PART 1

Normal and Abnormal Craniofacial Structures

CHAPTER 1

Anatomy and Physiology

CHAPTER OUTLINE

INTRODUCTION

The nasal, oral, and pharyngeal structures are all very important for normal speech and resonance. Unfortunately, these are the structures that are commonly affected by cleft lip and palate and other craniofacial anomalies. Before the speech-language pathologist can fully understand the effects of oral and craniofacial anomalies on speech and resonance, a thorough understanding of normal structure (anatomy) and normal function (physiology) of the oral structures and the velopharyngeal valve is essential.

This chapter reviews the basic anatomy of the structures of the orofacial and velopharyngeal complex as they relate to speech production. The physiology of the subsystems of speech, including the velopharyngeal mechanism, is also described. For more detailed information on anatomy and physiology of the speech articulators, the interested reader is referred to other sources (Cassell & Elkadi, 1995; Cassell, Moon, & Elkadi, 1990; Dickson, 1972; Dickson, 1975; Dickson & Dickson, 1972; Dickson, Grant, Sicher, Dubrul, & Paltan, 1974; Dickson, Grant, Sicher, Dubrul, & Paltan, 1975; Huang, Lee, & Rajendran, 1998; Kuehn, 1979; Maue-Dickson, 1977; Maue-Dickson, 1979; Maue-Dickson & Dickson, 1980; Maue-Dickson, Dickson, & Rood, 1976; Moon & Kuehn, 1996; Moon & Kuehn, 1997; Moon & Kuehn, 2004; Perry, 2011; Seikel, King, & Drumright, 2005).

ANATOMY

Craniofacial Structures

Although the facial structures are familiar to all, some aspects of the face are important to point out for a thorough understanding of congenital anomalies and clefting. The normal facial landmarks can be seen on **FIGURE 1-1**. The reader is encouraged to identify the same structures on the photo of the normal infant face shown in Figure 1-1B.

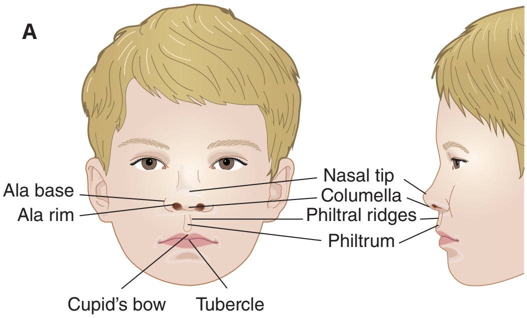

FIGURE 1-1 (A) Normal facial landmarks. Note the structures on the diagram. **(B)** Normal face. Try to locate the same structures on this infant's face.

Craniofacial Bones and Sutures

The bones of the cranium include the **frontal bones**, which cover the anterior portion of the brain; the **parietal bones**, which cover the top and sides of the cranium; the **temporal bones**, which form the sides and base of the skull; and finally, the **occipital bone**, which forms the back of the skull (**FIGURE 1-2**).

Each bone is bordered by an embryological suture line. The frontal bones are divided in midline by the **metopic suture** and bordered posteriorly by the coronal suture. The **coronal suture** is across the top of the skull horizontally (like a crown) and separates the frontal bones and parietal bones. The **sagittal suture** crosses the skull vertically and, therefore, divides the two parietal bones. Finally, the **lambdoid suture** is between the parietal, temporal, and occipital bones.

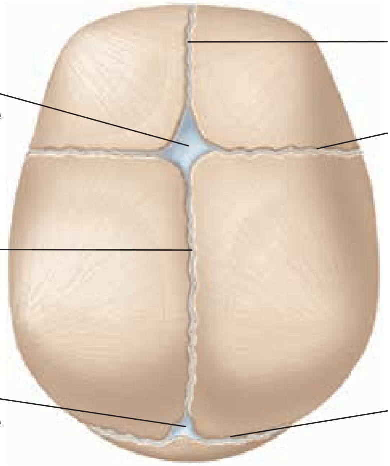

FIGURE 1-2 Cranial suture lines.

The **anterior fontanelle** ("soft spot" of an infant) is on the top of the skull at the junction of the frontal and the coronal sutures. The metopic suture closes between 3 and 9 months of age. The coronal, sagittal, and lambdoid sutures close between 22 and 39 months of age.

The facial bones include the **zygomatic bone** (also called **malar bone**), which forms the cheeks and the lateral walls of the orbits; the **maxilla**, which forms the upper jaw; and the **mandible**, which forms the lower jaw.

Ear

The ear has three distinct parts—the external ear, the middle ear, and the inner ear (**FIGURE 1-3**). A description of the anatomy of each part follows.

The **external ear** consists of the pinna and the external auditory canal. The **pinna** is the delicate cartilaginous framework of the external ear. It functions to direct sound energy into the **external auditory canal**, which is a skin-lined canal leading from the opening of the external ear to the eardrum.

The **middle ear** is a hollow space within the temporal bone. The **mastoid cavity** connects to the middle ear space posteriorly and consists of a collection of air cells within the temporal bone. Both the middle ear and mastoid cavities are lined with a **mucous membrane** (also known as **mucosa**), which consists of stratified squamous epithelium and lamina propria. (This should not be confused with **mucus**, which is the clear, viscid secretion from the mucous membranes.)

The **tympanic membrane**, also called the **eardrum**, is considered part of the middle ear. The tympanic membrane transmits sound energy through the ossicles to the inner ear. The **ossicles** are tiny bones within the middle ear and are called the malleus, incus, and stapes. The **malleus** (also known as the hammer) is firmly attached to the tympanic membrane. The **incus** (also known as the anvil) articulates with both the malleus and the stapes. The **stapes** acts as a piston to create pressure waves within the fluid-filled cochlea, which is part of the inner ear. The tympanic membrane and ossicles act to amplify the sound energy and efficiently introduce this energy into the liquid environment of the cochlea.

The **eustachian tube** (also known as the **auditory tube**) connects the middle ear with

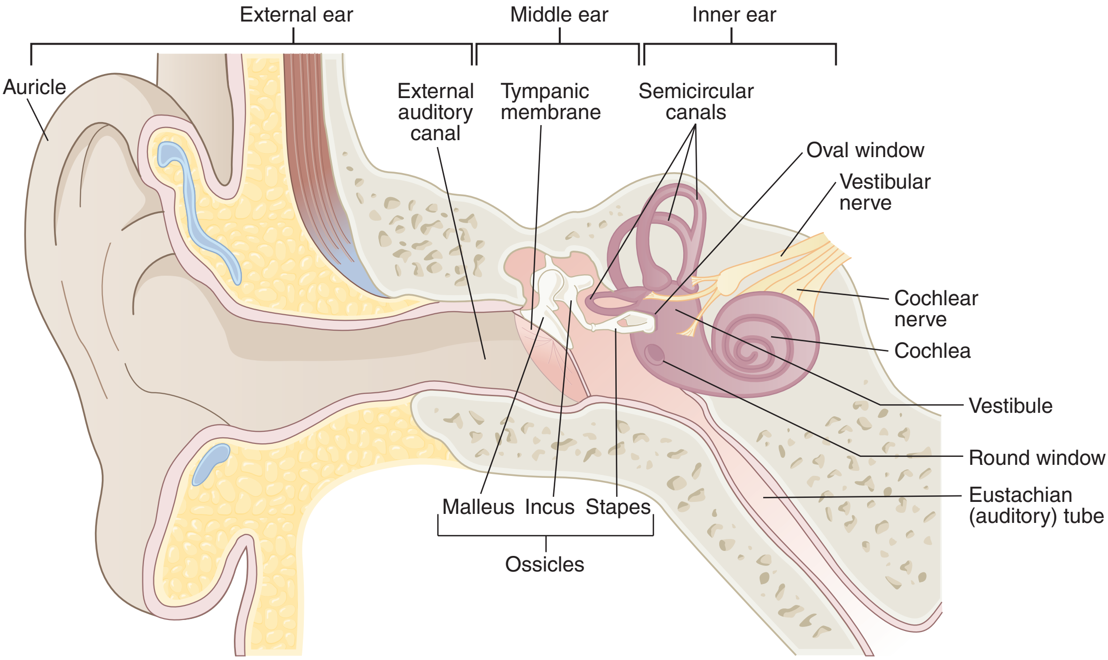

FIGURE 1-3 Ear showing external, middle, and inner ear structures and the eustachian tube.

the nasopharynx. The end of this tube, which terminates in the nasopharynx, is closed at rest but opens during swallowing. When it opens, it provides ventilation for the middle ear and mastoid cavities and results in equalization of air pressure between the middle ear and the environment (Cunsolo, Marchioni, Leo, Incorvaia, & Presutti, 2010; Licameli, 2002; Smith, Scoffings, & Tysome, 2016; Yoshida, Takahashi, Morikawa, & Kobayashi, 2007). It also allows drainage of fluids and debris from the middle ear space. (More information about the eustachian tube is noted in the Pharyngeal Structures section.)

The **inner ear** consists of the cochlea and semicircular canals. The **cochlea** is composed of a bony spiral tube that is shaped like a snail's shell. Within this bony tube are delicate membranes separating the canal into three fluid-filled spaces. The **organ of Corti** is the site where mechanical energy introduced into the cochlea is converted into electrical stimulation. This electrical impulse is conducted by the auditory nerves to the auditory cortex, which results in an awareness of sound. Inner and outer **hair cells** (sensory cells with hair-like properties) of the cochlea may be damaged by a variety of mechanisms, leading to sensorineural hearing loss.

In addition to hearing, the inner ear is responsible for balance. The **semicircular canals** are the loop-shaped tubular parts of the inner ear that provide a sense of spatial orientation. They are oriented in three planes at right angles to one another. The **saccule** and **utricle** are additional sensory organs within the inner ear. Hair cells within these organs have small calcium carbonate granules that respond to gravity, motion, and acceleration.

Nose and Nasal Cavity

The nose begins at the **nasal root**, which is the most depressed, superior part of the nose and at the level of the eyes. The **nasal bridge** is the saddle-shaped area that includes the nasal root and the lateral aspects of the nose. Finally, the **nasion** is a midline point just superior to the nasal root and overlying the nasofrontal suture.

The nostrils are separated externally by the **columella** (little column). The **anterior nasal spine** of the maxilla forms a base for the columella. The columella is like a supporting column in that it provides support for the nasal tip. The columella must be long enough so that the nasal tip has an appropriate degree of projection. Ideally, the columella is straight and backed by a straight nasal septum.

The nostrils are frequently referred to as **nares**, although an individual nostril is a **naris**. The **ala nasi** (ala is Latin for "wing") is the outside curved side of the nostril. The alae (plural version of ala) are the two curved sides of each nostril. The **alar rim** is the outside curved edge that surrounds the opening to the nostril on either side, and the **alar base** is the area where the ala meets the upper lip. The **nasal sill** is the base of the nostril opening. The **nasal vestibule** is the most anterior part of the nasal cavity and is enclosed by the cartilages of the nose.

