Relative contribution of various airway protective mechanisms to prevention of aspiration during swallowing

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The normal pharyngeal phase of swallowing includes two intertwined functions: 1) transport of the bolus from the mouth into the esophagus, and 2) protection of the airway (14, 18, 24). The efficacy and coordination of these two functions are essential for the safety of the airway during deglutition. Biomechanical events contributing to bolus transport have been extensively studied (2, 5, 8, 15, 22) and include posterior tongue thrust and pharyngeal peristalsis. Deglutitive airway protective mechanisms include closure of the introitus to the trachea by vocal cord adduction, approximation of the adducted arytenoids to the base of the epiglottis, epiglottal descent, and anterosuperior displacement of the larynx away from the path of the bolus (8, 14, 18). The latter event also results in opening of the upper esophageal sphincter (3, 7, 8, 11, 19).

Glottal closure, which includes vocal cord closure and approximation of arytenoids to the base of the epiglottis, is the only one of these mechanisms that forms a physical barrier against aspiration. Laryngeal paralysis (7) or postoperative laryngeal deficits (16, 17) resulting in incomplete airway closure are associated with aspiration. The contributions of the other mechanisms in the prevention of aspiration are hypothetical and based on videofluoroscopic and videoendoscopic observations. For example, the epiglottis may assist in preventing aspiration, but epiglottectomy does not result in aspiration (25). Therefore, while mechanisms such as epiglottal descent and anterosuperior displacement of the larynx may assist in airway safety, their relative contribution to the prevention of deglutitive aspiration is unclear.

Videofluoroscopic and endoscopic studies of the temporal relationship between aspiration of swallowed material and the pharyngeal phase of swallowing have identified three periods: pre-, intra-, and postdeglutitive aspiration (1). The role of the mechanisms of deglutitive airway protection described above in prevention of aspiration during these three periods has not been systematically studied.

Therefore, the objectives of this study were 1) to determine whether mechanisms other than glottal closure have a role in the prevention of aspiration during swallowing, and if so, 2) to determine the relative contribution of each mechanism to this process, and 3) to determine in which phase of deglutitive airway protection each functions.

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METHODS

Surgical Preparation

Studies were carried out on 14 adult cats of either sex, weighing 2.5–4.5 kg. Food, but not water, was withheld overnight before the study. Under initial ketamine (15 mg/kg im) anesthesia, each cat was first cannulated with a femoral vein catheter for infusion of lactated Ringer solution containing 5% dextrose (~15 ml/h) to maintain body fluid balance. A midline tracheostomy was performed to allow insertion of a tracheal tube. The anesthesia was maintained under halothane (0.8–1.5 vol/100 vol O₂), and decerebration was accomplished at the midcervical level, so that further anesthesia would not be necessary during the remainder of the study. All anesthetics were withheld after decerebration was completed. The body temperature was maintained by a circulating hot water heating pad placed underneath the animals and by a heating lamp placed over the animal.

All of the suprahyoid muscles including the mylohyoid, geniohyoid, hypoglossus, stylohyoid, and digastricus muscles were carefully identified. Although the digastricus muscle elevates the hyoid in humans, its role in cats is unclear. To investigate all of the muscles that may elevate the hyoid or larynx in the cat, we considered the digastricus a hyoid elevating muscle. A bipolar silver wire EMG electrode (AS 632, Cooner wire; Chatsworth, CA) was placed on the thyropharyngeus muscle (with one pole on each side of the muscle) for recording EMG activity induced during deglutition. The trachea, cricoid cartilage, thyroid cartilage, hyoid bone, and tip of the epiglottis were marked by injecting a radioopaque tantalum marker into the respective structure (Fig. 1) for ease of tracking their deglutitive movement under fluoroscopy.

Fluoroscopic Studies

Each cat was placed in supine position on the fluoroscopy table. Fluoroscopic images of deglutitive movement of the markers were videotaped using a super-VHS multiple videocassette recorder (Panasonic, AG 1960, 30 frames/s). Fluoroscopic and EMG events were synchronized by video pulse timer (Thalner Electronics), which concurrently recorded time (in hundredths of a second) on the video fluoroscopic display and simultaneously sent a pulse signal to the polygraph at 1-s intervals.

