VOICE DISORDERS

Fourth Edition

CHRISTINE SAPIENZA • BARI HOFFMAN

PLURAL PUBLISHING INC.

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FOURTH EDITION

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Contents

Foreword

Christine Sapienza and Bari Hoffman offer an up-to-date, highly revised edition of *Voice Disorders, Fourth Edition*. The authors share their extensive clinical and research experiences, combined with an array of current findings from the world voice community, with clinicians, scientists, and others who study voice and voice disorders. Drs. Sapienza and Hoffman are highly successful educators and have expanded this edition to the current needs of those who study and work in the areas of laryngeal and respiratory physiology and who treat a wide variety of voice disorders. This fourth edition updates Chapters 1 and 2 with brilliant illustrations of the respiratory and laryngeal anatomy and physiology, providing a gold box of guidance to the student and teacher.

The authors have again chosen to begin their text with a chapter on respiration. That unique feature has been amplified with color illustrations and makes this book quite distinctive from many other books on voice. This chapter provides an in-depth study of the respiratory system and its unique relationship with phonation. Respiratory structures, from the lungs to the subglottis, and their anatomy, physiology, and contribution to phonation are explained with detailed drawings and graphs. The chapter is written with great detail, yet is easy enough to understand, thanks to the well-written text that accompanies the illustrations. The addition of clear illustrations and tables in Chapters 1 and 2 highlight this edition.

This book extends the study of respiratory anatomy and physiology specifically as it relates to breathing for phonation. Chapters 1 and 2 serve as a basis for the remainder of the book, as the respiratory system serves as the foundation for the larynx and vocal fold vibration.

The latest research on laryngeal biomechanical modeling is presented for ease in discussion with patients and caregivers. In this edition, the authors demonstrate a breadth of knowledge in their research and clinical histories and practicality in their teachings. The authors strive to educate students how to synthesize complex material and present it to patients and other clinicians.

This fourth edition of *Voice Disorders* builds on the earlier editions and offers the student and clinician a comprehensive combined study of the respiratory, laryngeal, and neurological subsystems that make up voice production. The authors blend voice science with voice treatments ranging from traditional interventions to recent advances in cellular therapies, muscle strength training, and treatments for special populations such as singers and actors and those with complex medical conditions. Cases highlight various intervention strategies. With this fourth edition, the study of voice disorders comes out of its infancy and into the modern era of comprehensive care for the voice.

It is the unique mix of basic science and treatment strategies that Sapienza and Hoffman are known for, and which they successfully brought into their first edition of *Voice Disorders* in 2009. That edition was highly successful with a large readership and brought compliments from instructors and students. The second and third editions of *Voice Disorders* built on that framework with their detailed descriptions of the anatomy, physiology, and clinical presentations of voice disorders. The fourth edition brings the study of voice disorders up to date with additional chapters on laryngeal reflexes, immunology, and the effects of medications on the voice, and expands on the key clinical entities of the previous editions. In addition, a completely revised chapter related to gender-affirming voice has been included. The authors have kept abreast of the latest developments in the medical, behavioral, and patient-oriented aspects of this rapidly changing discipline.

In the current management of voice disorders, the clinician now needs medical, surgical, and behavioral knowledge of the vocal mechanism and of the structures and systems that contribute to voice production. The authors discuss the importance of understanding office-based surgical treatments, medical intervention, and psychological management as part of the treatment protocols. The authors update the unique role of the speech-language pathologist and his or her relationship with the other members of the voice care team: research scientist, psychologist, surgeon, singing specialist, vocal coach, and so forth. Each of those individuals has varying roles in the care of patients with voice disorders, but it is often the speech-language pathologist who provides the leadership of the team.

There are other added features in the fourth edition, as well. New images of laryngeal pathology and a variety of cases are incorporated throughout the text. The cases are presented to elucidate the importance of proper assessment and management. Hoffman and Sapienza update the reader on new medications and their effects on the voice and on the treatment of voice disorders. The student will learn the classes of medications and their effects on the voice.

The fourth edition expands the approaches to voice therapy and better defines clinical decision making with information about humanistic communication strategies, adherence, and the multitude of variables that influence patient outcomes. The authors have chosen to categorize therapy approaches by type, such as symptomatic, combined modality, and hygienic. For each approach, they describe specific treatment methods, case examples, and expected outcomes.

It is not surprising that the management of singers has its own chapter. Both Hoffman and Sapienza are well known to the performing arts community. Their partnership in the study and treatment of performers has extended over 25 years. In the chapter on vocal performance, they describe the relationship of the voice pathologist to the singer, performer, and other professionals who care for singers. This may be the only book used by the voice rehabilitation team in which descriptions of the Alexander technique and the Feldenkrais method are found in one place. Special sections like this make this book a textbook for today's speech-language pathologist who wants to be up-to-date in treating voice disorders.

The authors have substantially updated the chapter on head and neck cancer, with new case study presentations and statistics on the disease, information on safety for the laryngectomy patient, and more images to guide the reader in understanding the various modes of communication after laryngectomy. The authors also introduce robotic surgery and include images from the operating room and video footage of several surgical procedures.

I have had the privilege of reviewing previous editions of *Voice Disorders* and share a rich professional and personal relationship with the authors. They both reflect the title of teacher–scientist–clinician and this edition punctuates that title perfectly. Since they are both teachers, they understand students' needs and have developed educational approaches to nourish those needs in the classroom as well as in the research lab and in clinical practice.

Both authors put a high level of energy into their work and this book offers a prime example. They have transformed their keen levels of observation, testing, and analysis into a book rich with their experience and knowledge.

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Preface

The human ability to produce voice, shape it into meaningful tones and sounds, and use it for so many varied purposes is truly special. Those who have the opportunity to study voice will experience teachings from many disciplines and observe outcomes both clinically and from the literature that exemplify a truly emerging relationship between knowledge and practice.

With enhancements in medical technologies and medical care, treatment plans are reaching an efficiency that optimizes vocal recovery in a favorable and timely manner. Continual education is critical to stay contemporary and abreast of new techniques and technologies and respond to the ever-changing clinical environment. You will find an increasing responsibility to collaborate and communicate with all members of the patient's health care team and a need to familiarize yourself with the ever-changing medical models. You must continue to educate yourself to keep up with the advances in technology. This need may not be due solely to a rapidity of change in your discipline, but also to the swiftness of change in other disciplines (e.g., imaging, molecular biology, surgery).

The physical, social, and spiritual issues surrounding your patients will require more skills and fluid knowledge in human anatomy and physiology, neuroanatomy and physiology, instrumentation, computer applications, and multitudes of topics surrounding medical management issues, including phonosurgical options and drug treatments. Learning how to communicate with your patient, and understanding marriage and family systems and the dynamics of variables such as race, gender identity, and religion, will be some of the more intricate complexities surrounding your patient's care. Sometimes, the changes to which we, as clinicians, must adapt to are sweeping and sometimes they occur slowly over time.

In writing this textbook we wanted you, the student, to have access to contemporary information that could be easily read. We took pride in developing the original anatomical figures for the text so they would portray the structures precisely. Additionally, we wanted to give you the opportunity to have laryngeal examinations of vocal pathology for your reference, including the opportunity to view phonosurgical procedures and outcomes. In short, we wrote the book in a manner that would enable you and your instructor to have the best resources in one source.

This fourth edition of *Voice Disorders* is written so that you, the student, can comprehend complex material by using sidebars for complex terms, providing a comprehensive glossary of terms and case examples throughout the chapters, such as those found in the vocal pathologies and voice therapy chapter, the chapter on singer's voice, and the comprehensive chapter on head and neck cancer. With updated statistics on the demographics of voice users, this new edition now helps you learn the clinical pathways that lead to the most efficient, cost-effective outcomes. The pathophysiology of disease is thoroughly explained, helping to guide you on choices for best treatment outcomes. By clearly documenting the important anatomical and physiological properties of voice, you can determine the best course of treatment action, and the case examples, with accompanying audio samples, will help you identify and practice your assessment skills. Two newly distinct chapters are now included on laryngeal reflexive behavior and the immune system. And, while these chapters contain high-level information, the material is a treasure of knowledge synthesized for your level of learning. Finally, we have updated our information for web sources and all additional resources.

Cherish your time to learn. The care of the voice has already evolved from a traditionally behaviorally oriented discipline to one that has responsibilities within the medical domain. For example, the role of the voice pathologist has broadened and includes vocal imaging specialist, researcher, therapist guiding recovery and restoration of healthy voice, trainer guiding effective voice use, counselor, and more. Our field has developed ad hoc position statements, such as *The Role of the Speech-Language Pathologist and Teacher of Singing in the Remediation of Singers With Voice Disorders* (1992). We have guidelines for training in endoscopy and laryngostroboscopy and guidelines for the role of the speech-language pathologist (2001), with respect to the evaluation and treatment of tracheoesophageal fistualization/puncture and prosthesis (2004). These position statements indicate that a certain level of skill must be obtained prior to administering particular assessment and treatment techniques.

Specific to the assessment and treatment of voice, we find ourselves challenged with cases involving syndromic complexities and are asked to delve into histories involving multiple disease processes or polypharmacies. Also, the reorganization of the health care industry has created an extensive array of changes in the organization, ownership, and regulation of health care providers and in the delivery of services. Cost concerns, increasing competition, influence of investor priorities, technological advances, changing social attitudes, and an aging and increasingly diverse population are factors that sustain this dynamic condition.

There is a requirement to objectively document the outcomes of specific treatments to provide hard evidence that can be analyzed, based on data, studied, and modeled. Not all aspects of physiology can be seen. And, while technology is racing forward in the field of laryngeal imaging, subsystem processes that create, for example, the air pressure and airflow for voice are often equally important to examine. At the same time, overcollection of data is not a wise way to spend time with a patient. Most of you have probably heard the saying "if it walks like a duck, quacks like a duck—it's a duck." The bottom line is: If the collection of more data is not going to alter the treatment plan, then do not subject the patient to unnecessary procedures.

Since 1998, there have been significant advances in the following areas of medicine, all of which have impact on the care of the voice:

- pharmacogenomics
- brain damage and spinal cord injury
- cancer therapy and viruses
- antibiotics and resistant infections
- autoimmune disease
- slowing of the aging process

Within our discipline, technological advances include functional magnetic resonance imaging, high-speed video image analysis, computer-assisted biofeedback techniques, advanced animal modeling techniques, enhanced surgical procedures, and many others. It wasn't long ago that we witnessed the first laryngeal transplant performed at the Cleveland Clinic in 1999 by Dr. Marshall Strome and his team of physicians.

To appreciate such groundbreaking events, we need to acknowledge the fact that advances in the core science of our discipline are being made nationally and internationally at facilities dedicated to the advancement of science and medical practice. Recall one area of voice research that began in Groningen, Netherlands, at the Institute of Physiology of the Faculty of Medicine by Van den Berg in the late 1940s. His fundamental article on the myoelastic-aerodynamic theory of voice production in 1958 forever shaped our perceptions on the function of the vocal folds. The contributors referenced in this book, as well as all of our contemporary colleagues dedicated to the study of voice, are included in historical lists of contributors to voice, voice care, and voice science.

We hope this book serves you well in your graduate coursework in voice disorder. We believe it provides the core information needed for your training. For those practicing in the area of voice and its disorders, we currently expect the following academic preparation: understanding of the normal and physiologic process of voice production; understanding of the etiological bases of voice disorders; the ability to examine and interpret laryngeal structure and function; understanding of the instrumentation used to examine laryngeal structure and function; understanding of the principles of diagnosis; understanding of the structural and functional differences across the life span; the ability to assist in differentially diagnosing the disorder and classifying it as structural, functional, idiopathic or neurological; the ability to develop a treatment plan that considers the patient's func-tional outcome goals; and others.

