The Hearing Sciences

Third Edition

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Third Edition

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Preface

This text provides resources to guide the student in all areas of hearing science: acoustics, instrumentation, anatomy/physiology, and psychoacoustics. It also provides a brief introduction to speech acoustics. Introductory/intermediate chapters are intended for introductory courses in hearing science. The advanced chapters are suitable for doctoral courses in audiology. The professor can select from among the introductory chapters as he or she feels appropriate for introductory courses, or more advanced chapters in order to introduce topics within doctoral courses in hearing science. The later introductory chapters require only material from other introductory chapters, and similarly one can read and understand intermediate chapters without having read any of the advanced chapters. At the end of this Preface is a breakdown of which chapters have which level of information.

Our goal was to create a very readable text. We endeavored to explain concepts as simply as possible.

Some books are reference texts—they present an idea concisely and have information in one and only one location. They are great resources for reviewing information already learned. Some books are instructional texts, and this is one of them. We assume that the reader has no prior exposure to the information. If the novice reads a reference text, there will likely be times when he or she thinks "I'm not sure I understand." When this happens to professionals learning new information, they search out different articles and books to expand their understanding. The student who has paid a high price for a textbook and does not yet know where to find, or has limited access to, other texts finds this frustrating. This book is to attempt to present information clearly and to repeat that information when presenting more detailed information. The intentional redundancy in the more advanced chapters allows them to serve as reference chapters for students who have already learned the more basic information.

Learning theory says that repetition (e.g., reading information more than one way and both hearing and reading) increases retention, but recall practice is much more effective. The reader is encouraged to attempt to predict summaries. Chapters include review questions to practice recall. The website www.audstudent.com has a resources section that provides additional review questions and supplemental materials.

The hearing sciences are interesting but not necessarily easy. We hope this text with its somewhat colloquial writing style and repetition of key information facilitates mastery of the topic.

Although we think the hearing sciences are intrinsically interesting, we know that some students have a strong preference for those aspects that relate directly to patient care. We have included "Clinical Correlates," which show examples of how the hearing sciences relate directly to clinical applications, for those who can use some motivation to master the scientific underpinnings.

ACOUSTICS AND INSTRUMENTATION

Introductory:	Chapters 1, 2, 3, 4, 5
Intermediate:	Chapters 6, 7
Advanced:	Chapter 8

SPEECH ACOUSTICS

Intermediate:	Chapters 9, 10

ANATOMY AND PHYSIOLOGY

Introductory:	Chapters 11, 12, 13, 16, 18, 20
Intermediate:	Chapters 14, 15, 19, 21, 23, 24, 25
Advanced:	Chapters 17, 22, 26

PSYCHOACOUSTICS AND SPEECH PERCEPTION

Introductory:	Chapter 27
Intermediate:	Chapters 28, 30, 32, 33, 36, 37, 38
Advanced:	Chapters 29, 31, 34, 35, 39

Some chapters have "prerequisites." Understanding the material in these chapters requires that the reader be familiar with the material covered in earlier chapters. These are listed in the following chart.

Chapter	Prerequisite Chapters
1	None
2	None
3	1
4	1
5	1, 2, 3, 4
6	1
7	2, 4, 6
8	1, 2, 3, 6, 7
9	1, 2, 3, 4, 5
10	1, 2, 3, 4, 5, 9
11	None
12	11
13	1, 2, 3, 4, 5, 11, 12
14	1, 3, 11, 12, 13
15	1, 4, 12, 13, 14
16	1, 3, 11, 12, 13
17	6, 16
18	16
19	18
20	11, 16, 18
21	20
22	1, 3, 4, 7, 16, 17, 18, 19, 20, 21
23	16, 20
24	16
25	12, 16, 20, 24
26	24, 25
27	None
28	1, 11, 16, 18
29	27, 28
30	1, 2, 3, 11, 16, 18, 20, 27, 28
31	1, 2, 12, 13, 18, 30
32	1, 11, 16, 18, 30
33	1, 11, 16, 18, 21, 27
34	2, 23, 33
35	21, 33, 34
36	26, 30, 32
37	23, 27, 30, 33
38	1, 3, 30
39	1, 3, 9, 10, 12, 14, 16, 18, 20, 27, 30, 31, 32, 33, 34, 35, 36, 37, 38

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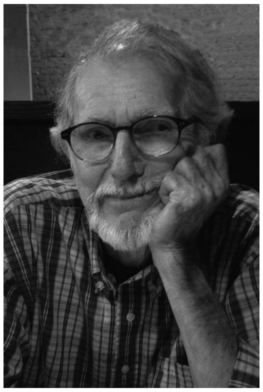

Lloyd L. Price, PhD, Professor Emeritus of Audiology, taught undergraduate and graduate student courses in the hearing sciences at Florida State University. His teaching career spanned 31 years and he worked clinically before teaching.

