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Anatomical studies on larynx and voice production in historical perspective

Andrzej Żytkowski[1], Jerzy Walocha[2]

[1]Faculty of Philology, Department of Polish Dialectology and Logopedics, University of Lodz, Poland
[2]Department of Anatomy, Jagiellonian University Medical College, Kraków, Poland

Corresponding author: Jerzy Walocha, Prof.
Department of Anatomy, Jagiellonian University Medical College
ul. Kopernika 12, 31-034 Kraków, Poland
Phone/Fax: +48 12 422 95 11; E-mail: jwalocha@cm-uj.krakow.pl

Abstract: Voice production — emission, raised interest of humans from almost the beginning of the humanity. First written information dates back to the Egyptian times 2500–3000 BC. Practically from early Greek period until XIX century studies of the larynx and the speech apparatus brought new and new facts, both regarding the structures, physiology and clinics. Such ancient researchers as Galen, Morgagni, Eustachii, Casserius created milestones for modern laryngology. Authors hoped to present some facts on the anatomical researches in the field of organs responsible for voice production from historical perspective.

Key words: larynx, voice production, history, anatomy.

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Introduction

Phonation is a process of voice production as a result of vibrations of the vocal ligaments under the influence of exhaled air, occurring in the larynx and leading to the formation of the so-called larynx sound. To create a sound, it is necessary for the respiratory system and larynx to work together. During speech or singing, the vocal folds stretch and approach each other to a few tenths of a millimeter creating a small gap. It is different in the case of breathing, because then the vocal folds are spread apart. To produce the sound, an adequate amount of air is needed, which when inhaled causes the vocal folds to vibrate. These vibrations consist of a cyclical, orderly, successive opening and closing of the glottis. However, this knowledge about the

participation of the larynx in the process of voice production has developed gradually. This work aims to trace, based on the available literature, the development of knowledge about the role of the larynx in the voice production and how this knowledge has evolved since ancient times. By design, the time-frame of this paper was limited; From ancient times to the 19th century, to trace the beginnings and development of basic anatomical knowledge. The 20th century brought such significant development of medicine and technology, including laryngology and phoniatrics, that tracking the discoveries during this period would require separate studies.

Ancient observations on human body and speech production

In ancient times, views on the functioning of the human body were derived from philosophical theories. One of the oldest known sources regarding medical knowledge is Edwin Smith papyrus dated to 17th century B.C. It is probably a copy of a much older text, which dates between 3000 and 2500 B.C. [1]. 48 medical cases have been described in the Smith papyrus, including head and neck traumas, as well as prognosis and treatment methods for individual injuries [2]. Smith's papyrus is proof that due to the ability to careful observations, ancient doctors were able to recognize many symptoms and assign them a prognostic value, while acquiring some knowledge of anatomy [2, 3]. The word "brain" was used in Edwin Smith papyrus for the first time in history, preceded by descriptions of gyri ("convolutions") and meninges [3]. Some data linking head injury with speech impediments can be found in description of sixth case, regarding an open fracture of the skull with displacement of the bones toward the brain and disruption of dura mater. As badly prognostic factors in head injuries were recognized fragments of the skull affecting the meninges, exposure of the brain, infected skull wounds, craniofacial fractures, deep penetrating skull wounds, and associated aphasia [4]. Thus, the Edwin Smith papyrus is one of the oldest medical sources, in which association between some brain injuries and inability to comprehend or formulate language (i.e. aphasia) was noted. Mentions of the throat and larynx as a source of voice can also be found in ancient medical documents from India, called Sushtrata, from 300 B.C. and Charaka, from the year 100 B.C. [5–7].

It can be assumed that ancient Greece, together with its area of influence, became the cradle of modern civilization [8]. Greeks are among the precursors of the natural philosophy and gave rise to the development of morphological sciences. Futhermore, the word larynx is derived from a similar Ancient Greek word *λάρυγξ* (which means *lárynx*) [1]. Alkmeon of Croton, living about 500 B.C., is considered the first to be known to have practiced dissections of animals. In addition, Alkmeon was the first who recognized the brain as an organ responsible for intelligence [1]. He believed that the senses were related to brain function through the channels (*poroi*); He is also thought to be the first to mention the pharyngotympanic tube, which was only rediscovered by Eustachi in the 16th century [1].