Additional courses we recommend include: issues surrounding continuum of care; interdisciplinary approaches; pharmacology; medical terminology; patient advocacy; and accreditations. This is not an inclusive list but one that suggests that our literature, as well as academic coursework, must accommodate our needs more fully.

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"Do not follow where the path may lead. Go, instead,
where there is no path and leave a trail."
—Ralph Waldo Emerson

Dr. Christine Sapienza

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Dr. Bari Hoffman

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Multimedia

Purchase of Voice Disorders, Fourth Edition comes with complimentary access to videos, which can be accessed at the end of this book.

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CHAPTER 1

Respiratory Anatomy and Physiology

This chapter describes intricacies of the human anatomy of the respiratory system and explains how it functions to produce voice. Anatomy is the study of structures and physiology is the study of how structures function to produce a particular action. In the case of voice production, respiratory structures play a very important role by providing the necessary driving force to initiate and sustain vocal fold vibration.

Breathing appears to be a relatively simple process—seemingly automatic and unconscious. Yet, it is highly controlled and complex. And, breathing for voice production is a unique process—different from the act of ventilation or circulation for the life purpose of exchanging O_2 and CO_2. Anatomically, the most basic elements of the respiratory system are the lungs, rib cage, and diaphragm and abdominal unit.

After reading this chapter, you will:

- Understand the basic components of respiratory anatomy
- Understand the passive and active forces involved in breathing
- Understand the role of the respiratory system for producing voice
- Understand how disordered respiratory function may affect voice production

> *Ventilation* means bringing oxygen into the lungs. *Circulation* is the transportation of oxygen all over the body, to where it is needed.

The Lungs

The lungs are elastic tissue that inflate and deflate and, as a result of the inflation and deflation, move air. Anatomically, there are three lobes on the right lung and two lobes on the left lung. The right lung is larger than the left lung to make room for the heart (Figure 1–1).

Inspiration is the act of taking air into the lungs and *expiration* is the act of expelling air out of the lungs. By bringing air into the lungs during inspiration, oxygen can be circulated into the bloodstream to the cells in the body. Expiration allows for the release of CO_2.

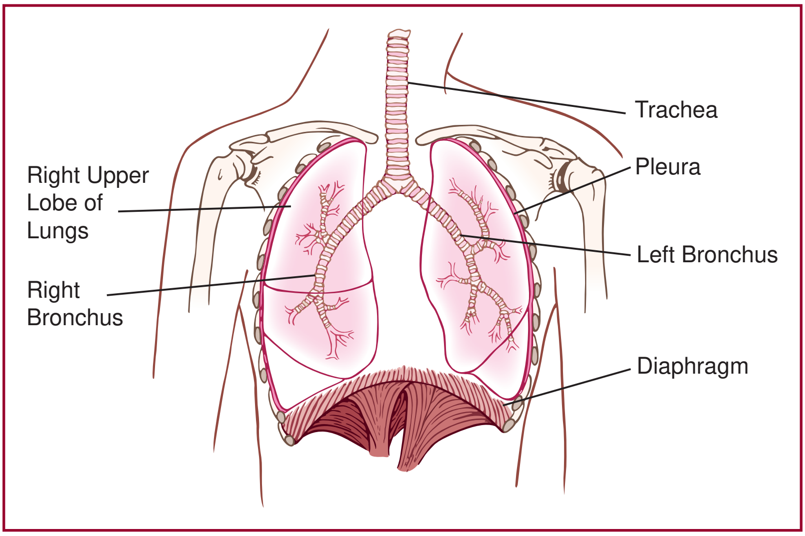

Figure 1–1. Lower airway and right and left lungs.

For airflow to increase, a greater pressure differential must be created.

In a clinical report you may see the term, *hypercapnia*, which is when excessive carbon dioxide in the bloodstream occurs, typically caused by inadequate respiration.

The Trachea

The trachea is a cartilaginous structure that allows air to pass from the nose and mouth into the lungs. It is made up of 16 cartilaginous rings. The larynx sits on top of the uppermost tracheal ring. Damage to the trachea is potentially life threatening. In the event the trachea is damaged, a tube is placed into the airway to allow air to flow into the lungs. This is called *intubation*. Intubation may be necessary due to injury or illness, or during a surgical procedure where the muscles of respiration are paralyzed and ventilation requires support.

The Bronchi

There are two main bronchi that branch off the trachea, one going to each lung. Smaller branches from the bronchi continue to divide, known as *secondary bronchi*. There are three secondary bronchi supplying the right lung and two secondary bronchi supplying the left lung. *Bronchioles* are the smallest branches stemming from the secondary bronchi and lead to the alveoli, where gas exchange occurs, allowing air to enter into the blood. The cartilage and mucous membrane of the primary bronchi are similar to that in the trachea. The amount of hyaline cartilage in the bronchial walls decreases as the branching continues throughout the bronchial tree. Hyaline cartilage is absent in the smallest bronchioles (Figure 1–2).

Hyaline cartilage forms most of the fetal skeleton and is found in the trachea, larynx (see Chapter 2), and joint surfaces of the adult.

The Thorax

The thorax is the chest cavity that surrounds and protects the lungs, as well as the heart and other respiratory structures, such as the bronchial tree. Made up of the ribs and muscles, the most inferior aspect of the thorax is the diaphragm.

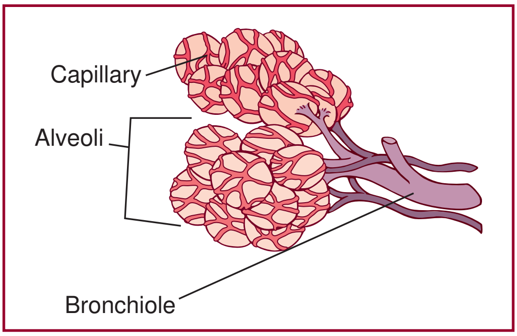

Figure 1–2. Final branches of the respiratory tree where primary gas exchange occurs.

The Ribs

There are 12 pairs of ribs. Ribs 1 to 7 are called the *true ribs* and ribs 8 to 10 are called the *false ribs*. Ribs 11 and 12 are called *floating ribs* because they do not attach to the sternum like ribs 1 to 10.

The Diaphragm

The diaphragm anatomically separates the chest from the abdomen. It is the major muscle of inspiration (Figures 1–3 and 1–4). At rest, the diaphragm sits in a dome-shaped position, and when it contracts during inspiration, it

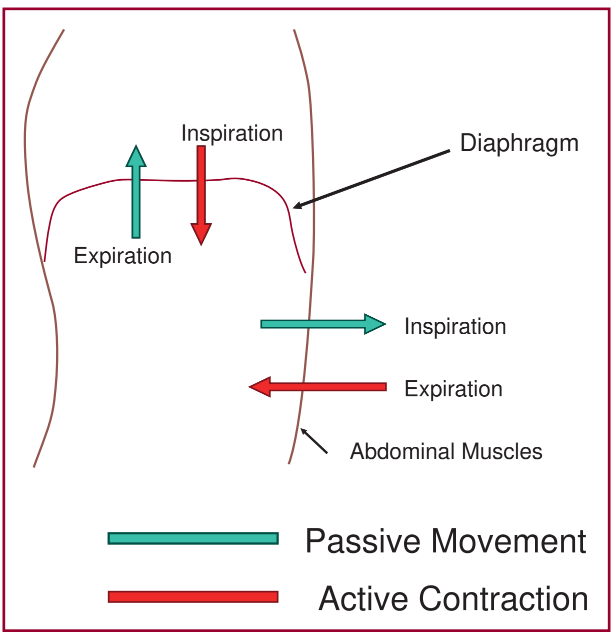

Figure 1–3. Direction of thoracic cavity movement with inspiration and expiration.

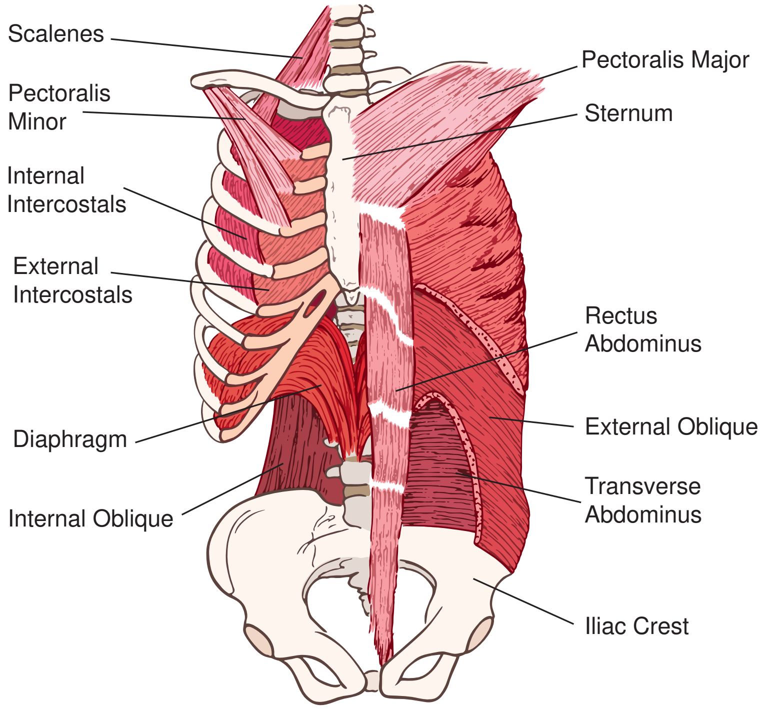

Figure 1–4. The diaphragm muscle and the supporting abdominal muscle structures.

moves downward and flattens, enlarging the chest cavity. As the diaphragm moves downward, the force is transferred to the lower ribs, moving them outward. As the diaphragm contracts, it is opposed by the passive properties of the abdominal wall, the tone of its muscles, and the inertia of the abdominal contents. When this occurs, the intra-abdominal pressure rises and the lower rib cage expands (Goldman, Rose, Morgan, & Denison, 1986). This, in turn, enlarges the thoracic dimension, creating an inspiratory maneuver.

When the diaphragm contracts during normal breathing, it moves down about 1 to 2 cm and, interestingly, can move as much as 10 cm during deep inspiration.

The Abdominal Wall

The abdominal wall is a layered structure with external, internal, and innermost regions. Made up of central and lateral muscles that arise from the ribs and the pelvic girdle, the abdominal wall has passive and active properties that are described in more detail below. During passive expiration, the abdominal wall draws in, and during effortful tasks such as coughing, sneezing, and certain voicing tasks, the abdominal muscles contract to compress the abdominal contents. This, in turn, increases the intra-abdominal pressures. This compression is also important for other functions such as defecation and childbirth. The next section describes other important anatomical structures to the respiratory system.

Sternum

The sternum has three processes that serve as attachments for respiratory muscles such as the diaphragm and intercostal muscles. The three processes include the manubrium, body, and xiphoid process.

The first seven ribs are attached to the sternum. The manubrium appears as a handle and serves as an attachment for ribs 1 and 2; the corpus is the body of the sternum and serves as the attachment for ribs 2 to 7; and the xiphoid process is the smallest of the three parts and serves as a partial attachment for many muscles, including some of the abdominal wall muscles.

When giving CPR, pressure on the xiphoid process should be avoided as it can cause a piece of the xiphoid process to break off, creating potential damage to the heart lining and muscle and/or resulting in punctures or lacerations of the diaphragm.

Clavicle

The clavicle is known as the *collarbone*, and the two bones of the clavicle extend from the manubrium. The clavicle serves for attachment of certain respiratory muscles such as the trapezius, pectoralis major, and sternocleidomastoid.

Driving Forces of the Respiratory System

The process of moving air requires a driving force. The force comes from a pressure gradient or difference between the alveolar pressure and the atmospheric pressure (Figures 1–5 and 1–6). *Alveolar pressure* is the pressure within the alveoli.