Teri A. Hamill, PhD, Professor Emeritus of Audiology at Nova Southeastern University, recently took early retirement. She had taught AuD students for 21 years at Nova Southeastern University, and taught at two other universities and was a hospital-based audiologist.

Dr. Hamill's knowledge of instrumentation was furthered by having worked with engineers: Her postdoctorate in 1987 to 1988 was with Project Phoenix/Nicolet, which produced a commercially unsuccessful fully digital hearing aid. Her knowledge of digital signal processing also comes from being married to a computer scientist.

Dr. Price is retired to Havana, Florida, with his wife, Cindy. They frequently travel, particularly to Europe. Dr. Hamill retired in order to sail at least half the year on her antique Shannon 38 cutter-rigged sailboat, and to have more time to read about hair-cell physiology.

24

Introduction to Peripheral Vestibular Anatomy and Physiology

The history of audiology's involvement in vestibular testing dates back to the mid-1970s, when Barber and Stockwell published a text on how to evaluate the balance system. Since the vestibular system is part of the ear, and as Dr. Barber was an otoneurologist, it made sense that the testing of the balance system became part of the practice of audiology. The involvement of the field grew along with knowledge of the pathologies of the vestibular system, and the diagnostic tests for balance disorders have expanded. Most doctor of audiology programs have two or three courses in vestibular evaluation and management. This chapter and Chapters 25 and 26 provide background on the anatomy and physiology to prepare students for this coursework, and to provide the undergraduate student with an understanding of how humans maintain balance.

Most of us give little thought to our sense of balance. Having a normal balance system means more than not being dizzy. A healthy vestibular system allows moving without falling, knowing where our bodies are in space as we move, and it permits us to see a steady world as we move. Without our vestibular systems, when we move our view of the world would be similar to a video taken with one's cell phone—jumping, blurry images.

The balance systems comprise more than just the vestibular structures in the inner ear. The vestibular sense organs are connected to brainstem structures that reflexively control the movement of the eyes. This permits unblurred vision as we turn our heads. Nerve fibers in the brainstem go to the cerebellum, to the neck, and to motor pathways, all of which control body motions and allow us to remain upright. This chapter introduces the peripheral vestibular system; Chapter 25 provides more detail, and Chapter 26 describes advanced vestibular concepts including how the central nervous system integrates information to help us make the eye movements that allow us to keep focused vision as we move our heads and bodies.

THE VESTIBULAR SYSTEM: BONY AND MEMBRANOUS LABYRINTHS

As was discussed in Chapter 16, the same fluids are in both the vestibular system and the cochlea. Perilymph is found between the bony walls of the vestibular system and the membranes; endolymph is within the membranes. A small stalk, **ductus reuniens, connects** the endolymph-filled **scala media of the cochlea to the saccule**, which is connected to the **utricle**. The utricle and saccule are portions of the membranous labyrinth that **sense when our bodies are moving**

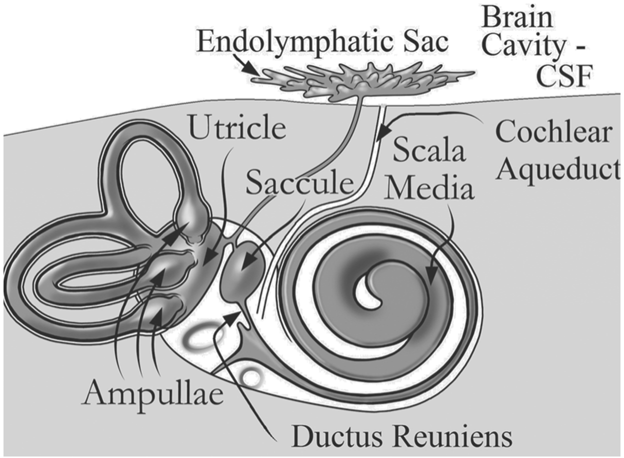

Figure 24–1. The membranous labyrinth includes the scala media of the cochlea, the utricle and saccule in the vestibule, and membranous arcs within the semicircular canals. Perilymph is found outside the membranous labyrinth. There is a stalklike extension of both the endolymph-filled membranous labyrinth and the perilymph-filled scala tympani. The perilymph in the scala tympani connects via the cochlear aqueduct to a space in the cranium filled with cerebrospinal fluid (CSF). The membranous labyrinth connects to the endolymphatic duct, which connects to the endolymphatic sac, tucked into the dura mater covering the brain. Source: Modified from copyright © Miguel Reynel 2013, used with permission.