The opening to the bony inside of the nose is called the **pyriform aperture** (also spelled as "piriform," means "pear shaped"). This pear-shaped opening (thus the name) is bordered by the nasal and maxillary bones (**FIGURE 1-4**).

The **nasal septum** is located in the midline of the nose and serves to separate the nasal cavity into two nostrils (**FIGURE 1-5**). It consists of both cartilage in the anterior portion of the nose and bone in the posterior portion. The **quadrangular cartilage** forms the anterior nasal septum and projects anteriorly to the columella. The bones of the septum include the maxillary crest, the vomer, and the perpendicular plate of the ethmoid. The

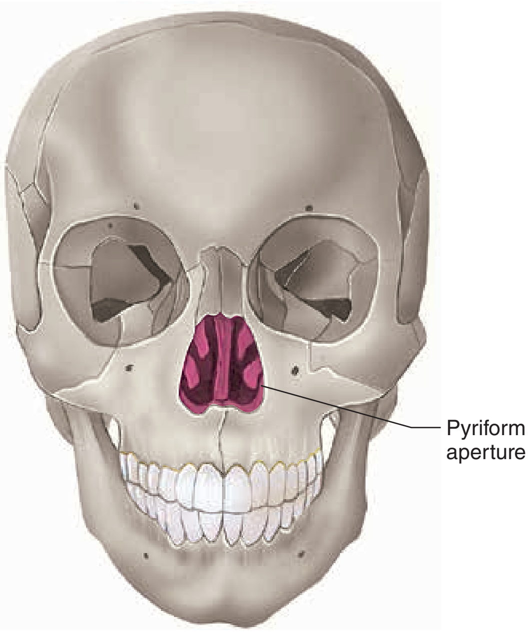

FIGURE 1-4 Pyriform aperture.

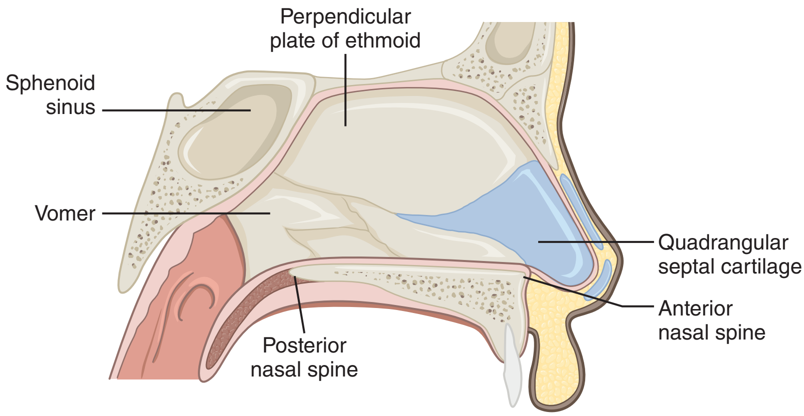

FIGURE 1-5 The nasal septum and related structures.

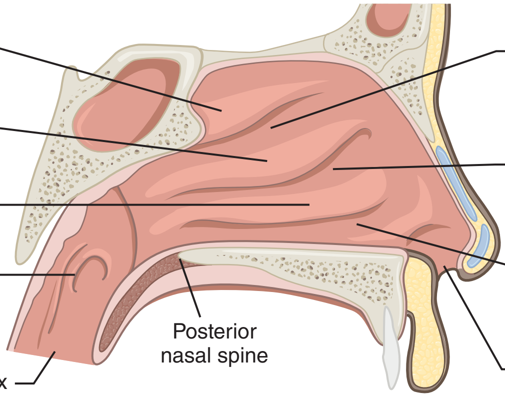

FIGURE 1-6 The lateral wall of the nose showing the turbinates.

vomer is a trapezoidal-shaped bone in the nasal septum. It is positioned perpendicular to the palate, and as such, the lower portion of the vomer fits in a groove formed by the median palatine suture line on the nasal aspect of the maxilla. The **perpendicular plate of the ethmoid** projects downward to join the vomer. It is not uncommon for the nasal septum to be less than perfectly straight, particularly in adults. The nasal septum is covered with mucous membrane, which is the lining tissue of the nasal cavity, oral cavity, and the pharynx.

The **nasal turbinates**, also called **nasal conchae** (concha, singular), are paired bony structures within the nose that are covered with mucosa (**FIGURE 1-6**). They are attached to the lateral walls of the nose and protrude medially into the nasal cavity. They are long, narrow, shelf-like, and curled in shape. As air flows underneath them, the curled shape helps to create turbulent airflow (thus the name "turbinate") to maximize contact of the inspired air with the nasal mucosa.

The nasal turbinates within the nose have three distinct functions. First, the mucus that covers the nasal mucosa filters inspired air of gross contaminants by trapping particulate contaminants. Second, the turbinates warm and humidify the inspired air. Finally, the turbinates deflect air superiorly in the nose in order to enhance the sense of smell.

Directly under the turbinates are the superior, middle, and inferior **nasal meatuses** (meatus, singular), which are the openings or passageways through which the air flows. At the back of the nasal cavity, on each side of the posterior part of the vomer, is a **choana** (choanae, plural), which is a funnel-shaped opening that leads to the nasopharynx.

Finally, the **paranasal sinuses** are air-filled spaces in the bones of the face and skull. These structures are each about the size of a walnut. There are four pairs of paranasal sinuses: frontal sinuses (in the forehead area), ethmoid sinuses (between the eyes), maxillary sinuses (under the cheeks), and sphenoid sinuses (deep in the skull). These sinuses are connected to the nose by a small opening called an **ostium** (ostia, plural). **FIGURE 1-7** shows the sinuses through computed tomography.

Lips

The features of the upper lip can be seen in Figure 1-1A. An examination of the upper lip reveals the **philtrum**, which is a long dimple or indentation that courses from the columella down to the upper lip. The philtrum is bordered by the **philtral ridges** on each side. These ridges are actually embryological suture lines that are formed as the segments of the upper lip fuse. The philtrum and philtral ridges course downward from the nose and terminate at the edge of the upper lip.

FIGURE 1-7 Radiograph of the nasal sinuses.

The top of the upper lip is called the **Cupid's bow** because of its characteristic shape of bilateral rounded peaks with a midline indentation. On the upper lip, the inferior border of the midsection of the vermilion is referred to as the **labial tubercle** because it comes to a slight point and can be somewhat prominent. The lips are surrounded by border tissue, called the **white roll**. The skin of the lips is called the **vermilion** because it is redder (and darker) than the skin of the rest of the face.

In its naturally closed position, the upper lip rests over and slightly in front of the lower lip, although the inferior border of the upper lip is inverted. Movement of the lips is primarily because of the orbicularis oris muscle. The **orbicularis oris** muscle is actually a complex of four independent quadrant muscles in the lips that encircle the mouth (**FIGURE 1-8**). This group of muscles is responsible for pursing and puckering of the lips for kissing and whistling.

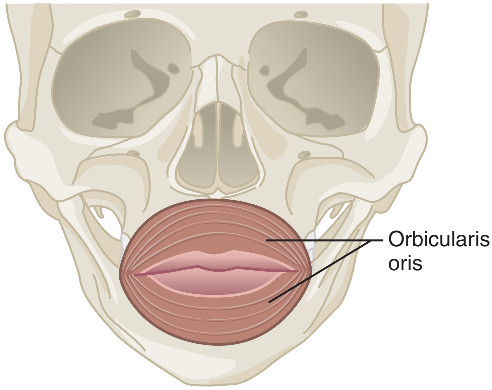

FIGURE 1-8 Orbicularis oris muscles, which circle the mouth.

Intraoral Structures

The intraoral structures include the tongue, faucial pillars, tonsils, hard palate, soft palate, uvula, and oropharyngeal isthmus (**FIGURE 1-9**). These structures are discussed in detail as follows.

Tongue

The tongue resides within the arch of the mandible and fills the oral cavity when the mouth is closed. With the mouth closed, the slight negative pressure within the oral cavity ensures that the tongue adheres to the palate and the tip rests against the alveolar ridge. The **dorsum** (dorsal surface) is the superior surface of the tongue and the **ventrum** (ventral surface) is the inferior surface of the tongue.

Faucial Pillars, Tonsils, and Oropharyngeal Isthmus

At the back of the oral cavity on both sides are the paired curtain-like structures called the **faucial pillars** (Figure 1-9). Both the anterior and posterior faucial pillars contain muscles that assist with velopharyngeal movement. (See section called *Muscles of the Velopharyngeal Valve*.)

Most people think of the **tonsils** as the tissue in the oral cavity that can become infected,

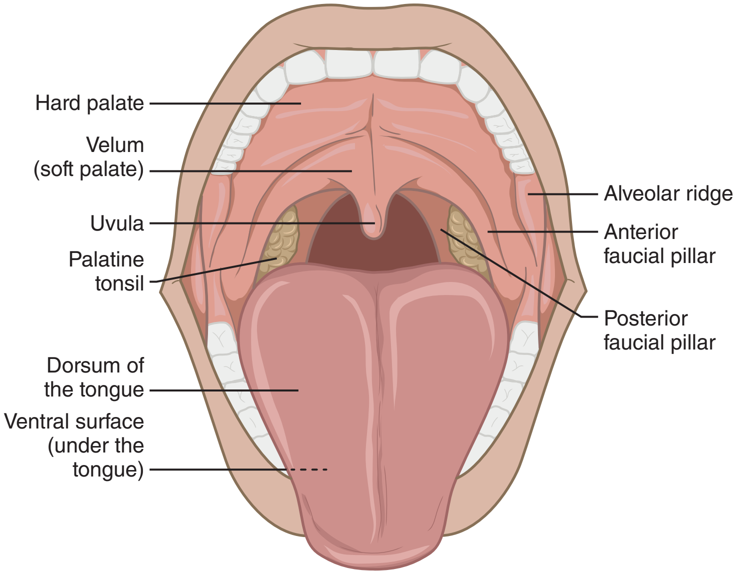

FIGURE 1-9 The structures of the oral cavity.

causing **tonsillitis**. Actually, there are three sets of tonsils, which surround the opening to the oropharynx, collectively known as **Waldeyer's ring**.

The **palatine tonsils** (usually known as just the tonsils) are located at the back of the mouth and between the anterior and posterior faucial pillars on both sides. Although the palatine tonsils are bilateral, differences in size are common, so it is not unusual for one tonsil to be larger than the other. The **lingual tonsil** is located at the base of the tongue and extends to the epiglottis (**FIGURE 1-10**). Finally, the pharyngeal tonsil, also known as the adenoids, is located in the nasopharynx. All tonsils consist of tissue similar to lymph nodes. They are covered by mucosa with various pits, called **crypts**, throughout.