Swallows were induced by the injection of 3 ml barium (liquid E-Z, E-Z-EM; Westbury, NY) into the pharynx using a catheter attached to the syringe containing the liquid barium. The tip of the catheter was also marked with a radiopaque tantalum bar that was used for determining the area of the pharynx that the barium was delivered to under fluoroscopic control. The injection port was at the side of the catheter near the tip and was faced posteriorly using fluoroscopic guidance. To simulate the impairment of the deglutitive muscles and laryngeal elevation and study their effects on airway protection and occurrence of aspiration, the suprahyoid muscles (mylohyoid, geniohyoid, hypoglossus, digastricus, and styloglossus) were identified and bilaterally transected. Two to five barium swallows were obtained before and after each surgical procedure. To study the role of the epiglottis in airway protection, muscle transections were followed by epiglottectomy using an electric cautery knife in all animals. Unilateral cordectomy was performed after the epiglottectomy in 10 animals. In these animals, the vocal cord was accessed through the mouth using a mouth retractor and a laryngoscope. A fine, delicate, straight Moria forceps (11399-80, Fine Scientific Tools) was used for holding the vocal cord during unilateral dissection by a Student Vannas Spring scissors (Straight, 15028-18, Fine Scientific Tools) without any surrounding damage. In three additional animals, unilateral cordectomy was performed without other lesions being induced. In these cats, the vocal cord was exposed through a small incision on the cricothyroid ligament. The unilateral cordectomy was accomplished leaving the cricothyroid muscles intact. The complete cordectomy was confirmed visually after the completion of the study. Barium swallows were repeated two to five times after epiglottectomy and cordectomy.

With the use of these techniques, we determined the magnitude of deglutitive hyoid, thyroid, and cricoid excursions, maximum anteroposterior diameter of the upper esophageal sphincter (UES) opening, the presence or absence of tracheal aspiration (before, during, and after swallowing), and pharyngeal residue. In addition, we noted the magnitudes of the bolus volumes entering the trachea relative to the esophagus and the timing of these events.

Evaluation of Data

The anteroposterior UES diameter and excursions of the hyoid bone and cricoid and thyroid cartilages were measured using a computerized video-digitization system. The computer analysis system used for analyzing the videofluoroscopic data consisted of a 486 IBM compatible computer operating at 33 MHz. The computer system drives an analog-to-digital conversion board (Targa”; True Vision) and program specifically designed for image capture and analysis. The image analysis and capture software (JAVA; Jandel Scientific, San Matao, CA) allows capture of standard raster images and morphological analysis of digitized image data. The digitized images are stored as computer files for any subsequent recall or analysis.

Images were spatially calibrated using a two-point scheme wherein an image was captured using the computerized image-digitization system described above as an array of

Fig. 1. Still frame of the videofluoroscopic recording of a cat's cervical area in the supine position immediately before initiation of a swallow, showing the resting position of the radioopaque tantalum marker on the thyroid, cartilages, hyoid bone, and tip of the epiglottis.

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picture elements, or pixels, and a known spatial scale was then programmed into the image analysis software. The catheter used for barium perfusion contained a radioopaque tantalum bar of known length. This tantalum bar represented a known scale of distance in the fluoroscopic plane of interest for spatial measurements. The video analysis software provides a means of scaling the distance represented in pixels by the bar on the digitized image to the known length of the bar. In its spatial calibration mode, the image analysis software allows the user to specify the endpoints of the known length and calculates the number of pixels between the two calibration points. The user then specifies the known calibration length in the appropriate units. All subsequently captured images are scaled to the specifications of the originally calibrated image until these specifications are changed by the user. The size of the images captured for the present study was 756 × 486 pixels. The calibration scale changes from study to study as the distance between the cat and fluoroscopic image intensifier varies, but a representative value for our calibration scale was 6–10 pixels to 1 mm, providing a resolution of 0.10–0.16 mm.

Occurrence of aspiration (before, during, or after swallow) was evaluated and categorized using real-time, slow motion, and frame-by-frame replay of the video recordings. Statistical comparisons were performed using two-way repeated-measures ANOVA, χ²-analysis, and Fisher’s exact test as appropriate. Values in the text are presented as means ± SE unless stated otherwise; n in all analyses was the number of animals unless stated otherwise.