In the writings of Aristotle, who was not a physician but a thinker and philosopher, one can find references to zoology, anatomy and embryology. Aristotle's observations were based on animal dissections and on philosophical deliberations [1]. According to Aristotle, the heart was the focal point (*akrópolis*) of the body from which tendons and nerves emerged [8]. In addition, Aristotle correctly described the diaphragm with its muscular part and tendon center and determined the location of the trachea forward of the esophagus, although he considered the bifurcation of the trachea as connected to the large veins and the aorta. According to Aristotelian view, the heart was ultimate sense organ necessary for the thought process, pleasure-pain reaction, sense perception and imagination. The heart was also considered the thermal center of organism, as well as center of emotional response and movement. It is significant, that Aristotle recognized the heart as the origin of voice production [9]. Voice production was thought to be result of the soul activity around the heart. Anthon *et al.* cites the view of Aristotle, in the light of which: "nature uses breath for two purposes, refrigeration and the voice production"; Voice is striking of inhaled air against the windpipe (trachea) "under the influence of soul in these parts" [9]. According to Aristotle, the voice was the kind of sound that conveys meaning and its production is accompanied by image making faculty. Thus, the soul was thought to function during sense perception, affective reactions, communication of emotions by production of adequate sound, breath control and control of internal organs. In one of Aristotle's treatises (Historia Animalium, Book I, chapter XII) the larynx was first mentioned [10]. Nogueira *et al.* [10] provide an original Aristotelian description of the larynx: "the neck is the part between the face and the chest. Anteriorly is the larynx. Speech and breathing happens through it, which is protected by a structure known as the 'windmill' [probably the cricoid cartilage]".

From about 300 B.C. two Greek colonies — Alexandria in Egypt and Pergamos in Myzja — became one of the most important medical centers. The activity of two scholars — Herophilus of Chalcedony (335–280 B.C.) and Erasistratos of Keos (born around 250 B.C.) —took place at the heart of the medical developments (Harris, 1916). Erasistratos is credited with performing vivisection of animals and with a description of the laryngeal muscles [10]. In contrast, Herophilus is considered the "father of modern anatomy" [1]. Herophilus recognized the brain as a seat of intelligence, in Aristotle's it was the heart) and also described the arachnoid matter which he considered a seat of the soul (Persaud, Loukas and Tubbs, 2014). He linked the nerves that originated in the brain with the senses and distinguished those nerves from the nerves supplying the muscles responsible for the deliberate movements (Herophilus observed paralysis when group of nerves derived from the spinal cord was damaged). He used the term *neuron* to describe ligaments and tendons. He also discovered the hyoid bone (this bone provides attachment for the muscles of the floor of the mouth and of the tongue, for the larynx, and the epiglottis and pharynx).

Galen was a researcher who made a significant contribution to knowledge about voice production. The influence of Galen's works on medical sciences, including the understanding of the structure of the human body, stretched from Antiquity, through the Middle Ages, to the beginning of Modernity. Prioreschi [11] describes Galen as "second only to Hippocrates in medical hagiography". Galen was born in Pergamon, but data on the date of this event differ from one author to another — for example, Prioreschi [11] mentions the year 129 C.E., while Persaud, Loukas and Tubbs [1] give the year 131 C.E. Galen's birth coincided with the greatest flourishing of the Roman Empire [1, 11, 12]. In 162 C.E., Galen went to Rome, where he practiced and conducted public anatomical demonstrations on animals. His reputation grew rapidly, and with it the jealousy of other doctors. In 166 C.E. he returned to Pergamon, probably leaving Rome to avoid the plague. However, in 169 C.E., at the request of Emperor Marcus Aurelius, he returned to Rome, where he remained and worked until his death [11].