Tonsillar tissue serves as part of the body's immune system by developing antibodies against infections, and therefore, this tissue is especially important during the child's first 2 years of life (Brodsky, Moore, Stanievich, & Ogra, 1988). Over time, the tonsil and adenoid tissue tends to atrophy, particularly with puberty, so that by around the age of 16, only small remnants of this tissue remain. Fortunately, atrophy (and even surgical removal) of tonsil and/or adenoid tissue has little effect on immunity because of the redundancy in the immune system. In fact, the entire gastrointestinal tract is lined with the same type of tissue as found in the tonsils so that it also supports immunity.

The **oropharyngeal isthmus** is the opening between the oral cavity and the pharynx. It is bordered superiorly by the velum, laterally by the faucial pillars, and inferiorly by the base of the tongue.

Hard Palate

The **hard palate** is a bony structure that separates the oral cavity from the nasal cavity. It serves as both the roof of the mouth and the floor of the nose. The anterior portion of the hard palate is called the **alveolar ridge** (Figure 1-9). This ridge forms the bony support for the teeth. The rest of the hard palate forms a rounded dome on the upper part of the oral cavity, called the **palatal vault**.

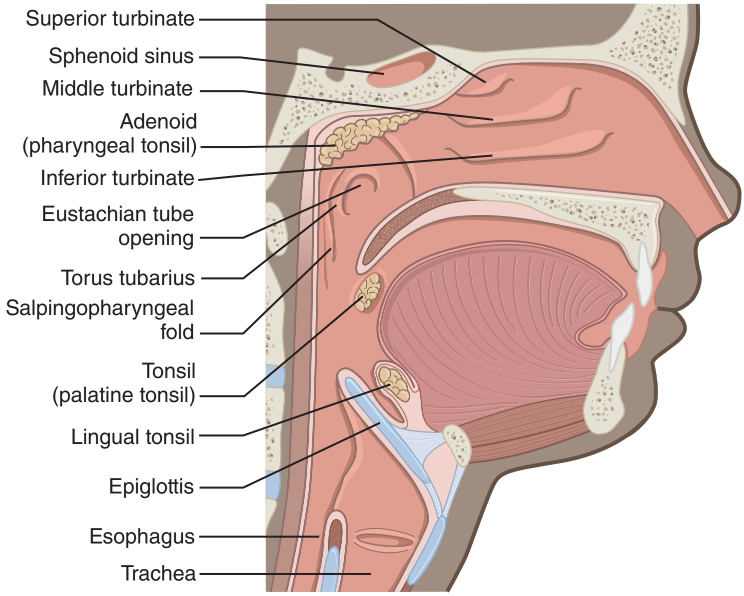

FIGURE 1-10 Lateral view of the nasal, oral, and pharyngeal cavities and the structures in these areas.

The hard palate is covered by a mucoperiosteum. **Mucoperiosteum** consists of a mucous membrane and periosteum. Mucous membrane (often called mucosa) is an epithelial tissue that lines many body cavities, in addition to the hard palate, and secretes mucus. Mucus (note the difference in spelling) is a clear and viscid (sticky) secretion. **Periosteum** is a thick, fibrous tissue that lies just under the mucous membrane and covers the surface of bone.

The mucosal covering of the hard palate has multiple ridges, called **rugae**, which run transversely. There is often a slight elevation of the mucosa in the middle of the anterior part of the hard palate, called the **incisive papilla**. A narrow seam-like ridge in midline (actually an embryological suture line), called the median **palatine raphe** (pronounced /ræfeɪ/), runs from the incisive papilla posteriorly over the entire length of the hard palate and velum. Bilateral midline depressions at the junction of the hard and soft palate, called the **foveae palati**, can often be seen. These are openings to minor salivary glands.

The bones of the hard palate include the premaxilla (a single midline bone), the palatine processes of the maxilla, and the horizontal plates of the palatine bone. These bones are separated by embryological suture lines.

The **premaxilla** is a triangular-shaped bone located in front of the maxillary bones (**FIGURE 1-11**). The alveolar ridge of the premaxilla contains the central and lateral maxillary incisors. The premaxilla is bordered on either side by the incisive suture lines and posteriorly by the incisive foramen. By definition, a **foramen** is a hole or opening in a bony structure that allows blood vessels and nerves to pass through to the area on the other side. The **incisive foramen** is an opening at the junction between the premaxilla and the maxillary bones. The incisive foramen also serves as a dividing point between two embryological processes. This will be discussed in the chapter *Clefts of the Lip and Palate.*

Behind the premaxilla are the paired **palatine processes of the maxilla**, which form the anterior three quarters of the maxilla. These bones terminate at the **transverse palatine suture line**

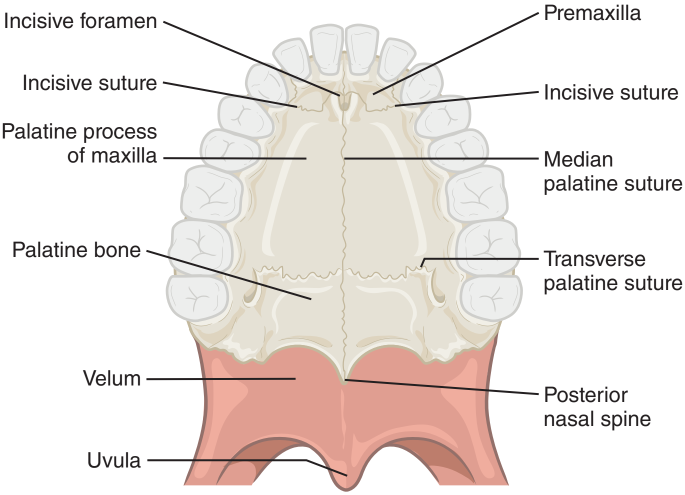

FIGURE 1-11 Bony structures of the hard palate.

(also known as the **palatomaxillary suture line**). Behind the transverse palatine suture line are the paired **horizontal plates of the palatine bones**. These bones form the posterior portion of the hard palate and end with the protrusive **posterior nasal spine**. The palatine processes of the maxilla and the horizontal plates of the palatine bones are both paired because they are separated in the midline by the **median palatine suture** (also known as the **intermaxillary suture line**). This midline suture line begins at the incisive foramen and ends at the posterior nasal spine.

In some individuals, a **torus palatinus**, or **palatine torus**, can be seen as a prominent longitudinal ridge on the oral surface of the hard palate in the area of the median suture line (**FIGURE 1-12**). It can become larger with age. This finding is a normal variation, rather than an abnormality, and is most commonly seen in Caucasians of northern European descent, Native Americans, or Eskimos. It tends to occur more in females than in males (Garcia-Garcia, Martinez-Gonzalez, Gomez-Font, Soto-Rivadeneira, & Oviedo-Roldan, 2010).

The **sphenoid bone** (an unpaired bone located at the base of the skull) and the temporal bones (located at the sides and base of the skull) provide bony attachment for the velopharyngeal musculature. The **pterygoid process** of the sphenoid bone contains the medial pterygoid plate, the lateral pterygoid plate, and the **pterygoid hamulus**, which provides attachments for muscles in the velopharyngeal complex (**FIGURE 1-13**).

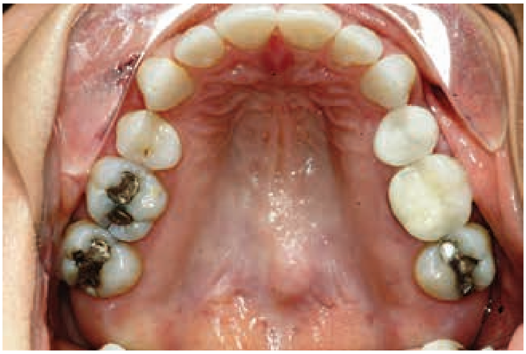

FIGURE 1-12 Small torus palatinus.

Velum

The **velum** (commonly referred to as the **soft palate**) is located in the back of the mouth and is attached to the posterior border of the hard palate (see Figure 1-9 and Figure 1-11). The velum consists of muscles (rather than bones), making it soft. As with the hard palate, the oral surface is covered by mucous membrane. The

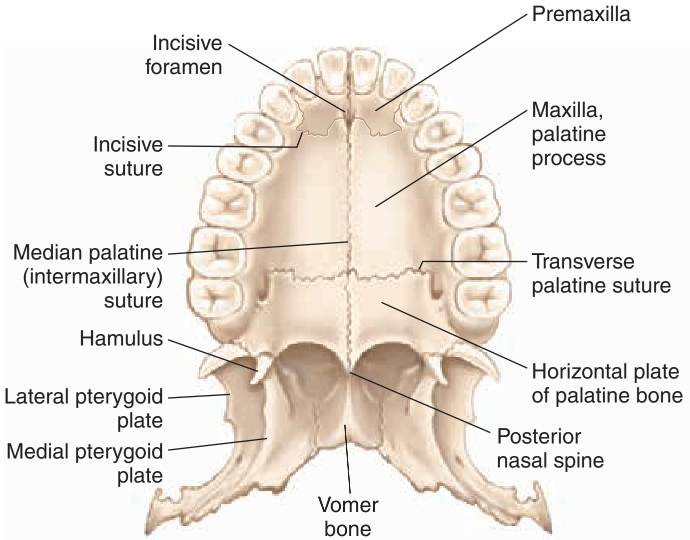

FIGURE 1-13 Inferior view of the hard palate. Note the hamulus, the lateral pterygoid plate, and the medial pterygoid plate.

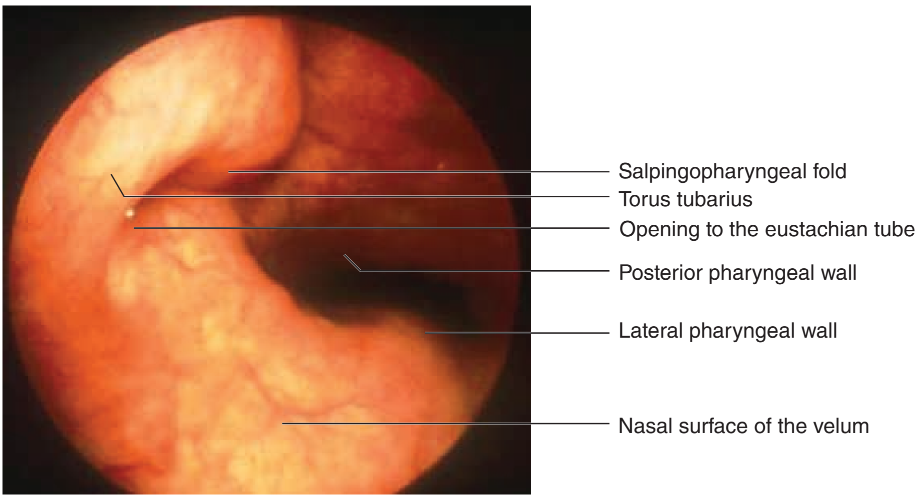

FIGURE 1-14 View of the nasal surface of the velum as seen through nasopharyngoscopy. Note the opening to the eustachian tube.

median palatine raphe continues to course from the midline of the hard palate posteriorly through the velum to the uvula. The nasal surface of the velum (**FIGURE 1-14**) consists of pseudostratified, ciliated columnar epithelium anteriorly, and posteriorly of stratified, squamous epithelium in the area of velopharyngeal closure (Ettema & Kuehn, 1994; Kuehn & Kahane, 1990; Moon & Kuehn, 1996; Moon & Kuehn, 1997; Serrurier & Badin, 2008).