RESULTS

Effect of Suprathyroid Myotomy on Deglutitive Excursions of the Hyoid Bone, Thyroid, and Cricoid Cartilages

Superior excursions. Analysis of videofluoroscopic recordings of the deglutitive excursions of the hyoid bone, larynx, and cricoid cartilages before myotomies showed that during 3 ml barium swallows, all three studied structures moved superiorly from their resting pre-swallow position (5.9 ± 0.9, 9.1 ± 1.0, and 8.5 ± 0.9 mm, respectively). After myotomy, the superior excursions of all three studied structures were significantly diminished (P < 0.05; Fig. 2).

Anterior excursions. Slow motion and frame-by-frame analysis of deglutitive anterior excursion of the hyoid bone and thyroid and cricoid cartilages showed that before myotomy, nine animals exhibited anterior excursions of 0.24 ± 0.20, 0.86 ± 0.32, and 0.96 ± 0.40 mm, respectively, during 3 ml barium swallows. In the two remaining animals, no appreciable anterior excursion was detected; instead, they exhibited a posterior movement of these three structures ranging between 0.1 and 2.5 mm in some repetitions and no appreciable anteroposterior movement in other repetitions during swallowing. Therefore, contrary to the superior excursion that was the constant feature during deglutition in all animals and during all trials, there were two types of excursions observed in the anterior/posterior plane: 1) anterior excursion (observed in the majority of animals), and 2) variable posterior excursion or negligible excursion in the minority of animals. After myotomy, all animals except for two cats (at different times) exhibited posterior excursion of the hyoid bone, larynx, and cricoid cartilages during 3 ml barium swallows (1.93 ± 0.42, 2.92 ± 0.44, and 1.93 ± 0.35 mm, respectively; Fig. 3), and this posterior excursion occurred in all trials.

Effect of Suprathyroid Myotomy on Deglutitive-UES Opening

Suprathyroid muscle myotomy was associated with a significant reduction in the anteroposterior diameter of
maximum UES deglutitive opening compared with premyotomy values (2.6 ± 0.6 vs. 4.2 ± 0.6 mm, respectively, \( P < 0.05 \)).

**Effect of Suprahyoid Myotomy on Pharyngeal Bolus Clearance**

Before suprahyoid myotomy, there was appreciable (51 ± 12% incidence, 8 of 11 animals) pharyngeal residue after the completion of swallowing; i.e., postdeglutitive residue. After suprahyoid myotomy, the incidence of pharyngeal residue was 88 ± 15% (11 of 11 animals), a significant increase compared with premyotomy values (\( P < 0.001 \)).

**Effect of Surgical Procedures on Deglutitive Aspiration**

**Predeglutitive period.** None of the animals (0 of 11 animals) exhibited aspiration of the barium bolus into the trachea in the predeglutitive stage, either before or after suprahyoid myotomy, epiglottectomy, or cordectomy (Table 1). No aspiration was observed (3 of 3 animals) during the predeglutitive period before or after unilateral cordectomy when no other surgeries (Table 1).

**Intradeglutitive period.** None of the animals (0 of 11) exhibited aspiration during the intradeglutitive period before surgical manipulation. After myotomy, the average incidence of aspiration was 20 ± 10% (4 of 11 animals), and this was not changed by epiglottectomy. After cordectomy, all 11 animals exhibited aspiration in all trials (Table 1). On the basis of visual observation, the volumes of the intradeglutitive aspirations were small compared with that which entered the esophagus before cordectomy, but after cordectomy the volumes of barium entering the trachea and esophagus were of a similar magnitude. In addition, after cordectomy (done in 10 animals), the barium always (100 ± 0% incidence in 10 animals) entered the trachea before entering the esophagus (Fig. 4, A–D). No aspiration was observed (3 of 3 animals) during the intradeglutitive period before unilateral cordectomy when no other surgery was performed, but the incidence increased to 100 ± 0% (3 of 3 animals) after cordectomy (Table 1).

