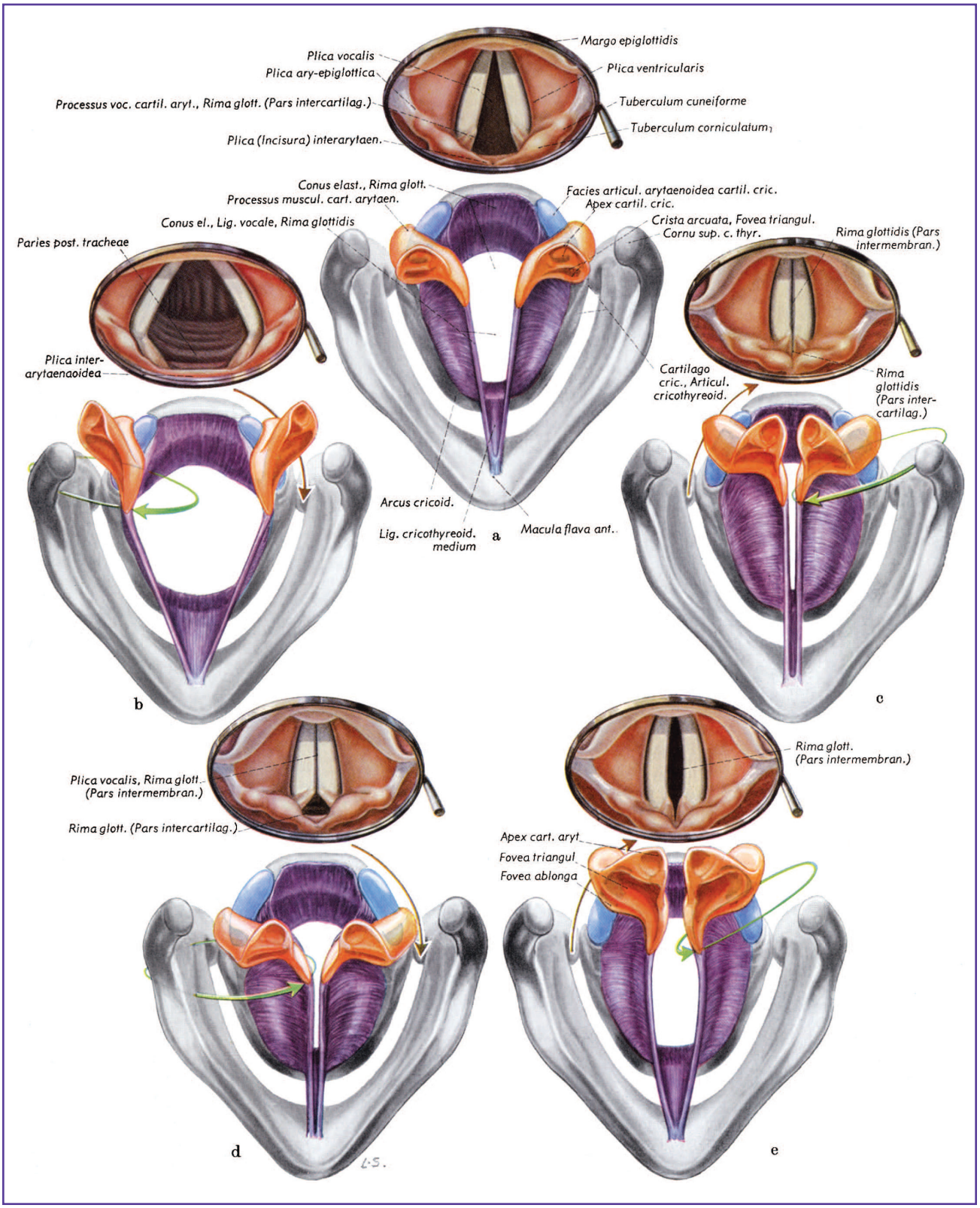


B

Figure 6–7. *(continued)* **B.** The shapes of the glottis as seen on mirror examination and on anatomic preparations during rest (a), inspiration (b), phonation (c), whispering (d), and falsetto singing (e). (Reproduced with permission from Pernkopf.[1])

14

Vocal Tract Resonance

Johan Sundberg

Generation of Vocal Sound

The human voice organ consists of 3 parts, as is illustrated schematically in Figure 14–1. One is the breathing apparatus, which acts as a compressor: It compresses the air contained in the lungs. The second is the pair of vocal folds, which act as a sound generator: By vibrating they chop the airstream from the lungs into a sequence of air pulses, which is actually a sound. It sounds like a buzz and contains a complete set of harmonic partials. The third part is the cavity system constituted by the pharynx and mouth cavities, the *vocal tract*: It acts as a resonator, or a filter, which shapes the sound generated by the vocal folds. In producing nasal sounds, we lower the velum, and so supplement the vocal tract resonator by the nasal cavity, the *nasal tract*. Of the 3 parts, the breathing apparatus, the vocal folds, and the vocal tract, only the latter 2 contribute directly to forming vocal timbre. In other words, the acoustic characteristics of the voice are determined by 2 factors: (1) the voice source (i.e., the functioning of the vocal folds) and (2) the vocal tract and sometimes also the nasal tract.[1] This chapter focuses on the role of the vocal tract resonator.