The anterior portion of the velum consists of the tensor veli palatini muscle tendon, glandular tissue, **adipose** (fat) tissue, and **palatine aponeurosis** (also called **velar aponeurosis**)

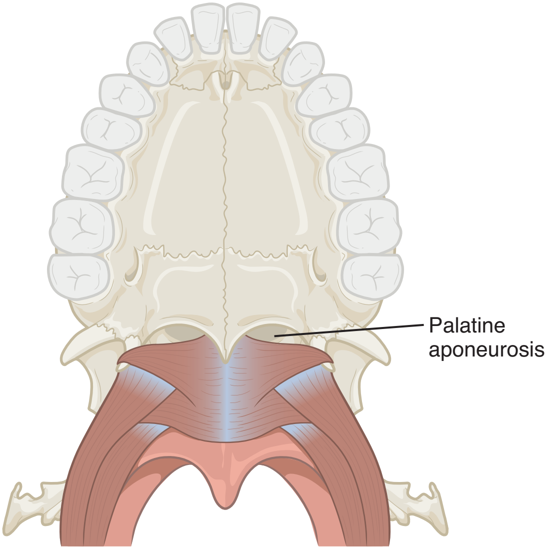

FIGURE 1-15 Position of the palatine (velar) aponeurosis. This is a sheet of fibrous tissue that is located just below the nasal surface of the velum and consists of periosteum, fibrous connective tissue, and fibers from the tensor veli palatini tendon. It provides an anchoring point for the velopharyngeal muscles and adds stiffness and velopharyngeal flexibility.

(**FIGURE 1-15**). The palatine aponeurosis consists of a sheet of fibrous connective tissue and fibers from the tensor veli palatini tendon. It attaches to the posterior border of the hard palate and courses about 1 cm posteriorly through the velum. The palatine aponeurosis provides an anchoring point for the velopharyngeal muscles and adds stiffness to that portion of the velum (Cassell & Elkadi, 1995; Ettema & Kuehn, 1994; Hwang, Kim, Huan, Han, & Hwang, 2011). The medial portion of the velum contains most of the fibers of the levator veli palatini muscles, which are described later in this chapter. The posterior portion of the velum consists of the same glandular and adipose tissue as can be found in the anterior portion.

Uvula

The **uvula** is a teardrop-shaped structure that is typically long and slender (see Figure 1-9 and Figure 1-11). It hangs freely from the posterior border of the velum. The uvula consists of mucosa on the surface and connective, glandular, adipose, and vascular tissue underneath. It contains no muscle fibers, however. The uvula does not contribute to velopharyngeal function and actually has no known function.

Pharyngeal Structures

Pharynx

The throat area between the nasal cavity and the esophagus is called the **pharynx**. The pharynx is divided into three sections, as can be seen in **FIGURE 1-16**. These sections include the **nasopharynx**, which is just posterior to the nasal cavity and behind the velum; the **oropharynx**, which is just posterior to the oral cavity; and the **hypopharynx**, which is below the oral cavity and extends from the epiglottis inferiorly to the esophagus. The back wall of the throat is called the **posterior pharyngeal wall**, and the side walls of the throat are called the **lateral pharyngeal walls**. The **adenoids** (also called the **pharyngeal tonsil**, **adenoid pad**, or just **adenoid**) consist of a

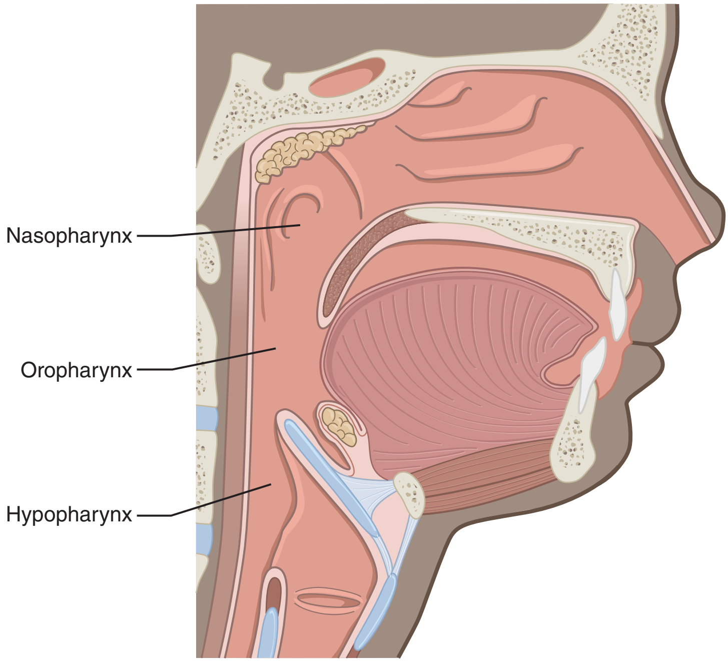

FIGURE 1-16 Sections of the pharynx. The oropharynx is at the level of the oral cavity or just posterior to the mouth. The nasopharynx is above the oral cavity, and the velum and is just posterior to the nasal cavity. The hypopharynx is below the oral cavity and extends from the epiglottis inferiorly to the esophagus.

singular mass of lymphoid tissue on the posterior pharyngeal wall, just behind the velum. Adenoids are usually present in children, but they atrophy with age. Adults have little, if any, adenoid tissue, and that which remains is relatively smooth on the surface.

Eustachian Tube

The eustachian tube is a membrane-lined tube that connects the middle ear space with the pharynx (see Figure 1-3 and Figure 1-14). The pharyngeal opening of the eustachian tube on each side is located on the lateral aspect of the nasopharynx and is slightly above the level of the velum during phonation. Bordering the posterior opening of each eustachian tube is a projection of the cartilaginous tissue, called the **torus tubarius**. Coursing down from the torus tubarius are folds of glandular and connective tissue, called the **salpingopharyngeal folds** (Cunsolo et al., 2010; Dickson, 1975; Lukens, Dimartino, Gunther, & Krombach, 2012).

The eustachian tube is closed at rest, which helps prevent the inadvertent contamination of the middle ear by the secretions in the pharynx and back of the nose. During swallowing and yawning, however, the velum raises and the **tensor veli palatini muscles** contract to open the pharyngeal end of each of the tubes. As noted, this allows middle ear ventilation to ensure that the pressure inside the ear remains nearly the same as ambient air pressure. In addition, the opening of the tube allows drainage of fluids and debris from the middle ear space.

In the infant or toddler, the eustachian tube is essentially horizontal, and the pharyngeal opening is small. As the child grows, however, the tube changes to a downward-slanting angle from middle ear to the pharynx, and the pharyngeal opening becomes larger. As a result, the eustachian tube of an adult is at a 45° angle, and the opening is about the size of the diameter of a pencil. This gradual change in both the inclination and width of the tube during growth results in improved ventilation and drainage of the middle ear.

PHYSIOLOGY

Velopharyngeal Valve

The velopharyngeal valve consists of the velum (soft palate), lateral pharyngeal walls, and the posterior pharyngeal wall. During nasal breathing, the velopharyngeal valve remains open so that there is a patent airway between the nasal cavity and the lungs. For functions that require the nasal cavity to be separated (uncoupled) from the oral cavity, the velopharyngeal valve closes as a result of the highly coordinated movements of its component structures.

Velopharyngeal closure occurs during oral speech production as well as singing, whistling, blowing, swallowing, gagging, vomiting, and sucking (Nohara et al., 2007). In connected speech, the velopharyngeal valve must close quickly for oral sounds and open quickly for nasal sounds (Moon & Kuehn, 1996). Therefore, the velopharyngeal valve regulates and directs the transmission of sound energy and airflow into the oral and nasal cavities as appropriate.

It is important to recognize that the velopharyngeal valve is a three-dimensional structure that includes an anterior–posterior (AP) dimension, a sagittal dimension, and a vertical dimension. During closure, there must be coordinated movement of all structures in all dimensions so that the velopharyngeal valve can achieve closure like a sphincter. This can be seen in **FIGURE 1-17**, which shows an inferior view of the entire sphincter.

Velar Movement

During nasal breathing, the velum drapes down from the hard palate and rests against the base of the tongue (**FIGURE 1-18A**). This position contributes to a patent pharynx for unobstructed movement of air between the nasal cavity and lungs during nasal breathing. During velopharyngeal closure, the velum moves in a superior and posterior direction to contact the posterior pharyngeal wall or, in rare cases, the lateral pharyngeal walls (**FIGURE 1-18B**). During elevation, the velum bends at about three-quarters of the

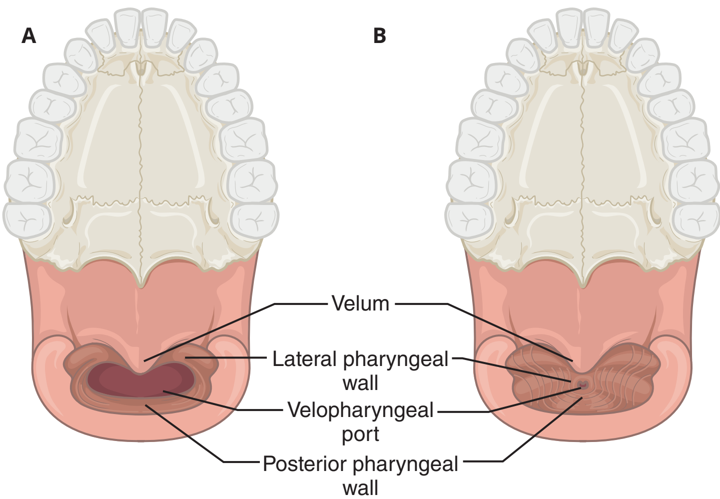

FIGURE 1-17 An inferior view of the velopharyngeal port. **(A)** The velopharyngeal port is open for nasal breathing. **(B)** The velopharyngeal port is closed for speech.

