2 Anatomy, Embryology, Physiology, and Normal Development

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Summary

The human upper aerodigestive tract is the most complex neuromuscular unit in the body. It is the intersection of the digestive, respiratory, and phonatory systems. Normal swallowing requires precise integration of the important functions of breathing, eating, and speaking. A thorough understanding of the anatomy, embryology, and physiology of these systems is necessary to appreciate the etiology, diagnosis, and treatment of swallowing and feeding disorders in infants and children.

Attention to functional anatomy provides a basis for the discussion of clinically relevant embryologic development. The physiology of swallowing, with emphasis on neurophysiology, posture, and muscle tone, is presented in detail in this chapter. The challenges of developmental change beginning with premature infants and extending through adolescents are nowhere more apparent than for swallowing and feeding. Swallowing and feeding are explained in the context of normal oral sensorimotor development of the infant and child. Special focus on the anatomy and physiology of the airway and gastrointestinal (GI) tract will help to enhance the reader's understanding of the clinical manifestations, diagnosis, and treatment of swallowing and feeding problems in children.

Introduction

Deglutition, more commonly referred to as swallowing,[1] is defined as the semiautomatic motor action of the muscles of the respiratory and GI tracts that propels food from the oral cavity into the stomach (Miller, 1986). Swallowing functions not only to transport food to the stomach, but also in clearing the mouth and pharynx of secretions, mucus, and regurgitated stomach contents. Thus, the function of swallowing is nutritive as well as protective of the lower airways.

The act of swallowing is complex because respiration, swallowing, and phonation all occur at one anatomic location—the region of the pharynx and larynx. To

[1] The common usage term, *swallowing*, is used throughout this textbook for ease of reading. Similarly, ingestion, the taking in of food, will be referred to as *feeding* or *eating* (as age appropriate) throughout.

be successful, normal swallowing requires the coordination of 31 muscles, six cranial nerves, and multiple levels of the central nervous system (CNS), including the brain stem and cerebral cortex (Bosma, 1986). Thus, understanding the anatomy, embryology, physiology, and normal development of this functional neuromuscular unit is of paramount importance to the proper diagnosis and treatment of swallowing and feeding disorders in children.

Anatomy

The upper aerodigestive tract consists of the nose, oral cavity, pharynx, larynx, and esophagus. The trachea, bronchi, and pulmonary parenchyma are considered the lower airways. The upper digestive tract ends at the entrance to the stomach. Each area is discussed separately.

Nose

The nose is important for respiration throughout life, but particularly in neonates (first 28 days of life) and young infants (up to 6 months), when preferential nasal breathing is present. The nose also cleans, warms, and humidifies inspired air. As the nasal passage continues posteriorly, it opens at the bilateral posterior nasal choanae into the nasopharynx, which is an important anatomic chamber that serves as a resonator for speech production. In addition, the nasopharynx is one of the two airway conduits into the hypopharynx (Figure 2–1). The lateral nasal walls are composed of three bones covered with a highly sensitive