in a straight line (e.g., riding in a car, descending in an elevator) and when our heads are tilting. The **semicircular canals** contain the sense organs that **detect rotation**, such as the head pivoting on the neck. The three semicircular canals open into the utricle, as shown in Figure 24–1. Each of the semicircular canals has an enlargement, or ampulla, at one end. The sensory cells are in the ampullae. (*Ampulla* is singular, *ampullae* is the plural form.)

A tube, called the **cochlear aqueduct,** runs from the **perilymph-filled space** of the bony labyrinth **to the brain above**. It appears that the opening to the cerebrospinal fluid (CSF) space of the brain is not patent; CSF is not freely flowing. (The chemistry of CSF and perilymph are a bit different.) Perilymph is thought to be derived from "blood serum substrate," that is, the part of the blood other than the red and white blood cells. Endolymph in the cochlea is produced by stria vascularis; in the vestibular system, a type of cell within the ampulla, dark cells, are believed to produce and nourish the endolymph. There is also a connection, called the **endolymphatic duct, between the saccule and utricle and the endolymphatic sac**. The endolymphatic sac rests in the dura mater of the brain—the outside of the meninges, the covering of the cranium. The presence of these ducts to the brain hints at the inner ear's ability to regulate the pressure of the inner ear fluids. If the system were to create too much endolymph or perilymph, there would be some room for expansion. The endolymphatic sac could bulge a bit; the cochlear aqueduct might allow some pressure relief into the CSF-filled brain cavity.

Arrangement of the Semicircular Canals

Each of the three semicircular canals of one ear is oriented at right angles to each other. This is easier to envision in the sketch of the circles superimposed on three of the sides of a cube, shown in Figure 24–2.

However, the actual arrangement of the semicircular canals is not as simple as sketched in Figure 24–2; it is more like that in Figure 24–3. The semicircular canals are named for their anatomic

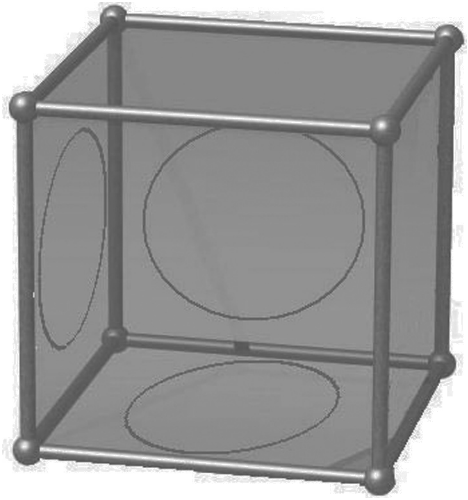

Figure 24–2. The three semicircular canals lie perpendicular to each other, just as three sides of a cube are perpendicular to each other.

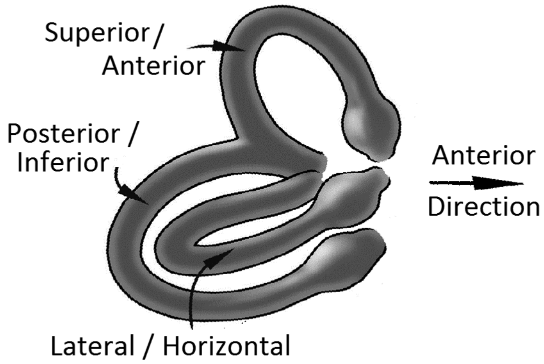

Figure 24–3. The semicircular canals are named by their anatomic arrangement. Each canal may be known by one of two names. Source: Modified from copyright © Miguel Reynel 2013, used with permission.

location. The **horizontal** or **lateral semicircular canal** is **tilted about 30 degrees off horizontal**. It is lower in the back than in the front (Figure 24–4A). The canal that is most anterior also is the highest one; thus, this canal is called either the **superior** or the **anterior semicircular canal**. The third canal is named either the **inferior** or the **posterior semicircular canal**.