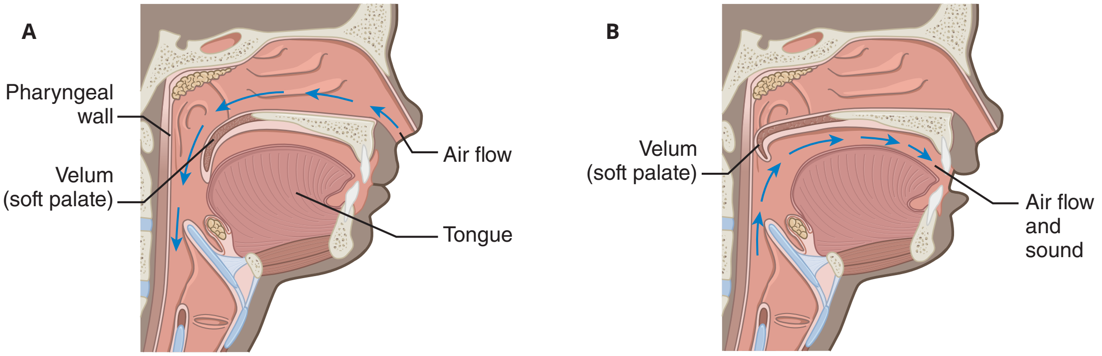

FIGURE 1-18 Lateral view of the velum and the posterior pharyngeal wall. **(A)** The velum rests against the base of the tonque during normal nasal breathing, resulting in a patent airway. **(B)** The velum elevates during speech and closes against the posterior pharyngeal wall. This allows the air pressure from the lungs and the sound from the larynx to be redirected from a superior direction to an anterior direction to enter the oral cavity for speech.

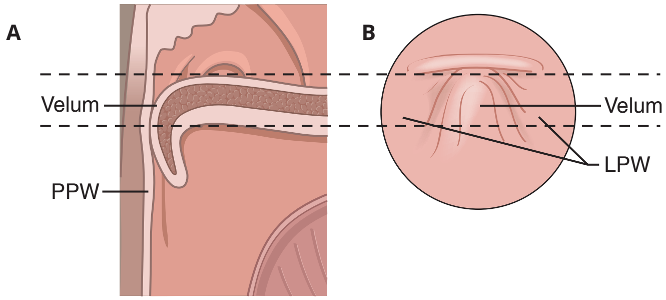

FIGURE 1-19 Frontal view of the lateral pharyngeal walls. **(A)** The lateral pharyngeal walls move medially to close against the velum on both sides. **(B)** Lateral view of the velum as it contacts the posterior pharyngeal wall (PPW).

way back from its entire length. This bending (sometimes called "knee action") results in a **velar eminence** (projection, like the knee cap, on top of the velum) on the nasal surface of the velum and a **velar dimple**, which can be seen in midline on the oral side. When a nasal phoneme is produced after an oral sound, the velum is pulled down so that sound energy can enter the nasal cavity.

As the velum elevates, it also elongates through a process called **velar stretch** (Bzoch, 1968; Mourino & Weinberg, 1975; Pruzansky & Mason, 1969; Simpson & Chin, 1981). The effective length of the velum, therefore, is the distance between the posterior border of the hard palate and the point on the posterior pharyngeal wall where there is velar contact during speech. This is measured in a line on the same plane as the hard palate (Satoh, Wada, Tachimura, & Fukuda, 2005). The amount of velar stretch and effective length of the velum vary among individuals and are dependent on the size and configuration of the pharynx.

Lateral Pharyngeal Wall Movement

The lateral pharyngeal walls contribute to velopharyngeal closure by moving medially to close against the velum or, in rare cases, to meet in midline behind the velum (**FIGURE 1-19**). Both lateral pharyngeal walls move during closure, but there is great variation among normal speakers as to the extent of movement (Lam, Hundert, & Wilkes, 2007). In addition, there is often asymmetry in movement so that one side may move significantly more than the other side. Although some lateral wall movement may be noted from an intraoral perspective, the point of greatest medial displacement occurs at the level of the hard palate (Iglesias, Kuehn, & Morris, 1980) and velar eminence (Lam et al., 2007; Shprintzen, McCall, Skolnick, & Lencione, 1975). This area is well above the area that can be seen from an intraoral inspection. In fact, at the oral cavity level, the lateral walls may actually appear to bow outward during speech (Lam et al., 2007).

Posterior Pharyngeal Wall Movement

Although there may be some anterior movement of the posterior pharyngeal wall during velopharyngeal closure, the contribution of the posterior pharyngeal wall to closure seems to be much less than that of the velum and lateral pharyngeal walls (Iglesias et al., 1980; Magen, Kang, Tiede, & Whalen, 2003).

Some speakers demonstrate a Passavant's ridge on the posterior pharyngeal wall (**FIGURE 1-20**).

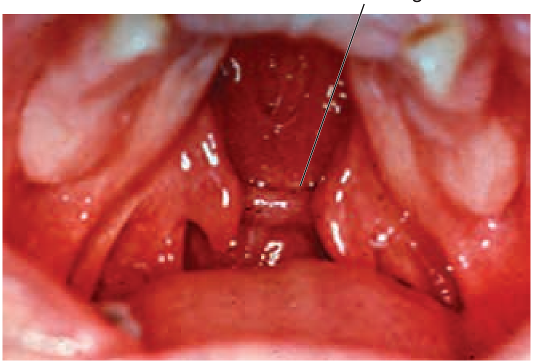

FIGURE 1-20 Passavant's ridge as noted during phonation. This patient has an open palate because of surgery for maxillary cancer. During phonation, the Passavant's ridge presents as a ridge of muscle on the posterior pharyngeal wall.

A **Passavant's ridge**, first described by Gustav Passavant in the 1800s, is not a permanent structure. Instead, it is a defined area on the posterior pharyngeal wall that bulges forward inconsistently during velopharyngeal movement and then disappears during nasal breathing or when velopharyngeal activity ceases (Glaser, Skolnick, McWilliams, & Shprintzen, 1979; Skolnick & Cohn, 1989). Passavant's ridge is thought to be formed by the contraction of specific fibers of the superior constrictor muscles (Dickson & Dickson, 1972; Finkelstein et al., 1993; Perry, 2011). The vertical location of the ridge is variable among individuals, but it is usually well below the site of velopharyngeal contact and, therefore, does not seem to be a factor in velopharyngeal closure (Glaser et al., 1979). Reports of the prevalence of Passavant's ridge in normal speakers range from as little as 9.5% to as high as 80% (Casey & Emrich, 1988; Finkelstein et al., 1991; Skolnick, Shprintzen, McCall, & Rakoff, 1975; Yamawaki, 2003; Yanagisawa & Weaver, 1996). In a look at the collective results of several studies, Casey and Emrich (1988) found that Passavant's ridge probably occurs in about 23% of individuals with a history of cleft and in 15% of normal speakers.

Muscles of the Velopharyngeal Valve

The velopharyngeal valve requires the coordinated action of several muscles, all of which are paired with one muscle on each side of the midline (Moon & Kuehn, 1996; Perry, 2011) (**FIGURE 1-21**). Coordinated movement of the velopharyngeal valve is very complex, requiring the interaction of not only these muscles but also that of the articulators, particularly the tongue (Kao, Soltysik, Hyde, & Gosain, 2008; Moon, Smith, Folkins, Lemke, & Gartlan, 1994; Perry, 2011; Perry & Kuehn, 2009).

Levator Veli Palatini Muscles

The **levator veli palatini** muscles, often referred to as the **levator sling** (Mehendale, 2004), are responsible for elevation of the velum during

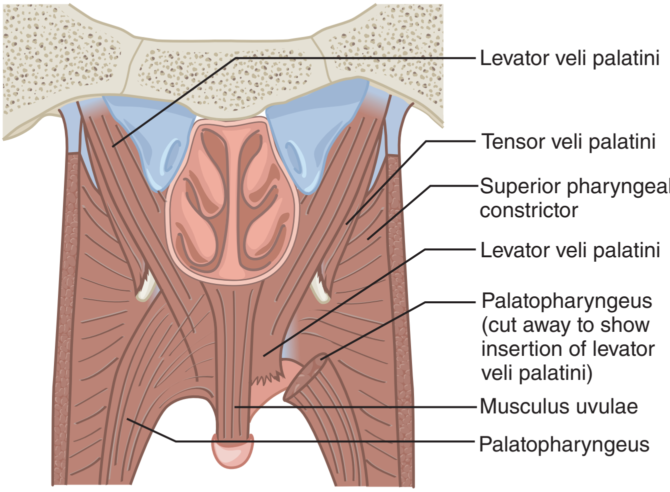

FIGURE 1-21 The muscles of the velopharyngeal mechanism.

velopharyngeal closure. These muscles enter the velum on both sides at a 45° angle and interdigitate (blend together) in midline (Smith & Kuehn, 2007). Because of the 45° angle, the contraction of the levator muscles pulls the velum in a posterior and superior direction to close against the posterior pharyngeal wall. The point where these muscles interdigitate forms the velar dimple, which can be seen in the midline of the oral surface of the velum during phonation.

On each side of the nasopharynx, the levator veli palatini muscle originates from the apex of the petrous portion of the temporal bone at the base of the skull. The muscle then courses through an area that is anterior and medial to the carotid canal and inferior to the eustachian tube (Moon & Kuehn, 1996; Moon & Kuehn, 1997; Smith & Kuehn, 2007). The levator muscles take up the middle 40% of the entire velum and, therefore, provide its main muscle mass (Boorman & Sommerlad, 1985; Kuehn & Moon, 2005; Nohara, Tachimura, & Wada, 2006; Perry, Kuehn, & Sutton, 2011; Shimokawa et al., 2004).

Superior Constrictor Muscles

The **superior constrictor** (also called **superior pharyngeal constrictor**) muscles are responsible for constriction of the lateral pharyngeal walls around the velum (Iglesias et al., 1980; Shprintzen et al., 1975; Skolnick, McCall, & Barnes, 1973). The paired superior constrictor muscles are located in the upper pharynx and arise from the pterygoid hamulus, pterygomandibular raphe, posterior tongue, posterior mandible, and palatine aponeurosis. They insert posteriorly in the pharyngeal raphe in the midline of the posterior pharyngeal wall.

Palatopharyngeus Muscles

The **palatopharyngeus** muscles are responsible for the medial movement of the lateral pharyngeal walls to bring them against the velum (Cassell & Elkadi, 1995; Cheng & Zhang, 2004; Sumida, Yamashita, & Kitamura, 2012). The palatopharyngeus muscles are contained within the posterior faucial pillars. They originate from the palatine aponeurosis in the anterior portion of the velum and posterior border of the hard palate. They then course down through the posterior pillars to the pharynx.

Palatoglossus Muscles

The **palatoglossus** muscles are responsible for the rapid downward movement of the velum for production of nasal consonants that follow an oral sound (Kuehn & Azzam, 1978; Moon & Kuehn, 1996). Given the speed at which the velum must be lowered for nasal phonemes and then raised for oral phonemes, gravity alone would not be effective (Cheng, Zhao, & Qi, 2006; Lam et al., 2007). The palatoglossus muscles are contained within the anterior faucial pillars. They arise from the palatine aponeurosis and then course down through the anterior pillars to insert into the posterior lateral aspect of the tongue.

Salpingopharyngeus Muscles

The **salpingopharyngeus** muscles are responsible for raising the pharynx and larynx during swallowing and helping to open the eustachian tube during swallowing. These muscles do not have a significant role in achieving velopharyngeal closure given their size and location. These muscles arise from the inferior border of the torus tubarius, which is at the upper level of the pharynx. They then course vertically along the lateral pharyngeal wall and under the salpingopharyngeal fold.

