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Intrinsic fibre architecture and attachments of the human epiglottis and their contributions to the mechanism of deglutition

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ABSTRACT

Two mechanisms have been proposed which address the downfolding of the epiglottis during swallowing. The passive mechanism (Fink et al. 1979) focuses on passive mechanical forces transmitted through the median hyoepiglottic ligament and pre-epiglottic adipose tissue to the epiglottis. The active mechanism (Ekberg & Sigurjonsson, 1982) expands the passive mechanism to include active contributions from the aryepiglotticus and thyroepiglotticus muscles. By means of laryngeal microdissection and whole mount orcein staining, distinct bands of fascial condensations were identified running from the lateral edge of the epiglottis just superior to the attachment of the median hyoepiglottic ligament to the hyoid bone near the ends of the greater horns. Neither the proposed active nor the passive mechanisms address the possible contribution of these paired lateral hyoepiglottic ligaments to epiglottic downfolding. Computer image analysis of videofluoroscopic examinations of swallowing was then used to assess the dynamic movements of the larynx during swallowing. It was observed that the downfolding of the epiglottis occurred in the same video frame as initiation of anterior displacement of the hyoid bone and thyrohyoid approximation. Based on the anatomical and dynamic relationship of the epiglottis to other laryngeal structures, we propose that as the larynx elevates and the hyoid bone moves anteriorly, these lateral ligaments exert traction preferentially on the upper third of the epiglottis to bring it to a position below the horizontal.

Key words: Larynx; hyoepiglottic ligaments.

INTRODUCTION

The movements of the human epiglottis as they relate to the closure of the laryngeal aditus during the pharyngeal stage of swallowing have been a topic of interest since the 2nd century A.D. when Galen described the epiglottis as 'a lid [placed] to fall down upon the larynx when anything is swallowed' (May, 1968). By observing canine swallows, Magendie came to a similar conclusion about epiglottic function but further commented that the epiglottis was merely an accessory organ since the leaf of the epiglottis could be completely removed with virtually no change in the integrity of the swallow (Magendie, 1813; Milligan, 1831). In his early work, Negus (1927, 1929, 1942), largely citing the work of Stuart (1891) and later Barclay (1930), argued that the epiglottis did not move down to cover the larynx during swallowing but rather subserved a primitive olfactory function. In his later work, Negus (1948, 1949) altered his position and stated that by the action of the tongue, the epiglottis moves to a somewhat horizontal position but that this movement is of no importance. Finally, several groups in the early 1950s independently verified through cineradiography that regardless of the evolution or importance of the epiglottis, it briefly moves down to cover the laryngeal aditus during swallowing (Ardran & Kemp, 1951, 1952; Rushmer & Hendron, 1951; Saunders et al. 1951).

The epiglottis has been reported as making two distinct movements to cover the laryngeal aditus (Ardran & Kemp, 1951, 1952, 1967; Saunders et al. 1951). The first epiglottic movement (FEM) which occurs at the attachment of the epiglottis to the

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thyroid cartilage brings the epiglottis from its somewhat vertical, resting position to a horizontal attitude. This movement occurs concurrently with the elevation of the larynx and hyoid as well as the posterior movement of the tongue during propulsion of the bolus toward the faucial pillars and into the pharynx. It was described without the benefit of radiographic evidence by Magendie as occurring in the following fashion:

> Whilst the os hyoides and the larynx are raised, they approach each other; that is, the superior edge of the thyroid cartilage engages itself behind the body of the os hyoides: the epiglottic gland is pushed back; the epiglottis descends, inclines downwards and backwards, so as to cover the entrance of the larynx. (Milligan, 1831)

The second epiglottic movement (SEM), which occurs as the bolus passes through the pharynx, brings approximately the upper one-third of the epiglottis to a position below the horizontal. This SEM has been reported to occur over 60–90 ms and at the point of maximum elongation of the hyoepiglottic ligament (Fink et al. 1979). As the larynx and hyoid bone begin to descend after bolus passage, the epiglottis returns to its preswallow position.

Based on radiographic evidence and classical anatomical relationships there are currently two theories which attempt to explain how these epiglottic movements are generated. The passive theory of Fink and colleagues (Fink & Demarest, 1978; Fink et al. 1979) is similar to that of Magendie (Milligan, 1831) and holds that the FEM is brought about passively by backward movement of the tongue and by forces generated by compression of adipose tissue located between the thyroid cartilage and the epiglottis. This adipose tissue is compressed when the larynx is elevated. According to this theory, the SEM, which may or may not be assisted by the action of the bolus on the epiglottis, occurs when the median thyroepiglottic fold produces bulging of the epiglottic tubercle resulting in a concavity in the epiglottis thus downfolding its upper part.

The theory of Ekberg & Sigurjonsson (1982) with regards to the FEM is similar to the passive theory; however, an alternative explanation of the SEM is presented. These authors contend that an active muscular mechanism must be present because the SEM occurs in dry swallowing as well as when liquids are ingested. Thus they propose that after the FEM, the aryepiglotticus and thyroepiglotticus muscles are mechanically well placed to pull the epiglottis over the laryngeal aditus. While this action could explain the presence of the SEM in dry swallowing, the objection has been raised that these epiglottic muscles are too sparse to be able to generate the force required to overcome the resilience of the epiglottis (Ramsey et al. 1955; Fink et al. 1979).

The purpose of this investigation was to examine the internal fibre architecture of the epiglottis and its attachments to palatal, oral, pharyngeal, and laryngeal structures and then to examine the movements of the epiglottis radiographically as they relate to the movements of other laryngeal and pharyngeal structures. Although a histological investigation into the vascularisation and degeneration of the epiglottis has been reported (Kreutz, 1980), a detailed examination of the internal fibre architecture of the human epiglottis has not been discussed since Lewis (1905) briefly covered it in a report on the elastic tissue of the entire larynx. Furthermore, an original examination of the attachments and associated musculature of the epiglottis has not been reported in this century. The attachments of the epiglottis provided information about the static relationships between the epiglottis and other structures, and the internal fibre architecture information provided us with clues to the effects of those attachments on the epiglottis. The radiographic analysis provided us with dynamic information about the movements of those structures attached to the epiglottis. The kinematic data, gained from the static and dynamic analyses, were then used to elucidate a novel mechanism of epiglottic downfolding.

ANATOMICAL MATERIALS AND METHODS

Specimens were obtained from embalmed human cadavers donated to the University of Iowa Deeded Body Program. No information about age or sex was available. A specimen generally consisted of a tongue, hyoid bone, and larynx with associated pharyngeal musculature.

Twenty larynxes were macrodissected to determine the attachments of the epiglottis to the tongue, hyoid bone, and thyroid and arytenoid cartilages. To facilitate mucosal stripping, the specimen was frozen (at -20 °C) the night before it was to be dissected and thawed the next morning. The macrodissection included manual stripping of the mucosa to explore fully the extent of the inferior attachment of the palatopharyngeus muscle, the quadrangular membrane, the hyoepiglottic ligaments, the thyroepiglottic ligament, the thyroepiglotticus muscle, the oblique and transverse arytenoid musculature, and the attachments of the tongue to the epiglottis. Photographs were taken at various stages of dissection.

In 6 cases, the attachments of the hyoepiglottic

ligaments on the epiglottis were marked and the epiglottis was excised. Any mucosa remaining on the epiglottis was removed manually. The perichondrium was separated from the underlying cartilage using a combination of manual stripping and dispase (trypsin) enzymatic digestion. After much of the perichondrium was stripped manually, the epiglottis was digested at 37 °C for 20 min with dispase in a 1 % (w/v) $NaHCO_3$ (enzyme:buffer ratio 1:10) solution. This was repeated until the underlying cartilage was uncovered sufficiently for us to proceed to the India ink pinprick analysis. In general, this required 5 repetitions.

