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Pharyngeal, upper esophageal sphincteric and esophageal pressures responses related to vocal tasks at the light of high resolution manometry

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ABSTRACT – Background – High-resolution manometry (HRM) represents a potential tool for measuring pharyngoesophageal phonation pressures. **Objective** – This study aims to evaluate pharyngeal, esophageal upper sphincteric and esophageal pressures during different phonation tasks. **Methods** – 12 (six males, mean age 27 years) professional singers underwent HRM and produced four different vocal tasks at low, medium and high vocal loudness: vowel /ae/, ascending five note scale, word /hey/ and word /go/. Pressures were measured at pharynx, upper esophageal sphincter (UES) and esophagus. Visual analysis of the HRM topographic plots were performed. **Results** – Esophageal pressures are higher during vocalization than at rest. Pharyngeal and UES phonation pressures does not differ significantly from rest pressures. Visual analysis of the topographic plots showed an important UES pressure increasement during phonation. **Conclusion** – HRM is a valuable tool for measuring pharyngoesophageal pressures during phonation. Esophageal pressures are higher during phonation than at rest and tend to increase with vocal loudness increment. The topographic plot provides additional data about phonatory mechanism physiology, especially at the UES region.

Keywords – Pressures; pharynx; esophagus; manometry; voice; phonation.

INTRODUCTION

Phonation involves the conversion of aerodynamic energy into acoustic energy. Aerodynamic energy is produced in the pulmonary system to drive an airstream through the vocal tract when elastic energy is stored and retrieved in stretched tissues, and kinetic energy is developed in tissue and air during oscillation of the vocal folds[1]. All of those energy conversions involve pressure gradients along the vocal tract and thus pharyngoesophageal segment.

First attempts to obtain voice pressure gradients employed water and mercury manometers for esophageal recording pressure with a catheter introduced through the nose covered by a balloon or directly exposed[2-4]. Oral pressure transducers, a cumbersome indirect method that jeopardizes natural speaking or singing is still in use[5,6]. Percutaneous needle catheters inserted in the subglottis are also currently employed despite its invasiveness[7]. High-resolution manometry (HRM) – with multiple closely spaced pressure transducers along a transnasal catheter – offers a new possibility of voice pressure measurements along the entire pharynx and esophagus.

HRM application was initially aimed to evaluate esophageal motility. Recently; however, this technology demonstrated usefulness to the study of the pharynx due to its capacity of recording pressures in asymmetrical structures, offering the spatial and temporal resolution necessary to capture pharyngeal events[8-13]. HRM has already been recognized by the American Speech-Language-Hearing Association (ASHA) as an adequate tool for the evaluation of swallowing and represents one of the emerging procedures in speech-language and otolaryngology practice[14-16], although the number of dedicated studies on voice are; however, small[17-19].

This study aims to evaluate pharyngeal, esophageal upper sphincteric and esophageal pressures during different phonation tasks.

METHODS

Twelve professional singers (50% males, median age 27 (21–36) years) were prospectively studied. All subjects were professional popular singers with at least 3 years of singing practice. Subjects with gastroesophageal reflux disease symptoms, ear, nose or throat disorders or under medication that could affect esophageal motility were excluded.

As participants would have to perform different vocal tasks at the same pitch in different loudness, non-singers were excluded in order to control such variable.

Study protocol

Participants were positioned on an upright position after at least 8 hours of fasting to avoid nausea. HRM catheter was lubricated with 2% viscous lidocaine and inserted tans-nasally by a gastroenterologist into the esophagus and positioned in a distance to allow visualization from the pharynx to the middle esophagus. Participants were instructed to keep their heads in a neutral position. All participants were instructed to acclimate with the catheter before the recordings began.

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During those minutes of accommodation, participants were encouraged to talk in order to get adapted to phonate with the catheter in place.

Per protocol, participants were asked to perform the following phonation tasks at low, medium and high volume being the sound intensity self-monitored:

1. To sustain the vowel /ae/ at habitual pitch on modal register.
2. To perform a 5 note ascending scale with the vowel /ae/ at habitual pitch on modal register.
3. To pronounce the word /hey/.
4. To pronounce the world /go/.

Participants were instructed to make clear vocal differences between volume levels and keep the same pitch. All participants could repeat the vocal tasks until satisfied with their performance.