Galen dissected and vivisected various species of animals (Prendergast, 1928). Persaud, Loukas and Tubbs [1] suggest that probably in modern times Galen, the structure of humans and animals was basically considered same. Regarding larynx Galen wrote, that "This is constructed in the same way in the bodies of apes and men, a construction which is shared by other animals which have a voice" [1]. Galen's works presented new facts in every field of anatomy [13]. Galen observed "brain nerves", which he counted seven pairs, and also knew the course of spinal nerves [13, 14]. He conducted and accurately described medical experiments [15, 16]. He described the mechanism of pneuma circulation — a natural life force understood as "breath" or "spirit" [1]. Galen believed that it was only the blood coming into contact with the "breath" transported through the arteries that became the source of the "vital spirit" (Latin *spiritus vitalis*). The viable spirit was to reach the brain through the arteries, where it was transformed into "causative force" (Latin *spiritus animalis*) [1]. He also experimented with nerves — he knew the effects of transection of the laryngeal nerves (thereby undermining the view that the voice came from the heart), as well as he did damage to the spinal cord at various levels and observed the effects of these procedures [16]. He distinguished sensory and motor nerves [17, 18]. As Swanson [18] stresses, Galen provided brilliant description of the vagus nerve in macrodissected adult beef, pig and macaque, but not in human. Galen, as already mentioned, showed in his experiments, the connection between the intersection of recurrent laryngeal nerve and the disappearance of the voice produced by the larynx [17, 18]. Galen referred to vagus nerve as "sixth pair of nerves from brain", "great nerve" or "nervus tornabilis"; He also described the recurrent laryngeal nerve, which he described as "upward recurrend nerve" [18]. Gross [17] reports that Galen accidentally cut the recurrent laryngeal nerve during the vivisection of the pig (during experiments on nerves that control breathing); The animal stopped squealing, but still struggled.

After those incidental finding, Galen traced and dissected recurrent laryngeal nerve in various species, including long-necked birds [17]. Thus, Galen was first who proved, that bilateral section of the recurrent laryngeal nerve cause inability of vocalization. Galen also properly described topographical relations of the recurrent laryngeal nerves as wrapping around aorta, on the left side, or around the subclavian artery, on the right side [17]. Galen understood the significance of nerves in a purely mechanical way; The nerve caused movement by pulling the tendon [19]. Based on this assumption, explained the retrograde course of the larynx nerves by wrapping around the vessels behaving like a rope wrapped around a pulley. According to Galen, the tendon and partly the nerve were responsible for the movement [19].

From a renaissance scientific revolution to the 19th century

Many researchers and thinkers have contributed to knowledge of larynx anatomy and voice production since the period of the renaissance scientific revolution. During this period, both the doctors and some artists dealt with exploring the secrets of anatomy. At the down of medieval period Mondino de Luzzi made efforts to introduced dissections of the human body to the medical curriculum, He also provided a very basic explanation of the larynx [1]. The famous artist, Leonardo da Vinci, dealt with human anatomy. He presented his own concepts and descriptions of function of the larynx. The first laryngectomy was probably performed by Brasavola in Italy in 1545 [10]. Realdo Colombo corrected many misconceptions regarding the muscles found in the magnificent work of Andreas Vesalius and described the larynx [1].

Bartolomeo Eustachi, also known as Eustachius, was a supporter of Galen's physiology and an opponent of Vesalius. However, the conservative attitude did not prevent him from making numerous discoveries on the field of anatomy. He was the first to give an accurate anatomical description of the pharyngotympanic tube (hence the eponym "Eustachian tube") — only scant references to the existence of this structure had previously existed in the ancient writings of Alkmeon, Aristotle and Celsus [20]. He was also the first to consider the chorda tympani as a nerve [21]. In addition, Eustachi correctly described the onset of the optic nerve and made detailed descriptions of — the thoracic duct, the uterus; cochlea; tensor tympani and stapedius muscle; as well as laryngeal muscles [1] (Fig. 1). He also illustrated some "ossicles of the larynx" [1] (Fig. 1). These achievements caused that Eustachi gained the opinion of one of the most eminent researchers of his time [22]. It is worth to mention, that separate drawing showing larynx may also be found in *Tabulae anatomicae* of Pietro de Cortona (1596–1669) and in *Essai d'Anatomie* by Gautier D'Agoty (produced in 1745 in Paris).