Musculus Uvulae Muscles

The **musculus uvulae** muscles contract during phonation to create a bulge, called the velar eminence, on the posterior border of the nasal surface of the velum. This bulge provides additional stiffness and helps to assure a firm velopharyngeal seal (Huang, Lee, & Rajendran, 1997; Kuehn, Folkins & Linville, 1988; Moon & Kuehn, 1996; Moon & Kuehn, 1997). The paired musculus uvulae muscles originate from the area of the palatine aponeurosis and are positioned side by side in the midline of the velum, just above the levator veli palatini muscles. They are the only intrinsic muscles of the velum (Kuehn & Moon, 2005; Moon & Kuehn, 1996). It should be noted that the name of these muscles is somewhat misleading in that they do not exist within the uvula. In fact, the uvula contains very few muscle fibers and does not contribute to velopharyngeal closure (Ettema & Kuehn, 1994).

Tensor Veli Palatini Muscles

The tensor veli palatini muscles are responsible for opening the eustachian tubes in order to enhance middle ear aeration and drainage (Ghadiali, Swarts, & Doyle, 2003). Although these muscles are the main contributors to the palatine aponeurosis, the tensor is not positioned in a way to either raise or lower the velum. Therefore, these muscles probably contribute little, if anything, to velopharyngeal closure. The tensor veli palatini muscle on each side originates from the membranous portion of the eustachian tube cartilage and the scaphoid fossa spine of the sphenoid bone (Barsoumian, Kuehn, Moon, & Canady, 1998; Schonmeyr & Sadhu, 2014). Additional slips arise from the lateral aspect of the medial pterygoid plate and the spine of the sphenoid. The tensor veli palatini muscle then courses vertically down from the skull base to pass around the pterygoid hamulus. This redirects the muscle tendon 90° medially, where it contributes to the palatine aponeurosis in the superior and anterior regions of the velum.

See **TABLE 1-1** for a summary of the primary function of each of the paired muscles.

Velopharyngeal Motor and Sensory Innervation

The motor and sensory innervation of the velopharyngeal mechanism arises from the cranial nerves in the medulla. The following section describes the specific innervation for motor movement and sensation.

Motor innervation for the muscles that contribute to velopharyngeal closure comes from the pharyngeal plexus (**FIGURE 1-22**). The **pharyngeal plexus** is a network of nerves that lies along the posterior wall of the pharynx and consists of the pharyngeal branches of the glossopharyngeal nerve (ninth cranial nerve [CN IX]) and the vagus nerve (tenth cranial nerve [CN X]). Innervation of the velar muscles with these nerves occurs through the brainstem nucleus ambiguus and retrofacialis (Cassell &

TABLE 1-1 Muscles of the Velopharynx and Their Primary Functions

Muscle	Primary Function
Levator veli palatini	Elevating of the velum during velopharyngeal (VP) closure
Superior constrictor	Constricting the pharyngeal walls around the velum during VP closure
Palatopharyngeus	Medial movement of the lateral pharyngeal walls during VP closure
Palatoglossus	Depressing velum causing VP opening for nasal sounds
Salpingopharyngeus	Elevating the pharynx and larynx and opening the eustachian tube during swallowing
Musculus uvulae	Providing bulk on the nasal surface of the velum during VP closure
Tensor veli palatini	Opening the eustachian tube during swallowing

Elkadi, 1995; Kennedy & Kuehn, 1989; Moon & Kuehn, 1996). The palatoglossus muscle has also been found to receive innervation from the hypoglossal nerve (CN XII) (Cassell & Elkadi, 1995). The tensor veli palatini, which does not contribute to velopharyngeal closure, receives motor innervation from the mandibular division of the trigeminal nerve (CN V).

Sensory innervation of both the hard and soft palate is believed to derive from the greater and lesser palatine nerves, which arise from the maxillary division of the trigeminal nerve (CN V). The faucial and pharyngeal regions of the oral cavity are innervated by the glossopharyngeal nerve (CN IX). The facial nerve (CN VII) and vagus nerve (CN X) might also contribute to sensory innervation (Perry, 2011). Although the peripheral distribution of sensory fibers may travel along different cranial nerve routes, they all appear to terminate in the spinal nucleus of the trigeminal nerve (Cassell & Elkadi, 1995). It has been reported that the cutaneous sensory nerve endings are more prolific in the anterior portion of the oral cavity but diminish in quantity as they course toward the posterior regions of the mouth (Cassell & Elkadi, 1995).

Variations in Velopharyngeal Closure

Patterns of Velopharyngeal Closure

The relative contribution to closure of each of the velopharyngeal structures varies among speakers. This is because of minor differences in muscular orientation of the soft palate and pharyngeal walls (Finkelstein, Talmi, Nachmani, Hauben, & Zohar, 1992; Finkelstein et al., 1993). As a result of these differences, three distinct patterns of velopharyngeal closure can be identified within a population of normal speakers and speakers with velopharyngeal dysfunction (Finkelstein et al., 1992; Igawa, Nishizawa, Sugihara, & Inuyama, 1998; Jordan, Schenck, Ellis, Rangarathnam, Fang, & Perry, 2017; Perry, 2011; Shprintzen, Rakoff, Skolnick, & Lavorato, 1977; Siegel-Sadewitz & Shprintzen, 1982; Skolnick & Cohn, 1989; Skolnick et al., 1973; Witzel & Posnick, 1989). This can be seen on **FIGURE 1-23**.

The most common pattern of closure is the **coronal pattern**. This pattern is characterized by contact of the velum against a broad area of the posterior pharyngeal wall. There may be slight anterior movement of the posterior pharyngeal wall but minimal contribution of the lateral pharyngeal walls. It is estimated that about 70%

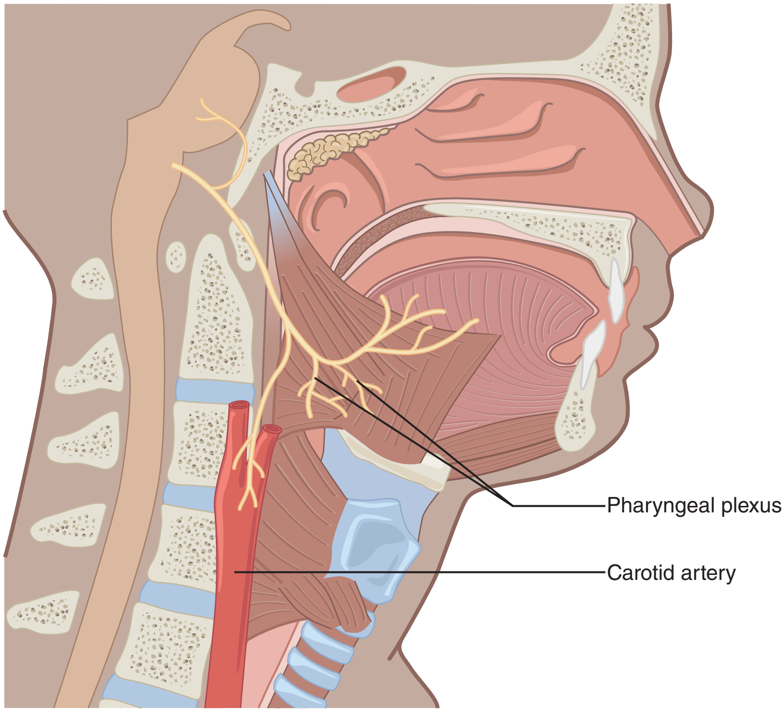

FIGURE 1-22 Position of the pharyngeal plexus.

of speakers have the coronal pattern of closure (Witzel & Posnick, 1989).

The second most common pattern of closure is the **circular pattern**. This pattern occurs when all the velopharyngeal structures contribute almost equally to closure, and therefore, the valve resembles a true sphincter when it closes. A Passavant's ridge is often seen in individuals with a circular pattern of closure (Skolnick & Cohn, 1989). It is estimated that about 25% of all speakers have the coronal pattern of closure (Witzel & Posnick, 1989).

The least common pattern of closure is the **sagittal pattern**. With this pattern, the lateral pharyngeal walls move medially to meet in midline behind the velum (rather than against the velum), and there is minimal posterior displacement of the soft palate to achieve closure. This pattern seems to occur in 5% or less of speakers (Witzel & Posnick, 1989).

The variations in the basic patterns of closure among individuals are important to recognize, particularly in the evaluation process (Siegel-Sadewitz & Shprintzen, 1982; Skolnick et al., 1973). For example, on a lateral videofluoroscopy (a radiographic procedure), it may appear as if there is inadequate velopharyngeal closure with the sagittal pattern of closure, even when closure is complete, because the velum does not close against the posterior pharyngeal wall. Therefore, evaluating all of the velopharyngeal structures and their contribution to closure is important so that the basic closure pattern can be identified and considered when making treatment recommendations.

Pneumatic versus Nonpneumatic Activities

Velopharyngeal closure occurs during speech production, but it also occurs for other functions. If these functions are categorized into pneumatic versus nonpneumatic activities, a characteristic

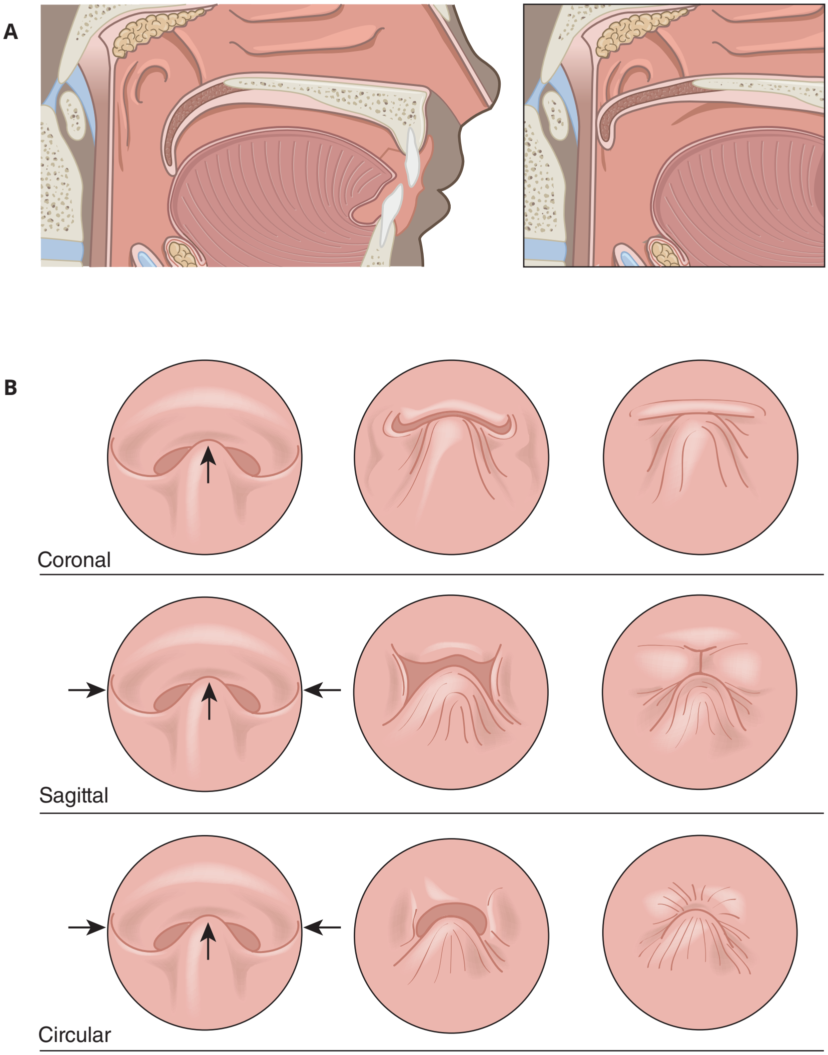

FIGURE 1-23 (A) Lateral view of VP closure as viewed through nasopharyngoscopy. **(B)** Patterns of velopharyngeal closure as viewed from above.

and distinct closure pattern can be identified for each category (Flowers & Morris, 1973; Shprintzen, Lencione, McCall, & Skolnick, 1974). In fact, there seems to be a separate neurological mechanism for closure during nonspeech activities, especially nonpneumatic activities, versus closure for speech.