Each epiglottic cartilage was then subjected to an India ink pinprick analysis using the method previously employed with human articular cartilage of the shoulder, hip, knee, and ankle joints (Meachim et al. 1974) as well as the cricoarytenoid joints of the larynx (Kahane & Kahn, 1986; Kahn & Kahane, 1986). In short, the tip of a dressmaker's pin was charged with alcohol soluble India ink and used to prick the surface of the cartilage. Under a dissecting microscope, the pin was inserted into the cartilage approximately normal to the surface at random points to cover the entire cartilage. The depth of the prick was not controlled, and excess ink was removed with alcohol. The pricks of the pin generated split lines in the cartilage indicative of the preferential alignment of the internal fibres, and the ink served to outline them.

After each epiglottis had been subjected to the analysis, both the anterior and posterior (pharyngeal) aspects were photographed, and the photographs were enlarged to 8 × 10. The outline of the epiglottis, the placement of the holes, and the individual split lines were traced onto mylar tracing paper, and the relationship of the split lines to the attachments of the epiglottis was assessed.

To verify the preferential alignment of the fibre bundles, a 7th epiglottis which was not subjected to pinprick analysis was examined using scanning electron microscopy. The method employed preferentially dissolved much of the matrix components of the cartilage while leaving the collagen in place (Steven & Thomas, 1973) and has been applied to human articular cartilage (Minns & Steven, 1977) but not to human elastic fibrocartilage such as the epiglottis. As such, the method had to be slightly modified but only in the number of repetitions of the treatment. Briefly, the mucosa and the perichondrium of the epiglottis were stripped away manually leaving only cartilage. The epiglottis was then shaken with 30 % (v/v) H_2O_2 in the dark at 20 °C for 18 h followed by repeated washing with water and 0.9 % (w/v) NaCl. The epiglottic cartilage was digested with dispase (trypsin) in 1 % (w/v) $NaHCO_3$ (enzyme:tissue ratio approximately 1:100) for 18 h at 20 °C with constant shaking. After the tissue had been washed with water and 0.9 % NaCl, it was washed 3 times with 0.1 M acetic acid. The epiglottis was washed yet again with water and 0.9 % NaCl, and the entire procedure was repeated twice more. The sample was then prepared for the scanning electron microscope first using a careful dehydration procedure involving increasing strengths of acetone (50–100 %, in steps of 10 %, 20 min each), followed by critical point drying procedure with HMDS. The whole of the epiglottis was mounted on a scanning electron microscope stud using copper tape and carbon glue and left in a desiccator overnight. The specimen was sputter coated with gold–palladium (60/40) and scanned in a Hitachi model S-4000 scanning electron microscope. Polaroids were taken of the scanning electron microscope at various magnifications and were used to make photomicrographs.

To determine the elastic component of the hyoepiglottic ligaments, 2 specimens were stained preferentially for elastic fibres using a whole mount orcein technique. The structures inferior to the hyoid bone were removed as well as the tongue and associated musculature. The specimen was first dehydrated using alcohol in strengths of 50, 70, and 90 % before it was soaked for 30 min in an orcein solution consisting of 0.8 g of synthetic orcein, 0.6 ml of concentrated hydrochloric acid, and 100 ml of 70 % alcohol. Following the staining the specimen was washed for 15 min under tap water and dehydrated again using alcohol in increasing strengths of 50, 70, 90 and 100 %, then cleared in methyl salicylate. Photographs of the cleared specimen were taken using transillumination.

Fifty-five bisected head specimens were macrodissected to determine the muscle fibre constituent of the aryepiglottic folds. In these specimens, the mucosa of the aryepiglottic folds and other parts of the laryngopharyngeal mucosa were stripped. Then the mucosal stripping continued superiorly into the posterior palatopharyngeal arch. Once the mucosa was stripped and muscle fibres were found within the aryepiglottic folds, their course was traced superiorly. Photographs were taken of the specimens after mucosal stripping.

RADIOGRAPHIC MATERIALS AND METHODS

Videotapes from 5 individuals who had been referred for videofluoroscopic examination of oropharyngeal swallowing and were judged to have normal

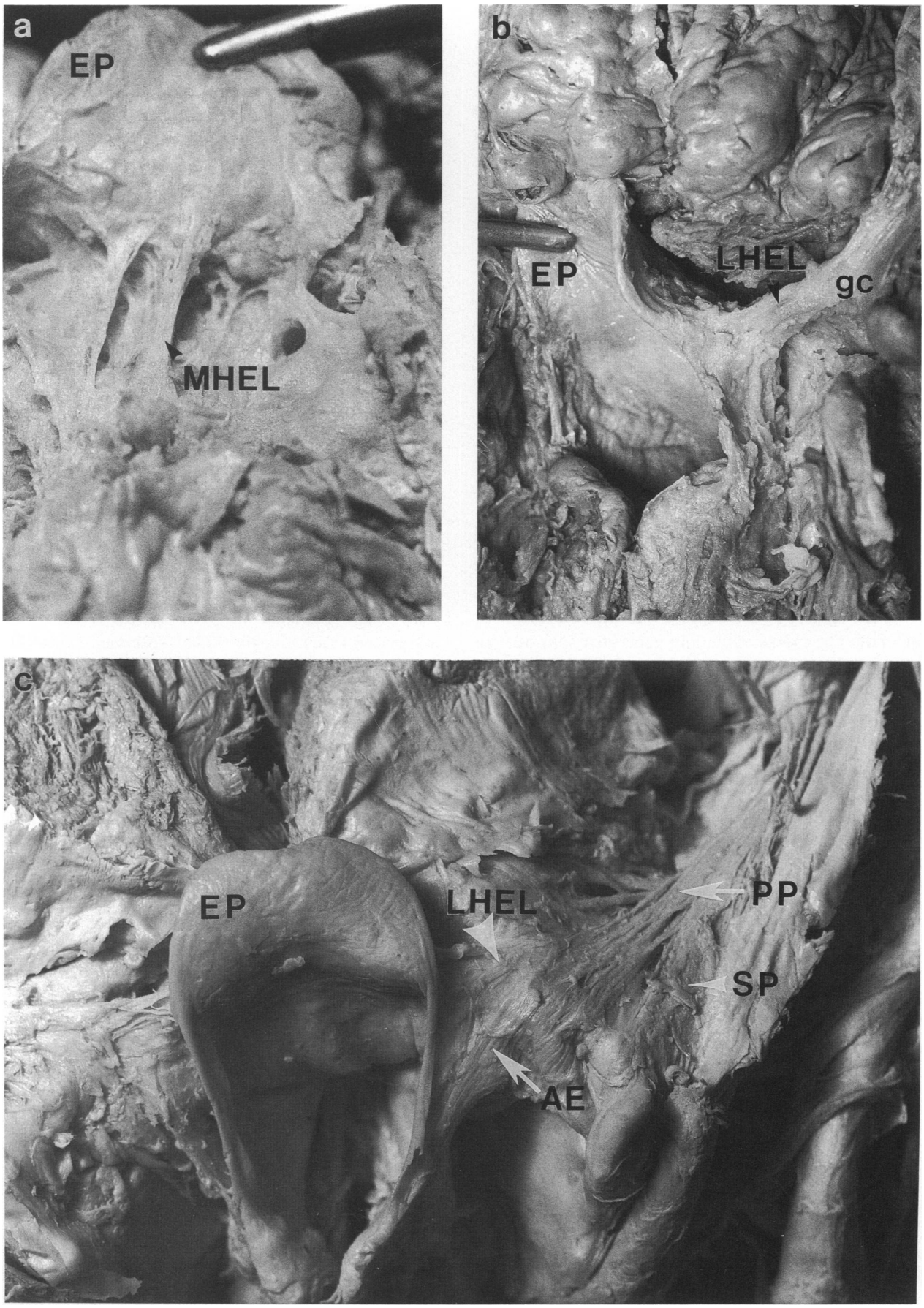

Fig. 1. For legend see opposite.

swallowing function were used for analysis (ages 23–75 y). These tapes were selected from a pool of male patients whose swallowing had been evaluated clinically by the second author while on the staff of the VA Medical Center in Iowa City, Iowa, USA. As such, informed consent was obtained in the manner consistent with all clinical procedures at the VA Medical Center.