Also, Giovanni Morgagni in the work *Adversaria Anatomica Prima* presented detailed illustrations of the larynx (Fig. 2). He also described the recurrent laryngeal nerve as "posterior fibers of the vagus nerve" [18]. However, the term vocal cords was

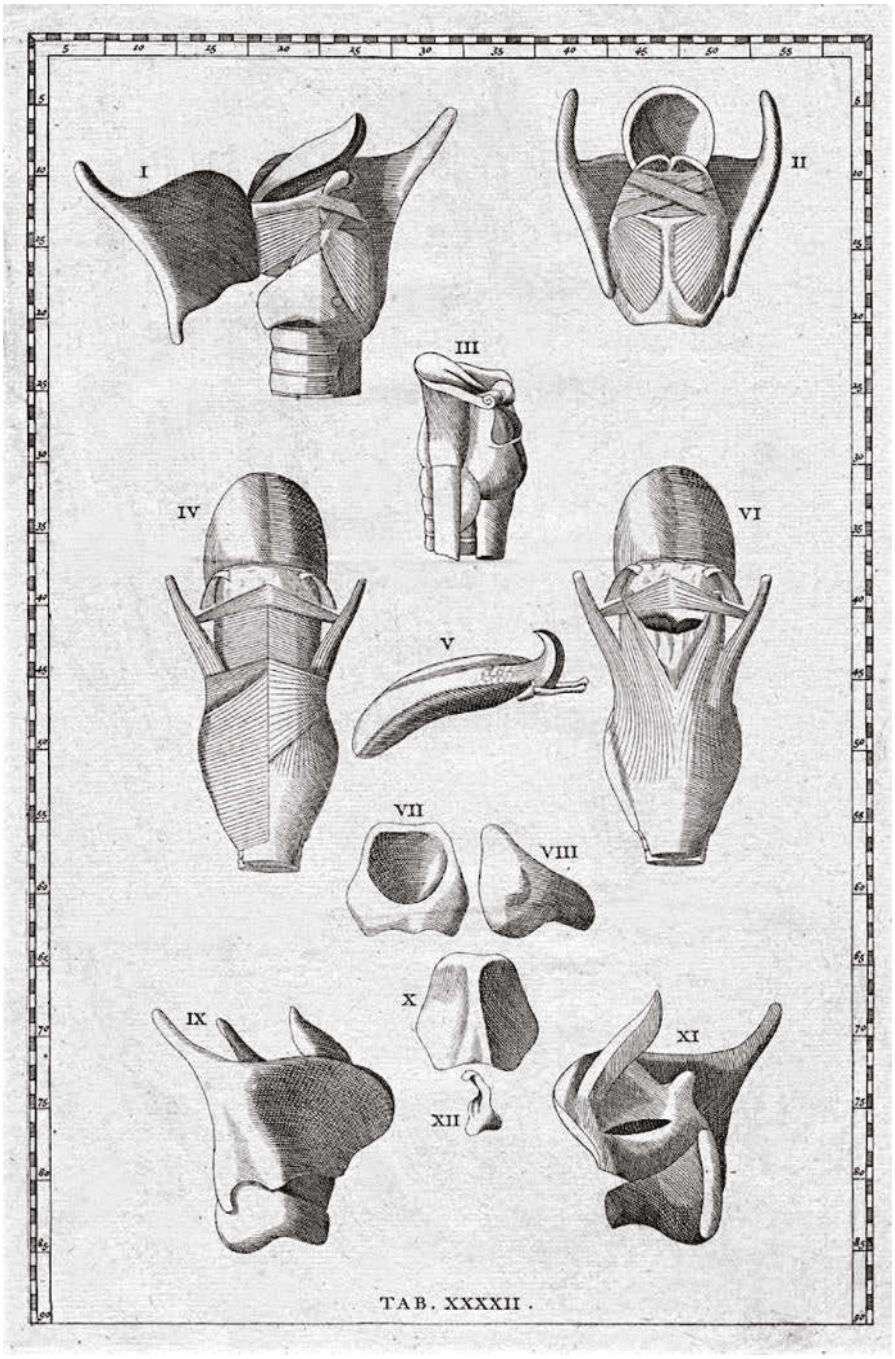

Fig. 1. Bartolomeo Eustachi. *Tabulae anatomicae*. Five miniatures showing the structure of the larynx. From the first author's own collection.