Alveolar pressure is the smallest gas exchange unit of the lung and is about 105 mm Hg or 142.8 cm H_2O.

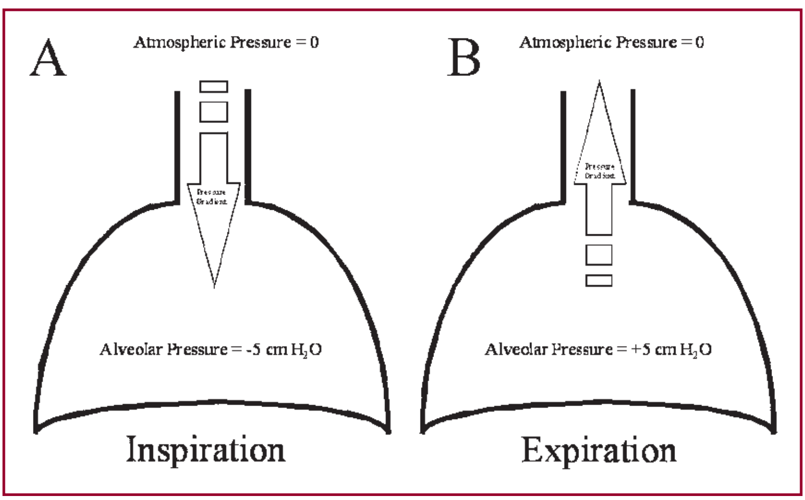

Figure 1–5. Schematic depicting pressure relationships for inspiration and expiration. The arrow indicates the direction of the driving force.

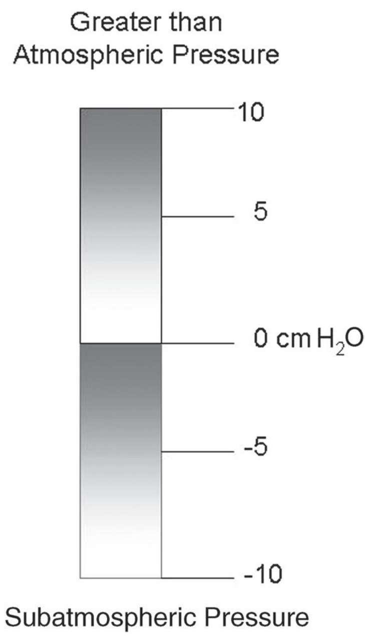

Figure 1–6. Schematic depicting positive pressure and negative pressure generation relative to atmospheric pressure (0 cm H_2O).

> Alveolar pressure is typically referenced with respect to atmospheric pressure, which is always set to zero. When alveolar pressure is above atmospheric pressure, it is positive; when alveolar pressure is below atmospheric pressure, it is negative.

For the lungs to inflate, the inward driving force must be an alveolar pressure less than atmospheric pressure. This creates a pressure gradient that causes air to flow into the lung (inspiration). On the other hand, for air to flow out of the lung (expiration), the driving force must be an alveolar pressure greater than atmospheric pressure. The pressure of a gas equals the perpendicular force exerted by the gas divided by the surface area on which the force is exerted.

To produce voice, air moves from the alveolar spaces through the conducting airways, including the trachea; through the glottis, or the space between the vocal folds; and vibrates the medial edges of the vocal folds. Sound from the vocal folds is then transferred to the pharynx and oral cavity, where it is shaped by the articulators into speech sounds. Discussion of how the voice is produced by vocal fold vibration is discussed in Chapter 2.

How Does the Human Body Generate These Respiratory Forces?

The alveolar pressure is changed by two forces. The first, a passive force, is due to the elastic properties of the respiratory system. The second force, an active force, is developed by the contraction of the respiratory muscles. One example that is often used to illustrate and explain the passive and active forces of the respiratory system is a balloon, as it helps explain the concepts of respiratory forces (Figure 1–7). Inflation of a balloon requires an active stretching of the balloon. This illustration shows how inspiratory muscles contract to expand the chest wall. It takes active muscle force to overcome the balloon stiffness and force air into the balloon. This increases the balloon's volume, just as the lungs increase in volume, creating a pressure gradient that allows air to flow into the balloon/lungs. With the balloon inflated and the opening to the balloon closed, the balloon retracts toward its rest position and produces a pressure inside the balloon causing the air inside the balloon to compress. This is an elastic force, which is an inherent property of the balloon, just like the lungs (see Figure 1–7). The strength of the elastic force is a passive property of the balloon/lungs and is directly proportional to the stretch of the balloon/lungs. The greater the balloon/lung volume (i.e., the greater the stretch of the balloon/lung wall), the greater the elastic recoil of the balloon/lung and the

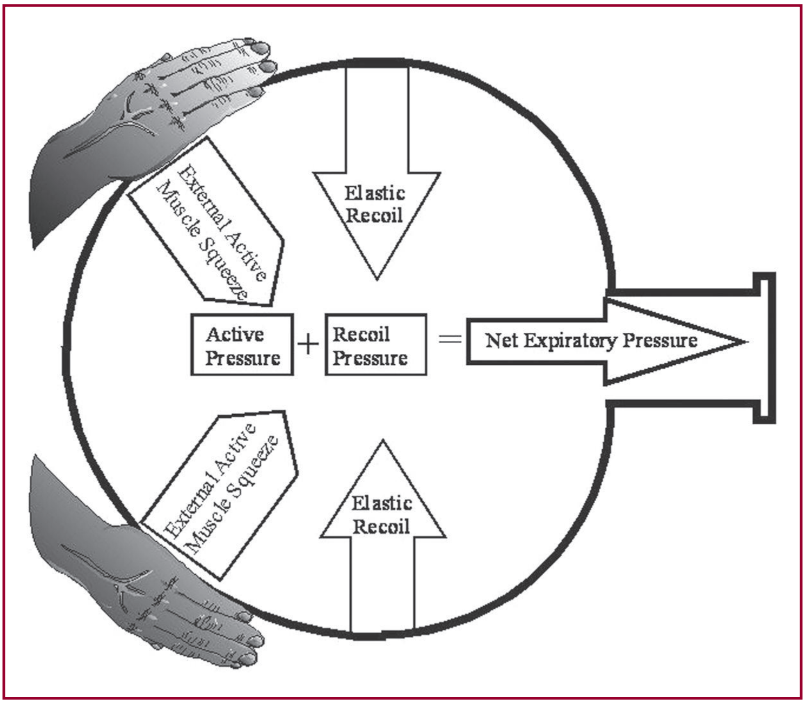

Figure 1–7. Schematic of a balloon depicting active and passive mechanisms during expiration. The hands squeezing the balloon illustrate the addition of an active expiratory force.

greater the pressure inside the balloon/lung. The pressure inside the balloon/lung can be further increased if the outside of the balloon/lung is squeezed (see Figure 1–7). This squeeze is the result of the active contraction of expiratory muscles and is referred to as an *active pressure*. The total pressure within the balloon/lung is then the sum of the passive elastic pressure and the active squeeze pressure.

When the respiratory system is at rest, the lung is partially inflated to approximately 40% of the total lung capacity (TLC). This is important to remember because the lungs are actually not deflated at rest but rather are partially inflated. This rest position is called the functional residual capacity or FRC (Figure 1–8). At FRC, neither the lung nor the thorax is really at its respective rest position. With age, the lungs may lose some of their elasticity.

The lungs are apposed (or connected) to the thorax by pleural linkage. In fact, three-quarters of the lung's surface contacts the thoracic wall by pleural linkage. With a pneumothorax, a lung immediately collapses, but the thorax expands. A pneumothorax occurs when the pleural space is disrupted.

A pneumothorax can happen with a blast injury, as a result of a fractured rib, and sometimes with diseases such as cystic fibrosis and chronic obstructive pulmonary disease.

When a pneumothorax occurs, the lungs and thorax achieve a natural position, which is the natural preference if they were anatomically independent from one another.

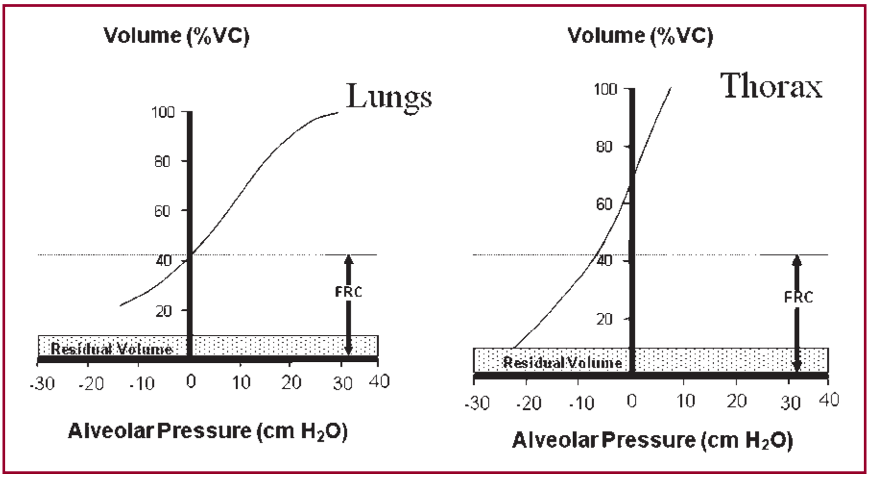

Figure 1–8. Pressure-volume curves for lungs and thorax.

The lungs' natural position is a volume much smaller than FRC. That is why the lungs have a natural tendency to collapse. The thorax's natural position is a volume much greater than FRC—approximately 70% of TLC—which means the thorax has a natural tendency to expand at FRC (see Figure 1–8).

When the lung is placed in the thorax, the outer surface of the lung is apposed to the inner surface of the thorax by the pleural linkage mentioned above. The pleural linkage is actually a hydrostatic force. A membrane called the *visceral pleura* covers the lung. A similar membrane called the *parietal pleura* covers the thorax. A small amount of fluid, the *pleural fluid*, separates these membranes. If you were to place two smooth surfaces against each other with fluid between them, like two microscope slides with water between them, you would see how easily they move back and forth but how very hard they are to pull apart. This is the hydrostatic force holding the two smooth surfaces together yet allowing free movement between the surfaces. In the respiratory system, the pleural fluid between the visceral and parietal pleurae holds the lung against the thoracic wall while allowing the lung to slide freely during volume changes. However, mechanically linking the lung and thorax means that the combined systems' elastic behavior is a result of the interaction of the lungs' and thoracic elastic forces. As stated above, this causes the lung to be at a volume that is above its elastic natural position, yielding a collapsing force. The thorax is at a volume smaller than its elastic natural position, yielding an expanding force. At FRC, the expanding elastic force of the thorax balances the collapsing elastic force of the lung.

Passive and Active Forces of the Respiratory System

Active inspiration is a muscle action that increases the dimensions of the chest wall. A portion of the inspiratory muscle energy used to expand the thorax is recaptured by the passive collapsing force of the elastic recoil pressure that is volume dependent. This is the passive property of expiration. Remember, the act of inspiration is always active. This means that for inspiration to occur, muscle contraction must happen. Mentioned briefly above, and of such importance to remember, is that the diaphragm is the main muscle of inspiration. The diaphragm is a large sheet of muscle and tendons. It attaches to the lumbar vertebrae of the spinal column, the lower ribs (ribs 7–12), and the xiphoid process of the sternum. The cervical nerves of the spinal cord called C3, C4, and C5, also known as the *phrenic nerves*, supply innervation to the diaphragm.

> A saying goes "C3, C4, C5, keeps you alive" . . . but there is now evidence that bilateral loss of the phrenic nerve might not necessarily result in death.

> Did you know that a hiccup is caused by a spasmodic, involuntary contraction of the diaphragm?