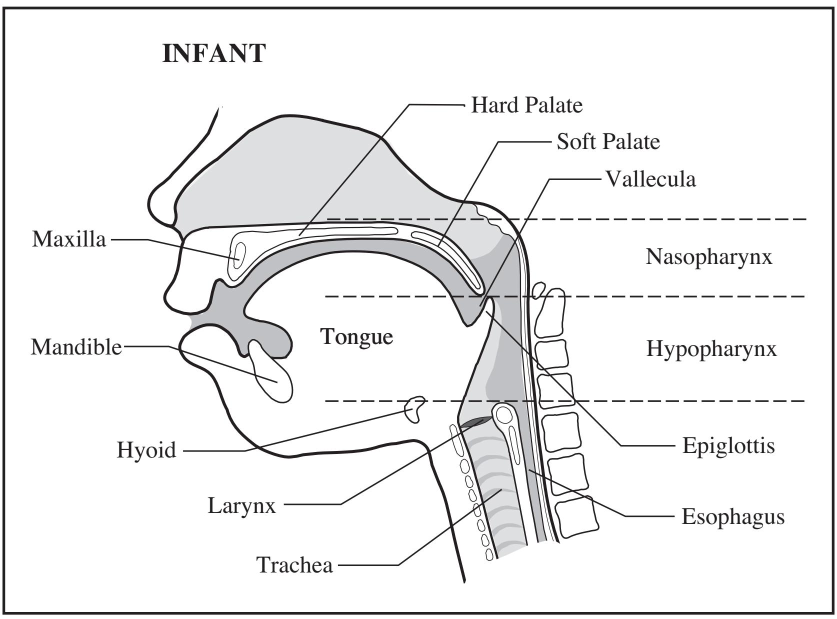

Figure 2–1. Lateral view of the infant's upper aerodigestive tract. Structures and boundaries of the oral cavity, pharynx, and larynx are noted. The soft palate is in close approximation to the valleculae. This anatomic proximity effectively separates the oral route for ingestion from the preferred nasal route for respiration.

mucosa—the nasal turbinates. The nose is separated into two nasal cavities by the midline septum, which is cartilage anteriorly and bone posteriorly. Septal deviation in the newborn may occur from birth trauma and result in severe nasal obstruction leading to perinatal feeding difficulties (Emami, Brodsky, & Pizzuto, 1996). Other etiologies of nasal obstruction include, but are not limited to, choanal atresia, encephalocele, glioma, nasal dermoid, nasolacrimal duct cyst, pyriform aperture stenosis, and rhinitis (Gnagi & Schraff, 2013; see Chapter 4). Soft palate elevation and retraction seal off the nasal cavity from the oropharynx and the oral cavity.

Oral Cavity (Mouth)

The oral cavity is involved in ingestion of food, vocalization, and oral respiration. Structures include lips, mandible, maxilla, floor of the mouth, cheeks, tongue, hard palate, soft palate, and anterior surfaces of the anterior tonsillar pillars. Older infants and children also have teeth for chewing. The lateral sulci are spaces between the mandible or maxilla and the cheeks. The anterior sulci are spaces between the mandible or maxilla and the lip muscles.

The structures in the mouth are important for bolus formation and oral transit (described in detail in the following text). In infancy, the cheeks with fat pads or sucking pads are important for sucking. The tongue has attachments to the mandible, hyoid bone, and styloid process of the cranium by the extrinsic muscles of the tongue (genioglossus, hypoglossus, and styloglossus muscles) (Bosma, 1972). When anatomic defects of the lips, palate, maxilla, mandible, cheeks, or tongue are present, normal sucking and swallowing may be compromised (see Chapters 4 and 12). In children with oral sensorimotor problems, food or liquid can be lodged in both the anterior and lateral sulci, making bolus preparation difficult. Muscles involved in bolus formation and oral transit include the digastric, palatoglossus, genioglossus, styloglossus, geniohyoid, mylohyoid, buccinators, and those muscles intrinsic to the tongue (no bony attachment, classified by orientation of the muscle fibers: longitudinal, vertical, and transverse). Cranial nerves involved include V, VII, IX, X, XI, and XII (Bosma, 1986; Derkay & Schechter, 1998; Perlman & Christensen, 1997).

Pharynx

The pharynx consists of three anatomic areas (Figures 2–1 and 2–2): the nasopharynx, the oropharynx, and the hypopharynx. In the infant, the nasopharynx and hypopharynx blend into one structure, and thus there is no true oropharynx as seen in the older child. The nasopharynx begins at the nasal choanae and ends at the elevated soft palate. The eustachian tubes originate in the nasopharynx (Bosma, 1967).