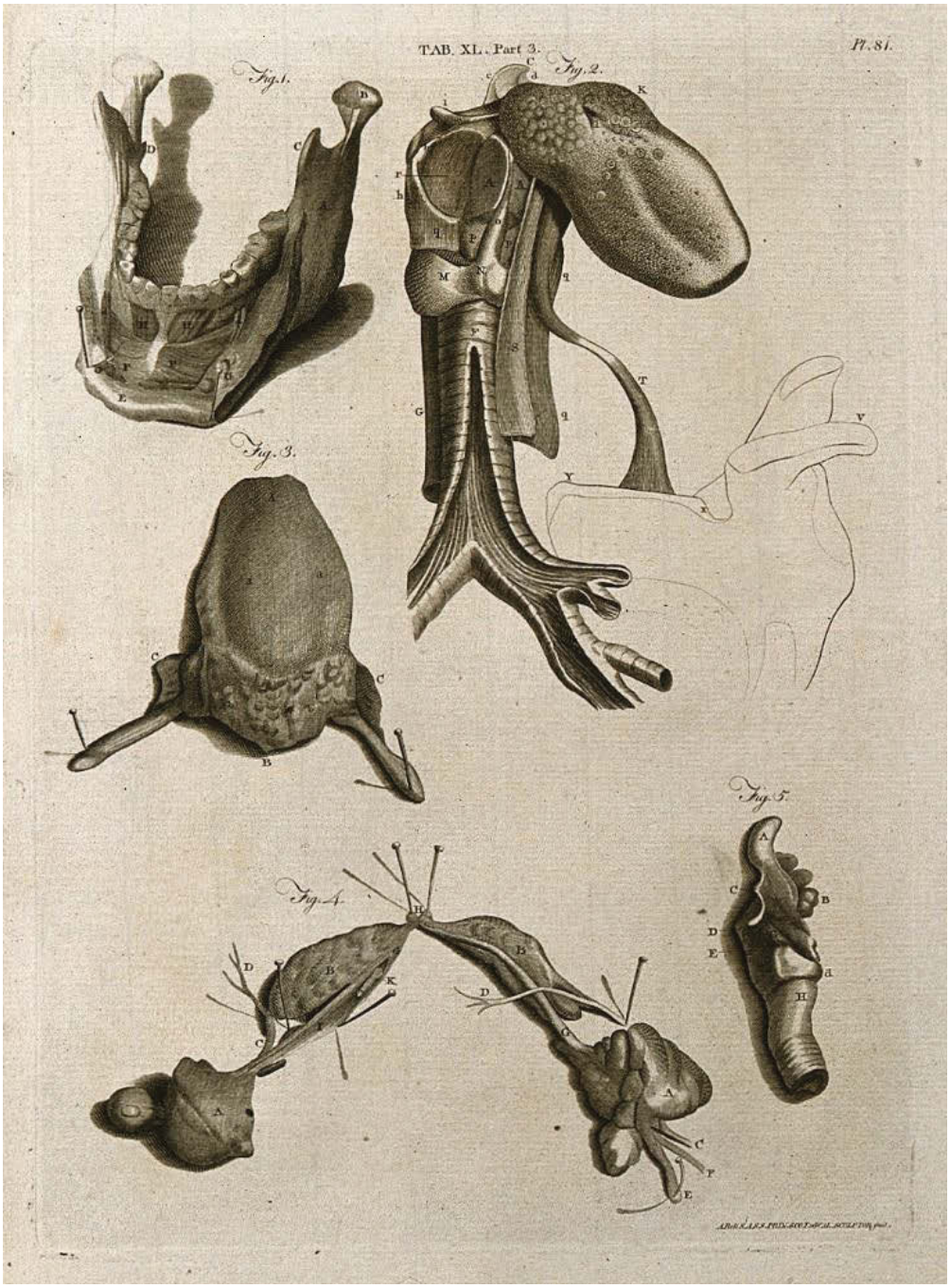

Fig. 2. Parts of the jaw, tongue and larynx: five figures. Line engraving by A. Bell after W. Cowper and G.B. Morgagni, 1798. Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

first used by Ferrein in 1741. Ferrein compared the vocal cords to the violin; According to this researcher, the vocal cords were activated by contact with a stream of air coming out of the respiratory tract [23]. Bertin in 1745 supplemented the description of the vocal cords, introducing the concept of vocal folds [23].

Iulius Casserius was a revolutionary anatomist, teacher and pioneer of the sixteenth and seventeenth century [24]. Giulio Cesare Casseri (1552–1616), also known as Iulius Casserius, was born in the Italian city of Piacenza. To earn for a living, he took a job as a servant of Girolamo Fabrici d'Acquapendente — the famous anatomist and professor of Università Artista in Padua — who soon became his mentor (William Harvey was also one of Fabricius pupils) — [24, 25]. Probably around 1580 Casserius graduated from the Università Artista with a diploma in medicine and philosophy. After acquiring medical education, Casserius performed autopsies for Fabrici and practiced medicine and surgery, quickly gaining recognition.