Planes of the Canals of the Right and Left Ears Are Aligned

As shown in Figure 24–5, **the right anterior and left posterior canals are both angled in the same orientation**. The acronym RALP is commonly used to describe the two canals. The **left anterior and right posterior canals also line up**; this pair goes by LARP. Thus, movement of the head in one direction will cause stimulation in pairs of canals. That holds true for the horizontal canals, too. Moving the head as if shaking no causes the **pair of horizontal canals** (right and left) to be stimulated.

Clinical Correlate: Orienting the Horizontal Semicircular Canal

When testing people with dizziness using a test called videonystagmography or electronystagmography, there is a portion of the test that requires that the horizontal semicircular canal be positioned straight up and down. To do this, recline the patient into a supine position, and then elevate his or her head 30 degrees. This will place the semicircular canal in the desired direction (see Figure 24–4).

Figure 24–4. A. Orientation of the horizontal semicircular canal in the upright patient. **B.** When supine, the horizontal canal is not oriented vertically. **C.** Tilting the head up approximately 30 degrees aligns the horizontal canal straight up and down.

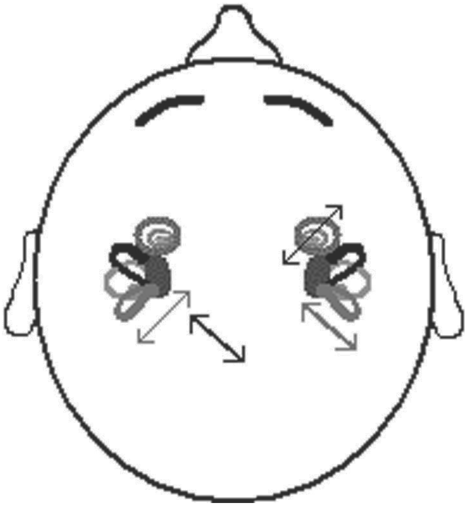

Figure 24–5. Orientation of the right anterior and left posterior (RALP) and left anterior and right posterior canals (LARP) are in line. Thus, these pairs of canals will be stimulated by the same directional head motion.

ANATOMY AND PHYSIOLOGY OF THE SEMICIRCULAR CANALS

Structures within the Ampullae of the Semicircular Canals

Recall that the cochlea has a membrane covering the hair cells (reticular lamina) and that the hair cells themselves are bathed in perilymph. The vestibular system's setup is similar. The movement-sensing **vestibular hair cells are below a membrane barrier in perilymph**; the sensing cell **cilia** will **project into** the potassium-rich **endolymph**. Collectively, the **cells in the ampulla** are called the **crista** or **crista ampullaris**. You will sometimes read that the crista is made up of **sensory epithelium**.

The crista contains hair cells. Just like in the cochlea, there are two types of hair cells. They are not arranged in the same way, so the terms *outer* and *inner* would not be appropriate, as the two types of cells are mixed together in the same locations. We call them **type I** and **type II vestibular hair cells**. The **type I** cells are shaped somewhat like a vase with a pinched neck, **similar in shape to the inner hair cells**. This shape is also called globular. The **type II hair cells are taller and straighter, like the** cochlea's **outer hair cells**. Both types of cells have cilia on them, and when deflected, the **cilia will open microchannels, allowing potassium into the cell, depolarizing the hair cells**.

In the cochlea, the cilia of the outer hair cells project into the gelatinous tectorial membrane. In the ampulla of the semicircular canals, the type I and II hair cell **cilia project into a gelatinous mass called the cupula**. The cupula hangs from the top of the ampulla, as illustrated in Figure 24–6.

The cupula is essentially floating in endolymph, although it is attached to the roof of the ampulla. This means that it can move somewhat when the fluid moves. An analogy for this situation is the twisting of a Hula-Hoop. When the Hula-Hoop spins, the pebbles inside lag behind because of their inertia. If viewed from a camera mounted inside the Hula-Hoop, the pebbles would appear to be moving backward. Rotating the head moves the semicircular canals, which are firmly attached to the head, which causes the cupulas to lag behind.

The cupula can move only so far: It will hit the walls of the ampulla if the movement continues, for example, if you are on a merry-go-round. As you spin and spin on the merry-go-round (at a constant speed), the fluid eventually is going to catch up to the speed of the body and the cupula will float in a relatively neutral position again. When you slow down, the fluid will still be

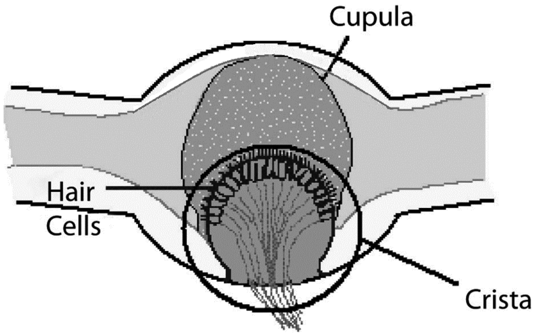

Figure 24–6. Arrangement of structures within the ampulla. The hair cells are in the crista and are not within the membranous labyrinth, although the hair cell cilia project into it. The cupula is a gelatinous structure into which the cilia embed.