As growth and development occur, two important anatomic changes emerge: (a) the angle of the nasopharynx at the skull base becomes more acute and approaches 90°, and (b) the pharynx elongates so that an oropharynx is created. The faucial arches form a bridge between the mouth and the oropharynx. This junction and the tongue base form the anterior boundary of the oropharynx, which extends inferiorly to the epiglottis. The oropharynx includes the epiglottis and the valleculae. The valleculae are bilateral pockets formed by the base of the tongue and the epiglottis (Donner, Bosma, & Robertson, 1985). The hypopharynx (sometimes called the laryngeal pharynx) extends from the base of the

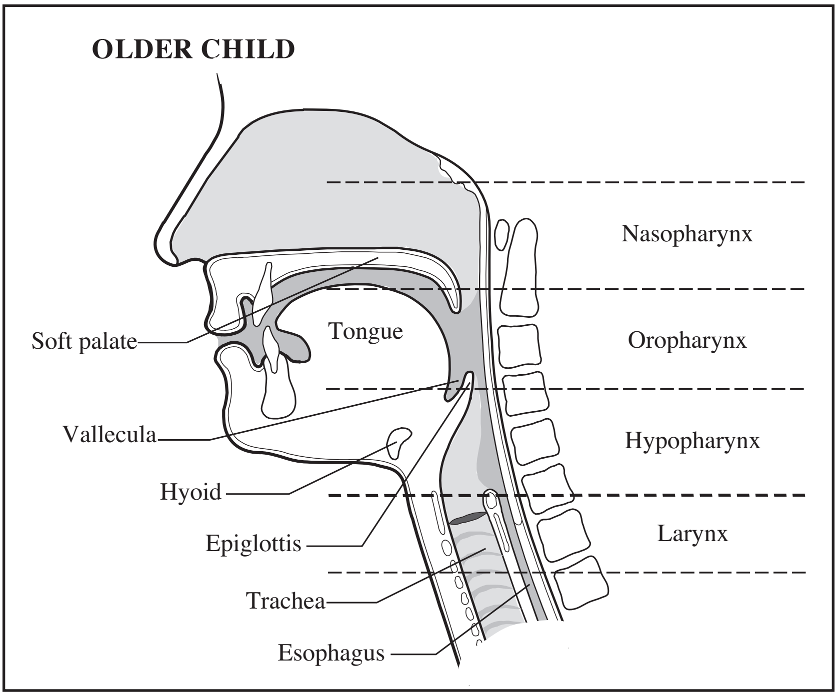

Figure 2–2. Lateral view of the older child's upper aerodigestive tract. Note the wide distance between the soft palate and the larynx. The elongated pharynx is unique to humans and has allowed the development of human speech production.

epiglottis to the cricopharyngeal muscles in the upper esophageal sphincter. The anterior wall of the hypopharynx includes the laryngeal inlet and the cricoid cartilage. The pyriform sinuses are pockets lateral and just below the inlet to the larynx. The vertical enlargement of this space enables the development of human speech. Phonation of a wide variety of speech sounds can thus occur. However, this elongation challenges the timing and coordination needed for functional swallowing and breathing as a common and enlarged intersection of the respiratory and digestive tracts is created (Laitman & Reidenberg, 1993).

The walls of the pharynx consist of three pairs of constrictor muscles—the superior, medial, and inferior constrictors. These striated muscle fibers arise from a median raphe in the midline of the posterior pharyngeal wall. They extend laterally and attach to bony and soft tissue structures located anteriorly. Initiation of the pharyngeal swallow function is under voluntary neural control and becomes involuntary for completion of the pharyngeal swallow. This function is under the control of cranial nerves (CN) V, IX, and X that synapse in the swallowing center located in the medulla.

Nasopharynx

The nasopharynx is a boxlike structure located at the base of the skull. It connects the nasal cavity above with the oropharynx below, and serves as a conduit for air, a drainage area for the nose and paranasal sinuses and eustachian tube/middle ear complex, and a resonator for speech production. The boundaries of the nasopharynx are the posterior nasal choanae (anteriorly), the soft palate (anterior-inferior), the skull base (posteriorly), and the hypopharynx in infants and oropharynx in children and adults (inferiorly). Tongue propulsion moves a bolus posteriorly and thus assists in the elevation of the soft palate and closes off the nasopharynx from the rest of the pharynx. Anatomic or functional defects of the soft palate may result in nasopharyngeal backflow/reflux during oral feedings (Chapters 4 and 12).