Casserius was the author of three anatomic treatises, of which only two — *De vocis auditusque organis historia anatomica* (1600–1601) and *Pentaestheseion, hoc est de quinque sensibus liber...* (1609) — appeared during his lifetime. Casserius's first anatomical — work *De vocis auditisque* — consisted of two treatises: *De larynge vocis organo* (printed in 1601) and *De aure auditionis organo* (printed earlier, in 1600). Choulant [26] reports that the work contained 34 anatomical plates, of which 22 concerned the organs of voice production (for example see Figs. 3, 4) and 12 the ear (Fig. 5). Heister [27] also referred to elegant engravings in treatises of Casserius. In *De vocis,* one can find innovative elements both in the descriptions and in the figures (Figs. 3–5). A precise description of the larynx also comes to the fore in this work [28]. For the first time, it is stated in *De vocis* that the skeleton of the larynx is cartilaginous, not bony. The Italian anatomist, Giovanni Domenico Santori (1681–1737), in turn, was the first who described the corniculate cartilage of the larynx [1].

The laryngeal ventricles and muscles of larynx have been correctly illustrated (Fig. 3) [29]. In his treatise, Casserius also contained detailed illustrations of recurrent laryngeal nerves, which, as already mentioned, were first examined (in experiments carried out on live pigs) and described by Galen in the second century — hence the eponym *nervus recurrens Galeni* [18, 30]. Casserius also described the muscles of the tongue as well as supra and infrahyoid muscles. Unlike his contemporaries, he believed that the tongue is not a single muscle. However, he incorrectly recognized the vagus nerve and the glossopharyngeal nerve as a single cranial nerve. He also considered the parotid duct to be a nerve (only Wharton in 1656 gave the correct description of the duct) [29].

Casserius, based on Galen's system, subordinated his research to determining the structure, function and significance of a given organ. The model for his anatomical inquiries was the human organism, at various stages of individual development, which he compared with various animal species. A huge achievement of Casserius was the