The voice source passes through the vocal tract resonator; it is formed acoustically. The nature of this shaping depends on the vocal tract configuration. The act of changing the shape of the vocal tract is called *articulation*. The structures that we use to arrange the shape of the vocal tract in different ways are called *articulators*. For example, the lower mandible and the tongue are articulators.

The vocal tract is a *resonator* (ie, an object in which resonance occurs). Resonance is a phenomenon created by synchronization of input and reflected energy. To realize the meaning of this, it is helpful to imagine what will happen if one hits one end of a very long tube with both ends closed. A clap sound will be generated that runs to the opposite end, where it is reflected. After a while, it returns and is reflected again, and the process is repeated. Thus, the clap sound will travel back and forth in the tube. The result is that we will hear a repeated clap. The time intervals between the claps are determined by the distance that the sound has to travel to the opposite end and back; the longer the tube, the longer are the intervals between the sounds (ie, the lower the frequency of the claps). Because some sound energy is consumed during the travel, the returning clap sounds gradually will become softer. If one or both ends of the tube are open, reflection still occurs, as sound is reflected also by an open end; but the decay will be quicker, because more sound energy is lost at an open end than at a closed end.

This is exactly what happens in tube resonators. If a resonator is hit, it responds with a tone that dies rather quickly. The frequency of the tone is determined by the time it takes for the sound to travel to the opposite end and back. In the case of the vocal tract, the distance is short, so the frequency of a response to a clap is comparatively high, about 500 Hz, if the tube is cylindrical. Thus, if one flicks one's neck above the larynx with a finger with closed glottis and open mouth, one can hear a quickly decaying tone; it sounds similar to the sound produced when one hits an empty bottle, which, incidentally, is another example of a resonator.

Imagine now that you hit the end of the long tube repeatedly with a time interval that equals the intervals between the returning clap sounds and furthermore that you hit it exactly when a clap sound returns. Then, the new and the returned clap sound will cooperate so that a loud clap sound is produced.