The external intercostal muscles are the other primary muscles of inspiration and are found between the ribs. The external intercostal muscles slant downward and outward, and their diagonal position allows them to do more work upon their contraction. Due to their hinged anatomical relationship at the spine and sternum, when they contract, they lift the ribs up and outward (Figure 1–9). Other secondary inspiratory muscles are listed in Table 1–1. Accessory muscles of inspiration are only most active with high ventilatory tasks (e.g., deep inspiration) and are not used during quiet inspiration.

Active expiratory pressure can be added to the passive, elastic expiratory driving force by generating muscle contraction that decreases the chest wall dimension. The decrease in chest wall dimension can happen by pulling

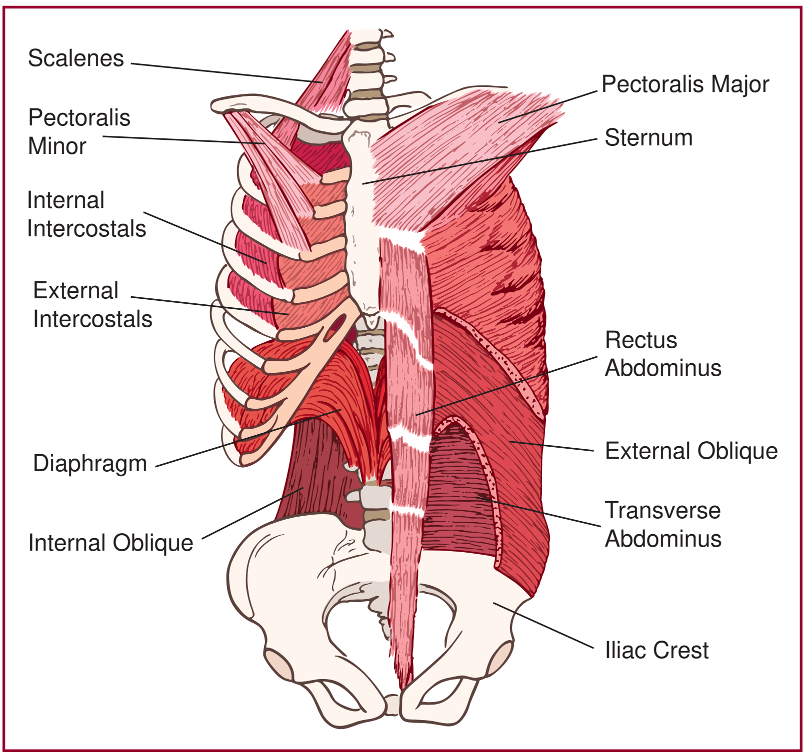

Figure 1–9. External and internal intercostal muscles, and abdominal wall muscles.

Table 1–1. Accessory Inspiratory Muscles and Their Origins and Insertions and Major Expiratory Muscles and Their Origins and Insertions

Muscle	*Function*	*Origin*	*Insertion*
Levatores costarum	Accessory Inspiratory	Transverse processes of C7 to T12 vertebrae	Superior surfaces of the ribs immediately inferior to the preceding vertebrae
Serratus posterior superior	Accessory Inspiratory	The spinous processes of C7 through T3	The upper borders of the 2nd through 5th ribs
Sternocleido-mastoid	Accessory Inspiratory	Manubrium and medial portion of the clavicle	Mastoid process of the temporal bone
Scalenus	Accessory Inspiratory	C2–C7 vertebrae	The first and second ribs
Trapezius	Accessory Inspiratory	The spinous processes of the vertebrae C7–T12	At the shoulders, into the lateral third of the clavicle, and into the spine of the scapula
Pectoralis major	Accessory Inspiratory	The anterior surface of the clavicle; the anterior surface of the sternum, as low down as the attachment of the cartilage of the 6th or 7th rib	The crest of the greater tubercle of the humerus
Pectoralis minor	Accessory Inspiratory	3rd to 5th ribs, near their costal cartilages	The medial border and upper surface of the scapula
Serratus anterior	Accessory Inspiratory	The surface of the upper eight ribs	The entire anterior length of the medial border of the scapula
Subclavius	Accessory Inspiratory	Arises by a short, thick tendon from the first rib and its cartilage at their junction, in front of the costoclavicular ligament	The groove on the under surface of the clavicle
Levator scapulae	Accessory Inspiratory	Arises by tendinous slips from the transverse processes of the atlas and axis and from the posterior tubercles of the transverse processes of the 3rd and 4th cervical vertebrae	The vertebral border of the scapula
Rhomboideus major	Accessory Inspiratory	The spinous processes of T2 to T5	The medial border of the scapula
Rhomboideus minor	Accessory Inspiratory	The spinous processes of C7 and T1	The vertebral border near the point that it meets the spine of the scapula

Table 1–1. *continued*

Muscle	Function	Origin	Insertion
Transversus thoracis	Accessory Inspiratory	The posterior surface of the body of the sternum, from the posterior surface of the xiphoid process, and from the sternal ends of the costal cartilages of the lower 3 or 4 true ribs	The lower borders and inner surfaces of the costal cartilages of ribs 2–6
Quadratus lumborum	Accessory Inspiratory	Arises by aponeurotic fibers from the iliolumbar ligament and the adjacent portion of the iliac crest	The lower border of the last rib for about half its length, and the apices of the transverse processes of the upper 4 lumbar vertebrae
Subcostal	Accessory Inspiratory	The inner surface of one rib	The inner surface of the 2nd or 3rd rib above, near its angle
Serratus posterior	Accessory Inspiratory	The spinous processes of T11 and T12 and L1–L3	The inferior borders of the lower 4 ribs, a little beyond their angles
Latissimus dorsi	Accessory Inspiratory	The spinous processes of T6–T12, iliac crest, and inferior 3 or 4 ribs	The humerus
Internal oblique abdominis	Expiratory	Inguinal ligament, iliac crest, and the lumbodorsal fascia	Linea alba, xiphoid process, and the inferior ribs
External oblique abdominis	Expiratory	Lower 8 ribs	Crista iliaca, ligamentum inguinale
Rectus abdominis	Expiratory	Pubis	Costal cartilage of ribs 5–7, xiphoid process of sternum

the ribs downward. The ribs are attached at the costochondral joint of the thoracic vertebrae and the sternum or costal arch. The arch of the ribs is oriented downward. Pulling the ribs up produces a "bucket handle" effect (Figure 1–10) and increases the diameter of the upper chamber. Pulling the ribs down similarly decreases the diameter of the upper chamber. Any muscle that acts to pull the ribs down will assist in producing an active expiratory driving force. Keep in mind that the active expiratory driving force is like squeezing a balloon from the outside, and the force of the squeeze generates a pressure that adds to the passive, elastic recoil pressure.

The muscles that produce this squeezing pressure are usually identified as the *internal intercostal muscles* and *abdominal muscles*. The internal intercostal muscles attach to the inner, lower margin of the cranial rib and the inner, upper margin of the adjacent caudal rib.

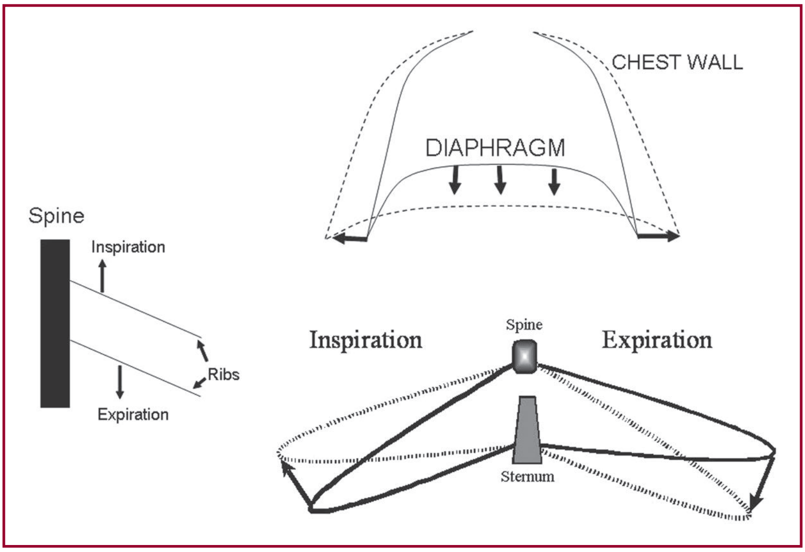

Figure 1–10. Schematic representation of the motion of the diaphragm and ribs during respiratory muscle contraction. The diaphragm contracts and flattens, producing an upward pulling force on the ribs and an outward distending force on the abdomen. The intercostal muscles assist the upward pulling force on the ribs during inspiration and downward pulling force on the ribs during expiration. The bucket-handle nature of the parasternal ribs is illustrated with the ends attached to a vertebra and the sternum. Inspiratory muscles pull the rib up and increase the thoracic diameter. Expiratory muscles pull the rib down and decrease the thoracic diameter.

Cranial means toward the head of the body. *Caudal* means toward the posterior end of the body.

The fibers are oriented ventrodorsally. When turned on during active breathing efforts, the internal intercostal muscles contract in synchrony with expiratory airflow. Contraction of these muscles decreases the intercostal space and pulls the ribs down.

The abdominal muscles include the rectus abdominis, external abdominal oblique, internal abdominal oblique, and transversus abdominis (see Figure 1–9). The rectus abdominis is attached to the lower margin of the sternum and the lower edge of the lower parasternal ribs, a few centimeters lateral to the sternum. The caudal attachment is ventral (i.e., pertaining to the front) to the pelvic girdle. The internal and external abdominal oblique muscles attach cranially to the caudal edge of the costal ribs. The caudal attachment is the rectus abdominis and the pelvic girdle. The external abdominal oblique fibers are oriented from a cranial to caudal direction, in a dorsoventral angle. The internal abdominal oblique fibers are oriented cranial to caudal in a ventrodorsal angle.

The transversus abdominis fibers are oriented circumferentially (i.e., forming a circumference) between the rectus abdominis and the spine. The action of the rectus abdominis is to stabilize the ventral midline and stiffen the ventral abdominal midline. The external abdominal oblique, internal abdominal oblique, and transversus abdominis act to decrease the diameter of the abdomen and pull the costal ribs down. This increases the abdominal pressure and forces the abdominal contents upward, providing the force that drives the piston action of the diaphragm up into the thorax.

Any muscle group that attaches to the rib cage with a fiber orientation acts to pull the ribs downward or to compress the abdomen in an expiratory direction. The longissimus dorsi, iliocostalis dorsi, iliocostalis lumborum, and serratus posterior inferior muscles in the dorsal side of the back attach to the lower margin of the ribs with the pelvic girdle spine. Portions of the quadratus lumborum on the ventral side of the spine attach the caudal border of the last rib with the pelvic girdle. These muscles are found on the dorsal and ventral sides of the spine. Their orientation provides a downward pull of the ribs, decreasing the diameter of the thorax. The dorsal muscles are also in a position to stabilize the spine during strong ventral contraction of the ventral abdominal muscles, preventing a forward-bending action from rectus abdominis contraction. Thus, an erect posture is important in the action of these muscles, assisting in the generation of an active compression of the thorax producing the active expiratory pressure.

In summary, the act of breathing on the generation of alveolar pressure is an inspiratory action caused by the contraction of the diaphragm and external intercostal muscles to increase the lung volume. The active, expiratory pressure driving force is the coordinated action of a variety of muscles that decrease the diameter of the thorax and compress the abdomen. Compressing the abdomen increases abdominal pressure, thereby providing the driving force for the piston action, which then stretches the relaxed diaphragm.

The Respiratory System and Voice Production

Adequate control of lung volume and respiratory muscle activity during expiration is crucial for the regulation of subglottal pressure (Hixon, Goldman, & Mead, 1973). The subglottal pressure controls a variety of parameters related to voice production such as airflow, glottal area, fundamental frequency (i.e., the pitch of the sound), and sound pressure level (i.e., the loudness of the sound). *Subglottal pressure* is the driving force for the initiation of vocal fold vibration. As stated above, both active and passive forces regulate the main alveolar pressure, and in turn a certain percentage of the generated alveolar pressure is used for voice production.