Nonpneumatic activities are those that are done without airflow. They include gagging, vomiting, and swallowing. With gagging and vomiting, the velum is raised very high in the pharynx and the lateral pharyngeal walls close firmly along their entire length. This is the only type of velopharyngeal closure that can be felt. This high and firm closure is necessary to allow substances to pass through the oral cavity without nasal regurgitation. With swallowing, the back of the tongue pushes the velum upward, and therefore, velar elevation occurs passively rather than by the contraction of the levator muscles (Flowers & Morris, 1973). It is important to note that velopharyngeal closure may be complete for nonpneumatic activities but insufficient for speech or other pneumatic activities (Shprintzen et al., 1975).

Pneumatic activities are those that utilize airflow and air pressure (both positive and negative) as a result of velopharyngeal closure. Positive pressure is necessary for blowing, whistling, singing, and speech. Negative pressure is needed for sucking and kissing. With these activities, closure occurs lower in the nasopharynx than with nonpneumatic activities.

Although closure for pneumatic activities is very different than closure for nonpneumatic activities, closure for different pneumatic activities is also physiologically different from each other (Nohara et al., 2007). Blowing, for example, requires generalized movements of the velopharyngeal structures—and levator activity for blowing is higher than for speech (Kuehn & Moon, 1994). On the other hand, speech requires precise, rapid movements of these structures. The point of contact even varies slightly for different speech sounds, as is discussed in the next section. When comparing velopharyngeal closure during singing and speech, the velopharyngeal port is closed longer and tighter in singing than in speech, particularly on the higher pitches (Austin, 1997).

Timing of Closure

Voice onset and velopharyngeal closure must be closely coordinated during speech. Velar movement for oral sounds must begin before the onset of phonation so that the velopharyngeal valve is completely closed when phonation begins. If complete closure is not achieved before activation of the sound source, then the speech will become **hypernasal** as a result of the escape of sound into the nasal cavity during oral speech production (Ha, Sim, Zhi, & Kuehn, 2004).

The timing of closure for an oral sound has been found to be somewhat dependent on the type of phoneme. Kent and Moll (1969) found evidence to suggest that the velar elevating gesture for a stop begins earlier and is executed more rapidly when the stop is voiceless rather than voiced. The production of nasal consonants during an utterance has an additional effect on velopharyngeal function and timing. The velum remains elevated, and closure is maintained throughout the utterance as long as oral consonants or vowels are being produced. As a nasal consonant (/m/, /n/, /ŋ/) is produced, the velum lowers quickly, and the pharyngeal walls move away from midline, thus opening the velopharyngeal valve to allow for nasal resonance. Speech segments with many oral–nasal combinations make the temporal requirements for velar movement more challenging. This can be a problem if there is tenuous velopharyngeal closure (Jones, 2006). In addition, vowels that precede or follow the nasal consonant will be slightly affected by the anticipatory lowering of the velum just before the nasal consonant and by the slight delay in raising the velum just after the nasal consonant (Bunnell, 2005). Therefore, the timing of closure requires constant fine adjustments throughout an utterance, depending on the phonemic needs. Missed timing may have implications for the perception of resonance or nasality.

Height of Closure

Even as velopharyngeal closure is maintained throughout oral speech, there are slight variations in contact because of the type of phoneme being produced and its phonemic environment (Flowers & Morris, 1973; Moll, 1962; Moon & Kuehn, 1997; Shprintzen et al., 1975; Simpson & Chin, 1981).

In general, velar heights are slightly greater for the following: consonants versus vowels, high-pressure consonants (plosives, fricatives, and affricates) versus low-pressure consonants, voiceless consonants versus voiced consonants, and high vowels versus low vowels (Moll, 1962; Moon & Kuehn, 1997). As such, velar position is constantly modified slightly with each sound production (Karnell, Linville, & Edwards, 1988).

Firmness of Closure

The exact same factors that increase the height of velar contact during speech also increase the firmness of closure. Therefore, velopharyngeal firmness is greatest when the contact is relatively high (Kuehn & Moon, 1998; Moon, Kuehn, & Huisman, 1994). Vowels adjacent to a nasal consonant, particularly when preceding the consonant, have less closure force than those adjacent to oral consonants (Moll, 1962).

Effect of Rate and Fatigue

Rapid speech can affect the efficiency of velopharyngeal movement and, thus, reduce the height and firmness of closure. This can cause an increase in the perception of hypernasality.

Muscular fatigue can also affect the height and firmness of closure, even in individuals with normal speech (Kuehn & Moon, 2000). In fact, young children are often described as “whiny” when they are tired, which is just another word for “nasal.” Even blowing for an extended period of time, as when playing a wind instrument, can result in velar fatigue (Tachimura, Nohara, Satoh, & Wada, 2004).

Changes with Growth and Age

The maturational changes in the craniofacial skeleton result in changes in the relationships of the pharyngeal structures and the size of the cavities of the vocal tract (pharyngeal, oral, and nasal). The differences in the vocal tract anatomy among an infant, a child, and an adult are significant and account for the differences in the quality of the “voice” at different stages of development.

Although the cranium approaches adult size relatively early in childhood, the facial bones continue to grow into adolescence or early adulthood. The growth of the mandible and maxillary bones is somewhat affected by the development of dentition. As these structures grow and mature, they move down and forward relative to the cranium. Both the maxilla and mandible are similar in size in males and females until around 14 years of age. After that age, these facial bones continue to grow in males until around age 18, whereas there is very little additional growth in females (Tineshev, 2010; Ursi, Trotman, McNamara, & Behrents, 1993). Despite the changes in the size of the mandible and maxilla over time, there are relatively minor changes in shape, even during the various occlusal stages (Kent & Vorperian, 1995).

The velopharyngeal structures undergo significant change during the first 2 years of life. With the birth cry and early vocalizations, the velopharyngeal valve remains open. As the larynx descends and the pharynx lengthens, the velum and epiglottis begin to separate, allowing for velar movement. As such, the velopharyngeal valve begins to function during some spontaneous vocalizations between 3 and 6 months of age and is fully functional around 19 months of age (Bunton & Hoit, 2018).

In addition, the size of the pharynx changes greatly during maturation. The newborn pharynx is estimated to be approximately 4 cm long. In fact, the velum and epiglottis are in close proximity, resulting in a very short pharynx (which partly accounts for the infant’s high-pitched voice). In contrast, the adult pharynx is approximately 20 cm long. It has been shown that with age and height, there is a linear increase in the length of the pharynx for both boys and girls (Rommel et al., 2003; Stellzig-Eisenhauer, 2001).

In addition to the increase in length, there is an increase of approximately 80% in the volume of the nasopharynx from infancy to adulthood. Because there is more vertical than horizontal growth, there is very little change in the anterior–posterior dimension of the nasopharynx (Kent & Vorperian, 1995; Tourne, 1991). However, there is significant change in the angle of the posterior pharyngeal wall and its relationship to the velum.

In a newborn, the oropharynx curves slightly to form the nasopharynx. At around age 5, the posterior pharyngeal wall of the nasopharynx and oropharynx meet at an oblique angle. Because of the position of the pharyngeal wall, velopharyngeal closure in children typically occurs with the back of the velum (just below the velar eminence) against the pharyngeal wall, and most likely against the adenoid tissue. By puberty, however, the inclination of the nasopharynx changes so that the posterior pharyngeal wall meets the velum at almost a right angle (Kent, 1976; Kent & Vorperian, 1995). As a result, velopharyngeal closure in adults tends to be with the top of the velum against the pharyngeal wall that is slightly above it. Also, the vertical distance between the palatal plane and cervical vertical 1 (C1) becomes greater with age, resulting in the level of velopharyngeal closure being located higher above C1 (Mason, Perry, Riski, & Fang, 2016). Fortunately, the angle of the pharyngeal wall changes at the same time as the downward and slightly forward growth of the maxilla and thus the velum. In addition, the velum increases in both length and thickness at this stage. Therefore, despite these changes in structure and velopharyngeal relationships, the competency of velopharyngeal closure is maintained.

Another factor that changes the relative dimensions of the pharyngeal space and can introduce some instability in velopharyngeal function is the presence and size of the adenoid tissue. The adenoid pad is positioned on the posterior pharyngeal wall in the area of velopharyngeal closure. In young children, the adenoid pad can be prominent in size, and in many cases, it actually assists with closure. As a result, young children actually have veloadenoidal (rather than velopharyngeal) closure (Kent & Vorperian, 1995; Maryn, Van Lierde, De Bodt, & Van Cauwenberge, 2004; Skolnick et al., 1975) (**FIGURE 1-24**).

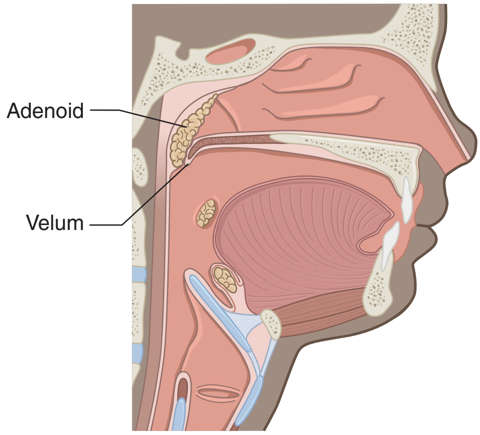

FIGURE 1-24 The adenoid pad assists in velopharyngeal closure in children.