Those specific vocal tasks were selected in order to observe and compare pressure patterns during a sustained voiced phonation (task 1), during voice pitch variations (task 2), during phonation initiating with a non-voiced segment (task 3) and during phonation initiating with a plosive velar segment (task 4).

Equipment

A solid-state manometric assembly with 36 sensors spaced 1 cm apart (4.2 mm outer diameter) was used (ManoScan 360; Medtronics, Minneapolis, USA). Each sensor includes 12 radially placed elements creating an average pressure of all circumferential transducers. All of these sensors are capable of recording pressure transients in excess of 6.000 mmHg/s. Pressure calibration at 0-300 mmHg was done before each study by using the automatic external calibration system of the catheter assembly.

Manometric variables

Data was obtained by dedicated software (ManoScan, Medtronics, Minneapolis, USA). As the software is standardized to extract only swallowing events measures, the extraction of phonation pressure values were performed manually at the point of highest pressure. Pressures were measured at the following areas during rest and vocal tasks: (1) Pharyngeal pressure – at the level of the velum[20], (2) upper esophageal sphincter (UES) pressure; and (3) Esophageal pressure – 2 cm bellow the lower border of the UES (FIGURE 1).

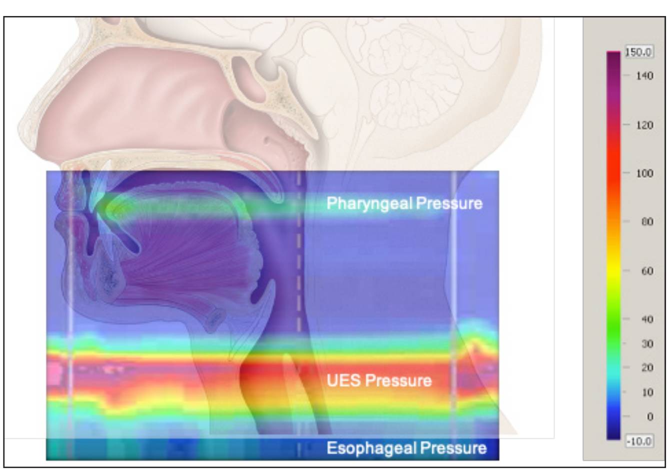

FIGURE 1. High resolution manometry plot demonstrating pharynx, upper esophageal sphincter and esophageal regions.

Plots were reviewed for visual identification of possible pharyngoesophageal observations during phonation. HRM software converts manometric information into distinct patterns that illustrate the physiology of contractile coordination where red represents high-level pressure and blue low-level pressure. So, areas with increased pressure are easily identified by color changes in the pharyngoesophageal topography (FIGURE 1).

Additionally, pressure efficiency gradient (PEG) was proposed by the authors and defined as the difference between the esophageal pressure (EP) and the pharyngeal pressure (PP).

Manometric data was reviewed and analyzed by an experienced esophageal physiologist with over 15 years of experience.

Ethics

The project was approved by local Ethics Committee and all participants signed a consent form before entering the study. There is no conflict of interest. The authors are responsible for the study, no professional or ghost writer was hired.

Statistics

Shapiro Wilkins test was used to assess normality distribution. Wilcoxon test used for comparisons. Variables are expressed as median (interquartile). $P<0.05$ was used as significant.

RESULTS

Pressures in different segments according to vocal tasks are depicted in TABLE 1. Esophageal pressures during phonation was consistently higher than rest pressures. The speaking task of the words /go/ and /hey/ – performed at different loudness – only exhibited significant esophageal pressure increment at high intensity.

TABLE 2 shows PEG according to different vocal tasks and anatomic area. PEG increased according to vocal intensity for /ae/, /go/ and /hey/ vocalizations.

Visual analysis of the topographic plots during all phonation tasks at low, medium and high intensities are disposed at FIGURES 2–5. An increasement in UES pressure was noticed during sustained vowel /ae/ and five note ascending scale. When comparing low to medium intensity vocalization plots, the upper part of the UES seems to be first recruited followed by the lower part. Also, there is a noticeable increase in UES pressure in higher pitches as compared to low pitches during the ascending 5 notes scale.