The adenoid is a mass of lymphatic tissue located behind the nasal cavity, in the roof of the nasopharynx where the nose blends into the throat. The adenoid, unlike the palatine tonsils, has pseudostratified epithelium. The adenoid is part of the "Waldeyer ring" of lymphoid tissue, which includes the palatine tonsils and the lingual tonsils.

During the first years of life, the adenoid increases in size. Involution begins at about age 8 years and extends through puberty. Excessive enlargement of the adenoid may cause nasal obstruction and feeding difficulties, even in older children.

Oropharynx

The oropharynx is the posterior extension of the oral cavity. The oropharynx begins at the posterior surface of the anterior tonsillar pillars and extends to the posterior pharyngeal wall. The palatine tonsils are attached to the lateral pharyngeal walls between the anterior and posterior tonsillar pillars. The superior boundary of the oropharynx is parallel to the pharyngeal aspect of the soft palate in a line extending back to the posterior pharyngeal wall. The inferior boundary of the oropharynx is at the base of the tongue and includes the epiglottis and valleculae. The valleculae are wedge-shaped spaces at the base of the tongue and the epiglottis. The lingual tonsil is along the tongue base. When the lingual tonsil becomes enlarged, it can encroach on the valleculae and cause significant airway, feeding, and swallowing problems. Enlargement may be seen when severe gastroesophageal reflux disease (GERD)/extra-esophageal reflux disease (EERD)[2] is present. The lateral and posterior walls of the oropharynx are formed by the middle and part of the inferior pharyngeal constrictor muscles. The greater cornua of the hyoid bone are included in the lateral pharyngeal walls (Donner et al., 1985).

The body of the hyoid bone, located in the deep musculature of the neck, attaches to the base of the tongue. The base of the tongue and the larynx descend inferiorly during the first 4 years of life. By age 4, the base of the tongue is anatomically separated from the larynx in the vertical plane and thus becomes the anterior border of the oropharynx (Caruso & Sauerland, 1990). Because the infant's larynx is high in the neck, almost "tucked under" the base of the tongue, no true oropharynx exists (see Figures 2–1 and 2–2). Thus, in neonates and young infants, a single conduit for breathing is created from the nasopharynx to the hypopharynx that allows them to coordinate sucking, swallowing, and breathing.

[2]Gastroesophageal reflux disease (GERD) refers to the abnormal regurgitation of acid into the esophagus causing symptoms. When acid and other stomach contents emerge from the esophagus into the pharynx, larynx, mouth, and nasal cavities, the most commonly accepted term is extra-esophageal reflux disease (EERD) (Sasaki & Toohill, 2000).

Hypopharynx

The hypopharynx extends from the base of the epiglottis at the level of the hyoid bone down to the cricopharyngeus muscle. Anteriorly it ends at the laryngeal inlet above the true vocal folds at the level of the false vocal folds and includes the cricoid cartilage. Posteriorly, the hypopharynx ends at the level of the entrance to the esophagus, which is guarded by the cricopharyngeus muscle. This muscle has no median raphe, in contrast to the pharyngeal constrictors. Except during swallowing, belching, or regurgitation, the cricopharyngeus is in a state of tonic contraction functioning as the pharyngoesophageal sphincter or upper esophageal sphincter (UES)[3] (Caruso & Sauerland, 1990; Kahrilas et al., 1986). The fibers of the inferior constrictors attach to the sides of the thyroid cartilage. These spaces are known as the pyriform sinuses, and they extend down to the cricopharyngeus muscle (Figure 2–3). The oblique fibers of the inferior constrictor muscles end where the horizontal fibers of the cricopharyngeus muscle