During the examination, the patients were placed in the lateral plane with the area of interest ranging from the soft palate to the level of the 7th cervical vertebra in the vertical direction and from the lips to the spinal column in the horizontal direction. A 3 cm lead calibration bar was placed vertically on the patient's neck to allow for fluoroscope magnification. Liquid boluses of barium sulphate (5 ml) were presented from a calibrated syringe. Two presentations from each patient were analysed for a total of 10 swallows. Videofluoroscopic images were input to a FOR.A videotimer which placed timing information on the video image, and the images were then recorded on a JVC S-VHS videocassette recorder.

Video images were then transferred from videotape to a Macintosh Quadra 800 computer via a RasterOps video frame grabber board and MediaTime software. The images were acquired at an 8-bit 640 × 480 pixel resolution with 256 levels of grey scale. Individual images were selected from the examination for detailed analysis using Image 1.35 software. Frames of interest included but were not limited to: (1) a preswallow frame; (2) the first frame where the posterior aspect of the tongue began to bulge into the pharynx; (3) the initiation of elevation of the hyoid bone; (4) the initiation of anterior hyoid bone movement; (5) the initiation of thyrohyoid approximation; (6) the beginning of the SEM; (7) the maximum anterior hyoid bone displacement; (8) the beginning of hyoid descent; (9) a postswallow frame.

In each frame of interest, the atlas tubercle, the anterior inferior aspect of the 5th cervical vertebra, the anterior superior aspect of the subglottal air space, and the anterior inferior aspect of the hyoid bone were identified. Also noted was the time value generated by the videotimer and the position of the epiglottis. Through algebraic and trigonometric manipulation in an EXCEL spreadsheet (A. L. Perlman et al., unpublished observations), positions of the subglottal air space and the hyoid bone were translated from the traditional cartesian coordinate system into a frame of reference relative to the angle of the neck from the 1st to 5th cervical vertebrae. Thus the measurement of hyoid bone movement and of thyrohyoid distance (as indicated by the distance between the subglottal air space and the anterior inferior aspect of the hyoid bone) could be expressed as a vector in the anterior–superior plane not horizontal–vertical plane as in the traditional coordinate system.

The measurements from the examination for each of the 2 swallows from each of the 5 subjects were averaged and the standard error was calculated for (1) the time required for the epiglottis to completely downfold to cover the larynx, (2) the time required for the hyoid to move from its posterior position to its maximum anterior–superior position, (3) the magnitude of the maximum hyoid anterior movement, and (4) the magnitude of the maximum hyoid superior movement. These time values are accurate to ±33 ms due to the sampling rate of the videocassette recorder.

RESULTS

Fascial attachments of the epiglottis

In all bisected head and excised laryngeal specimens examined, the mucosa was removed in its entirety from the larynx and laryngopharynx to expose the underlying submucosa. Since the submucosal tissue (tela submucosa, N.A.) was fascial in nature, and continuous laterally with the internal pharyngeal fascia overlying the middle and inferior constrictor muscles, and medially with the submucosa of the laryngeal vestibule, the term laryngopharyngeal fascia (LPF) will be used here to describe it. Superiorly, the laryngopharyngeal fascia was continuous with the submucosa of the tongue. On the lower part of the posterior aspect of the tongue,the LPF was reflected over the median hyoepiglottic ligament and continued over the apex of the epiglottis into the laryngeal vestibule. Laterally, the LPF lined the valleculae and became continuous with the internal pharyngeal fascia over the middle constrictor. Laterally, the LPF continued down, covering the internal surface of the hyoid bone, thyrohyoid membrane and thyroid cartilage, eventually becoming continuous with the submucosa of the oesophagus. In the lateral wall of the piriform recess, the small fold (plica nervi

Fig. 1. Macrodissection photographs of the lateral pharyngeal wall and epiglottis (EP) in the area of the laryngeal aditus with the mucosa removed, illustrating in (*a*) the median hyoepiglottic ligament (MHEL), and in (*b*) the lateral hyoepiglottic ligaments (LHEL) in a close-up view of the lateral wall of the pharynx. In (*c*) the muscle fibre bundles of the aryepiglottic fold (AE) can be followed up over the greater cornu of the hyoid bone (gc) and into the palatopharyngeus (PP) musculature in the palatopharyngeal arch. The stylopharyngeus musculature (SP) can be identified adjacent to the palatopharyngeus musculature.

laryngea, N.A.) overlying the internal laryngeal nerve and vessels was seen only in 2 specimens. Anteromedially, the LPF was reflected off the thyroid cartilage and continued posteriorly, forming the fascia in the medial wall of the piriform recess. The LPF then extended over the posterior aspect of the arytenoid and cricoid cartilages and was continuous inferiorly with the submucosa in the anterior oesophageal wall. In the posteroinferior aspect of the larynx, the LPF was observed to be a distinct sheet that could be readily separated from the epimysial coverings of the transverse arytenoid and posterior cricoarytenoid muscles. Superiorly, this medial reflection of the LPF was continuous with the fascia covering the posterior aspect of the epiglottis and, in the region of the aryepiglottic folds and interarytenoid incisure, the submucosa of the laryngeal vestibule.

In the superomedial part of the piriform recess, 3 distinct folds were consistently observed in the laryngopharyngeal fascia on either side. Two of these folds ran into the fascia covering the epiglottis. The most prominent of these 2 folds passed horizontally from the laryngopharyngeal fascia covering the hyoid bone to the lateral margin of the epiglottis. This fold appeared to be beneath the so-called pharyngoepiglottic fold (plica glossoepiglottica lateralis, N.A.) of the mucosa. The second, smaller fold ran from the lateral epiglottic margin to the tip of the arytenoid cartilage, corresponding to the aryepiglottic fold of mucosa. The lateral (hyoid) end of the fascial fold underlying the lateral glossoepiglottic fold and the apex of the arytenoid cartilage were connected by an oblique fold of fascia that extended from 2 to 5 mm anteromedial to the tip of the greater cornu of the hyoid bone to the apex of the arytenoid cartilage. Above the hyoid bone, this fold was continuous with the fascia underlying the palatopharyngeal fold of mucosa. As this fold passed over the hyoid bone, 2 small, secondary folds were consistently observed passing laterally to the hyoid bone and inferiorly to the thyroid cartilage.

Ligamentous attachments of the epiglottis

The median hyoepiglottic ligament (MHEL) was observed in every case after removal of the fascia lining the valleculae. Consistent with the usual descriptions, the MHEL consisted of a fibrous, fan-shaped band of tissue running in the midline from the hyoid bone to the anterior surface of the epiglottis (Fig. 1*a*). The upper limit of the epiglottic attachment of the MHEL was at the level of the lower borders of the greater cornua of the hyoid bone. Its lower attachment varied and appeared to blend with the attachment of the median thyroepiglottic ligament (Fink et al. 1979). On either side of the MHEL, a variable amount of adipose tissue (corpus adiposa preglottica, N.A.; gland of Morgagni) was always seen in the preglottic space.

In addition to the median hyoepiglottic ligament, 2 short, fibrous bands of tissue were seen passing from the lateral edges of the epiglottis to the greater cornua of the hyoid bone beneath the lateral hyoepiglottic folds (Fig. 1*b*, *c*). The epiglottic attachments of these lateral hyoepiglottic ligaments (LHEL) were consistently observed to be above the level of the attachment of the MHEL.