**Postdeglutitive period.** Before surgical manipulation, the average incidence of aspiration was 5 ± 4% (2 of 11 animals). After suprahyoid myotomy, the average incidence of aspiration significantly increased (\( P < .05 \)) to 22 ± 10% (5 of 11 animals), but was not changed by subsequent epiglottectomy (Table 1). After cordectomy, the incidence of aspiration increased \(( P < 0.0)\) to 73 ± 13% (8 of 10 animals; Table 1). No aspiration was observed (3 of 3 animals) during the postdeglutitive period before unilateral cordectomy when no other surgery was performed, but the incidence increased to 100 ± 0% (3 of 3 animals) after cordectomy (Table 1).

**Relationship Between Pharyngeal Residue and Aspiration**

We found no relationship (Fisher’s exact test, \( P = 0.49 \)) between the incidence of pharyngeal residue and aspiration during the postdeglutitive period relative to suprahyoid myotomy. The incidence of residue before suprahyoid myotomy was 51% and increased to 88% after myotomy, and the incidence of aspiration before myotomy was 5% and increased to 22% after myotomy; however, only four of eight animals with residue had aspiration.

**DISCUSSION**

In this study, we determined the effect of selective impairments of various components of the deglutitive airway protective mechanism on the development of aspiration. Study findings indicate that glottal closure constitutes the major mechanism of prevention of aspiration during the intra- and postdeglutitive periods of swallowing and that laryngeal elevation may also have a significant role in protecting the airway during the intradeglutitive period.

Aspiration during swallowing has been divided into three phases (1). Predeglutitive aspiration has been defined as entry of bolus into the airway before activation of the oral/pharyngeal phase of swallowing. Intradeglutitive aspiration is the entry of swallowed bolus into the airway during the pharyngeal phase of swallowing while the bolus is traversing the pharynx. Postdeglutitive aspiration involves the entry of the swallowed bolus after completion of the act of swallowing by inhalation of residue left behind in the pharynx as a result of incomplete bolus clearance (1).

In the present study, predeglutitive aspiration was absent in all animals and remained absent after lesioning of the suprahyoid muscles, epiglottis, and vocal cords. The animals did not aspirate after these surgeries or after only vocal cord section because the fluid collected in the pyriform sinuses and the barium probably stimulated the pharyngoglottal closure reflex (9, 20, 21).

**Table 1. Incidence of aspiration**

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<tr>
<th></th>
<th>I</th>
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<th>M+E</th>
<th>M+E+C</th>
<th>Cn</th>
<th>Ca</th>
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<td>n</td>
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<td>11</td>
<td>11</td>
<td>10</td>
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<tr>
<td>Predeglutitive</td>
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<td>0 ± 0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
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<td>0 ± 0</td>
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<tr>
<td>Intradeglutitive</td>
<td>0 ± 0</td>
<td>20 ± 10</td>
<td>20 ± 10</td>
<td>100 ± 0</td>
<td>0 ± 0</td>
<td>100 ± 0</td>
</tr>
<tr>
<td>Postdeglutitive</td>
<td>5 ± 4</td>
<td>22 ± 10</td>
<td>22 ± 10</td>
<td>73 ± 13</td>
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Values are means ± SE (in %); \( n \), no. of animals. I, intact animals; M, postsuprahyoid muscle transection; E, epiglottectomy; C, unilateral cordectomy; Cn, before unilateral cordectomy; Ca, after unilateral cordectomy. Cn and Ca were assessed in 3 additional animals that underwent unilateral cordectomy only. *\( P < 0.05 \), comparison of I vs. M vs. M+E vs. M+E+C.
Intradeglutitive aspiration significantly increased due to supraphyoid myotomy, suggesting that either laryngeal elevation had an airway protective function or the lack of laryngeal distraction impaired airway protection function during this phase of swallowing. The diminished laryngeal elevation after myotomy may have resulted in malpositioning of the larynx during bolus transit such that the bolus arrived prematurely at the vocal cords before they were completely closed. Perhaps a more likely explanation for this postmyotomy intradeglutitive aspiration is the decrease in bolus clearance. The decrease in UES diameter during swallowing probably increased the resistance to flow through the UES (4, 19, 23), thereby