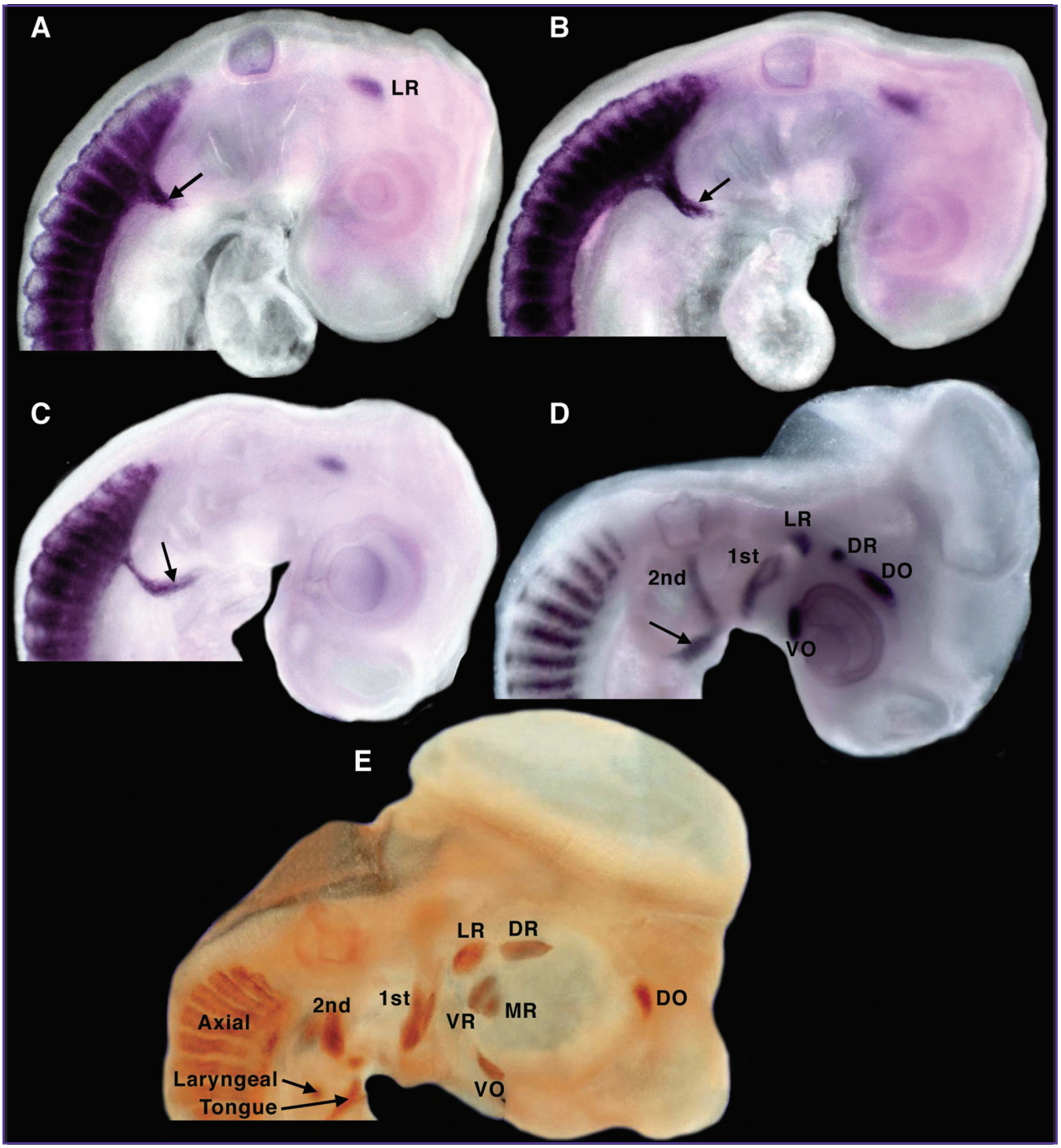


Figure 2–4. The development of tongue and laryngeal muscle precursors, shown in chick embryos at 2 to 5 days of incubation (equivalent to stages 12–18 [weeks 5–6] of human development). Arrows in **A–D** show the hypoglossal cord. This contains myoblasts that originate in the lateral margin of somites 1 to 5 and then migrate ventrally to the level of the pharynx. **A–C** are in situ hybridizations for expression of *Paraxis*, a transcription factor expressed in all somite-derived muscle progenitors and also in the lateral rectus (LR) primordium. **D** is probed for *Myf5*, which is expressed in all skeletal myoblasts. **E** is stained with an antibody to a myosin heavy chain. By this stage, the laryngeal and glossal muscle precursors have separated from one another; the former are beside the caudal pharynx immediately behind the fourth pharyngeal pouches but have not separated into individual muscles. The glossal muscles have not penetrated the tongue primordium. 1st, 2nd are muscle condensations in the corresponding branchial arches; DR, MR, VR, dorsal (superior), medial, and ventral rectus muscles; DO, VO, dorsal and ventral oblique muscles. (From Noden.[18])

