Chapter 8
Phonation

As was learned in the previous Chapter, the pulmonary system serves as the power source and actuator of the vocal instrument. All musical instruments, of course, must also possess a vibrator (oscillator) that creates the periodic variations in air pressure our ears interpret as sound. The vibrator for the human voice is the larynx, or more specifically, the vocal folds.

That the larynx is able to produce sound at all might be considered biological and evolutionary serendipity. All mammals have larynxes (alternate plural, *larynges*); however, not all produce sound. Biologically, the larynx is nothing more than a sphincter valve, not all that different from the valves found at either end of the alimentary canal. In this capacity, it serves two functions. First, it is the ultimate protector of the airway, helping to prevent foreign objects from entering the lungs. Second, it allows people to voluntarily block their airways to increase the intra-abdominal pressure that assists with activities such as elimination, childbirth, and the lifting of heavy objects.

Fundamental Concepts

The Vocal Folds

We begin our study of the larynx with the vocal folds themselves. Housed within the protective cartilage of the larynx, the actual vocal folds are remarkably small. Their total length at rest averages only eighteen *millimeters* for adult women (about the diameter of a dime) and twenty-three millimeters for men (about the diameter of a quarter). As small as that might seem, the portion of the fold responsible for sound production is even smaller. During phonation, only the anterior part is free to vibrate, a segment that ranges from about twelve to fifteen millimeters long for women and men (Zemlin, 1998). That anything this small can produce a sound loud enough to be heard over a symphony orchestra truly is remarkable.

Most readers will remember a time when singers had “vocal cords[22],” not vocal folds. This new nomenclature is more than a semantic change. The term *vocal fold* more precisely describes their true physical characteristics; they are small folds of tissue located in the anterior/posterior plane at the top of the airway. (I have encountered many people who mistakenly believed their “vocal cords” were a series of longitudinal bands arranged in their necks like the strings of an upright piano.)

Before we get down to the details, take a few moments to look at some photographs and short video clips of various larynges and vocal folds (**8/1-4**). The vocal folds themselves are visible as two pearly-white bands; they look like the letter V at rest, but come together, closing at the posterior, during phonation. For orientation, the bottom of this V points to the front of your neck and Adam’s apple. The space between the vocal folds is the area called the glottis, which opens for respiration, and closes during phonation. Lying directly above the folds are the pink-colored *ventricular* folds, also called the *false* vocal folds—the actual vocal folds alternately are called the *true* vocal folds to distinguish them from the ventricular or false folds. A curved structure called the *epiglottis* is seen to arise from the closed point of the vocal folds. Its purpose is to cover the airway during swallowing and direct food into the esophagus toward the stomach.

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[22] Some even had vocal *chords*—which begged the question: are they augmented or diminished?

Vocal Fold Structure

The internal, microscopic structure of the folds plays a significant role in sound production; they are composed of discreet layers of varying density and viscosity, which allows the inner and outer portions to move independently. This layered structure is clearly visible in Figure 8-1(**8/5**)

We speak of the vocal folds as having a body and cover that are loosely coupled together. The external layer, or cover, consists of a thin layer of skin cells called the *stratified squamous epithelium*. Its name is derived from its structure, which consists of several layers of skin cells (epithelium) that interlock like paving stones (squamous), which progressively become larger toward the bottom layer (stratified). Because this area is constantly bathed in mucus, it is also referred to as the *mucosa* of the vocal folds. The entire respiratory tract—from the lips to the bottom of the trachea—is lined with mucosa. This takes the form of stratified squamous epithelium only on the surface of the vocal folds and in some of the areas that lie immediately above them. The remainder consists of *columnar epithelium* (cells arranged in columns). Below the vocal folds, the columnar epithelium is *ciliated*. This region is covered with microscopic hairs that constantly transport mucus up the airway for disposal via the esophagus and stomach.[23]