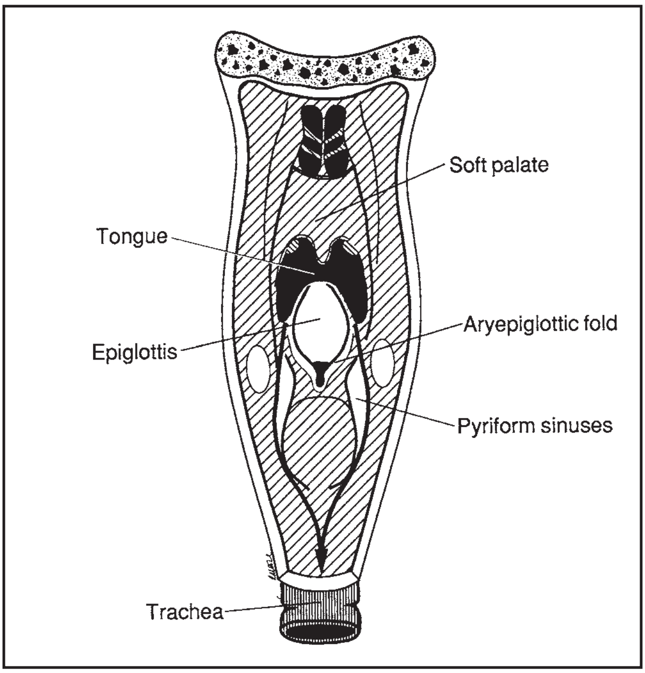

Figure 2–3. Posterior sketch of the upper aerodigestive tract (larynx and pharynx). Pathway for food bolus is around the larynx and down the channels made by the pyriform sinuses, which elongate during the act of swallowing. The bolus is moved through the upper esophageal sphincter (UES) partially via action of the hyolaryngeal complex decreasing tension on the open UES while the larynx is closed and protected high in the neck under the tongue base.

[3]Terminology is rapidly changing in this field. For purposes of this book, the more familiar term *upper esophageal sphincter* (UES) is used.

begin. The lateral and posterior walls of the hypopharynx are supported by the middle and inferior constrictors. The anterior boundary of the hypopharynx is the larynx.

Larynx

The larynx is a complex structure that is the superior entrance to the trachea. The larynx consists primarily of cartilages, suspended by muscle and ligament attachments to the hyoid bone and cervical vertebrae. The cartilages include the epiglottis, thyroid, cricoid, and paired arytenoids, cuneiforms, and corniculates. Intrinsic muscles of the larynx form the vocal folds (true and false) that are integral to respiration and phonation. The thyrohyoid and thyrocricoid ligaments aid in laryngeal suspension and stability. In order of priority, the three functions of the human larynx are the protection of the lower airways, respiration, and phonation. The structures important in swallow production and in airway protection during swallowing are described in detail. Detailed anatomic description of the intrinsic muscles of the larynx (involved primarily with phonation) is beyond the scope of this chapter.

The most important structures of the larynx that protect against aspiration are the paired arytenoid cartilages and the two pairs of vocal folds. In most humans, the epiglottis plays a role in airway protection. However, there are examples of children with congenitally absent epiglottis (Koempel & Holinger, 1998) and functional oral feeding. The epiglottis has a flattened lingual surface, which acts to direct food laterally into the recesses formed by the pyriform sinuses. The movement of food is directed away from the midline and the laryngeal inlet. The arytenoid cartilages and the aryepiglottic folds, reinforced by the smaller cuneiform and corniculate cartilages, move medially to further buttress the larynx from penetration. The larynx is elevated anteriorly under the tongue and mandible by the hyolaryngeal complex (hyoid bone and attached musculature).

The valvelike function provided by the paired false and true vocal folds is the next and most critical level of laryngeal structures involved in airway protection. The false vocal folds (ventricular folds) are primarily involved in regulating the expiration of air from the lower respiratory tract (Sasaki & Isaacson, 1988). In contrast, the true vocal folds do not resist expired air but can prevent inspired air (and foreign material) from entering the larynx. Thus, specific anatomic abnormalities at the laryngeal level must be precisely defined to avoid serious sequelae of an incompetent larynx.