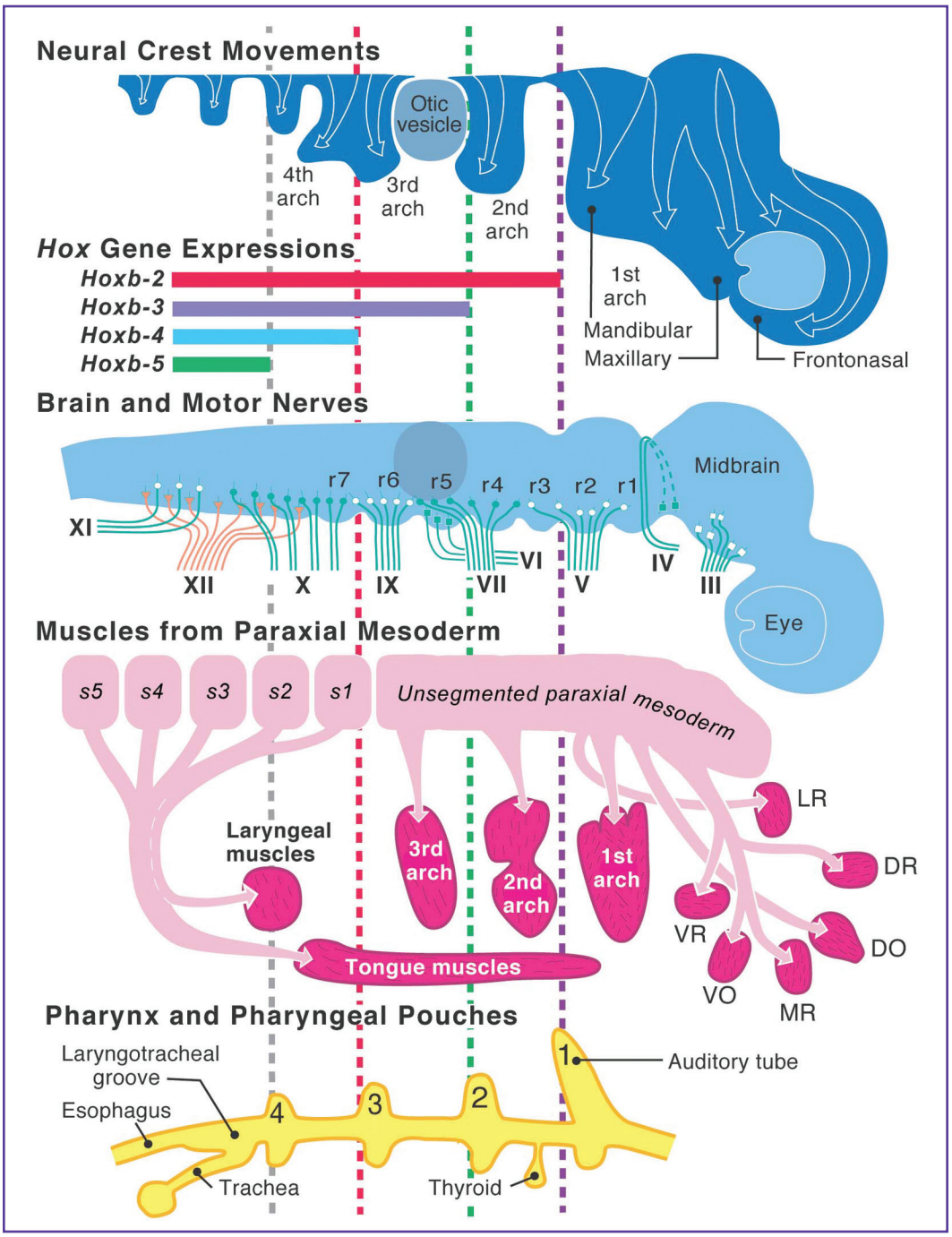


Figure 2–8. Schematic staggered view showing the spatial relations among progenitor populations of different embryonic origins. Sites of origin and patterns of movements for neural crest and myogenic mesodermal cells are shown, as are locations of cranial motor nerves and pharyngeal pouches. Note that the progenitors of all branchial arch tissues trace their origins to a common axial level, whereas musculoskeletal and neural progenitors for frontonasal and periocular regions have widely disparate origins. *Hox* genes have extensive longitudinal zones of expression, but it is the boundary of each that is critical in establishing spatial identity within rhombomeres and neural crest cells. Only one of the multiple sets of *Hox* genes that are active in the hindbrain and neural crest cells is shown. Note that these expression boundaries correspond to the gaps between crest cells destined to occupy each branchial arch. r1, r2, and so on identify rhombomeres in the hindbrain; 1, 2, and so on identify pharyngeal pouches. III, IV, V, and so on label cranial motor nerves.