DISCUSSION

The variation of air pressure in the vocal tract synchronized with the vibration of the vocal folds constitutes the voice. Since air pressure provides the energy for vocal folds vibration, the course of this pressure impact through the vocal tract is relevant to the study of phonation[21]. HRM has proved to be a feasible technology for some measurements providing valuable information regarding pharyngoesophageal pressures during phonation.

In our view, HRM represents a technological advance on Van den Berg's pioneering idea in 1965 of obtaining subglottic pressure from esophageal pressure acquisition, although a small discomfort is still present. We see three main advantages of the method: (1) HRM provides more data than the esophageal balloon based on multiple circumferential sensors closely spaced that together offer accurate location of each pressure zone, allowing not only more accuracy, but also greater area of coverage; (2) measuring phona-

TABLE 1. Pressures (mmHg) in different segments according to vocal tasks and statistical differences pressure values.

Vocal task	Pharynx		UES		Esophagus		Loudness comparison statistical differences	
	Median		Median		Median			
Rest	-1.6	(-3.5–3.7)	88.9	(78–115.2)	0	(-1.1–0.6)		
/ae/								
Low	0.9	(-0.6–5.9)	91.9	(67.9–153.1)	7.8	(3.5–17.7)	EP	PP
Medium	0.3	(-0.6–6.6)	96.5	(69.7–109.7)	9.1	(1.8–14.3)	Rest x Low *P*=0.0022	NS
High	1.3	(0–5.1)	130	(89.3–211.8)	16.2	(4.1–46.3)	Rest x Medium *P*=0.0061 Rest x Strong *P*=0.0007	UESp NS
Scale								
Low	0.6	(-0.3–4.4)	95.6	(81.3–141.3)	8.9	(4.3–15.9)	EP	PP
Medium	0.3	(-0.2–4)	96.9	(72.8–181.2)	9.1	(6.3–17.2)	Rest x Low *P*=0.0027	NS
High	0.3	(-0.3–6.9)	108.4	(96.5–179.3)	15.6	(9.3–33)	Rest x Medium *P*=0.0020 Rest x Strong *P*=0.0002	UESp NS
/hey/								
Low	0.5	(-0.2–7.7)	97.1	(77.7–151. 5)	2.4	(-1.5–7.7)	EP	PP
Medium	0.7	(-0.1–7.9)	116.6	(81.9–171.5)	6.7	(2.3–19)	Rest x Medium *P*=0.011	NS
High	1.0	(0–2)	156.1	(108.6–223.7)	11.3	(6.5–23.2)	Rest x Strong *P*=0.0002 Low x Strong *P*=0.035	UESp NS
/go/								
Low	0.9	(-0.2–4.3)	93.3	(79.3–136.5)	5.1	(0.7–14.7)	EP	PP
Medium	1.5	(0.6–6.6)	94.6	(75.1–119.4)	7.1	(0.5–11.4)	Rest x Low *P*=0.0153	Rest x Medium *P*=0.02
High	1.1	(0.1–3.5)	113.4	(94–143.6)	15.1	(10.1–30.9)	Rest x Medium *P*=0.0061 Rest x Strong *P*=0.0002 Medium x Strong *P*=0.0141	UESp NS

UES: upper esophageal sphincter; EP: esophageal pressure; PP: pharyngeal pressure; UESp: upper esophageal pressure; NS: non-significant.

TABLE 2. Pressure efficiency gradient in different segments according to vocal tasks.

Pressure values	/ae/		/scale/		/hey/		/go/	
	Median		Median		Median		Median	
Low	10.6	(1.3–10.6)	5.9	(0.3–12.4)	-1.3	(-2.6–2.8)	2.8	(-0.3–4.1)
Medium	2.8	(0.1–14)	8.6	(0.1–12.7)	1.3	(-3.2–1.3)	5.4	(-0.3–9)
High	42.8	(4.4–42.8)	12.8	(2.3–23)	9.9	(6.8–19.8)	15.1	(6.2–30)
Loudness comparison	MDif	*P*	MDif	*P*	MDif	*P*	MDif	*P*
Low x Medium	-0.75	0.79	1.66	0.56	1.91	0.50	-0.83	0.77
Low x High	-4.91	0.088*	-4.5	0.11	-8.41	0.0035*	-7.08	0.0141*
Medium X High	-5.75	0.0464*	-4.08	0.15	-5.16	0.073	-8.16	0.0046*

Nonparametric comparison Wilcoxon Test. MDif: mean difference. *Significant statistical difference.

tion pressures using HRM allows natural samples of speech and sing, as the larynx and mouth are free for vocalizations, despite the presence of a nasoesophageal tube; and (3) HRM offers valuable information about every pharyngoesophageal segment on a dynamical and real time way representing furthermore a feasible tool for biofeedback[22].