Neuroanatomy of the Larynx

Multilevel sphincteric closure of the upper airway is controlled by the recurrent laryngeal nerves. The aryepiglottic folds, made up of the superior part of the thyroarytenoid muscles, approximate to cover the superior inlet of the larynx. The anterior gap is protected by the posteriorly displaced epiglottis, the posterior gap closed by the arytenoid cartilages (Figure 2–4). The false vocal folds form the roof of the laryngeal ventricles and are the second level of protection within the larynx. The thyroarytenoid muscles aid in adduction of the false vocal folds. The third level of protection is the true vocal folds, with the inferior part of the thyroarytenoid muscles providing the bulk of these folds. The true vocal folds attach to the vocal processes of the arytenoid cartilages posteriorly, to the inside surface of the thyroid lamina laterally, and to the thyroid notch anteriorly. Muscular pull by the arytenoid cartilages controls movement of

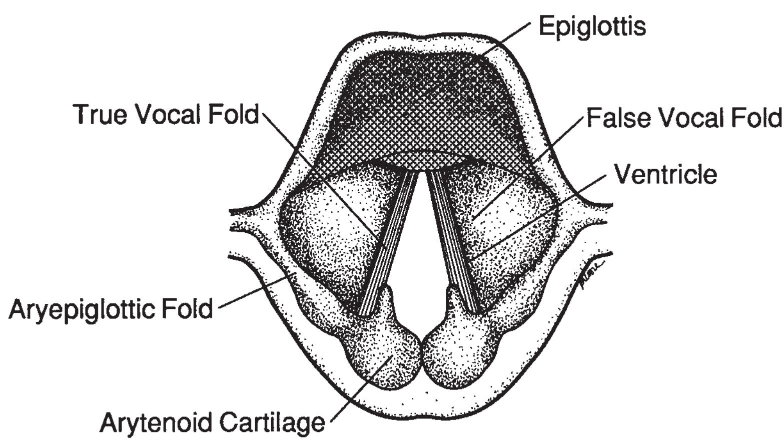

Figure 2–4. Superior view of the larynx showing the intrinsic structures of the larynx. The laryngeal ventricle is the space between the false and true vocal folds. Airway closure occurs from distal to proximal regions (i.e., first true vocal folds, next false vocal folds, and finally aryepiglottic folds).

the true vocal folds during both swallowing and phonation.

Innervation of the protective laryngeal and respiratory functions is centrally located in the brain stem. This control relies on fine sensory and motor innervation to the region. Sensory innervation of the supraglottic and glottic areas is provided by the internal branch of the superior laryngeal nerve (SLN), a branch of the vagus nerve (CN X). The recurrent laryngeal nerve (RLN) (also from CN X) provides sensory innervation to the subglottic mucosa. The posterior part of the true vocal folds and the superior surface of the epiglottis appear to be the most densely innervated part of the larynx (Sasaki & Isaacson, 1988). Chemical and thermal receptors are also found in the supraglottic larynx and are sensitive to a variety of stimuli. In particular, receptors sensitive to water in infants and young children may explain the favorable response to cool mist in children with laryngotracheitis, also known as "croup." The effect of the mist slows the rate of respiration while increasing tidal volume, resulting in an overall positive effect on the respiratory status (Sasaki, Suzuki, Horiuchi, & Kirchner, 1979). Other sensory receptors of the larynx include joint, aortic, baroreceptors, and stretch receptors. These afferent impulses are interpreted at the brain-stem level in the tractus solitarius.

The ipsilateral RLN (vagus—CN X) innervates all of the intrinsic muscles of the larynx except the cricothyroid muscles. The cricothyroid is innervated by the external branch of the SLN. Only the interarytenoid muscles receive bilateral innervation from the recurrent laryngeal nerves. All of the intrinsic muscles of the larynx are involved in adduction except the posterior cricoarytenoid muscles, the only abductors of the vocal folds. Control at the brain-stem level is within the nucleus ambiguus.

Anatomic changes in the larynx are evident when SLN paralysis occurs. The lateral cricoarytenoid muscle, a laryngeal adductor, rotates the posterior laryngeal commis-