Muscular attachments of the epiglottis

The laryngopharyngeal fascia was carefully removed from the piriform recess using a dissecting microscope and muscle fibres were carefully sought. In only 2 specimens were muscle fibres found in the aryepiglottic folds. When fibres were found, they did not insert into the lateral edge of the epiglottis, but instead, turned laterally and superiorly to become continuous with the vertical fibres of the palatopharyngeus muscle. Well defined bundles of muscle fibres were seen in almost every specimen examined beneath the fascial continuation of the palatopharyngeal arch (Fig. 1*c*). In all cases, these bundles of muscle fibres were part of a continuous fasciculus that could be followed superiorly through the palatopharyngeal arch into the vertical part of the palatopharyngeus muscle. Further, continuous bundles of muscle fibres could be followed running posterior to the arytenoid cartilage from the apex to the base of the contralateral arytenoid cartilage. In other specimens, few fibres were encountered below the hyoid bone although the oblique fold of fascia was present.

Following complete removal of the laryngopharyngeal fascia and exposure of the thyroarytenoid muscles, variable amounts of muscle tissue were observed in most cases running into the lower one-third of the epiglottis (into the petiolus), either from the anterolateral surface of the arytenoid cartilage or apparently from the thyroarytenoid muscle itself. These were the only muscle fibres consistently identified as inserting into the epiglottis.

India ink pinprick analysis

The posterior aspect of each epiglottis exhibited split lines (Fig. 2*a*, *c*, 3*a*) that ran primarily in a horizontal

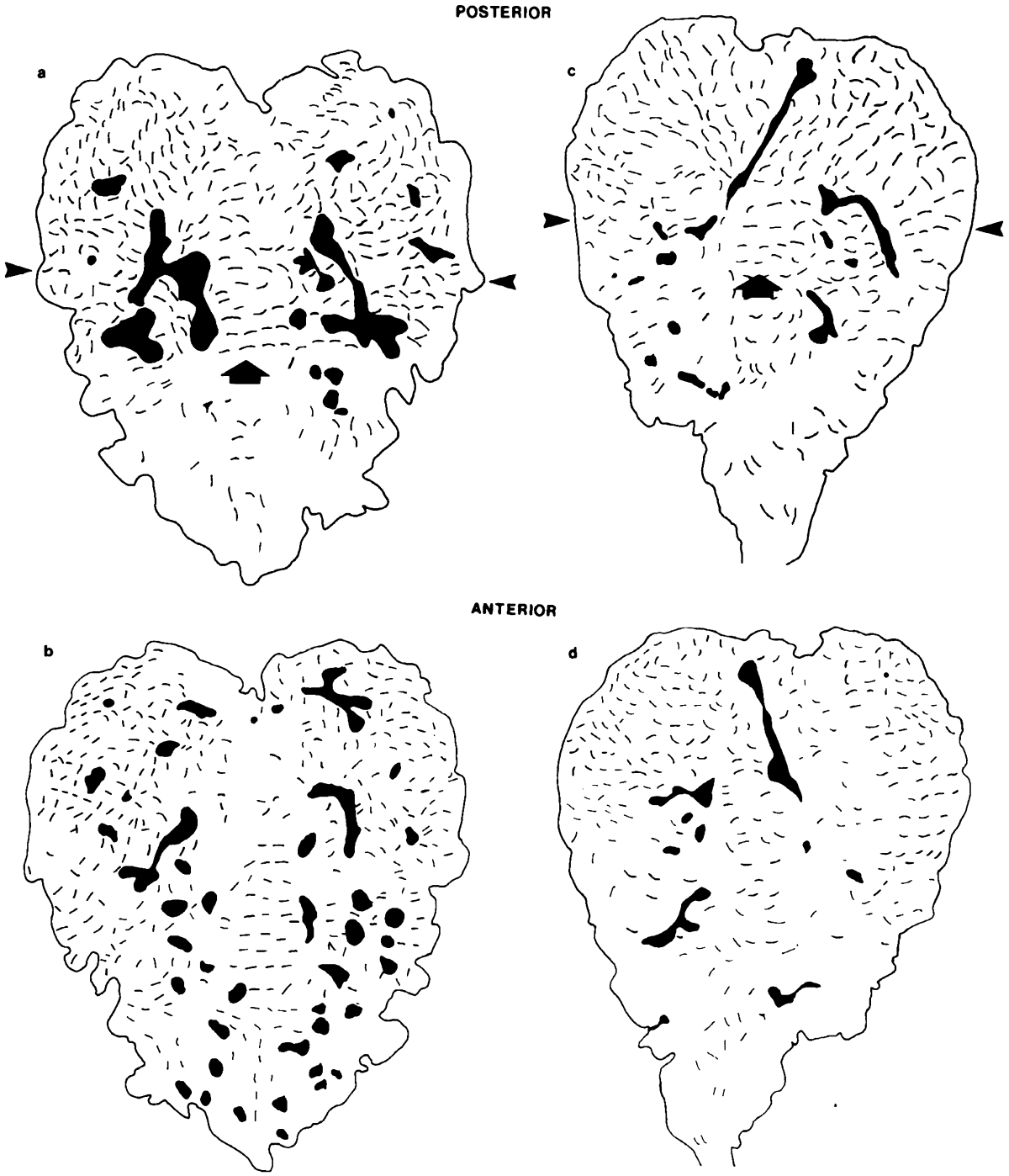

Fig. 2. Representative India ink pinprick tracings of 2 of the 6 epiglotti studied. The dark areas illustrate the positions of the natural pits within the epiglottis, the wide arrows point to the attachment of the median hyoepiglottic ligament, and the arrowheads indicate the attachments of the lateral hyoepiglottic ligaments (LHEL). The posterior aspect (*a*, *c*) of the epiglottis shows a preferential horizontal arrangement of collagen fibres in a band between the attachments of the LHEL while the anterior aspect (*b*, *d*) exhibits an arrangement which surrounds the pits in the epiglottic cartilage.

direction throughout the upper one to two-thirds of the epiglottis (above the epiglottic tubercle). These horizontal splits were most pronounced between the attachments of the LHEL and that of the MHEL (Fig. 2*a*, *c*). This area, approximately one-third of the way from the superior margin of the epiglottis, will be referred to as the epiglottic folding plane. The lower third, including the petiolus of the epiglottis, demonstrated a vertically directed orientation of split lines.

The anterior aspect of each epiglottis (Fig. 2*b*, *d*) showed a different, more complex orientation of split lines. On close examination, the split lines exhibited orientations that surrounded the holes and recesses in the epiglottis formed by mucous glands.