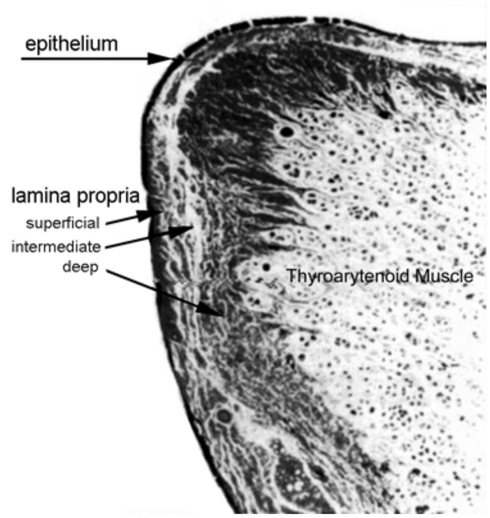

Figure 8-1: Cross section of vocal fold (Hirano, 1981) Used with permission

The body of the vocal fold consists of a muscle called the *thyroarytenoid*, which takes its name from its points of origin (thyroid cartilage) and insertion (arytenoid cartilage). A transitional layer called the *lamina propria* lies between this muscle and the epithelial cover (Figure 8-2). The lamina propria subdivides into three distinct regions with different physical characteristics, which are caused by changes in the distribution of elastin and collagen fibers. The *superficial* (outermost) layer is coupled to the epithelium through a basement membrane. This is the thinnest layer and also has the lowest viscosity. (Viscosity is a measure of fluid density. Water has low viscosity; pancake syrup has much higher viscosity.)

Lying in the middle of the lamina propria, the *intermediate* layer is both wider and more viscous than the superficial layer. A ligament, called the vocal ligament, passes through this region, resulting in a texture similar to gelatin that has been mixed with strands of cotton. The transition from vocal fold cover to body is completed by the *deep* lamina propria, which is the densest, most viscous of the three layers. Overall, the structure of the lamina propria might be compared to a three-layered gelatin dessert in which the superficial layer has not completely "set," the intermediate layer is like normal gelatin (but with those appetizing cotton fibers added), and the deep layer more closely resembles a "gummi worm."

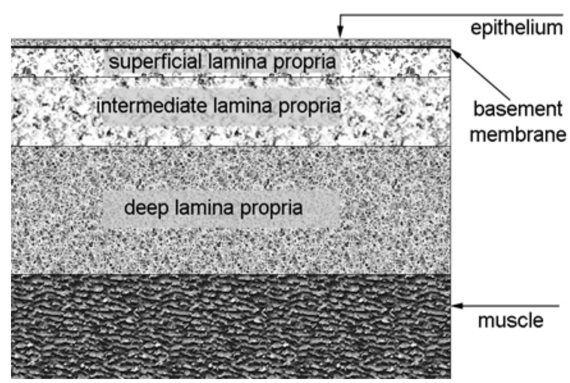

Figure 8-2: Schematic of vocal fold layers

[23] According to Dr. Anthony Jahn, M.D., otolaryngologist and coauthor of *Care of the Professional Voice*, smoking a single cigarette will paralyze the cilia for up to several hours, which is one of the reasons that smokers often develop a hacking cough.

Construction of the vocal folds in this manner allows the cover to slide gently in position relative to the body. To better understand how this works, try a little experiment on yourself: gently massage the back, and then the palm of your hand. Notice that the skin on the palm is firmly attached to the flesh beneath it. As you massage the back of your hand, however, the skin is relatively free to move (somewhat like the skin of a kitten). Next, gently poke a finger against the palm and back of your hand; the palm offers much more padding than the back, acting somewhat like a shock absorber. Your vocal folds share both of these characteristics; the cover slips over the body like the skin on the back of your hand, while the lamina propria cushions blows like the palm of your hand.

Why is this important? In healthy vocal folds, oscillation is facilitated through the gentle slippage of the cover over the body. When viewed in slow motion, using high-speed or stroboscopic cameras, the surface of the fold appears to ripple in a wavelike motion. This phenomenon is called the *mucosal wave*, which can be seen clearly in **8/6**. Some voice disorders impair phonation by impeding mucosal wave formation. For example, the hoarseness or loss of voice from laryngitis (laryngeal inflammation) results from vocal fold swelling that makes the cover adhere tightly to the body. The folds lose their suppleness and become too rigid to oscillate freely.