Alveolar pressure is the pressure within the alveoli of the lungs. Subglottal pressure is the pressure directly below the vocal folds that is used to dynamically move the vocal folds by airflow.

Intraoral pressure is air pressure measured within the mouth.

Subglottal pressure is the pressure measured below the vocal folds.

Alveolar pressure is air pressure measured at the level of the alveolus in the lungs.

Vital capacity (VC) is the greatest volume of air that can be expelled from the lungs after taking a maximal inspiration. It is equal to the sum of inspiratory reserve volume, tidal volume, and expiratory reserve volume.

Relaxation Pressure Curve

The clinician can use an image of the relaxation pressure curve to educate a patient about the respiratory mechanisms used to produce voice/speech and to explain what parts of voice/speech are active and passive during its production. Of course, the concepts of passive and active properties of the respiratory system described above must be simplified for the patient. Having a clear understanding of the respiratory mechanisms used to develop pressure for voice production can help the clinician determine if a particular breathing technique used with a patient should or should not be applied in voice therapy. Figure 1–8 is a depiction of a relaxation pressure curve produced along the lung volume continuum of 0% lung volume to TLC (100%). The relaxation pressure curve is presented here again to explain the types of forces generated by the respiratory system.

At each percentage of lung volume, there is a pressure generated by the inherent recoil forces of the lung, thorax, and abdominal or diaphragm unit. As noted earlier, Figure 1–8 illustrates that lung volumes between 45% and 60% VC produce pressures between 5 and 10 cm H_2O. At these lung volumes, the inspiratory and/or or expiratory muscle force to produce voice is minimal. Work, for the purpose of this description, is the recruitment of muscular forces used to depart from the relaxation pressure. By recruiting muscular effort, higher pressures can be generated; this may be necessary to meet the demands of certain voicing or speech tasks.

When a higher lung volume is approached, as indicated by Figure 1–8, at about 80% VC, an active inspiratory muscle force must be produced to combat the high recoil forces generated by the lung–thorax unit. At volumes as high as 80%, the tendency to recoil to those resting volumes is very high. To resist the high recoil force, inspiratory muscles must be recruited in a "checking-like fashion" (Hixon, 1987). At very low lung volumes, on the order of 20% VC, it is apparent from Figure 1–8 that there is not enough pressure to meet the demands required for comfortable effort voice/speech production.

The pressure needed to produce comfortable-level voice production is between 4 and 5 cm H_2O and, as the patient's vocal loudness increases, the subglottal pressure increases. At 20% TLC, on Figure 1–8, the relaxation pressure is negative. To create a positive pressure for voice, recruitment of abdominal musculature is necessary to decrease the volume within the chest wall. A pistonlike force is generated, increasing the pressure needed to meet the demands of the voice or speech task. The fact that abdominal muscles must be turned on for voice or speech to occur at very low lung volumes means the mechanism of action is active (i.e., muscle contraction). This active mechanism, from the clinician or patient perspective, is work.

A clinician's ability to interpret the relaxation pressure diagram helps in providing appropriate recommendations to the voice patient. For example, having your patient take big breaths before they start to voice does not make good physiologic sense, as they would have to recruit inspiratory muscles to resist high recoil forces. Rather, counsel the patient to take a small breath in before starting to voice and seek to determine if there are any lower or upper airway limitations that may be preventing them from utilizing the lung volumes they have created in an effective manner.

Therapeutic Considerations

There are many clinical instances where alveolar pressure cannot be produced effectively. Chronic obstructive pulmonary disease

(COPD) is one such condition. With COPD, narrowing of the upper airway occurs as a compensatory mechanism to regulate airflow and maintain lung volume during voice production. Symptoms self-reported by patients with COPD suggest both respiratory and laryngeal involvement and include dyspnea (i.e., sensation of breathlessness), reduced vocal loudness, and hoarseness. Lee, Friesen, Lambert, and Loudon (1998) developed a dyspnea questionnaire because questionnaires that are sensitive to those with lung disease are not plentiful in the voice literature. Lee et al.'s (1998) results showed that dyspnea is a relevant factor when assessing speech and voice abilities in those with lung disease, from both personal and vocational standpoints, and advocated the need for scales that are sensitive to the variable of dyspnea. The scale developed by Lee et al. (1998), although not used specifically with patients with voice disorders, could be used as a supplement to acquire information not available from other voice handicap indexes.

Cases involving spinal cord injury and neuromuscular degenerative diseases, such as multiple sclerosis, may lack normal muscle activity due to disordered neural input or control, resulting in difficulty generating high enough muscular forces to deviate from the relaxation pressure. Developing adequate subglottal pressure is critical for generating vocal loudness, varying the frequency of the voice, and sustaining the sound duration. Although the demands of speech will vary, pressure will be required to be constant regardless of the lung volume and task duration.

Some patients with voice disorders have a laryngeal condition that creates high laryngeal airway resistance. Cases such as adductor spasmodic dysphonia, muscle tension dysphonia, or other dynamic laryngeal dysfunction conditions that result in increased glottal closed time cause variable and high laryngeal airway resistance, restricting airflow (see Chapter 6). Static laryngeal conditions, on the other hand, such as laryngeal webbing, subglottal stenosis, bilateral abductor vocal fold paralysis, arytenoid joint dislocation, and others, can also result in high laryngeal airway resistance (see Chapter 5). There are other patients who present with variable, low laryngeal airway resistance. These are cases of hypofunctional voice disorders, and may include adductor vocal fold paralysis or any other condition that limits vocal fold mobility (Saarinen, Rihkanen, Malmberg, Pekkanen, & Sovijarvi, 2001). With these conditions, it is difficult to control expiratory airflow because of inadequate vocal fold movement. These patients may also complain of breathing symptoms.

Laryngeal compensation, documented by visual examination of the larynx and verified with laryngeal airway resistance measures, has been found in those with vocal nodules and adductor spasmodic dysphonia (Finnegan, Luschei, Barkmeier, & Hoffman, 1996; Plant & Hillel, 1998; Sapienza & Stathopoulos, 1994; Witsell, Weissler, Donovan, Howard, & Martinkosky, 1994). Initial research on breathing patterns in those with voice disorders comes from the work of Hixon (1987); Sapienza and Stathopoulos (1994); Sapienza, Stathopoulos, and Brown (1997); Hillman, Holmberg, Perkell, Walsh, and Vaughan (1998); and others. These studies indicate an interactive role between the shape of the glottal space and breathing behavior. Specifically, when high glottal airflows are produced during voice production, larger lung volumes are used during voicing; the voice task is ended at lower lung volumes, particularly below FRC; and there is deviant phrasing.

Dyspnea is the conscious awareness of labored breathing, or "air hunger," and occurs most commonly with heavy exercise but can occur with certain laryngeal conditions (Brunner, Friedrich, Kiesler, Chibidziura-Priesching, & Gugatschka, 2011; Shemble, Sandage, & Verdolini Abbott, 2016; West & Popkess-Vawter, 1994).

> Dyspnea is a critical symptom to understand because it is common to many pulmonary and laryngeal function disorders. However, its definition is complex and, as such, requires both psychological and physiological assessment of both the upper and lower airways.

Those with voice disorders often complain of dyspnea when they are walking or having to walk and talk simultaneously. Physiologically, the origin of dyspnea can be multifaceted, and understanding the cause of dyspnea requires assessment of both lower and upper airway function. Clinically, the speech pathologist's responsibilities when presented with patients complaining of dyspnea is twofold. The first responsibility is to make the patient aware of the importance of understanding the relationship between glottal configuration, upper airway resistance, and respiration. The second responsibility, prior to treating any breathing symptoms, and in conjunction with other medical professionals, is to rule out that the dyspnea is not related to heart disease, lung disease, or psychological state (i.e., anxiety).

Pulmonary Function Testing: Important to Make the Right Referral

Referral of a patient to a pulmonologist is recommended to help discern the cause of dyspnea. The standard pulmonary function tests that are used to help determine the origin of the dyspnea, and/or any other lower airway condition, are the forced vital capacity (FVC) maneuver, the forced expiratory volume in 1 second (FEV1) maneuver or maximum voluntary ventilation (MVV) maneuver, and the maximum inspiratory and expiratory flow-volume loop. These tests are done with spirometry. Spirometry is a common pulmonary test used to assess how well the lungs work by measuring how much air is inhaled, how much air is exhaled, and how quickly the air is exhaled. In particular, the flow-volume relationships diagnose the presence and assess the effect of large (i.e., central) airway obstruction. Characteristic patterns of the flow-volume loop also distinguish fixed from variable obstruction and extrathoracic from intrathoracic location. The speed of air movement in and out of the lungs is assessed by the flow rate. The volume measured indicates the amount of air moved.

Interpreting the Results of the Flow-Volume Loop

You may receive a clinical report that contains information of flow-volume loop data as a record of a patient's pulmonary condition. Therefore, familiarity with the major landmarks of a flow-volume loop is important for the clinical interpretation of the patient's condition.

The major landmarks of a flow-volume loop are shown in Figure 1–11. Peak expiratory flow rate (PEFR) is the first peak of air exhaled from the patient. The measure of peak flow rate can help judge if the patient is giving maximal effort, test overall strength of expiratory muscles, and determine the general condition of the large airways such as the trachea and main bronchi. Forced expiratory flow at 25% of FVC (FEF25%) is the flow rate at the 25% point of the total volume (FVC) exhaled. Assuming maximal effort from the patient during the generation of the flow-volume loop, this flow rate indicates the condition of the large to medium bronchi. Forced expiratory flow at 50% of FVC (FEF50%) is the flow rate at the 50% point of the total volume (FVC) exhaled. This landmark is at

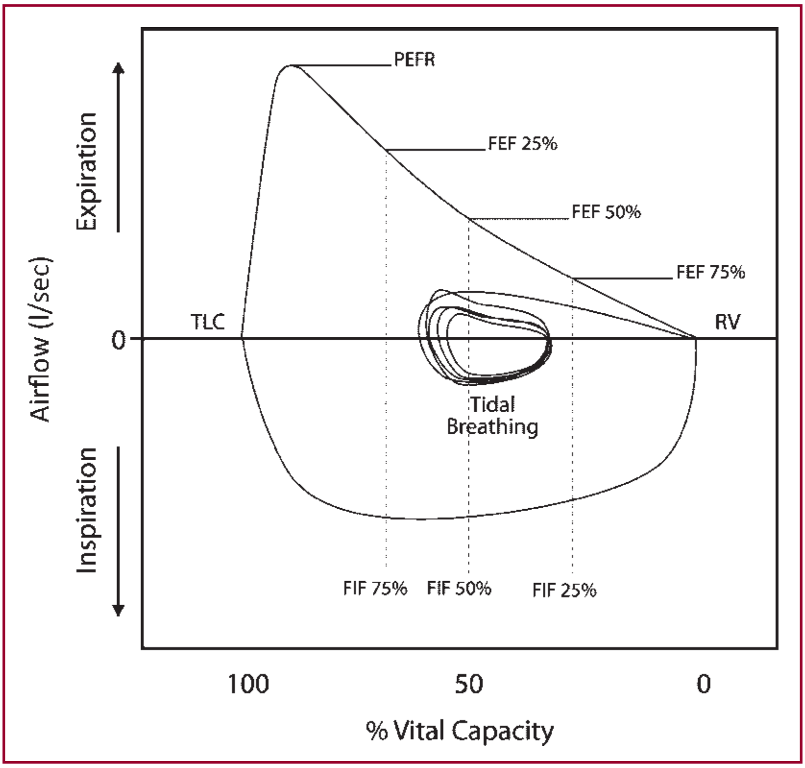

Figure 1–11. Flow-volume loop indicating major flow and volumetric landmarks during expiratory and inspiratory cycle. PEFR = peak expiratory flow rate; FEF = forced expiratory flow; RV = residual volume; FIF = forced inspiratory flow.

the midpoint of the FVC and indicates the status of the medium to small airways. Forced expiratory flow at 75% of FVC (FEF75%) is the flow rate at the 75% point of the total volume (FVC) exhaled. This landmark indicates the status of the small airways.