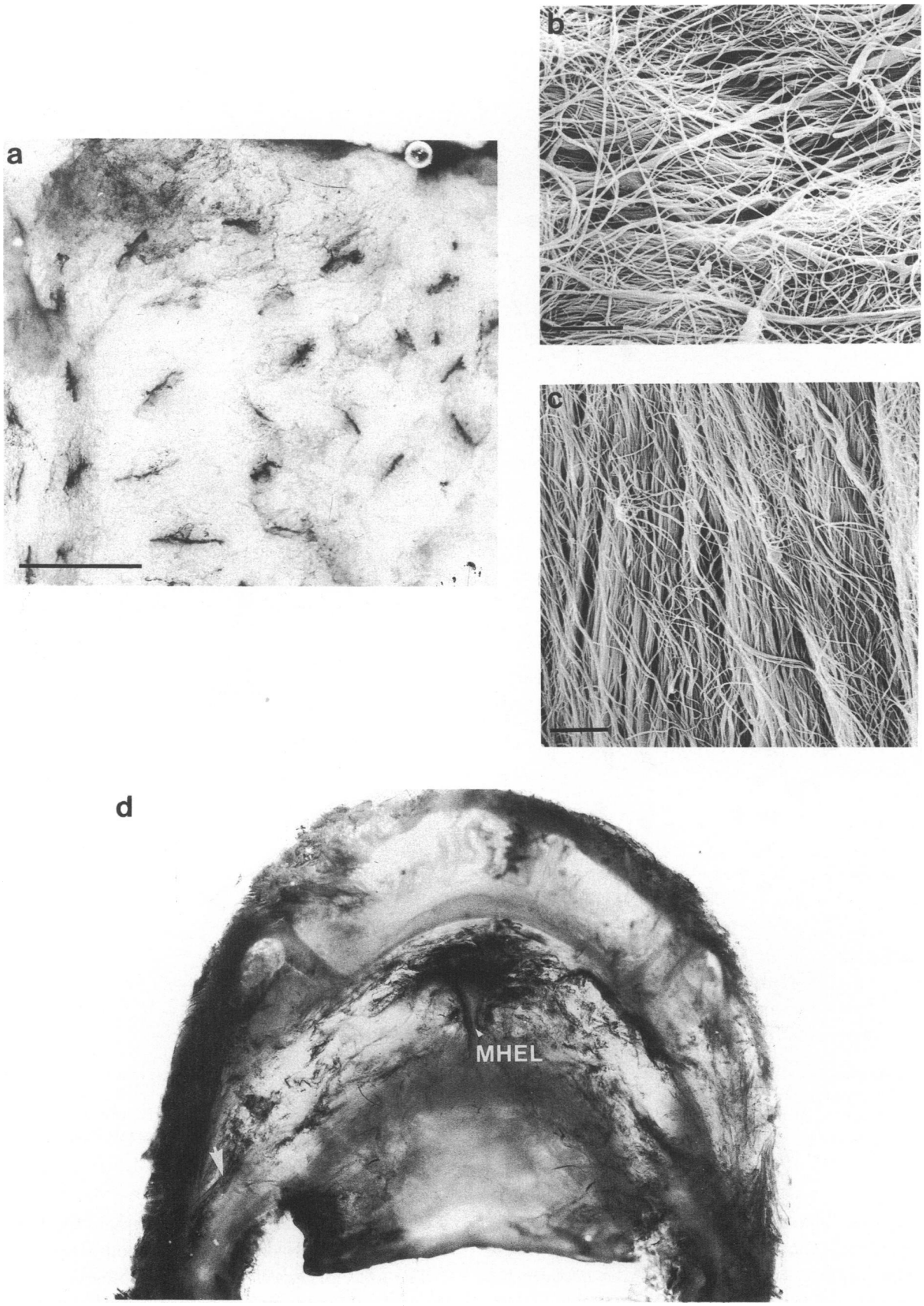

Fig. 3. High magnification photograph of the split lines generated in the India ink pinprick analysis (*a*), scanning electron micrographs of the collagen fibre arrangement of the epiglottis (*b*, *c*), and photograph of a whole mount orcein stain specimen (*d*). (*b*) illustrates the horizontal orientation of the fibres from the region of the lateral hyoepiglottic ligament attachments. The vertical orientation of the fibres is illustrated in (*c*) which is an example taken from the petiolus. In (*d*) most of the connective tissue has been cleared leaving only the darkly

Scanning electron microscope analysis

Scanning electron microscopic examination confirmed that the split lines reflected the arrangement of collagen bundles in the epiglottic cartilage. A horizontal orientation of collagen bundles was seen between the attachments of the LHEL (Fig. 3*b*). A vertical orientation of the fibres was observed in the petiolus (Fig. 3*c*).

Orcein stain

Cleared preparations of the orcein stained whole mounts revealed elastic fibres in the MHEL. The paired LHEL, which were localised to the lateral borders of the epiglottis running into the hyoid bone near the tips of the greater horns, also showed elastic fibres. It was clear that the elastic fibres in the MHEL and LHEL are distinct bundles running in different planes to insert onto the epiglottis. Further, the LHEL were clearly not lateral extensions of the MHEL. The MHEL appeared to contain a greater concentration of elastic fibres than the LHEL (Fig. 3*d*). The elastic fibres associated with the LHEL were concentrated at the sides of the ligaments rather than within the ligaments themselves.

Radiographic analysis

A classic FEM followed by an SEM was not present in all observations. In 1 subject, the epiglottis moved from its baseline, vertical position to a position below the horizontal in one continuous motion. A similar phenomenon was observed in approximately 20% of the subjects reported by Ekberg & Sigurjonsson (1982). When a classic FEM did occur, the bulging of the tongue posteriorly into the pharynx (Fig. 4*a*, *b*) was responsible for the horizontal positioning of the epiglottis as reported by Ardran & Kemp (1952). Furthermore, when an FEM was observed, the point of action was around the attachment of the epiglottis to the thyroid cartilage while the point of action of the SEM was about one-third of the way down from the superior edge of the epiglottis (Fig. 4*c–f*).

The time required for the epiglottis to move down below the horizontal for all subjects was an average of 109 ms (S.E. 12 ms) which is close to the mean of 98 ms reported by Curtis et al. (1984) and somewhat longer than the 60–90 ms reported by Fink (1979). The time between the thrust of the hyoid bone anteriorly to the attachment of the maximum hyoid position for all swallows was 286 ms (S.E. 38) which is within the range of 211 ms (S.E. 27) reported by Curtis et al. (1984) and 300 ms by Logemann et al. (1989). The mean maximum displacement of the hyoid bone was measured to be 7.6 mm (S.E. 1.0) anteriorly and 12.5 mm (S.E. 1.6) superiorly. Results for individual subjects are summarised in the Table.

The anterior–superior trajectory of the hyoid bone during a representative 5 ml barium swallow (Fig. 5) was similar to those previously reported (Logemann et al. 1989; Jacob et al. 1989). From the preswallow state, which has been defined arbitrarily as zero superior and anterior displacement and zero time, the hyoid moves slightly posteriorly as it elevates. In the same video frame as the hyoid begins its anterior movement, the epiglottis begins its downfolding. The epiglottis finishes its downfolding movement before the hyoid reaches its most anterior position. There is an increase in thyrohyoid distance in the initial phase of hyoid movement. This increase in distance mirrors the superior movement of the hyoid, thus suggesting that as the hyoid moves superiorly the larynx elevates only passively under the influence of hyoid motion (Fig. 6). However, as the hyoid begins its anterior thrust and the epiglottis begins its downfolding, the thyrohyoid distance begins to decrease rapidly while the superior motion of the hyoid ceases. This rapid decrease in thyrohyoid distance, along with cessation of superior hyoid movement, is probably due to contraction of the thyrohyoid musculature. The epiglottis finishes its downfolding manoeuvre before the maximum anterior–superior hyoid displacement has been reached and before thyrohyoid approximation has achieved its lowest value.

DISCUSSION

The purpose of the present study was to elucidate the mechanism for epiglottic downfolding during swallowing. Evidence was obtained by laryngeal macrodissection, whole mount orcein staining, India ink pinprick analysis, and scanning electron microscopy. Computer-based radiographic image analysis indicates that the FEM and the SEM occur by 2 distinct processes. The process which elicits the FEM is directly related to active tongue motion. The SEM is a result of passive biomechanical forces generated by movements of the hyoid bone and thyroid cartilage which are transmitted to the epiglottis through the lateral and median hyoepiglottic ligaments.

stained elastin fibres concentrated in the midline in the median hyoepiglottic ligament (MHEL) and around the edges of the lateral hyoepiglottic ligaments (white arrow).