The significance of the vocal fold mucosa was not really known until the pioneering discoveries of Hirano and others during the 1960's and early 1970's. Their work has enabled major advancements in vocal health care, including new surgical techniques that are less invasive and more likely to result in complete restoration of normal vocal function.

Vocal Fold Oscillation

Muscular activities alone are not able to open and close the glottis rapidly enough for sound production. To understand why, try another experiment. Tap one of your fingers as rapidly as possible on a solid object. If you are particularly dexterous, you might be able to do this as quickly as 7.5 times per second. If you alternate fingers as if playing a trill on the piano, you might approach 15 or more strokes per second. To sing, however, your vocal folds must open and close at a much faster rate—up to 1,400 times per second for the F6 sung by Mozart's *Queen of the Night*. No muscle in the human body is able to contract and relax at anything close to that rate. Vibration at this velocity only can be achieved with the assistance of airflow.

Theories of Vocal Fold Oscillation

Voice science has evolved significantly over the past 50 years, leading to greater comprehension of how and why the glottis opens and closes to produce sound. Three main theories have attempted to describe vocal fold oscillation: the myoelastic-aerodynamic model, the one-mass, and three mass-models. Because each new theory is built on the shoulders of the previous, we'll start at the beginning.

The Myoelastic-Aerodynamic Model

Myoelastic-Aerodynamic theory, which was current through the 1960's, believed oscillation of the vocal folds was maintained exclusively by muscular (myo-) and aerodynamic processes. The muscular portion of this equation is straightforward and easily understood; the body of the vocal fold is a muscle. To understand the aerodynamic contribution, however, we must return to the world of physics, specifically, the principles established by an eighteenth-century scientist named Daniel Bernoulli.

Bernoulli was particularly interested in fluid dynamics. His most lasting claim to fame was the discovery of the inverse relationship between pressure and volume in a fluid driven system. If the volume of a fluid or gas remains constant as it travels through a passageway, its energy–

expressed as pressure times velocity—also remains constant. Therefore, if pressure goes up, velocity must go down (and vice versa).

To model this principle, imagine water flowing through a garden hose. If you partially block the end of the hose with your thumb, the water shoots out much farther. Why? As long you don't block the end of the hose entirely, the same quantity of water will flow out as is put into it from the other end at the spigot. But the water must speed up to travel through the constriction you have created (**8/7**). Behind this constriction, the water pressure increases and velocity decreases; through the constriction, velocity increases and pressure decreases. Remember, the amount of water flowing through the hose is the same at all times—to get the same amount of water through a smaller space requires it to flow at a faster speed.

Commuters often are frustrated by another example of the Bernoulli Effect: traffic jams. Rush-hour traffic is moving down a three-lane highway at the speed limit. The road is well designed and can comfortably handle the number of cars currently driving on it. But if two of those lanes are closed for construction, a traffic jam will occur. Pressure increases behind the constriction—in the form of irate motorists in barely moving vehicles—and the velocity of each car decreases. Upon entering the single open lane, pressure from the traffic backup is relieved, allowing individual cars to accelerate and move steadily through construction zone. These kinds of traffic jams could be avoided if civil engineers would heed the Bernoulli principle. To maintain the same traffic flow, cars must *speed up,* not slow down while passing through the one-lane sections of highway. Of course, doubling the speed limit through construction zones has other potential consequences, most of which are not particularly safe!

Let's return now to vocal fold oscillation and the role of the Bernoulli Effect. This is most clearly seen if we describe the steps in a single cycle of vibration:

1. The vocal folds are gently closed by muscular forces within the larynx
2. Air pressure increases beneath the closed glottis
3. Increasing air pressure begins to open the glottis. Because of the ability of the cover to move independently of the body, this opening begins on the underside of the glottis
4. The glottis continues to open, from bottom to top, until air begins to escape
5. As the air begins to flow through the glottis, its velocity increases and its pressure decreases, as explained by the Bernoulli Effect
6. Elasticity of the vocal fold acts somewhat like a spring, exerting a return force that begins to close the glottis; negative pressure caused by the Bernoulli effect supplies additional closing force
7. The glottis closes again, from bottom to top
8. As soon as the glottis is fully closed, the process begins again, repeating as many times per second as the frequency of the pitch being spoken or sung