Forced inspiratory flow at 25% of FVC (FIF25%) is the flow rate at the 25% point of the total volume inhaled. Abnormalities here are indicators of upper airway obstructions. Areas of the mouth, upper and lower pharynx (i.e., back of the throat), and glottis impact the inspiratory flow rates. Peak inspiratory flow rate is the fastest flow rate achieved during inspiration. Forced inspiratory flow at 50% of FVC (FIF50%) is the flow rate at the 50% point of the total volume inhaled. Forced inspiratory flow at 75% of FVC is the flow rate at the 75% point of the total volume inhaled.

When a clinical report is received from a pulmonary clinic or pulmonologist, the spirometry values are typically presented in absolute numbers as well as percent predicted, based on normative values. The normative values are race, sex, and age dependent, and the standards may vary across clinical laboratories. If the spirometric data rule out lower airway disease, and the flow-volume loop data indicate upper airway obstruction, then appropriate care can focus on the remediation of the laryngeal condition and with intervention the sensation of dyspnea should diminish.

Using the Right Terminology

It is important to use the right terminology in clinical report writing. In the speech pathologist's assessment and treatment of voice disorders, many terms related to breathing have prevailed in the literature. These terms include *support*, *diaphragmatic breathing*, *clavicular breathing*, *circular breathing*, *breathing exercises*, and others. Use of the term support can be vague, and often, when used in clinical report writing, does not tell much about the physiologic status of the respiratory system. When the term support is used, it likely relates to the physiologic driving force (i.e., pressure) for voicing. As such, using the term *pressure* is definitive and physiologically more correct then the term support or *breath support*.

Likewise, the term diaphragmatic breathing, particularly when referring to voice production, is a bit of a misnomer, given that the diaphragm is a muscle of inspiration. Consequently, it doesn't make much physiologic sense to use this term when directing instruction of expiration to the patient. If the term is used to indicate the pistonlike mechanism of the abdominal wall, then the term should be changed to *abdominal force*, thus making more physiologic sense with regard to the discussion of mechanics of breathing. Similarly, the term clavicular breathing should only be used when a patient breathes by raising the pectoral area of the chest wall and shoulders. The term, clavicular breathing, has now become overused to identify patients with presumed poor breath support. And, in fact, many times it is used to classify the way women breathe. Commonly, the term clavicular breathing is inaccurately used since those who have healthy respiratory structure and function of the chest wall do not use a less efficient system of breathing, such as clavicular breathing, voluntarily or reflexively. For those with solely laryngeal conditions, and intact respiratory muscle tone, clavicular breathing is unlikely. In fact, the human body likes to work less, not more, per any given task. So, unless completely exhausted, patients who have voice disorders, and who have no neurologic impairment or lower airway disease, are unlikely to be clavicular breathers. Use of the term clavicular breathing should be cautiously employed to describe only those to whom it really applies. Finally, there is a breathing type called circular breathing, and it is associated with musicians (i.e., saxophonists). Difficult to achieve, the process starts with a half-full lung. The mouth is then supposedly filled with an air pocket, while still breathing out from the lungs. The person then switches from lung to mouth air with no interruption, and forces air out from the mouth with the cheeks. The person then switches back to the now-full lungs and repeats the process.

In the behavioral treatment of voice disorders, we often come across the term *breathing exercises*. This is again a broad categorical phrase covering a spectrum of exercises from relaxation to yoga methods. Many of these exercises have merit, particularly those that focus on teaching coordination of inspiration and expiration, postural alignment, and use of the abdomen to help produce pressure for speech. However, there are some exercises that do not offer specific physiologic guidelines. For example, within some promoted exercise programs, there have been regimens that place people on their back to facilitate better breathing or relaxation. Hoit (1995) examined how breathing differs in the upright and supine positions, and discussed in detail the clinical implications with the different postures when treating patients with voice disorders. It is our responsibility to realize which factors are being manipulated during these breathing exercises and which are valid to use with patients that have voice disorders.

Biofeedback Techniques

Finally, biofeedback techniques may help the patient monitor and control the inspiratory and expiratory cycles of breathing during voice production. *Biofeedback* is the feedback of biological information to gain control of bodily processes that normally cannot be controlled voluntarily. Electromyography (EMG) is one way to measure muscle activity through the use of strategically placed electrodes. Most commonly used because it is a noninvasive procedure, biofeedback involves placing surface electrodes on the general area of muscle that is being tested for its activity.

Theoretically, in the treatment of those with voice disorders, the clinician should have the patient monitor both perceptual and physiological processes associated with the voice disorder while implementing a particular treatment regimen that attempts to reduce hyperfunctional behaviors. Murdoch, Pitt, Theodoro, and Ward (1999) used biofeedback with the inductance plethysmography (or Respitrace) to provide real-time, continuous visual biofeedback of rib-cage circumference during breathing in a child with traumatic brain injury. Results showed very good success with the biofeedback technique when compared to traditional instructions for proper speech breathing. Murdoch and colleagues (1999) believed the visual biofeedback techniques brought about far superior outcomes when compared to traditional methods. The use of biofeedback with patients appears effective and is easily incorporated into treatment programs with a variety of patient types. Likewise, more recent literature shows application of breathing, voice, swallow, and movement therapy for patients with breathing disorders and head and neck cancer (Buchholtz, 1994; Martin-Harris et al., 2015).

Summary

The respiratory system is considered the power source for voice production and, as such, deterioration of its function can significantly impact a patient's ability to generate adequate ventilation for life purposes and, secondarily, the necessary subglottal air pressure for voice production. As such, the respiratory system is one of the most important subsystems, requiring evaluative and treatment attention in the care of the voice. The next chapter describes the sound source for voice production through the description of laryngeal anatomy and physiology.

References

Brunner, E., Friedrich, G., Kiesler, K., Chibidziura-Priesching, J., & Gugatschka, M. (2011). Subjective breathing impairment in unilateral vocal fold paralysis. *Folia Phoniatric Logopedica, 63*(3), 142–146.

Buchholtz, I. (1994). Breathing, voice and movement therapy: Applications to breathing disorders. *Biofeedback Self-Regulation*, *19*(2), 141–153.

Finnegan, E. M., Luschei, E. S., Barkmeier, J. M., & Hoffman, H. T. (1996). Sources of error in estimation of laryngeal airway resistance in persons with spasmodic dysphonia. *Journal of Speech and Hearing Research, 39*(1), 105–113.

Goldman, J. M., Rose, L. S., Morgan, M. D., & Denison, D. M. (1986). Measurement of abdominal wall compliance in normal subjects and tetraplegic patients. *Thorax, 41*(7), 513–518.

Hillman, R. E., Holmberg, E. B., Perkell, J. S., Walsh, M., & Vaughan, C. (1998). Objective assessment of vocal hyperfunction: An experimental framework and initial results. *Journal of Speech and Hearing Research*, *32*(2), 373–392.

Hixon, T. J. (1987). *Respiratory function in speech and song*. Boston, MA: College-Hill Press/Little Brown and Company.

Hixon, T. J., Goldman, M. D., & Mead, J. (1973). Kinematics of the chest wall during speech production: Volume displacement for the rib cage, abdomen and lung. *Journal of Speech and Hearing Research*, *19*, 297–356.

Hoit, J. D. (1995). Influence of body position on breathing and its implications for the evaluation and treatment of speech and voice disorders. *Journal of Voice*, *9*(4), 341–347.

Lee, L., Friesen, M., Lambert, I. R., & Loudon, R. G. (1998). Evaluation of dyspnea during physical and speech activities in patients with pulmonary diseases. *Chest*, *113*(3), 625–632.

Martin-Harris, B., McFarland, D., Hill, E. G., Strange, C. B., Focht, K. L., Wan, Z., . . . McGrattan, K. (2015). Respiratory-swallow training in patients with head and neck cancer. *Archives of Physical Medicine and Rehabilitation*, *96*(5), 885–893. doi:10.1016/j.apmr.2014.11.022

Murdoch, B. E., Pitt, G., Theodoros, D. G., & Ward, E. C. (1999). Real-time continuous visual biofeedback in the treatment of speech breathing disorders following childhood traumatic brain injury: Report of one case. *Pediatric Rehabilitation*, *3*(1), 5–20.

Plant, R. L., & Hillel, A. D. (1998). Direct measurement of subglottic pressure and laryngeal resistance in normal subjects and in spasmodic dysphonia. *Journal of Voice*, *12*(3), 300–314.

Saarinen, A., Rihkanen, H., Malmberg, L. P., Pekkanen, L., & Sovijarvi, A. R. (2001). Disturbances in airflow dynamics and tracheal sounds during forced and quiet breathing in subjects with unilateral vocal fold paralysis. *Clinical Physiology*, *21*(6), 712–717.

Sapienza, C. M., & Stathopoulos, E. T. (1994). Respiratory and laryngeal measures of children during vocal intensity variation. *Journal of the Acoustical Society of America*, *94*(5), 2531–2543.

Sapienza, C. M., Stathopoulos, E. T., & Brown, W. S. (1997). Speech breathing during reading in women with vocal nodules. *Journal of Voice*, *11*(2), 195–201.

Shembel, A. C., Sandage, M. J., & Verdolini Abbott, K. (2016). Episodic laryngeal breathing disorders: Literature review and proposal of preliminary theoretical framework. *Journal of Voice*. doi:10.1016/j.jvoice.2015.11.027

West, N., & Popkess-Vawter, S. (1994). The subjective and psychosocial nature of breathlessness. *Journal of Advanced Nursing*, *20*(4), 622–626.

Witsell, D. L., Weissler, M. C., Donovan, M. K., Howard, J. F., & Martinkosky, S. J. (1994). Measurement of laryngeal resistance in the evaluation of botulinum toxin injection for treatment of focal laryngeal dystonia. *Laryngoscope*, *104*(1), 8–11.

CHAPTER 2

Laryngeal Anatomy and Physiology

Just like the information on respiratory anatomy and physiology provided in Chapter 1, Chapter 2 describes the laryngeal anatomy and physiology and includes a general explanation of the theories of sound production, effects of development and aging on the larynx, and variations of physiology that accompany sound production. As you read this chapter, please think about what the laryngeal anatomical structures can accomplish based on their morphology (i.e., form and shape) and how they function via the structures they are attached to. Chapter 12 is an excellent resource detailing the cellular anatomy and function of the vocal folds. Use the anatomic diagrams to help visualize the movements of the laryngeal structures and how these movements occur during voice production (i.e., phonation). Then, as you watch the examples of both normal and disordered voice production that are included with this textbook, use the anatomic drawings to help guide the identification of these structures on the laryngeal videoendoscopic examinations.

After reading this chapter, you will:

- Understand the basic components of laryngeal anatomy
- Understand the basic developmental process of the larynx
- Understand laryngeal structural differences between sex and age
- Understand how the larynx functions to produce sound and its variations

Laryngeal Anatomy

Basic Structure and Function

As a multistructured organ within the vocal tract, the larynx serves as a passageway between the upper and lower airway (Figure 2–1). It is composed of one bone, multiple cartilages, numerous muscles, membranous and connective tissue, and movable joints, much like other structures in our body. The larynx acts as a sphincter, closing to protect the lower airways from foreign material, opening to aid breathing, and serving as the sound source for voice production as pressure from the respiratory system is transferred from the subglottal space through the glottal space into the supraglottal cavity (Figure 2–2).