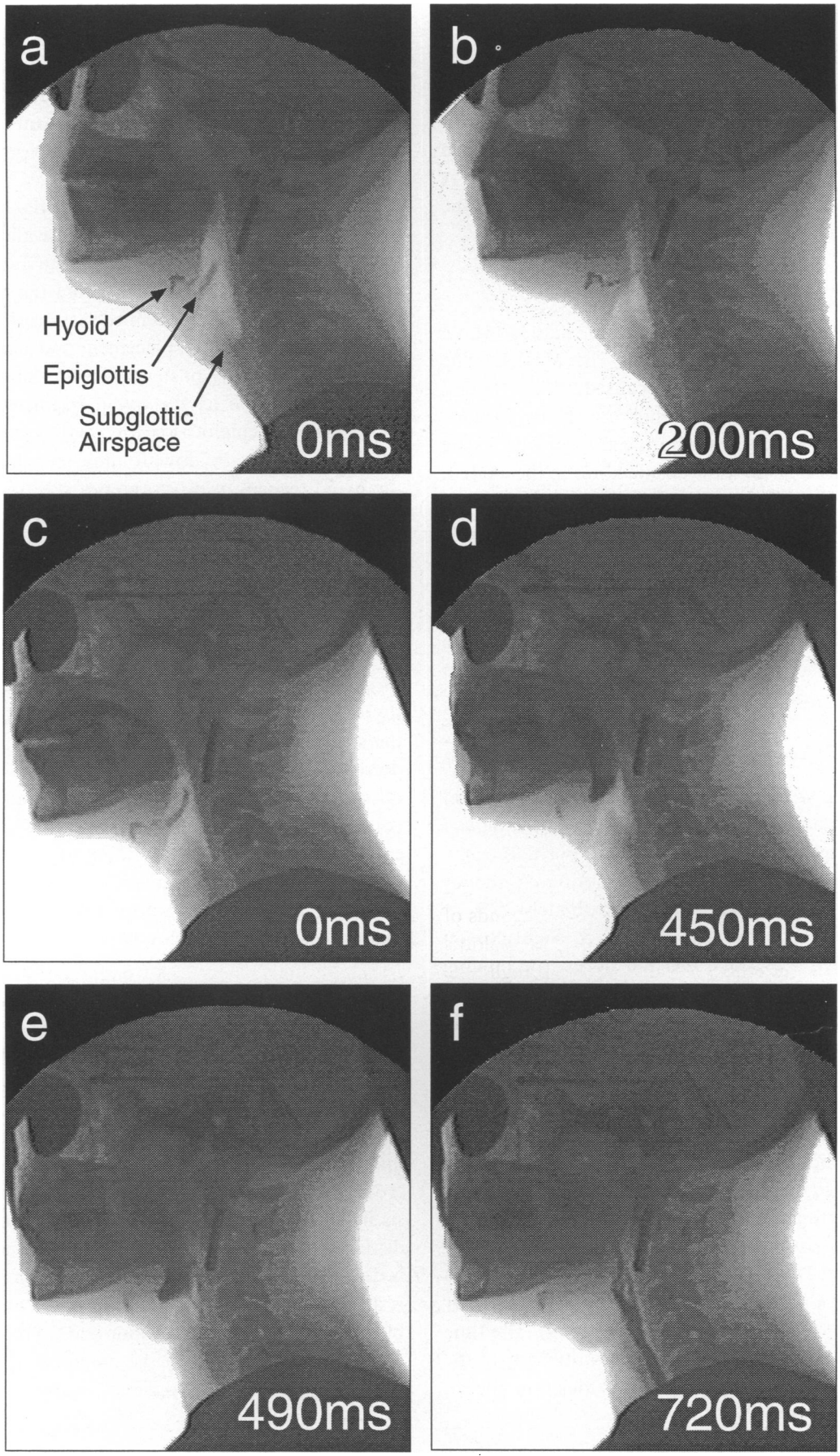

Fig. 4. For legend see opposite.

Table. *Radiographic analysis of laryngeal movement during swallowing*

Subject ID (age, y)	Epiglottic movement (ms)*	Anterior hyoid movement (ms)*	Anterior displacement (mm)*	Superior displacement (mm)*
1 (23)	95 (15)	215 (35)	5.13 (1.3)	11.59 (0.3)
6 (23)	120 (20)	345 (45)	7.7 (1.6)	11.1 (0.9)
7 (23)	90 (10)	400 (20)	9.2 (1.1)	7.8 (1.1)
1403 (70)	150 (20)**	265 (5)	10.1 (0.5)	16.9 (0.1)
1417 (75)	90 (10)	205 (65)	6.0 (2.2)	15.1 (2.0)
Overall	109 (12)	286 (38)	7.6 (1.0)	12.5 (1.6)

* Mean (standard error); ** no FEM.

The existence of lateral extensions of the hyoepiglottic ligament has been included in several anatomy textbooks though detailed descriptions are lacking. Schaeffer (1953) described the hyoepiglottic ligament as a broad sheet that spreads laterally to join the pharyngeal aponeurosis in the region of the piriform recess. Last (1978) described the hyoepiglottic ligament as projecting laterally to the tip of the greater horns of the hyoid bone to form the pharyngoepiglottic fold. These reports suggest that the hyoepiglottic ligament is one continuous sheet which projects laterally. The present findings indicate that there is a distinct median hyoepiglottic ligament (MHEL) and 2 distinct lateral hyoepiglottic ligaments (LHEL). These LHEL do project laterally to the tip of the greater horns of the hyoid bone to form the pharyngoepiglottic folds, but they are not simply lateral extensions of the MHEL. As indicated by the macrodissection and the orcein stains, the LHEL are distinct bands of tissue which probably exert force on the epiglottis independently of those transmitted through the MHEL.

The LHEL are attached to the lateral edges of the upper portion of the epiglottis in a plane located above that of the MHEL (Figs 1, 2). The horizontal arrangement of collagen fibres of the epiglottis just above the attachment of the MHEL and between the attachments of the LHEL suggests that this part of the epiglottis is organised to allow for folding to occur in that region (region of the epiglottic folding plane). The collagen fibre arrangement below the attachment of the MHEL was more difficult to appreciate with the pinprick analysis. However, the scanning electron micrographs (Fig. 3*b*, *c*) clearly indicate that the tightly packed collagen bundles in that region are vertically organised, presumably to resist deformation along the long axis of the epiglottis and to transmit force through the petiolus of the epiglottis to its upper portion.

The overall collagen fibre arrangement, as indicated by the India ink and scanning electron microscopic analyses, is a rather simple one suggesting that the forces transmitted to the epiglottis probably act upon it in simple, predictable ways. The passive mechanism proposed by Fink et al. (1979) requires complicated foldings of the epiglottis to occur in the area of the epiglottic tubercle. These complicated foldings would lead to distinctive patterns of collagen fibre organisation which were not identified in the analyses of this study.

The muscular constituent of the aryepiglottic fold has been the source of much debate. Testut & Latarjet (1949) described the aryepiglotticus muscle, when found, as small and weak. Negus (1949) described the muscle fibres of the aryepiglottic folds as continuous with the oblique heads of the interarytenoid muscle. Negus further described some muscle fibres finishing in the aryepiglottic folds while others reached the epiglottis or passed lateral to it towards the base of the tongue. The present findings suggest that the muscle

Fig. 4. Two-dimensional images illustrating movements of the epiglottis as seen fluoroscopically. (*a*) is a preswallow frame showing the relative positions of the structures prior to the first epiglottic movement (FEM). (*b*) illustrates the muscles of the tongue base and the floor of the mouth impinging upon the epiglottis to bring it to a horizontal position. (*c*) is a preswallow frame from a subject in which no FEM is observed and which shows the relative positions of the structures before a swallow. In (*d*) the hyoid bone has moved slightly posteriorly and superiorly while the tongue has begun to bulge into the pharynx; the epiglottis is still at a resting position. The movement of the epiglottis to below the horizontal has just finished in (*e*) but the laryngeal aditus is still slightly open. Note the caret (∧) shape of the epiglottis as it covers the laryngeal aditus, and that the folding plane is approximately one-third from the superior aspect of the epiglottis. (*f*) shows the hyoid at its maximum anterosuperior position, the epiglottis downfolded, and the laryngeal aditus closed during bolus passage through the oropharynx.