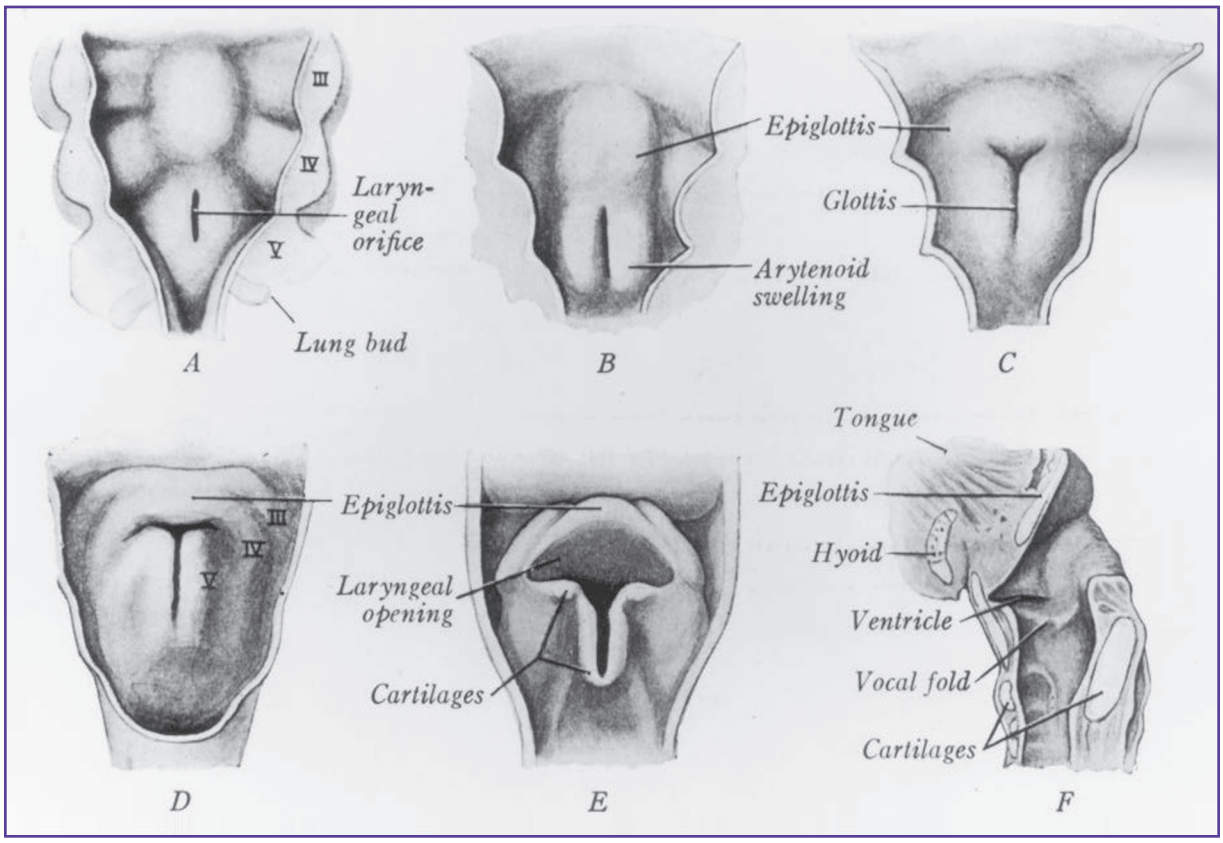


Figure 3–5. Development of the human larynx, as seen by unroofing the embryo to show the floor of the pharyngeal cavity. **A.** At 5 mm. **B.** At 9 mm. **C.** At 12 mm. **D.** At 16 mm. **E.** At 40 mm (×7). **F.** Sagittal hemisection, at birth (×15). In **A,** His[8] assumed the "ascending notch" reached the level of the pharyngeal floor, and the tracheoesophageal separation would be at the level shown. Hence, according to His, level **A** would represent the cephalic end of the trachea. According to Zaw-Tun[13] level **A** represents the entrance to the primitive laryngopharynx, which eventually becomes the supraglottis. (Used with permission from Arey.[17])

development is essentially uniform in all mammals, (2) the genetic analysis for murine development is well defined, and (3) embryos of a predetermined age can be easily and accurately staged. The results of this developmental study were in close correlation with the findings of Zaw-Tun and will be described in further detail.

Serial histological sections of the laryngopharyngeal region of mice embryos were obtained from day 9 of gestation to day 18. STERECON, a computer graphics system designed to allow 3-dimensional tracings of structural contours from 3-dimensional images, was used to generate the 3-dimensional models.[19,20] Photographic transparencies of each histological section were then projected onto a screen that was the same size as a high-resolution computer monitor. By means of a digitizing tablet, color-coded lines were drawn on the monitor, outlining the structures of interest, for example, the epithelial lining of the foregut, foregut lumen, muscles, cartilages, and arteries. The resulting contours were stored in a database and used to form wireframed models. Wireframe models were then transferred to a Silicon Graphics workstation and rendered as solid, shaded reconstructions with Wavefront Technologies software. This allowed anatomic structures to be viewed in continuity, in any desired orientation, and in relation to any other given structure. In addition, internal structures could be visualized by sectioning models in various planes.

Figure 3–6 is a lateral view of a 3-dimensional reconstruction of the epithelial lining of the developing laryngopharyngeal region. The first sign of the respiratory system is seen as an epithelial thickening along the ventral aspect of the foregut known as the respiratory primordium. The respiratory primordium is separated from the hepatic primordium