The steps in this process are shown in Figure 8-3 and are animated in **8/8**. These images present the glottis in a longitudinal cross-section, slicing the larynx from top to bottom through the medial/lateral plane. Note the vertical phase difference between the lower and upper edges of the vocal folds throughout the oscillatory cycle. During phonation, glottal opening and closure always occurs in this manner with movement of the lower edge preceding the upper edge (at high pitch, the folds often are so thin that this phase difference no longer is significant). Independent movement of the inferior and superior portions of the vocal folds is a major factor in the creation of the mucosal wave; as the folds make contact at their lower edge, a wave begins to ripple across their surface, much like a wave traveling across the surface of a pond into which a pebble has been dropped.

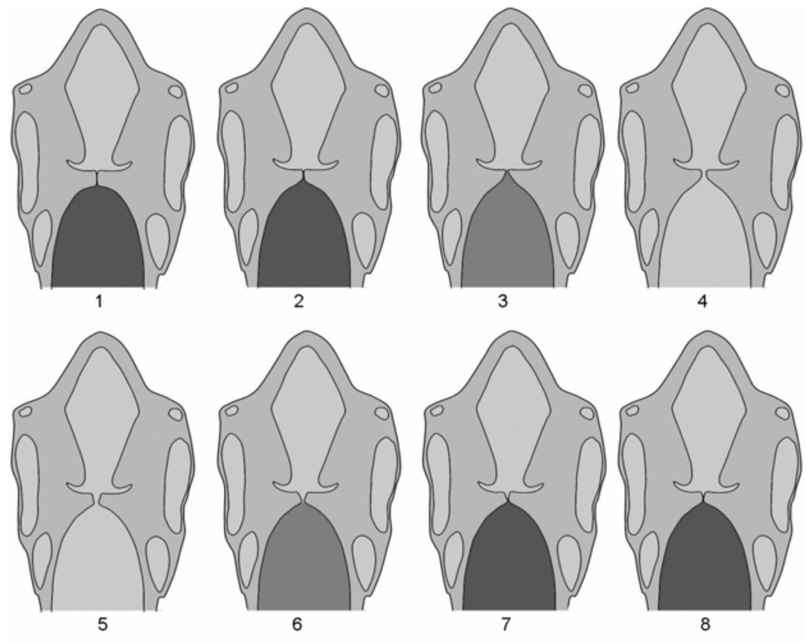

Figure 8-3: Steps in vocal fold oscillation

Scientific understanding of the role played by the Bernoulli Effect in maintaining vocal fold oscillation continued to evolve. Some reported that the reduced pressure through the glottal opening was strong enough to actively suck the vocal folds back together (Zemlin, 1998); others attributed a smaller contribution (Ishizaka and Matsudaira, 1972). Current voice scientists describe numerous interrelated factors that contribute to vocal fold vibration, including the natural oscillation frequencies of vocal fold tissue (which shares properties in common with a spring), the resistance to the movement of air through the supraglottal vocal tract, and the interaction of resonance with the vocal folds. This new information indicated that aerodynamic factors could initiate oscillation, but were insufficient to maintain it.

The One-Mass Model[24]

Myoelastic-Aerodynamic theory was significantly improved by adding the contribution of the vocal tract and its impact on airflow. In the physical world, objects experience *inertia*, which is resistance to starting and stopping movement. The vocal folds and the air moving through the vocal tract also are subject to this natural law. Let's see how it impacts vocal fold oscillation.

1. As in the A-M theory, the glottis initially is closed by muscles in the larynx
2. Subglottal air pressure increases until it overcomes the muscular and tissue resistance and opens the glottis
3. Reduced air pressure through the glottis (Bernoulli) and elasticity/inertia of the vocal folds brings the glottis back together, reducing the flow of air
4. Because of inertia, air above the glottis continues its forward motion in spite of reduced flow through the glottis, producing an area of low air pressure immediately above the glottis
5. The combined forces of elastic recoil of the folds, the pressure drop through the glottis, and the low pressure region above the glottis complete the cycle, closing the glottis
6. Asymmetry of air pressure below and above the glottis (steps 1-5) allows vocal fold oscillation to continue for as many times per second as F_o of the pitch that is spoken or sung

[24] I am deeply indebted to Dr. Ingo Titze and the National Center for Voice and Speech their assistance in formulating this concise description of one and three mass models of vocal fold oscillation. Readers and encouraged to visit www.ncvs.org for additional information.