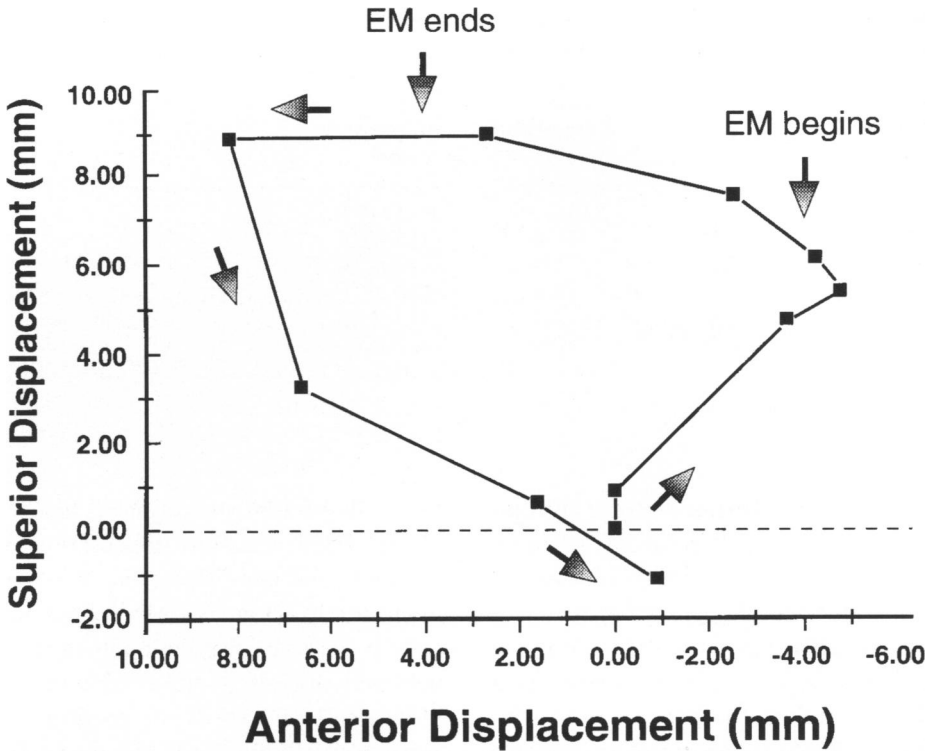

Fig. 5. Anterosuperior trajectory of the hyoid bone during a representative 5 ml barium swallow. This diagram is similar to others which have been reported (Logemann et al. 1989; Jacob et al. 1989) but includes an indication of where the initiation and termination of epiglottic downfolding (EM) occurs. The preswallow state has been arbitrarily defined as having zero position for the anterior and superior position.

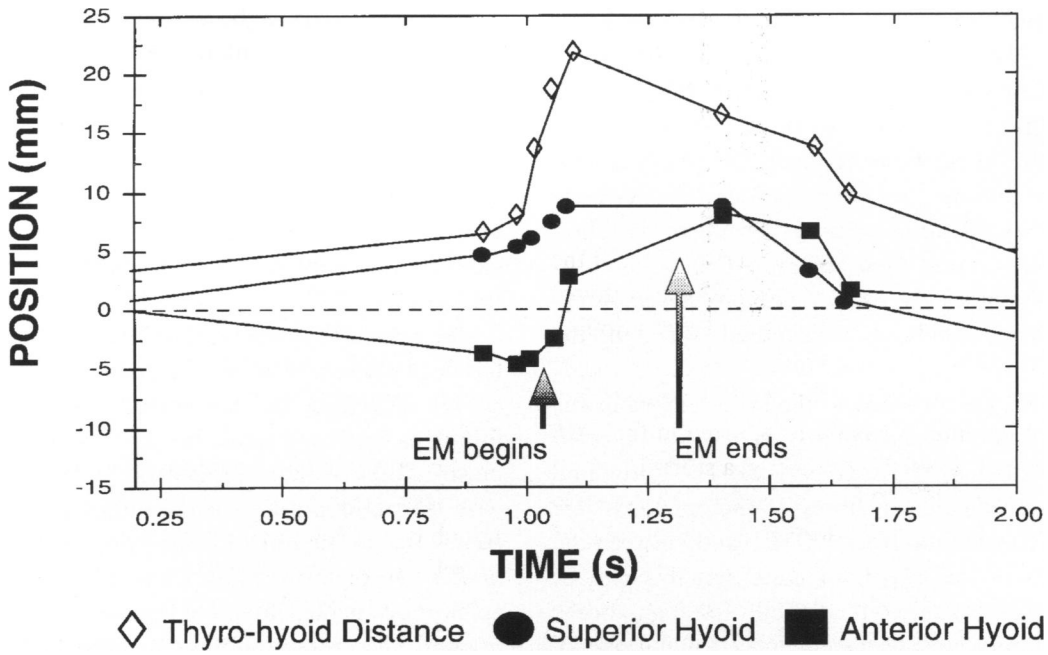

Fig. 6. Anterosuperior trajectory of hyoid movement with respect to time. This figure, which is the same 5 ml bolus as Figure 5, is similar to that of Logemann et al. (1989) but also includes an indication of when (in time) epiglottic movement begins and ends. This figure additionally includes a measure of the distance between the thyroid cartilage and hyoid bone. As in Figure 5, the preswallow state was arbitrarily defined as having zero hyoid position, zero thyrohyoid distance, and zero time.

fibres contained in the aryepiglottic fold do not insert into the epiglottis but, as Negus suggested, pass lateral to the epiglottis and continue superiorly towards the base of the tongue. However, instead of inserting into the tongue, our observations indicate that these muscle fibres continue into the posterior pharyngeal arch to become continuous with those of the vertical portion of the palatopharyngeus musculature (Fig. 1*c*). Because the muscle fibres of the aryepiglottic folds do not insert into the epiglottis, the action of

these fibres is not likely to directly affect the movement of the epiglottis.

The radiographic analysis performed in this study provided temporal information on the relationship between the anterior thrust of the hyoid bone and the downfolding of the epiglottis to a position below the horizontal. Results of this analysis revealed that the downfolding of the epiglottis began in the same video frame as the initiation of the anterior thrust of the hyoid. Unlike the report of Fink et al. (1979), we found that the epiglottis finished its movement to below the horizontal before the hyoid bone reached its maximum displacement in the anterior direction.

Based on both the anatomical and radiographic findings, we propose that during thyrohyoid approximation, the mechanical force of the superior movement of the thyroid cartilage will, as suggested by Magendie and Fink, compress the adipose tissue in the pre-epiglottic fat pad. This compression could cause some limited downward movement centred around the attachment of the epiglottis to the thyroid cartilage to bring the epiglottis to a horizontal position (Fig. 7*b*). More importantly because of the attachment of the epiglottis to the thyroid cartilage, thyrohyoid approximation would cause the epiglottic folding plane, as indicated by the pinprick analysis, to move above the horizontal plane defined by both the greater horns of the hyoid bone and the LHEL. The traction exerted by the LHEL will pull the upper one-third of the epiglottis down to below the horizontal (Fig. 7*c*). In the presence of a FEM, this movement would cause the SEM to occur. Thus approximation of the thyroid cartilage to the hyoid bone through contraction of the thyrohyoid musculature (i.e. decreasing the thyrohyoid distance) is the primary effector in positioning the epiglottis below the horizontal.

The phenomenon of epiglottic position being linked to thyrohyoid distance has been reported in the past. Vilkman & Karma (1989) performed a study in which they immobilised the thyroid cartilage of fresh laryngeal specimens then applied a force in the cranial direction to the hyoid bone. They reported that when the larynx was in a resting position before cranial force was applied, the hyoid bone was leaning on the thyroid cartilage and the epiglottis was tilted downwards. When cranial force was applied, the epiglottis moved to a position which was rotated ventrocranially from the resting position when no force was applied. This is consistent with our theory that decreasing thyrohyoid distance is a necessary condition for epiglottic downfolding to occur.

