *better* than the preoperative baseline values, probably because of the tight glottic closure achieved by arytenoid adduction, which produced greater acoustic intensity and higher subglottic pressure.

In conclusion, three methods of autologous hemilaryngeal reconstruction and hemilaryngeal transplantation were compared in the dog. As expected, hemitransplantation produced the best acoustic, aerodynamic, and stroboscopic results, because it most closely replicated the layered laryngeal anatomy. The vascularized buccal mucosa flap also produced a favorable surface for laryngeal vibration, and functioned better than the cartilage and muscle flaps studied. Only the hemilaryngeal transplant and buccal mucosa flap produced a mucosal wave. The endoscopic and whole organ axial sections provide additional anatomic data that support the concept that when the excised hemilarynx is replaced by increasingly similar tissue, there is a successive improvement in vocal function.

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