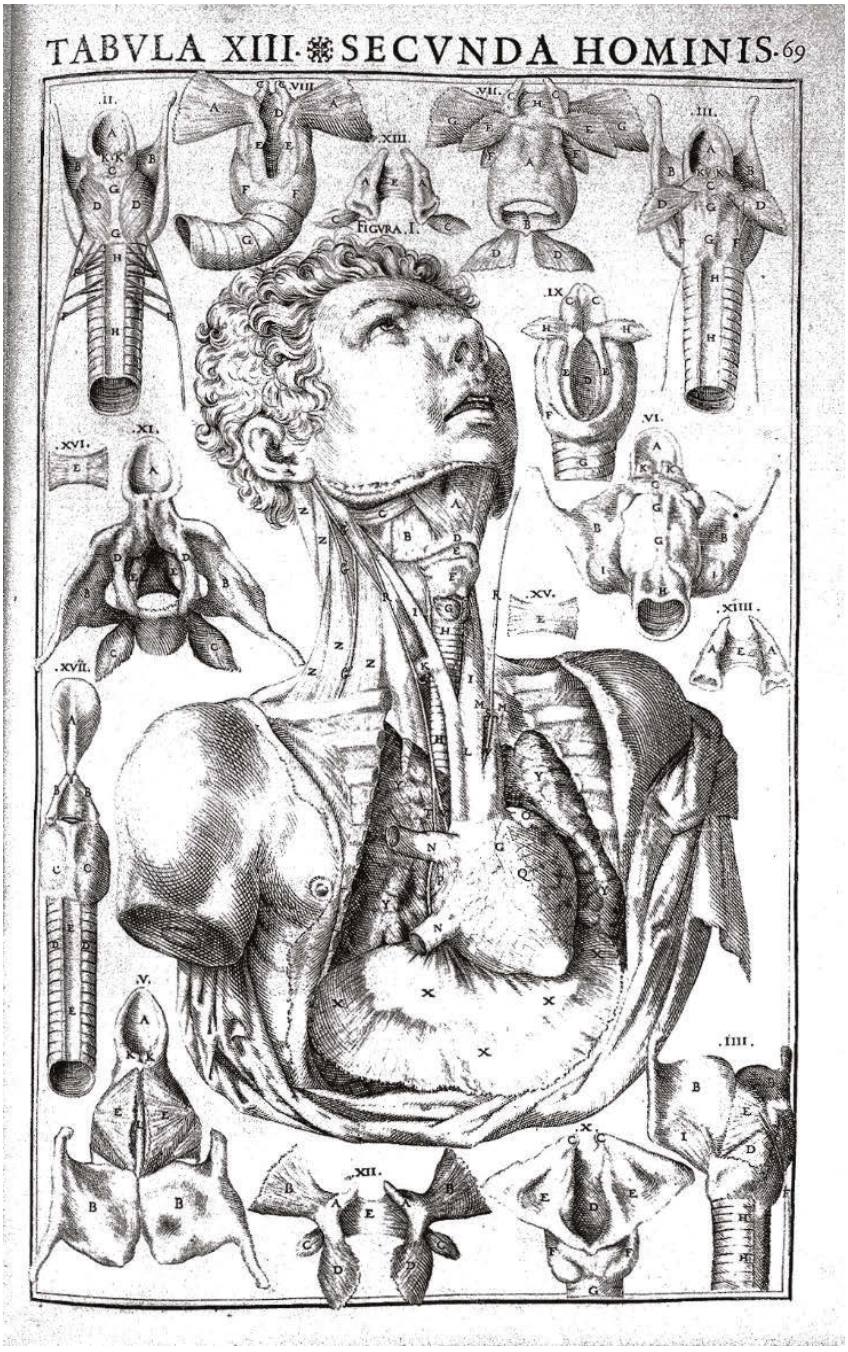

Fig. 3. Julius Casserius, *De vocis auditusque organis historia*... Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

first comparative study of vocal and hearing organs. In *De vocis auditisque* there are figures presenting the structure of the voice organ in various mammals. The individual illustrations show the larynx as well as the supra- and infrahyoid muscles in humans (Fig. 3), pigs, cattle and cats. Casserius was the first to give an accurate description of the cricothyroid muscle. The treatise also includes an illustration showing the sound organs of insects (including cicadas). Thus, *De vocis* was one of the most ambitious and detailed reports in the field of comparative anatomy that arose at the turn of the 16th and 17th centuries. In the second part — *De aure* — Casserius included the first detailed comparison of the auditory ossicles, a detailed description of the bony labyrinth, as well as the discovery of the inner ear in fish (Fig. 5) — the latter was remarkable because it was not known before that fish have a sense of hearing (Crombie, 1995, pp. 284–285).

In *De vocis*, there is also an illustration of laryngotomy (Fig. 4). This plate was a precursor reference to surgical anatomy. The technique of performing the laryngotomy procedure and the necessary equipment were also described. Regarding the name of the procedure, Heister [27] states that the operatin was carried out within the trachea (*trachea seu aspera arteria*), so the terms "laryngotomy" or "bronchotomy", widespread among contemporary doctors and surgeons, should be replaced by the term "tracheotomy". Pelizzo, Boschin and Ragona (2014, pp. 78–79) report that tracheotomy is one of the oldest known operations; Homer recalled that Alexander the Great saved one of the soldiers from suffocation by opening the larynx with a sword blade.

As Nogueira *et al.* [10] emphasized, a huge obstacle in anatomical examinations and clinical evaluation of the larynx was the inability to see the inside of this organ. This situation changed in 1806 when Bozzini developed special angled speculum with a mirror, used to "examine the most varied human cavities" [10, 23, 31]. Several years later, in 1837, physiologist Johannes Muller, in Berlin, analyzed the movement of vocal cords in cadavers, using electrical impulses to stimulate muscle contraction [10, 23, 32]. In 1829, Benjamin Ebbington performed laryngoscopy using a device called "glottiscope" [10]. However, the first successful use of the mirror to control the larynx was not made by physitian, but by the Spanish music professor – Manuel Garcia – in 1854 [10]. To this end, Garcia used a small mirror, used by dentists and adequate lighting. Using this equipment, Garcia observed the behavior of his own vocal folds during breathing and vocalization; As a result, he published many books on voice [10]. Based on those basic discoveries, further periods brought significant development of laryngology and phoniatrics.