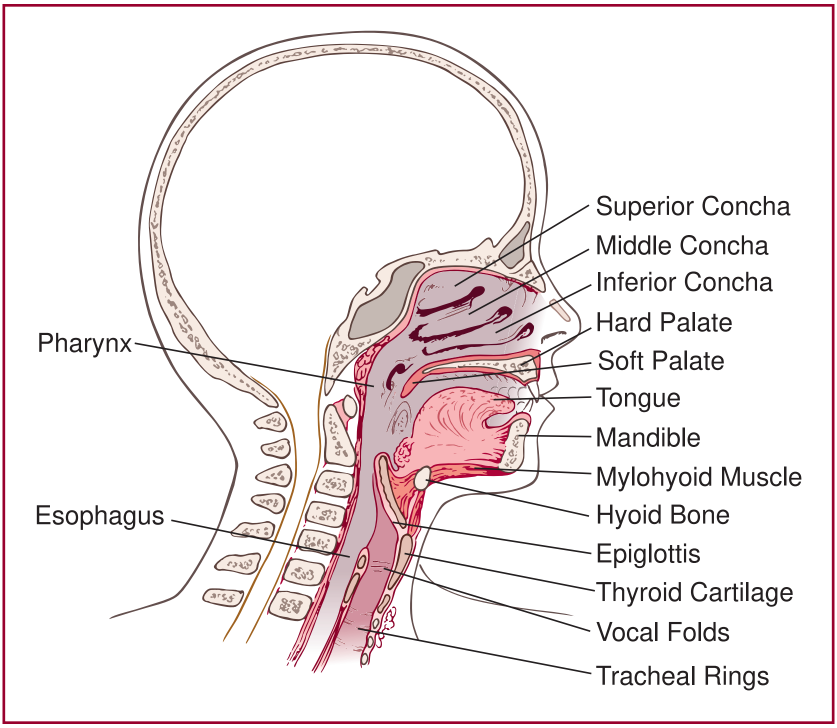

Figure 2–1. Lateral view of head and neck structures.

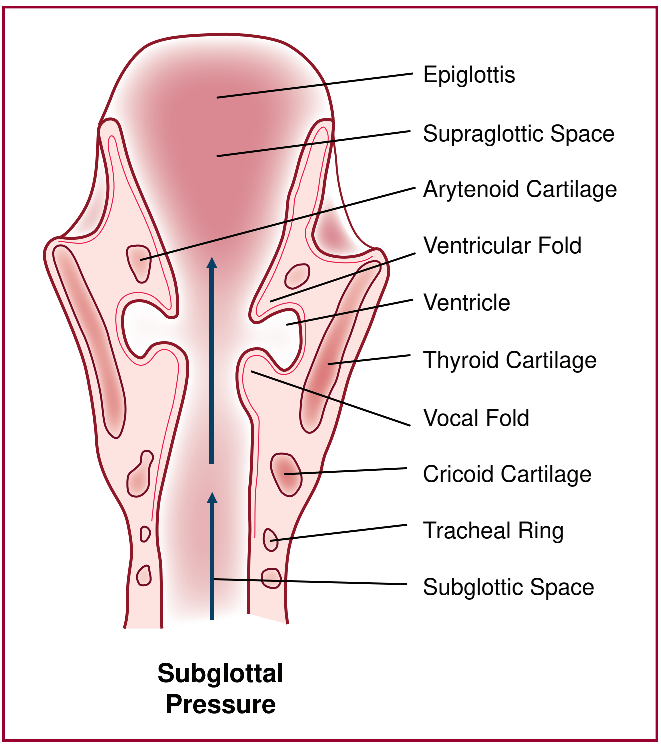

Figure 2–2. Coronal view of sub- and supraglottic space.

With their protective and pivotal role, the vocal folds within the larynx act like a valve to open and close the airway. The open airway allows the passage of air into and out of the lungs. Closure of the vocal folds acts in a protective function. The protective function of the larynx is completely reflexive (i.e., automatic) and involuntary (i.e., not under control), as occurs during a reflexive cough. The phonatory functions, on the other hand, are initiated voluntarily, but regulated involuntarily.

The glottis is simply the space between the vocal folds, and its size and shape changes as a function of the vibratory behavior of the vocal folds. When the vocal folds are open, the glottis widens; this is called *abduction* (Figure 2–3). When the vocal folds are closed, no air can flow through the glottis; this is called *adduction* (Figure 2–4). There are varying

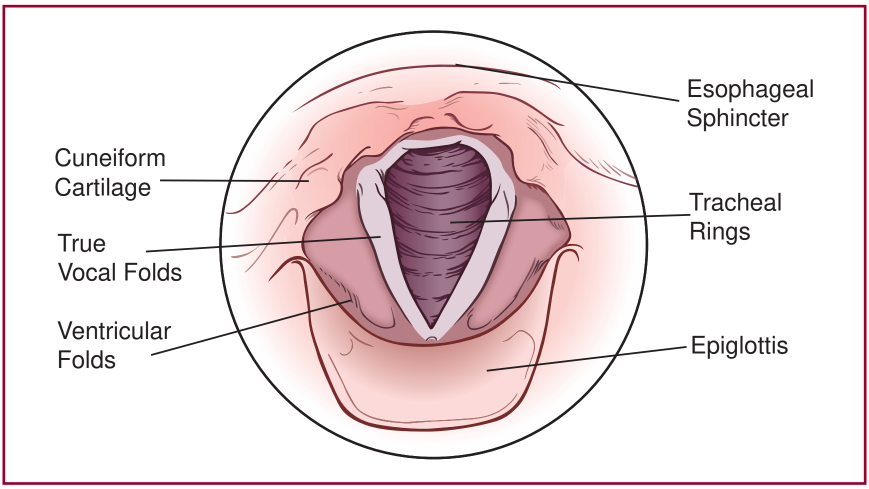

Figure 2–3. Superior view of laryngeal structures (vocal fold opening).

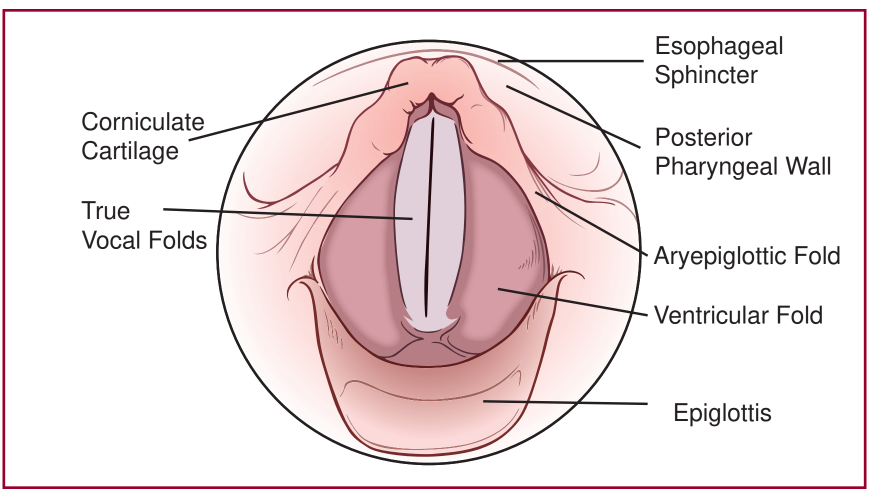

Figure 2–4. Superior view of laryngeal structures (vocal fold closure).

states of abduction and adduction, as shown in Figure 2–5. For example, during a maximum inspiration, when the goal is to achieve maximum inspiratory flow into the lungs, the vocal folds are maximally abducted, representing the functional synergy between vocal fold function and respiratory function. For the initiation of phonation, the vocal folds are positioned near the midline.

As indicated earlier, the larynx is part of the critical pathway for sustaining the life function of breathing. The function of the intrinsic laryngeal muscles for abducting and adducting the vocal folds serves to widen and narrow the glottal space. Without the movement of the primary laryngeal cartilages by the intrinsic laryngeal muscles for abduction, air cannot flow into the lungs and be controlled as it passes out of the lungs. Therefore, for normal breathing to occur, the larynx must be healthy. That is, the muscles of the larynx must receive the appropriate neurologic signal from the brain, and the peripheral nerve endings must be anatomically intact to control the function of the laryngeal muscles.

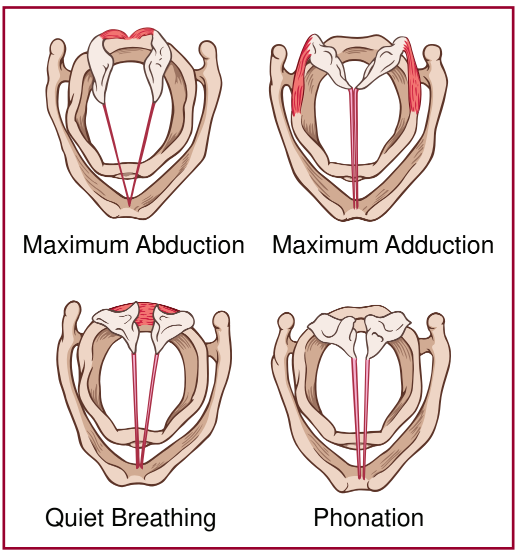

Figure 2–5. Depiction of glottal configurations during maximum abduction and adduction, quiet breathing, and phonation.

Paralysis of the vocal folds (i.e., altered neurologic signaling to the vocal fold muscle) can result in a reduction of the glottal space, thereby jeopardizing a patient's ability to ventilate adequately. If the glottal space is too narrow, then airway resistance is increased, altering normal inspiration and expiration (see discussion in Chapter 1).

The muscles, in turn, must be able to produce the appropriate forces to move the laryngeal cartilages, and the laryngeal cartilages themselves must be flexible. The muscles of the larynx are skeletal, meaning they are under voluntary control for voice production, and they are controlled by the central nervous system. Not every part of the larynx has a critical role in voice production, yet every laryngeal structure has a supporting role in voice production, whether it is anatomic or functional. If the larynx is unhealthy, there could be serious repercussions for regulating airflow as discussed in Chapter 1.

Biological Functions of the Larynx

In addition to its sphincteric function during breathing, the larynx plays an important biological role during the act of swallowing. During swallowing, the vocal folds adduct tightly to prevent food or liquid from entering into the glottal space and subsequently into the trachea or lower airway. This action helps in avoiding the possibility of getting a bacterial infection in the tracheobronchial tree, commonly known as *aspiration pneumonia*. The larynx, with its extrinsic muscle connections to the hyoid bone, elevates both anteriorly and superiorly during swallowing, closing off the laryngeal space and stopping breathing (Davenport, Bolser, Morris, 2011; McCulloch, Van Dael, & Ciucci, 2011). This stoppage of breathing is called *apnea*. The movements of the larynx during swallowing are vital and cofunction with the movements of the hyoid bone due to their anatomic connections.

The larynx also serves another biological function, such as thoracic fixation, which occurs when lifting heavy weights or forceful activities like giving birth. Thoracic fixation requires tight vocal fold adduction to build high intrathoracic pressure. After the high-effort task is completed, the vocal folds abduct and air is rapidly released through the glottal space. Inability to close off the glottis can result in a vocal disability in completing high-effort fixative functions. Other functions that require vocal fold adduction are cough and bowel movements.

Nonbiological Functions of the Larynx

Although the functions of breathing, swallowing, and thoracic fixation are considered to be primary biological functions of the larynx, the act of phonation is considered a nonbiological function. It is classified as a nonbiological function because our vitality is not reliant on the ability to produce voice. In fact, being able to produce voice in the way we do—talking, laughing, screaming, and singing—is a unique human characteristic.

> Excised larynges from animals (e.g., dog, cat, pig, rabbit) are often used to develop models of laryngeal function; or to test the outcome of new treatments prior to human use, such as the use of injectable substances for aiding vocal fold mobility problems; or to study the process of vocal fold healing. By studying animal models, scientists learn about the intricacies of the larynx and transfer their knowledge to the care of the human larynx.