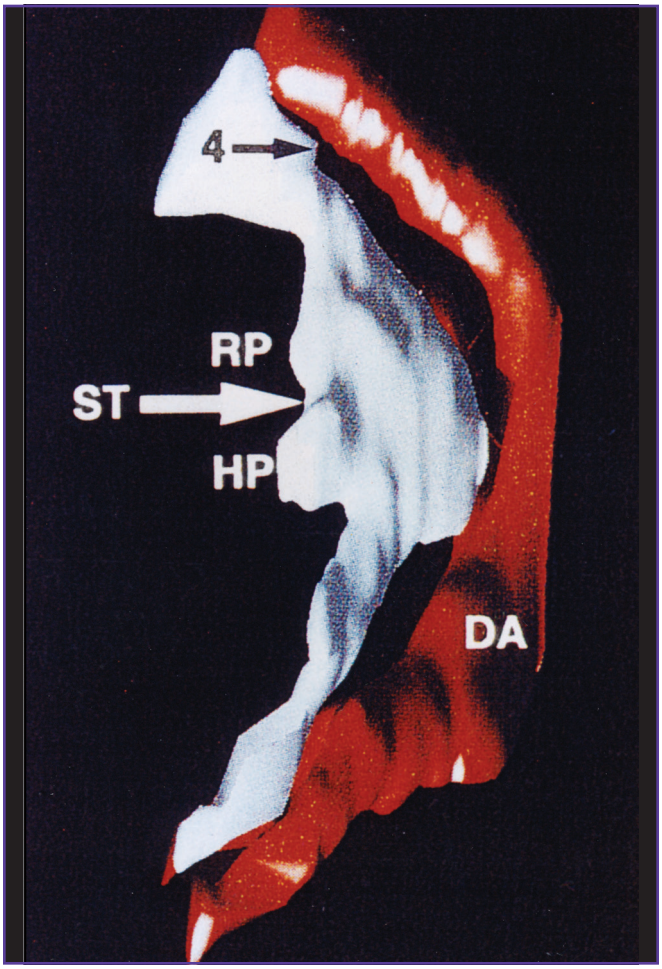
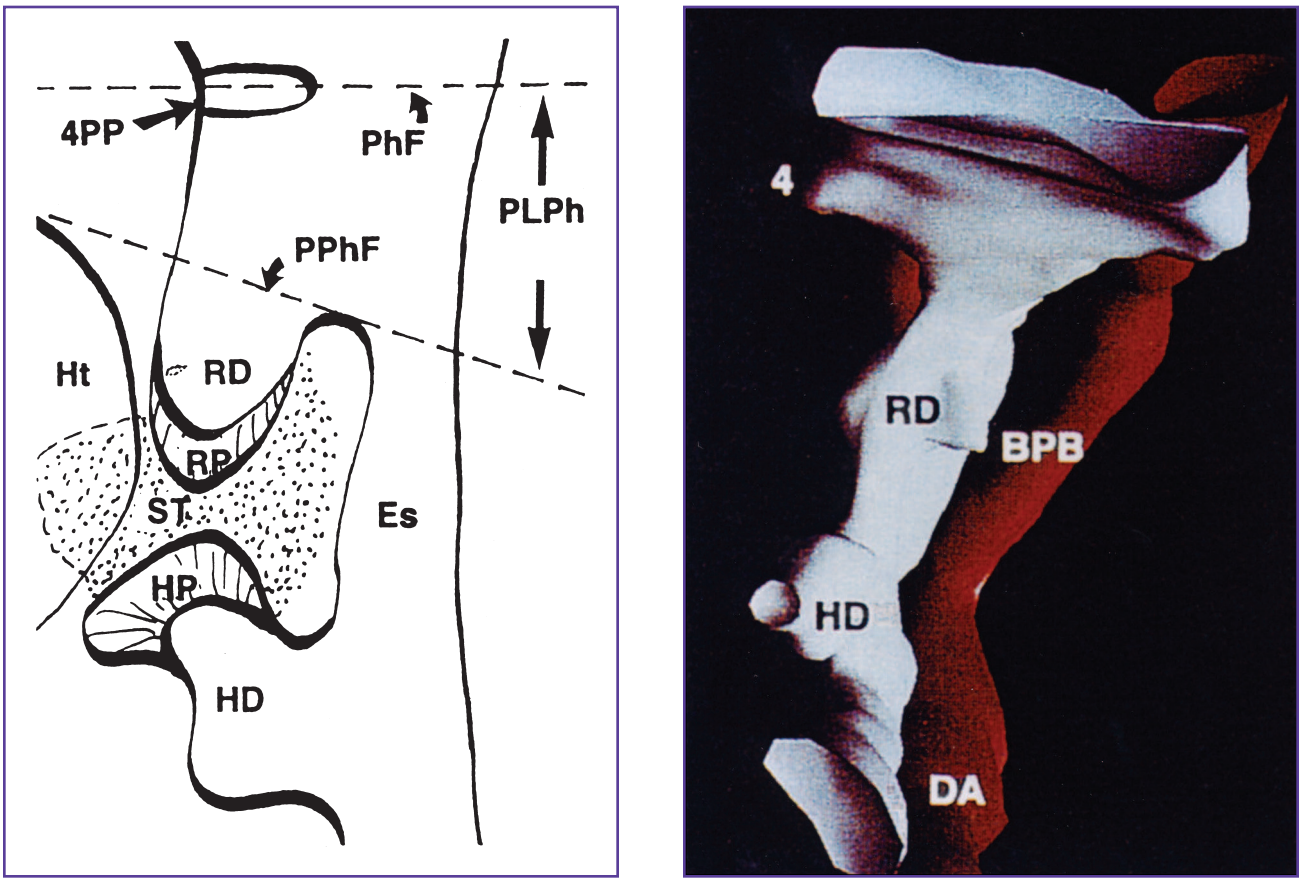


Figure 3–6. Stage 11 (17-somite mouse embryo). Lateral view of 3-dimensional reconstruction of epithelial lining for foregut. First evidence of respiratory system is indicated by epithelial thickening along ventral aspect of foregut called respiratory primordium (*RP*). Respiratory primordium is separated from hepatic primordium (*HP*) by septum transversum (*ST*), which is indicated by solid white arrow. Septum transversum will eventually develop into central tendon of the developing diaphragm. *4*, site of developing pharyngeal pouch; *DA*, dorsal aorta. (Courtesy of John S Rubin, MD, Robert T Sataloff, MD, DMA, Gwen S Korovin, MD, and Wilbur James Gould, MD, from the book *Diagnosis and Treatment of Voice Disorders*. New York, NY: Igaku-Shoin Medical Publishers; 1995.)