Fig. 4. Tracheotomy from Casserius, *De Vocis Auditusque Organis...* Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

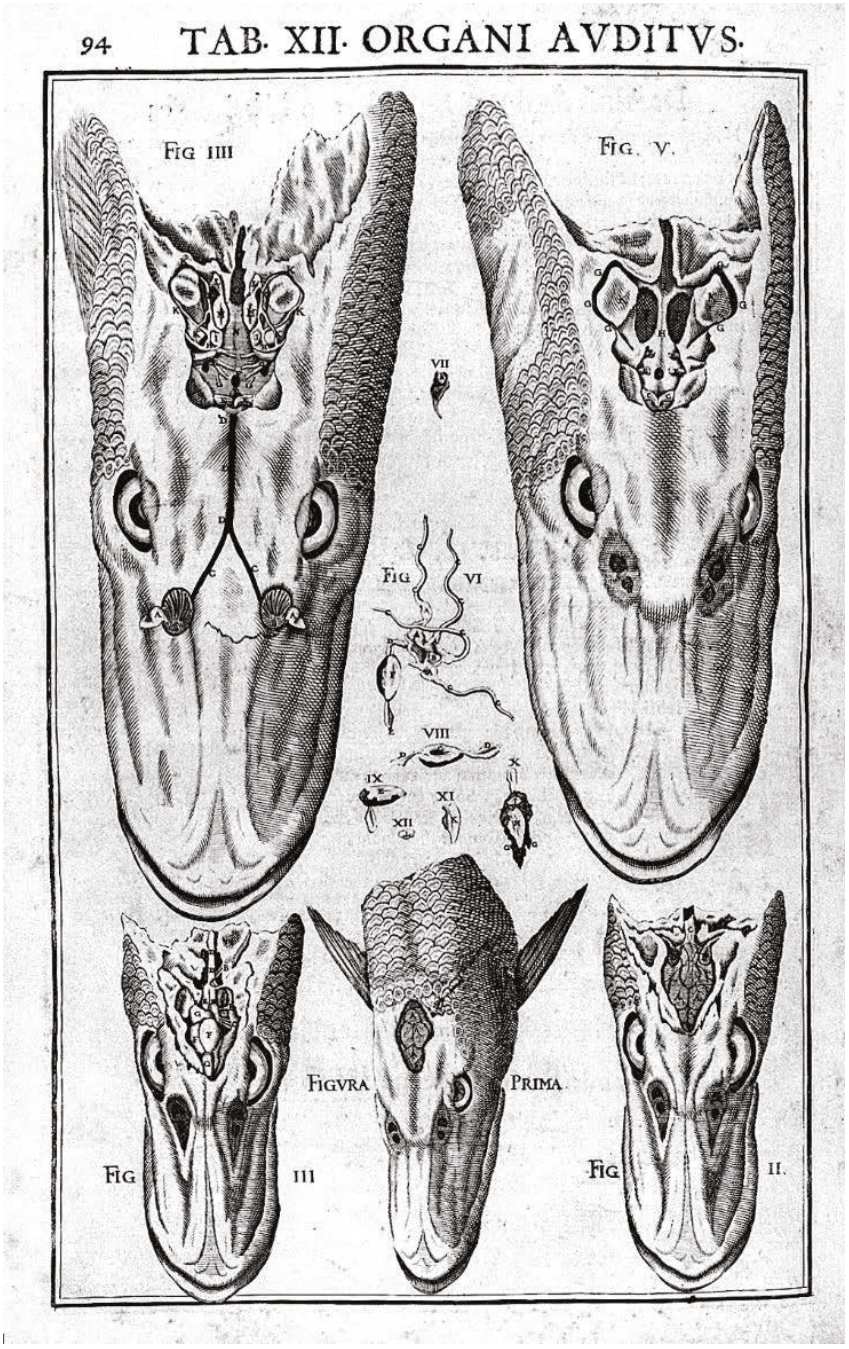

Fig. 5. Casserius, De Vocis Auditusque Organis Historia Anatomica... Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0).

Conclusions

Studies on anatomy of the larynx and voice production have rich and centuries-old tradition. Gradual development of anatomical knowledge and technique enabled a thorough understanding of both the detailed structure of the larynx and mechanisms conditioning the function of this organ.

Conflict of interest

None declared.

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