The One-Mass model is superior to the aerodynamic model, but still doesn't account for everything that is observed during vocal fold vibration. Because each vocal fold is viewed as a single mass that oscillates uniformly, the asymmetrical opening (vertical phase difference) of the glottis, which is clearly visibly during stroboscopic and high speed imaging, remains unexplained.

The Three-Mass Model

Further improvements are made to oscillation theory by describing the vocal folds as three interconnected masses. In this model, the body of the vocal fold (thyroarytenoid muscle) is the first and largest mass. The upper and lower portions of the cover (lamina propria and epithelium) comprise two smaller masses. In this model, the glottis opens and closes asymmetrically with vertical phase difference from bottom to top. Air pressure also is asymmetrical, increasing when the glottis is in a convergent shape (bottoms of the two folds are farther apart from each other), and decreasing when the glottis is divergent (tops of the two folds are farther apart) (Figure 8-4). This asymmetry of air pressure provided by the three-mass model, combined with the impact of pressure changes above the glottis caused by inertia, is sufficient to sustain vocal fold oscillation.[25]

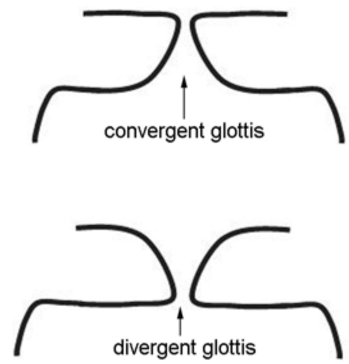

Figure 8-4: Glottal configurations

From the fringe…

While myoelastic/aerodynamic theory and the subsequent one and three-mass models dominate current voice science, they are not the only explanations of vocal fold oscillation that have been promoted. Raoul Husson (1901-67), a French scientist and voice enthusiast, developed what is called the *neurochronaxic* theory. Husson believed that nerve impulses from the brain are the sole cause of vocal fold vibration and that airflow only is needed to carry the sound outside the body. Even though this theory has been discredited scientifically, one still encounters a few singers who try to base their singing technique on it.

Structural Anatomy

Laryngeal Framework—Meet the "Oids"

To this point in the Chapter, we have been looking at vocal folds as independent entities abstractly fixed somewhere in space. This is not, of course, the case. The vocal folds are enclosed within the structural framework of the larynx, a complex biological device composed of bone, cartilage, membranes, ligaments, and muscles. The entire larynx is no larger than the size of a typical English walnut in the average adult male. In women, it is about 40% smaller—perhaps analogous to the size of a pecan. Take a moment to find your own larynx in your neck. It might be large and prominent, as often is the case in tall, slender males, or it might be so small that you barely can see or feel it in your

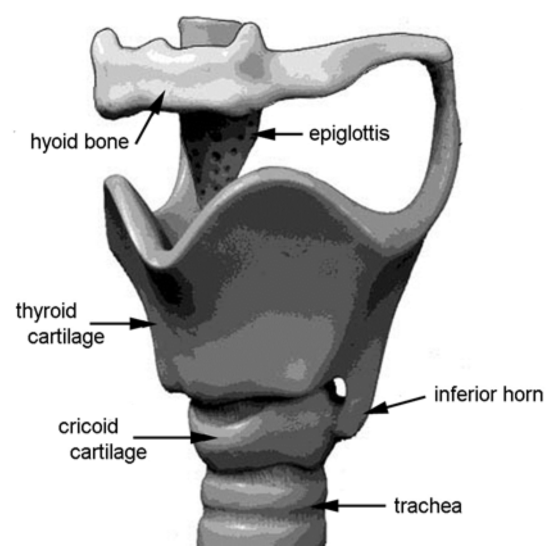

Figure 8-5: Laryngeal framework (anterior view)

[25] The three-mass model is not the final step in describing the vocal folds. The National Center for Voice and Speech website reports that researchers at the University of Iowa now base their computer simulations of vocal fold oscillation on 16-mass models.