According to our data, when comparing pharyngoesophageal rest pressures with phonation pressures, only the esophageal area presented a significant pressure augmentation. Moreover, it seems that voice intensity increment leads to higher esophageal pressure magnitude for both singing (sustained vowel and ascendant scale) and speaking tasks (words). Thus, esophageal pressure obtained may somehow reflect the subglottal pressure which is the determining force for obtaining different vocal intensities for singers[23,24]. During singing abdominal and thoracic muscles are recruited to increase subglottal pressure[25] this may lead to the consequent increased esophageal pressure found in our results. Whether increased intraabdominal pressure also corroborates to the increased esophageal pressure due to common cavity phenomena and consequent esophageal pan-pressurization or pan-presurization occurs due to increased intra thoracic pressure in the context of a closed UES and closed lower esophageal sphincter and esophageal shortening is uncertain.

The UES acts as a mechanical barrier against the entry of esophageal contents into the pharynx and also against the ingress of air into the esophagus[26]. Our results did not show a significant distinctive UES pressure when comparing rest and vocalization pressures unlike previous studies with HRM[17,19]. These previous studies suggested a UES reflex increase in response to higher intraesophageal pressure to prevent gastroesophageal reflux into the pharynx[17]. The disagreement between our data and previous publications may be related to variances in methodology that

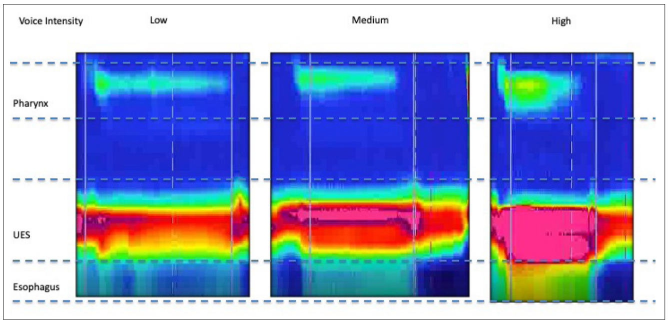

FIGURE 2. High resolution manometry topographic plot during vowel /ae/ performed at low, medium and high intensities.
UES: upper esophageal sphincter.

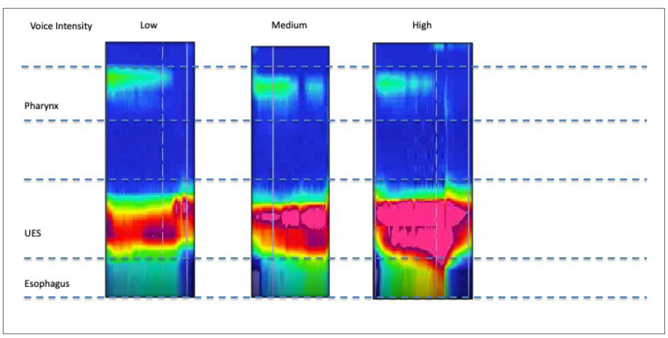

FIGURE 3. High resolution manometry topographic plot during ascending 5 note scale performed at low, medium and high intensities.
UES: upper esophageal sphincter.

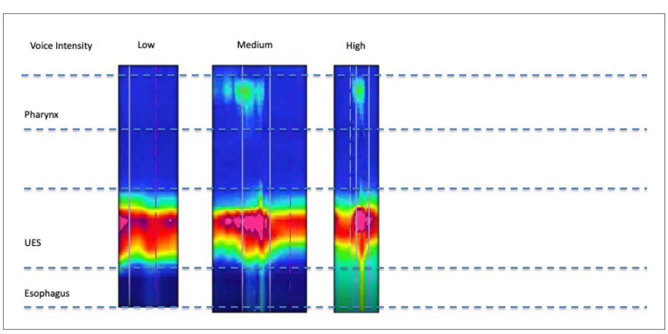

FIGURE 4. High resolution manometry topographic plot during word /hey/ performed at low, medium and high intensities.
UES: upper esophageal sphincter.