(HP) by the septum transversum, a structure that will eventually develop into the central tendon of the diaphragm.

Figure 3–7A is a schematic representation of the laryngopharyngeal regions of a stage 12 embryo in comparison with the mature fetal larynx in a midsagittal plane. The respiratory diverticulum is a ventral outpocketing of foregut lumen that extends into the respiratory primordium. The site of origin of the respiratory diverticulum is called the primitive pharyngeal floor and eventually develops into the glottic region of the adult larynx. The cephalic portion of the respiratory diverticulum eventually develops into the infraglottic region of the adult larynx. The primate pharyngeal floor is separated from the pharyngeal floor, or the level of the fourth pharyngeal



A B

Figure 3–7. Stage 12 (22-somite mouse embryo). **A.** Schematic representation of midsagittal section through laryngopharyngeal region. Respiratory diverticulum (*RD*) is ventral outpocketing of foregut lumen that extends into respiratory primordium (*RP*). Similarly, hepatic diverticulum (*HD*) results from extension of foregut lumen into hepatic primordium (*HP*). Cephalic portion of *RD* will eventually develop into infraglottic region of adult larynx. Site of origin of *RD* is called primitive pharyngeal floor (*PPhF*); it will eventually develop into glottic region of adult larynx. Esophagus (*Es*) separates from *RD* at level of *PPhF*. Primitive pharyngeal floor is separated from fourth pharyngeal pouch (*4PP*) by segment of foregut called primitive laryngopharynx (*PLPh*). Pharyngeal floor (*PhF*) is at same level as *4PP*. Primitive laryngopharynx will eventually develop into supraglottic region of adult larynx. *Ht*, heart; *ST*, septum transversum. **B.** Ventral view of 3-dimensional reconstruction of epithelial lining of laryngopharyngeal region. Respiratory diverticulum has given rise to bilateral projections called bronchopulmonary buds (*BPB*); they will eventually develop into lung parenchyma. *DA*, dorsal aorta; *4*, fourth pharyngeal pouch. (Courtesy of John S Rubin, MD, Robert T Sataloff, MD, DMA, Gwen S Korovin, MD, and Wilbur James Gould, MD, from the book *Diagnosis and Treatment of Voice Disorders*. New York, NY: Igaku-Shoin Medical Publishers; 1995.)

pouch, by a segment of foregut originally classified by Zaw-Tun as the primitive laryngopharynx, as discussed above. This will eventually become the adult supraglottic larynx.

Figure 3–7B is a ventral view of a 3-dimensional reconstruction of the epithelial lining of the laryngopharyngeal region of a stage 12 embryo. The respiratory diverticulum has given rise to bilateral projections called bronchopulmonary buds, which will eventually develop into the lower respiratory tract. The buds are tethered to the superior aspect of the septum transversum.

Dynamic changes to the developing foregut region are occurring at this and subsequent stages. For example, the heart and the hepatic primordium are proliferating at a rapid rate on opposing surfaces of the septum transversum. These differential forces are exerted on the adjacent foregut region, which leads to a dramatic lengthening of the foregut in a cephalocaudal plane. The result can be seen as the distance

between the respiratory primordium and the hepatic primordium increases over time.

In stages 13 and 14 (Figure 3–8), the bronchopulmonary buds are drawn caudally and dorsally because they are tethered to the septum transversum and the cephalic aspect of the foregut and the respiratory diverticulum migrates superiorly. As a result, (1) 2 primary mainstem bronchi develop and (2) the carina is seen as a distinct region that develops from the caudal aspect of the respiratory diverticulum, and it is the site of origin of the 2 primary bronchi.

Figure 3–9 shows the distance between the carina and the respiratory diverticulum by 2 white solid arrows in a stage 14 embryo. The lengthening of this foregut segment will eventually give rise to the developing trachea. At this point in development, dramatic lengthening of the trachea and esophagus occurs. Anatomically, the esophagus is in close proximity to the region of the carina. Vascular compromise to the developing esophagus may give rise to esophageal atresia or the spectrum of tracheoesophageal anomalies seen in Figure 3–10.