The sophistication of our voice production, as well as the complexity of our laryngeal anatomy and oral structures, provides us with the distinction from other, lower animals.

> Although the dog larynx is often used in laryngeal research, cross-species comparisons have revealed that the layered structure of the pig vocal fold shares more similarities with the human vocal fold (Hahn, Kobler, Starcher, Zeitels, & Langer, 2006a; Hahn, Kobler, Zeitels, & Langer, 2006b; Hunter & Titze, 2004).

Laryngeal Structure: Pieces and Parts

The main part of the laryngeal framework is made up of cartilage, and there are two types of cartilage that require description before detailing the individual structures of the larynx. The first is hyaline cartilage, which is flexible and elastic, made up of collagen (a basic building block of cartilage) and other proteins. Hyaline cartilage forms the thyroid, cricoid, and arytenoid cartilages within the larynx and, with age, these cartilages ossify. The next is elastic cartilage. Elastic cartilage is similar to hyaline cartilage, but in addition to the collagenous fibers, the matrix of the elastic cartilage also contains a network of branched yellow elastic fibers, and these do not ossify. The epiglottis is elastic cartilage.

Ossification is a process whereby cartilage is replaced by bone. Although it is often taught that cartilage turns into bone, as we age, cartilage is actually replaced by bone. Cartilage that does not go through the process of ossification is referred to as *permanent cartilage*, like that found in the tip of the nose, the external ear, the walls of the trachea, and the epiglottis, among others. In the larynx, the thyroid cartilage ossifies more frequently than the cricoid, but each starts to ossify about the third decade of life (Mupparapu & Vuppalapati, 2004).

The Hyoid Bone

A *U*-shaped bone consisting of several parts, the hyoid bone is suspended just above the thyroid cartilage, and is an important site for the muscular attachments of the larynx via the suprahyoid and infrahyoid muscles, which are discussed below. The hyoid bone is considered by some to be an anatomic structure separate from the laryngeal framework, acting as a supporting structure to the laryngeal framework by providing muscular attachments, linking tongue and laryngeal positions. The hyoid bone is attached to the tongue via a ligament called the *glossoepiglottic ligament*, and its unique position with the tongue is only present in humans. For our purposes, we consider the hyoid bone part of the laryngeal framework.

The hyoid includes two *greater cornua* (protrusions) and two *lesser cornua*. The greater cornua are posteriorly directed limbs of the *U*-shaped bone and articulate with the lesser cornua anteriorly (Figures 2–6 and 2–7). The lesser cornua provide a place for stylohyoid ligaments to attach. The hyoid bone is connected to the thyroid cartilage by the thyrohyoid ligament and the thyrohyoid membrane.

Thyroid Cartilage

The thyroid cartilage is the largest unpaired cartilage in the laryngeal framework and is the most visible when looking at the front of the neck, as well as the most palpable. The thyroid cartilage has several parts: two laminae, two superior cornua, two inferior cornua, an oblique line, and a superior thyroid notch. The thyroid cartilage is most often recognized for its anterior angle, which results in a prominence of the cartilage commonly known as the *Adam's apple*. This angle is wider in females

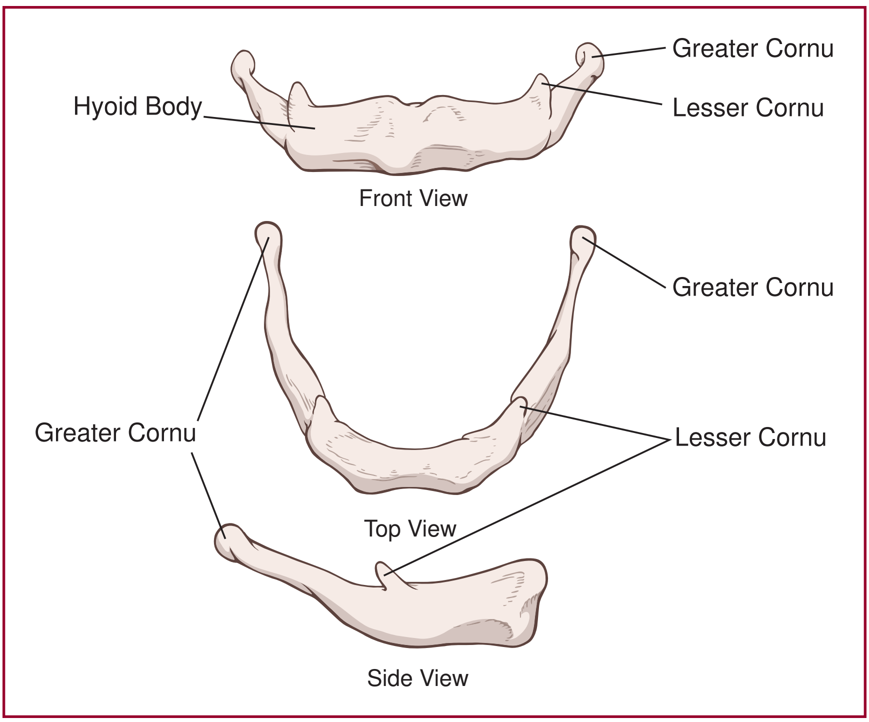

Figure 2–6. Hyoid bone and its landmarks.

(120 degrees in females) and more acute in males (approximately 90 degrees), resulting in a more prominent Adam's apple in men. The thyroid cartilage also connects to the cricoid cartilage, as described below.

Thyroid Laminae

The thyroid laminae are broad, flat plates of cartilages. The laryngeal prominence is a line of fusion between the two laminae. Each lamina is connected above to the hyoid bone by the thyrohyoid membrane. There exists an oblique line on each thyroid lamina that descends diagonally from superior to inferior on the lateral surface of the thyroid lamina. It is the place for other muscular attachments to the thyroid cartilage.

Superior and Inferior Thyroid Cornu

Again, cornua are simply projections of the cartilage. The superior horn of the thyroid cartilage attaches to the hyoid bone by the lateral thyrohyoid ligament. The inferior horn of the thyroid cartilage helps connect the thyroid to the cricoid cartilage, discussed next in this chapter. Rather than a ligament attaching the thyroid to the cricoid, the inferior horn of the thyroid cartilage forms a joint with the cricoid cartilage, called the *cricothyroid joint*. This joint is referred to as a *synovial joint*, which is a freely movable joint and the most common joint in the body. The cricothyroid joint specifically allows the thyroid to rotate anteriorly or posteriorly on the cricoid cartilage. When the thyroid is rotated anteriorly, the

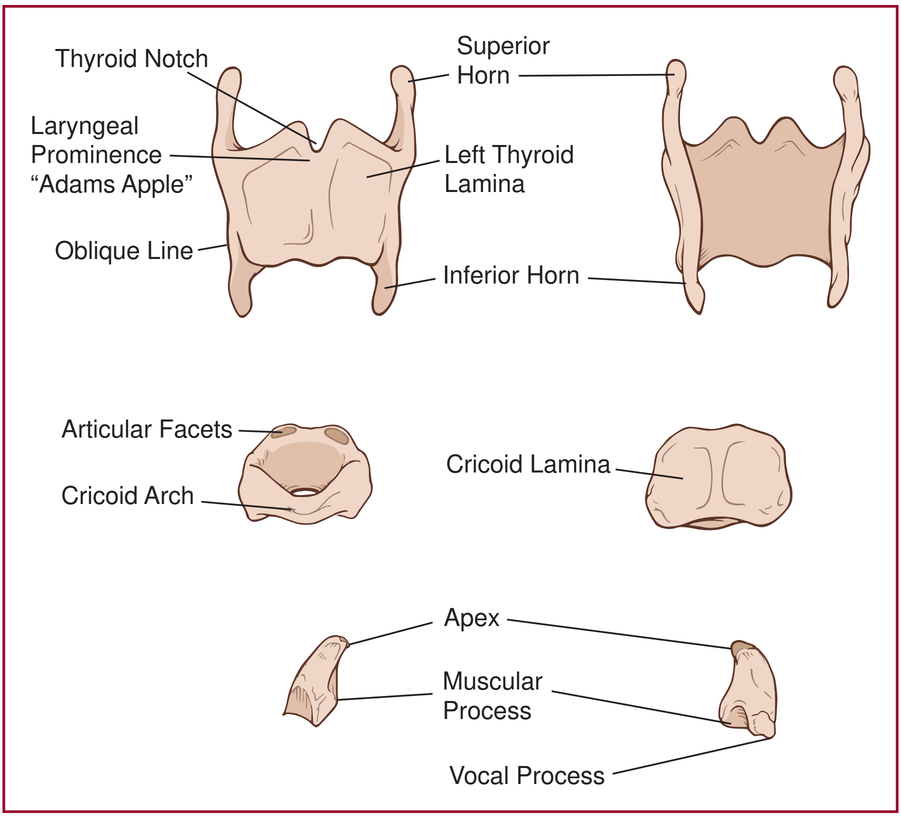

Figure 2–7. Laryngeal cartilages (thyroid, cricoid, and arytenoids).

distance between the front arch of the cricoid to the lower border of the thyroid cartilage is decreased. This lengthens the vocal folds, assuming the arytenoids are fixed in position, thus increasing the tension of the vocal ligaments. Both of the cricothyroid joints operate symmetrically during this movement.

Interestingly, the articulation between the cricoid and thyroid cartilages forms a narrower angle in men than women. This is important knowledge as it might explain the greater difficulty in exposing the cartilages during laryngeal framework surgery for men, which is discussed in more detail in Chapter 8.

> A prominent Adam's apple can be lessened for those seeking reduction as an elective procedure for gender transition. This procedure is called a *thyroid chondroplasty*.

Cricoid Cartilage

The cricoid cartilage is a single cartilage made up of hyaline tissue and forms the base, or inferior aspect, of the laryngeal framework. With a shape often compared to a signet ring, the cricoid cartilage has a broad posterior aspect and a thinner arch anteriorly. It is connected to the thyroid cartilage via the inferior horn, as explained previously, and superiorly by the cricothyroid membrane. The cricoid also attaches to the first tracheal ring by the cricotracheal ligament or membrane.

Arytenoid Cartilage

The arytenoid cartilages are paired and situated on the superior margin of the cricoid lamina, and consist of hyaline and elastic tissue. Usually described as pyramidal shaped, the arytenoids are connected to the epiglottis by a muscle called the *aryepiglottic muscle* or fold, and to the thyroid cartilage anteriorly by the vocal ligament. Arytenoid movement allows for vocal fold abduction and adduction, and these movements occur because of the cricoarytenoid joint. The arytenoid cartilages sit on top of the cricoid cartilage, and the cricoarytenoid joint allows the arytenoid joints to slide medially and rock at these joints (Selbie, Zhang, Levine, & Ludlow, 1998). These joints are also synovial joints and allow for downward and inward, and upward and outward movement. When the vocal process of the arytenoid moves medially, the vocal folds adduct. When there is lateral movement, the vocal folds abduct. Sliding of the arytenoid cartilages toward each other causes adduction, and sliding away from each other causes abduction.

There are two main processes on the arytenoids cartilage; one is called the *vocal process* and the other *muscular process*. The vocal process is the anterior and medial extension of the arytenoid cartilages, where the posterior vocal fold ligament attaches via a tendonlike structure called the *macula flava*. Ultrastructural examination by Sato, Hirano, and Nakashima (2000) showed that the vocal processes are very firm in forming the glottis with greatest pliability at the tip of the vocal process. The muscular processes of the arytenoids, on the other hand, are the extensions where the posterior and lateral cricoarytenoid muscles attach, hence the name muscular process.

> A laryngeal injury, such as a laryngeal fracture due to a motor vehicle accident, sporting activity, or fight, can possibly disrupt or dislocate the cricothyroid and cricoarytenoid joints, creating possible airway limitation and subsequent need for a tracheostomy.