A gradual process of involution of the adenoid tissue begins around the age of 6 but accelerates with puberty. Fortunately, the velopharyngeal mechanism is usually able to adapt to the anatomic changes that occur with adenoid atrophy so that velopharyngeal function is maintained. In addition, there may be an increase in velopharyngeal movement following adenoid involution—so that a more mature pattern of velopharyngeal closure is adopted (Kent & Vorperian, 1995). Finally, aging on velopharyngeal function has been studied, and the results suggest that there is virtually no deterioration in velopharyngeal function with advanced age (Hoit, Watson, Hixon, McMahon, & Johnson, 1994; Siegel-Sadewitz & Shprintzen, 1986).

Subsystems of Speech: Putting It All Together

During speech, all movements must be done quickly and with extreme accuracy. In fact, the action of every muscle for speech is influenced by the actions of other muscles in the system, and the movements of each structure are influenced by movements of other structures. In addition, every phoneme is influenced by other phonemes around it (Kollia, Gracco, & Harris, 1995). Because of this, there must be good coordination of all aspects of the physiological subsystems, which include respiration, phonation, velopharyngeal function, and articulation. To understand the importance of these subsystems and how they relate to the velopharyngeal valve, it may be helpful to review how sound is produced.

Respiration

Respiration is essential for life support, but it is also essential for speech. The air from the lungs is what provides the initiating force for phonation for consonant production. During quiet breathing, the inspiratory and expiratory phases are relatively long and usually about equal in duration. During speech, however, inspiration occurs very quickly. Subglottic air pressure is then maintained under the vocal folds during the entire phrase or sentence. The expiratory phase is much longer than the inspiratory phase and varies, depending on the length of the utterance being produced. Both the inspiratory and expiratory phases for speech are based on the phrasing of the speaker.

Phonation

Phonation (also called **voicing**) is the production of sound by vibration of the vocal folds. The sound created by vocal fold vibration is called the **voice**. The voice travels upward through the vocal tract and is then emitted through the mouth or nose during speech and singing. Voicing (or phonation) is necessary for the production of all vowels and more than half of the consonant sounds.

Phonation is initiated when air is expelled from the lungs and through the glottis. The vocal folds then close, which creates subglottic air pressure. This air pressure forces the bottom of the vocal folds open and then continues to move upward to open the top of the vocal folds. The low pressure created behind the fast-moving air column causes the bottom of the folds to close, followed by the top folds. The closure of the vocal folds cuts off the air column and releases a pulse of air. This completes one vibratory cycle. The cycles repeat for vocal fold vibration, resulting in a type of buzzing sound (which is later modified by resonance).

During connected speech, the vocal folds must vibrate for voiced sounds, stop vibrating abruptly for voiceless sounds, and then vibrate again for the next vowel or voiced consonant (Bailly, Henrich, & Pelorson, 2010; Kent & Moll, 1969; Takemoto, Mokhtari, & Kitamura, 2010; Tsai, Chen, Shau, & Hsiao, 2009). In the simple two-syllable phrase "a cup," the vocal folds vibrate on the vowel, stop on the /k/, vibrate on the vowel, and stop again on the /p/. This requires a great deal of neuromotor coordination and control. Also, airflow must be maintained throughout the utterance so that it can continue to provide the force for phonation.

Prosody

Prosody refers to the stress, rhythm, and intonation of speech as produced by the vocal folds during phonation. **Stress** is related to increased laryngeal and subglottic pressure during the production of a syllable. Stressed syllables are higher in pitch and intensity, longer in duration, and produced with greater articulatory precision as compared to unstressed syllables. **Rhythm** refers to the alteration of stressed and unstressed syllables and the relative timing of each. **Intonation** refers to the frequent changes in pitch throughout an utterance, as controlled by subtle changes in vocal fold length and mass. These changes influence the rate of vibration of the vocal folds and the tension of the muscles of the larynx. Although there are changes in pitch throughout connected speech, the pitch of the voice tends to drop to a lower frequency at the end of each statement and rise to a higher frequency at the end of a question. Both stress and intonation are used for emphasis and also to help to convey meaning. For example, the words "desert" and "dessert" have different meanings that are conveyed through differences in the place of stress. When the sentence "Well, that's just fine" is uttered as if it has an exclamation point, it has a different meaning than when it is spoken as if it has a period at the end. The differences in meaning are conveyed by differences in the stress and intonation.

Resonance and Velopharyngeal Function

Once phonation has begun, the sound energy from the vocal folds travels in a superior direction through the cavities of the vocal tract, beginning with the pharyngeal cavity and ending with the oral cavity and/or nasal cavity. **Resonance**, as it relates to speech, is the modification of the sound from the vocal folds through selective enhancement of certain frequencies as it travels through these cavities. The frequencies that are enhanced are determined by the size and shape of the cavities.

The effect of the size and shape of the cavities of the vocal tract can be simulated by blowing across the lip of a bottle filled by water. When the bottle is mostly full, the resonating airspace is small, and the resulting sound is high in pitch. When the bottle is almost empty so that there is a larger resonating cavity, the sound is deeper in pitch and richer in perception. Although the sound source was the same, the pitch of the sound is dictated by the size of the resonating cavity.

The generation of sound and the shaping of that sound has been called the **source-filter model** and was first described by Gunnar Fant (Fant, 1960). This model is based on the premise that every instrument that is capable of producing sound needs at least three components: (1) a vibrating mechanism to produce sound (the source), (2) a stimulating force that can set the vibration in motion, and (3) a resonating mechanism (the filter) to selectively damp or amplify various frequencies of the sound. In human speech, the vocal folds are the vibrating mechanism (the source), subglottic air pressure is the stimulating force, and the cavities of the vocal tract are the resonators (the filters) (Baken, 1987; Sataloff, Heman-Ackah, & Hawkshaw, 2007).

Variation in the size and shape of the resonating cavities among individuals is often determined by age and gender. For example, infants have very small resonating cavities; thus, the vocal quality is very high in pitch. Women and children usually have a shorter pharynx than men; therefore, they have higher formant frequencies in their vocal product than men. An additional consideration is the wall thickness of the cavities. A thick pharyngeal wall can absorb sound, whereas a thinner wall can reflect sound. The changes in vibration that result from all these factors produce the resonance and give the perception of timbre or vocal quality (Sataloff, 1992). This is what provides the unique quality to an individual's voice.

The velopharyngeal valve influences resonance by directing the transmission of sound energy (and airflow) into the appropriate cavities during speech. During the production of oral speech sounds (all sounds with the exception of /m/, /n/, and /ŋ/), the velopharyngeal valve closes, thus blocking off the nasal cavity from the oral cavity. This allows the sound energy and airflow to be directed anteriorly into the oral cavity. During the production of nasal sounds (m/, /n/, and /ŋ/), the velopharyngeal valve opens, which allows the sound to enter the nasal cavity.

Articulation

The sound that results from phonation and resonance is further altered for individual speech sounds by the oral articulators. The oral **articulators** include the lips, the jaws (including the teeth), and the tongue. (The velum is also an articulator for speech.) The oral articulators alter the acoustic product for different speech sounds in two ways. First, they can vary the size and shape of the oral cavity through movement and articulatory placement. Second, the articulators can modify the manner in which the sound, and particularly the airstream, is released.

Both vowels and voiced oral consonants require oral resonance for production, and many consonants also require oral air pressure. For the production of vowels, the tongue and jaws modify the size and shape of the oral cavity, but there is little constriction of the sound energy or airflow. The differentiation of vowel sounds is determined by tongue height (high, mid, or low), tongue position (front, central, back), and lip rounding (present or absent).

On the other hand, consonants are produced by partial or complete obstruction of the oral cavity, which results in a buildup of air pressure in the oral cavity. Intraoral air pressure provides the force for the production of all pressure-sensitive consonants (plosives, fricatives, and affricates). **Plosive phonemes** (/p/, /b/, /t/, /d/, /k/, /g/) are produced with a buildup of intraoral pressure and then a sudden release. **Fricative phonemes** (/f/, /v/, /s/, /z/, /ʃ/, /ʒ/, /h/) require a gradual release of air pressure through a small or restricted opening. **Affricate phonemes** (/ʧ/, /ʤ/) are a combination of plosive and fricative phonemes (/ʧ/ = /t/ + /ʃ/ and /ʤ/ = /d/ + /ʒ/). As such, affricate sounds require a buildup of intraoral air pressure and then gradual release through a narrow opening. Consonants are differentiated not only by the manner of production (plosives, fricatives, affricates, liquids, and glides) but also by the place of production (bilabial, labiodental, lingual-alveolar, palatal, velar, and glottal) and voicing (voiced or voiceless).

Subsystems as "Team Players"

During speech production, each subsystem is like a member of a team. For the "team" to reach its goal of normal speech production, each subsystem must be able to execute its individual role and also learn how to work with the other "players." If it is a good player, the other team players will be more effective. If it is a poor player, this will make the job of the other team players much more difficult, and they will function less effectively. For example, velopharyngeal dysfunction can affect respiration, phonation, and articulation. It can cause an alteration of respiration during speech because the loss of airflow through the nose causes the individual to take more frequent breaths to replenish the air. Phonation may be altered if the individual compensates for inadequate oral airflow for voiceless sounds by substituting phonated sounds (i.e., n/s). On the other hand, the individual may use a breathy voice to mask the sound of hypernasality. The loss of oral airflow because of velopharyngeal dysfunction can affect articulation of pressure-sensitive consonants, causing the individual to produce sounds in the pharynx rather than the oral cavity.

SUMMARY

The anatomy of the craniofacial, intraoral, and velopharyngeal structures is well documented. On the other hand, the physiology of the velopharyngeal mechanism, particularly as it relates to speech, is very complex and not well understood. There is still much to be learned regarding the roles of the various muscles, the interaction of velopharyngeal function with articulation, and the neuromotor controls required for coordination of velopharyngeal function with the other subsystems of speech. A thorough understanding of the anatomy and physiology of the head, face, and vocal tract is particularly important in the management of speech and resonance disorders.

FOR REVIEW AND DISCUSSION

1. Why is it important to understand normal structure when working with individuals with a history of cleft lip and palate?
2. What are the facial landmarks and structures that may be relevant to the study of cleft lip?
3. Describe the internal nasal structures and the various functions of the nasal turbinates.
4. List the oral structures that can be seen when looking in the mouth.
5. List the suture lines of the hard and soft palate. Why are they called "suture" lines?
6. Describe the movement of the velopharyngeal structures and the role of the velopharyngeal muscles in closing and opening the velopharyngeal valve.
7. What are the types of velopharyngeal closure patterns among normal and abnormal speakers? Why do you think it is important to understand the basic patterns of speech when evaluating abnormal speakers?
8. Discuss the effects of type of activity, type of phoneme, rate of speech, and fatigue on velopharyngeal closure. Given the known effect of these factors on velopharyngeal closure, how would this affect the way you evaluate velopharyngeal function for speech?
9. How does velopharyngeal closure change with growth and adenoid involution? How could these changes potentially affect speech?
10. What are the physiological subsystems of speech, and how do they interact with each other for normal speech? Describe how a problem with one subsystem may affect other subsystems.

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