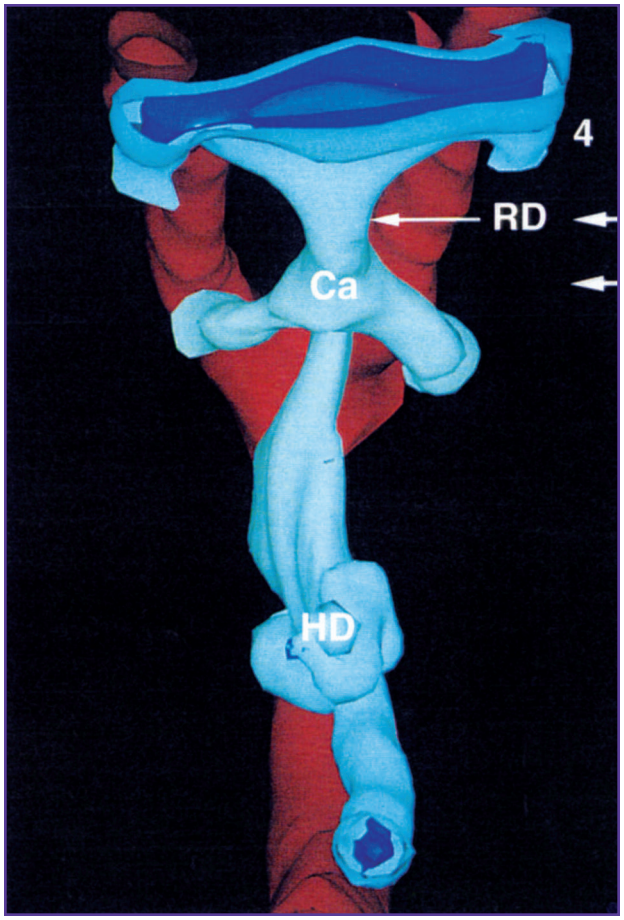


Figure 3–8. Stage 13 (28-somite mouse embryo). Ventral view of epithelial lining of foregut. Bronchopulmonary buds have continued to be drawn dorsocaudally from carina (*Ca*) due to cephalic rotation of embryo and because bronchopulmonary buds are tethered to septum transversum. Carina (*Ca*) develops from caudal aspect of respiratory diverticulum (*RD*). Two white solid arrows indicate distance between *RD* and *Ca*. *HD*, hepatic diverticulum. (Courtesy of John S Rubin, MD, Robert T Sataloff, MD, DMA, Gwen S Korovin, MD, and Wilbur James Gould, MD, from the book *Diagnosis and Treatment of Voice Disorders*. New York, NY: Igaku-Shoin Medical Publishers; 1995.)

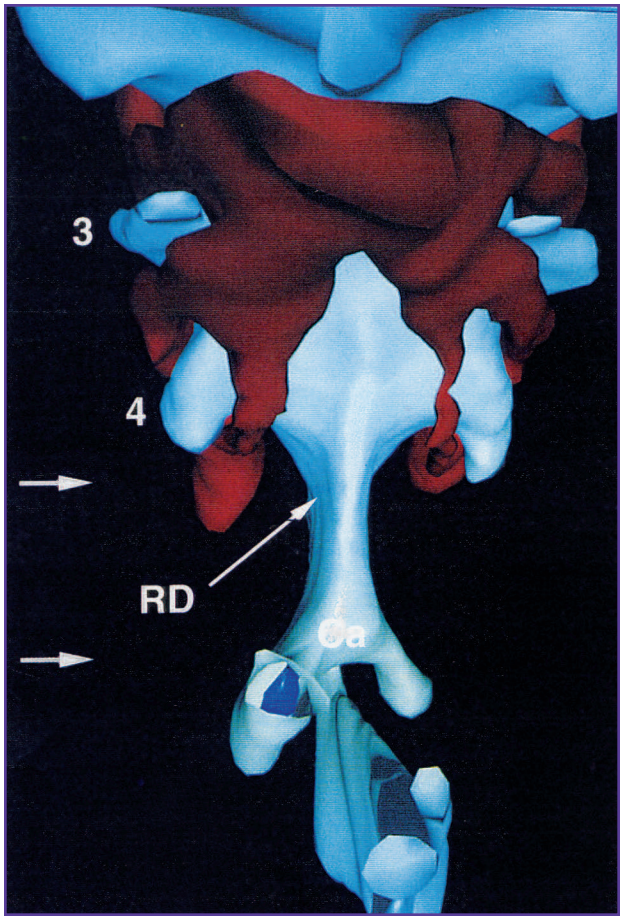


Figure 3–9. Stage 14 (35-somite mouse embryo). Ventral view of 3-dimensional reconstruction of epithelial lining of laryngopharyngeal region. Compared with Figure 3–8, lengthening of *Ca* from *RD* is demonstrated with two white solid arrows. Lengthening of this foregut segment will eventually give rise, in part, to developing trachea. Carina (*Ca*) continues to descend from site of respiratory diverticulum (*RD*). Numerals 3 and 4 are the third and fourth pharyngeal pouches. (Courtesy of John S Rubin, MD, Robert T Sataloff, MD, DMA, Gwen S Korovin, MD, and Wilbur James Gould, MD, from the book *Diagnosis and Treatment of Voice Disorders*. New York, NY: Igaku-Shoin Medical Publishers; 1995.)