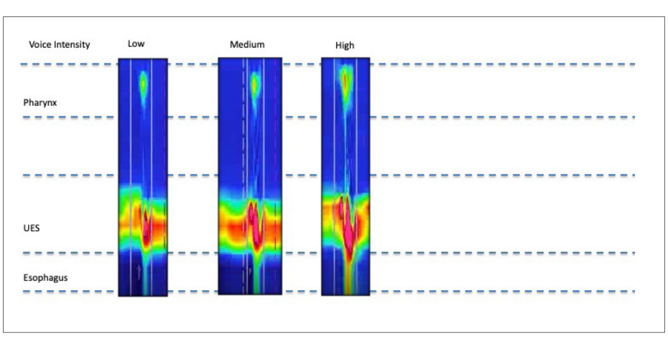

FIGURE 5. High resolution manometry topographic plot during word /go/ performed at low, medium and high intensities.
UES: upper esophageal sphincter.

led to distinct laryngeal movements that ultimately affect UES pressure(17,27). First, our study followed a rigid protocol asking each subject to vary the loudness and keep the same pitch while performing the vocal tasks – by the way, this is exactly the reason why we recruited only singers as subjects once during pilot studies, non-singers usually increased pitch while asked do increase volume. Second, pharyngoesophageal physiology may be different when singers and nonsingers are compared. Third, the degree of laryngeal muscle tension engaged by nonsingers to perform vocal tasks and the optimized airflow conduction performed by singers may somehow decrease the need of UES pressure engagement during phonation as it can suffer interference from the compression of any paralaryngeal musculature(10) frequently observed in subjects without vocal training while performing vocalizations in different intensities and frequencies(28).

Recent studies have evaluated pharyngeal configuration during different vocal tasks using magnetic resonance (29,30) but the assessment of the pressures at this area during vocalization have been neglected. In our study, we did not show a direct correlation between pharyngeal pressure and sound intensity. This fact may also be explained by our sample of experienced singers which is generally instructed to improve vocal tract inertance widening the pharynx walls for a better resonant voice(31). Among the tasks performed in our protocol, we included sustained and ascending scale using the vowel /ae/, voiceless sounds ("h" from "hey") and a plosive velar consonant ("g" from "gol"). The velar sound produces a brief blockage and a build up of pressure in the breath stream(32). As expected, the word "go" promoted higher pharyngeal pressures due to /g/ tract configuration. This characteristic has already been observed and explored by Takasaki(9) when requesting their subjects to vocalize a plosive consonant "ka" to easily locate the region of the velopharynx in the topographic manometric plot.

The possibility of a real time spatial temporal topographic plot is considered the greatest HRM contribution(33). In our research, this technological advance brought interesting elements about the pharyngoesophageal segment contraction physiology during phonation at different intensities. Most of the HRM studies related with voice focused on pressure values, but the greatest contribution of this technology is the real time observable anatomophysiologic characteristics based on visual analysis of the plots (FIGURE 1).

Interestingly, we found that UES muscle bundles recruitment may be related to vocal intensities. Our data indicates initial predominance of the inferior pharyngeal constrictor contraction during moderate phonation intensity followed by the cricopharyngeal contraction during higher intensity. This phenomenon can be better observed throughout sustained vowel task. Future HRM associated with electromyographic studies could confirm this possible selective contraction of the muscles that make up the UES. Furthermore, at the ascending 5 note scale plots, it is feasible to notice by the color intensity that as higher the pitches, higher the pressure patterns. Indeed higher subglottic pressure is required for increased vocal frequency(34-37) confirming that pharyngoesophageal structures pressures are susceptible to aerodynamic changes and also by laryngeal changes. As the cricopharyngeal insertion is precisely in the cricoid cartilage, the UES and larynx are required to move together(38). At the 5 note ascending scale topographic plot this connection becomes evident and it is possible to observe a slight elevation of the UES region tracing representing the laryngeal vertical excursion.