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**Fig. 4.** Examples of still frames of videofluoroscopic recording from a representative animal during 3 ml barium swallows before (A) and after supraphyoid muscle transection (B) and epiglottectomy (C) as well as postcordecotomy (D). A: in the predeglutitive period, some pharyngeal residue from prior swallows is seen. No aspiration is noted in the intradeglutitive period. In the postdeglutitive period, pharyngeal residue has been followed by small aspiration after resumption of respiration. B: deglutitive sequences after supraphyoid muscle transection; as seen, there is entry of some barium into the trachea during bolus transit through the pharynx. C: deglutitive sequence after epiglottectomy. In this instance, although the animal had undergone supraphyoid myotomy, epiglottectomy does not result in tracheal aspiration. D: after unilateral cordecotomy, almost one-half of the bolus is seen to enter the trachea, whereas the remaining bolus fills the esophagus in the intradeglutitive period.
increasing the time for bolus transit through the pharynx. This delay in transit may have caused aspiration because the glottis might have opened before the tail of the bolus had transited the pharynx.

Postdeglutitive aspiration was seen infrequently before surgery and increased significantly to about one-fifth of the swallowing, which suggests that, although the epiglottis may be positioned to assist airway protection, it may have no essential role in this function. This finding is supported by clinical studies that have found that epiglottectomy had no effect on any phase of aspiration, which suggests that, although the epiglottis may be positioned to assist airway protection, it may have no essential role in this function. This finding is supported by clinical studies that have found that epiglottectomy is not associated with aspiration in humans (25). Vocal cord hemisection greatly increased both intra- and postdeglutitive aspiration, suggesting that the glottal closure formed the primary barrier to aspiration during swallowing. The importance of glottal closure in airway protection is supported by clinical studies that found that aspiration often occurs after laryngeal paralysis or postoperative deficits that resulted in incomplete glottal closure.

Opening of the UES during swallowing is influenced by three factors: relaxation of the criopharyngeus muscle; distraction of the anterior wall of the UES by activation of suprahypoid and suprapharyngeal muscles, pulling the cricoid and thyroid cartilages anterosuperiorly (3, 7, 11, 19); and distention of the UES by the swallowed bolus (11). After myotomy of the suprahypoid muscles, UES opening during swallowing significantly decreased, but still maintained about two-thirds of its premyotomy diameter. This finding suggests that, whereas distraction of the larynx may be a major factor in opening the UES, the UES can be opened by bolus pulsion.

Our finding of a negligible anterior or posterior excursion of the larynx and cricoid during swallowing in the cat differs from what has previously been observed in adult humans (6, 8). This difference may be due to technical considerations or species differences (12). The cats were recorded while in the supine position with the head extended, and this nonanatomic position may have changed anterior movements to a more superior direction. The cats were decerebrated, but we found in prior studies that decerebration has negligible effects on swallowing variables. Some relevant species differences between humans and cats may explain the lack of anterior laryngeal movement. A significant species difference in the anatomic position of the larynx in relationship to the body and gravity exists between humans and cats. The larynx in cats is oriented perpendicular to gravity, whereas in adult humans the larynx/pharx is oriented parallel with gravity. In adult humans, the larynx is situated more caudally than in cats. Perhaps this difference in anatomic orientation of the larynx accounts for the difference in anteroposterior excursion during swallowing between cats and adult humans. The resting position of the larynx of cats may be closer to the optimum position needed during swallowing than that of humans and therefore does not have to be moved as much during the swallow.

We found that although all of the suprahypoid muscles were cut, the larynx still moved superiorly to a significant degree. This residual superior movement of the larynx may have been due to the action of suprapharyngeal muscle activation such as the stylopharyngeus. We found in prior studies (13) that during swallowing the suprapharyngeal muscles are activated strongly. The pull on the pharynx may have been transmitted to the larynx by connective tissue contacts.

In summary, glottal closure constitutes the primary mechanism for prevention of intra- and postdeglutitive aspiration, but laryngeal elevation may assist in this prevention. Distraction of the larynx is not only important for opening the sphincter but also for ensuring a low resistance through the UES to prevent aspiration. Bolus pulsion can open the UES but at risk of aspiration due to decreased pharyngeal clearance. The epiglottis provides no apparent airway protection during any phase of swallowing.

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REFERENCES