The anterior movement of the hyoid bone also contributes to epiglottic downfolding. First, the relative anterior movement of the hyoid bone allows the thyroid cartilage to attain a position posterior to the body of the hyoid and within the horns of the hyoid. If the hyoid bone were not to move anteriorly relative to the thyroid cartilage, the superior portions of the laminae of the thyroid would be limited in their superior movement by the body of the hyoid. Given the oblique orientation of the thyrohyoid musculature and its attachment to the anterior aspect of the hyoid bone and to the inferior third of the thyroid lamina, contraction of this muscle will cause the hyoid to move anteriorly and the thyroid to elevate. However, the thyroid will not be limited in its superior movement by the body of the hyoid bone given this position. In essence, the body of the hyoid bone is moved anteriorly out of the way and the superior portion of the laminae of the thyroid cartilage slips up behind it. This is important because the closer the association of the thyroid to the hyoid, the further the epiglottic folding plane is pushed above the hyoid bone plane and, as such, the greater the downward force exerted on the upper third of the epiglottis through the lateral hyoepiglottic ligaments (Fig. 7*d*).

Secondly, the anterior movement of the hyoid bone itself will have an effect on downfolding. The degree to which the epiglottis below the attachment of the MHEL can move anteriorly is restricted by the compression of the pre-epiglottic fat, but the upper portion of the epiglottis is not restricted in its movement anteriorly. Thus given that thyrohyoid approximation has resulted in the epiglottic folding plane breaking the hyoid bone plane, anterior movement of the hyoid bone will cause additional traction to be transmitted to the epiglottis via the LHEL. The SEM is thus completed by the anterior displacement of the hyoid bone and thyrohyoid approximation which brings the epiglottis down to cover the laryngeal aditus.

The thyrohyoid, geniohyoid, and mylohyoid muscles appear to be the primary effectors of anterior hyoid bone movement, and thus are the principal muscles affecting epiglottic movements (Hrycyshyn & Basmajian, 1961). Other muscles such as the anterior belly of the digastric may contribute to the anterior motion of the hyoid, but they have been shown to have variable activity during swallowing (Hrycyshyn & Basmajian, 1961), and their lines of action are in a more oblique plane than that of the geniohyoid. The classically described aryepiglotticus muscle has little direct effect on epiglottic function because the muscle fibres found within the aryepiglottic folds do not insert into the epiglottis. The action of the geniohyoid muscle is enhanced by the superior and posterior

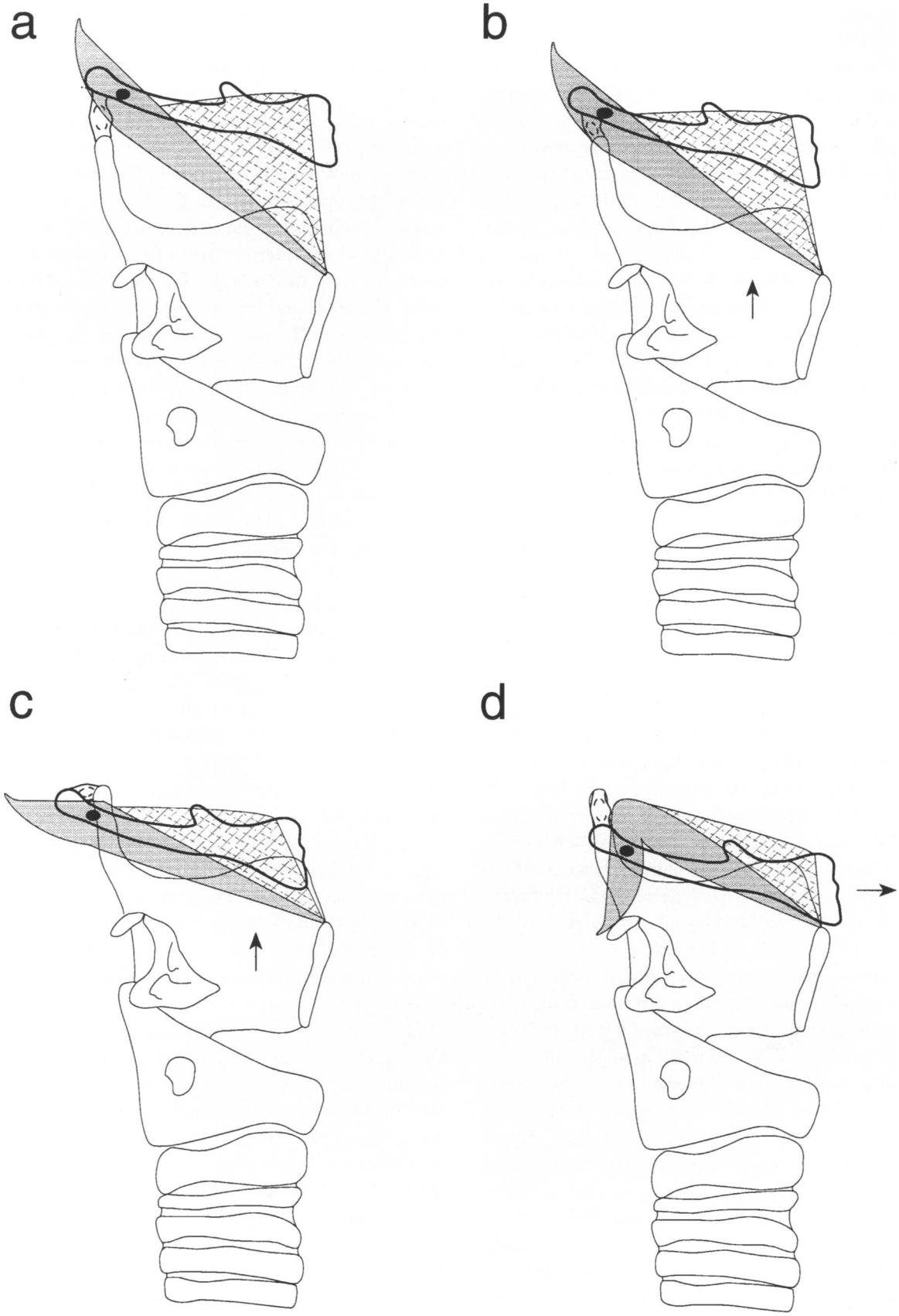

Fig. 7. Schematic representation of the proposed mechanism of epiglottic downfolding. In all panels, the epiglottis is shown in grey, the median hyoepiglottic ligament is cross-hatched, and the attachment of the lateral hyoepiglottic ligaments is shown by the black circle. (*a*) Preswallow position of the larynx and hyoid bone. (*b*, *c*) First epiglottic movement achieved by thyrohyoid approximation. (*d*) Second epiglottic movement produced by anterior displacement of the hyoid bone.

movement of the hyoid bone prior to its anterior thrust. In addition to its major role in bringing about thyrohyoid approximation, contraction of the thyrohyoid musculature will bring about a relative anterior movement of the hyoid bone with respect to the thyroid cartilage because of the oblique orientation of the thyrohyoid muscle discussed earlier. Together, these two actions of the large, strong thyrohyoid muscle make it of paramount importance in epiglottic movement.

When an FEM is observed, it is brought about by the action of the tongue on the epiglottis. In that instance the SEM is brought about after the FEM by the biomechanical mechanism described in this paper. When no distinct FEM followed by an SEM is observed, the one continuous movement of the epiglottis from its vertical, resting position to the downfolded position can also be accounted for by the mechanism presented in this paper. That is to say, the epiglottis is capable of downfolding to below the horizontal without the action of the tongue providing there are normal movements of the thyroid cartilage and the hyoid bone. However, the downfolding of the epiglottis can be assisted to the level of the horizontal by the action of the tongue.

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