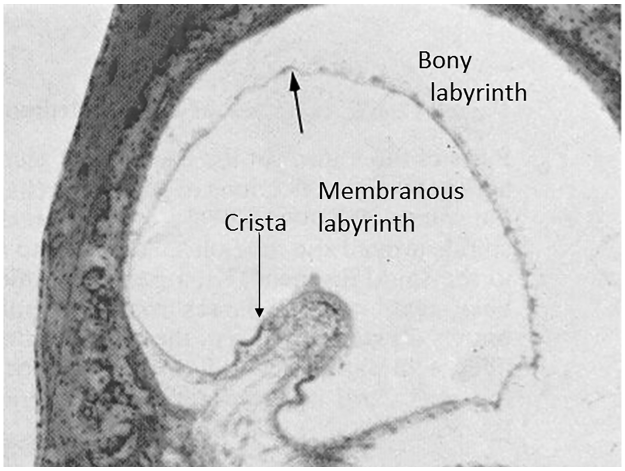

Figure 24–7. Scanning microscope view of a cross section of an ampulla. Source: Modified from Jozeppy26, https://commons.wikimedia.org/w/index.php?curid=10253283.

moving as the body decelerates, and the cupula would be forced in the opposite direction.

Figure 24–7 shows an electron microscope cross-section view of an ampulla. The cupula is not shown in this figure. It provides a nice illustration of the bony versus membranous labyrinths, and how the hair cell bodies in the ampulla are surrounded by perilymph. The cilia (not visible in this picture) project into the membranous labyrinth.

Angular Head Motion Directions

The semicircular canals are arranged to detect angular motion in any direction. Sometimes these motion directions are referred to as **yaw, pitch, and roll**. Yawing is moving around a vertical axis. Shaking your head no is an example of this motion. A boat at anchor in a shifting wind yaws back and forth. The horizontal semicircular canals would be stimulated with this type of movement. A boat crashing through the waves has its bow (front) tossed upward and downward; it is said to be pitching. Shaking your head yes creates the same sort of movement. Looking at Figure 24–5, note that both the anterior and posterior canals would be partially stimulated by this type of motion. Rolling is when a boat tips left to right, as when a wake from a passing boat hits the side of the boat. Repeatedly tilt your head toward your shoulder—left ear down to the left shoulder, then right ear down to the right shoulder. Again, the anterior and posterior canals sense this motion.

Cilia and Kinocilium in the Ampullae

The cilia on a vestibular hair cell look a bit different from those on an auditory hair cell. First, a kinocilium—a very tall cilium—exists on vestibular hair cells (both type I and type II). Second, the cilia are not neatly in rows—they form a central mound. The tallest stereocilia are nearest the kinocilium (Figure 24–8).

Just as with auditory hair cells, the adjacent cilia are linked together. **Deflecting the tallest cilia** therefore **moves the entire bundle**. And again, as in the auditory system, the **movement of the cilia will open and close** channels in the cilia. Moving the stereocilia in one direction (toward the kinocilium) will open the **mechanoelectrical transduction (MET) channels**, allowing potassium to enter the cell and excite it. Movement in the opposite direction closes the channel and slows the neural firing rate. (Vestibular nerve cells, like auditory ones, will fire spontaneously without stimulation.)

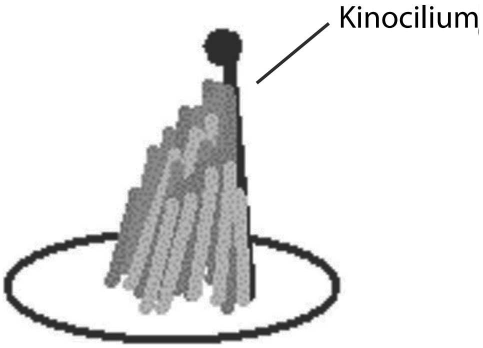

Figure 24–8. Illustration of the cilia on top of a vestibular hair cell. Hair cells in the vestibular system have a tall kinocilium. The cilia are clustered together and linked together, so that movement on any one part moves the entire bundle.