The possibility of getting simultaneous esophageal and pharyngeal pressure allowed the calculation of the PEG through which we indirectly estimate energy input at the esophageal pressure in response to subglottal and thoracic pressure (E_p) and energy dissipation along pharyngeal tract (P_p). The result of E_p minus P_p is the amount of aerodynamic pressure that can be converted into acoustic. Glottal efficiency has traditionally been defined as the radiated acoustic power from the mouth divided by the pulmonary aerodynamic power delivered by the lungs[39,40]. It has great theoretical appeal because it relates an acoustic output to an effort input[41]. Our proposal of PEG associated with sound pressure level (dBSPL) and airflow measures may benefit both voice professionals and patients who need to develop more economical vocalization patterns. This gradient would also offer valuable information about vocal tract adjustment interference, sound conduction and aerodynamic to acoustic energy conversion process.

Study limitations

This paper represents a modest contribution to the application of the HRM to the voice science; however, it is the first study attempting to study correlation between phonation pressures and voice intensity using HRM. In the future, this information may help to identify voice dysfunction caused by the lack of technique and many other vocal tract imbalances. These reference values also may be used to be compared in the study of patients with vocal disorders. In hyperfunction diseases, such as muscle tension dysphonia, pharyngeal pressures may be increased and HRM may be used as a biofeedback tool to balance these pressures. The same may apply to hypokinetic diseases such as Parkinson disease. Moreover, HRM may be used to measure tremor frequency in some spasmodic neurologic dysphonias.

The study is limited by the small number of individuals since most singers recruited refused to have a nasoesophageal catheter inserted due to fear of vocal tract injury. However, the participants tolerated well the test with no complaint of pain or vocal quality impairment after the procedure. The small number of individuals precluded subanalysis such as results based on gender and age. Other limitation is the lack of data for the lower esophageal sphincter and diaphragmatic crura to study the pathophysiology of esophageal pressurization due to the protocol that demanded the proximal placement of the probe to study high anatomical parameters. This may be studied in future protocols.

Although topical anesthesia was used in this study to diminish participant discomfort, we do not believe it significantly altered voice production with regard to our measurements. However, mechanoreceptors in the pharynx (deep to the mucosa) are largely responsible for modulating pharyngeal movements[42] these fibers were probably not affected by our topical anesthetic.

CONCLUSION

HRM represents a feasible tool for obtaining pharyngoesophageal structures pressures induced by vocalization. During vocalization, esophageal pressure is higher than at rest, additionally the higher the vocal intensity, the higher the pressure levels in this segment. The UES pressures during phonation are not significantly different from rest pressures. The topographic HRM plot provides additional data about phonatory mechanism physiology, especially at the UES region.

Authors' contribution

Vaiano T: conception and design, acquisition of data, analysis and interpretation of data, drafting the article, final approval of the version to be published. Herbella FAM: conception and design, acquisition of data, analysis and interpretation of data, drafting the article, final approval of the version to be published. Behlau M: conception and design, review for intellectual content, final approval of the version to be published.

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RESUMO – **Contexto** – A manometria de alta resolução (MAR) é uma ferramenta de grande potencial para mensuração das pressões faringoesofágicas durante a fonação. **Objetivo** – O estudo visa avaliar pressões faringianas, do esfíncter esofagiano superior e do esôfago durante manobras fonatórias. **Métodos** – Doze (seis homens, idade média 27 anos) cantores profissionais foram submetidos à MAR e produziram quatro tarefas vocais em intensidade baixa, média e alta: vogal / ae /, escala ascendente de cinco notas, palavras /hey/ e /go/. Pressões aos níveis da faringe, esfíncter esofagiano superior e esôfago foram aferidas além de análise visual dos traçados. **Resultados** – Pressões esofágicas foram maiores na vocalização que no repouso. Pressões da faringe e esfíncter esofagiano superior durante a fonação não foram diferentes que no repouso. Análise visual dos traçados mostrou importante incremento da pressão do esfíncter durante a fonação. **Conclusão** – MAR é uma ferramenta valiosa para mensurar as pressões faringoesofágicas durante a fonação. Pressões esofágicas são maiores durante a fonação que no repouso e tendem a aumentar com maior intensidade sonora. Análise visual dos traçados mostram dados adicionais sobre a fisiologia do mecanismo da fonação, especialmente na região do esfíncter esofagiano superior.

Palavras-chave – Pressões; faringe; esôfago; manometria; voz; fonação.

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