Experimental Investigation on Acoustic Parameters in Speech Analysis for Patients Diagnosed with Laryngeal Disorders

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Abstract: - This paper is concerned with an experimental investigation of acoustical parameters in speech analysis for hospitalized patients diagnosed with laryngeal malignant tumors. A software-based voice evaluation was performed by audio-recording a group of 22 patients, determining also the main characteristics of a human voice (F0, Jitter, Shimmer, and HNR). It was proved that the determination of the essential characteristics of the human voice by using vocal analysis facilities can be an effective non-invasive technique of great utility in identifying pathologies that may affect the phonatory system and the process of speech.

Keywords: - acoustic parameters, speech analysis, laryngeal disorders.

1. INTRODUCTION

Voice production represents one of the most important mechanisms performed by the human body. The process of phonation implies a few human organs that are part of the respiratory and masticatory systems, namely the lungs, trachea, larynx, and the vocal tract, which contains the resonating cavities (pharyngeal, nasal, and oral) and the articulatory organs (tongue, palatine veil, hard palate, teeth, and lips). Of utmost importance in the process of phonation are the vocal cords, also known as vocal folds [1], whose vibrations lead to the production of the voiced sound.

Any impairment of the organs, especially on the vocal folds, which participate in the phonation process, can have serious consequences on the personal, social, and professional life of the individual, as it can lead to the impossibility of being understood by those around. This is why researchers all over the world have continuously studied methods for the analysis of voiced sounds, in a way that they could find, understand, and describe the characteristics of normal voices [2-3]. In this way, they could assess the pathological field regarding the phonatory system.

In the last decades, the assessment of the pathologies of the vocal tract was conducted through various methods, starting with listening to a patient`s voice by an expert jury [4] and using numerous techniques based on complex medical equipment (stroboscopic, laryngoscopy, and so on), to use and developing different acoustic analysis programs for the objective description of voice characteristics. The emergence of these types of programs made it possible to observe the essential parameters and characteristics of voice description and their influence on the quality of speech.

Among the most important parameters and characteristics of voice production are the fundamental frequency, formants, Jitter, Shimmer, and Harmonics to Noise Ratio (HNR), which have been extensively used in many studies regarding the identification of the phonatory system pathologies.

The voice of each individual is characterized by the fundamental frequency (F_0), which refers to the number of vibration cycles produced by the vocal cords in the unit of time (second) and is measured in Hertz [Hz]. It is a characteristic that differs from one individual to another, as it is influenced by the length of the vocal tract, tension, mass, and length of the vocal folds, as well as the glottal area and subglottic pressure. In addition, the so-called formants, that represent resonant frequencies of the vocal tract depend on the frequency and amplitude of the vibrations of the vocal cords, which are added to the fundamental frequency. They can be identified on a spectrogram by the areas in which there is the greatest concentration of energy.

Parameters such as Jitter and Shimmer refer to irregular vibrations of the vocal folds with respect to frequency and amplitude of the oscillations. Jitter refers to variations in signal frequency, representing the measure of cycle-to-cycle variations of the fundamental glottal period (Figure 1), whereas Shimmer represents variations in signal amplitude, respectively the cycle-to-cycle variations of the fundamental glottal period amplitudes (Figure 2) [5].

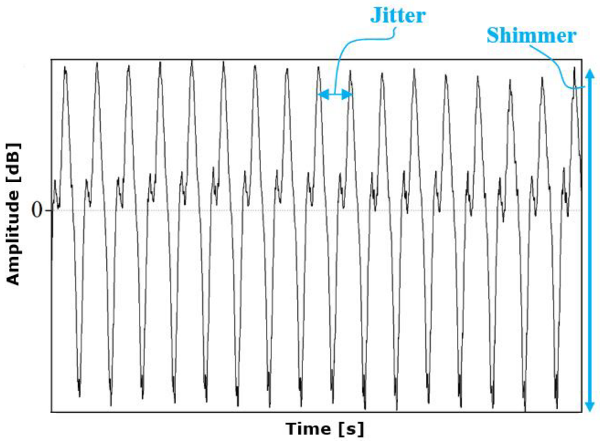

Figure 2. Jitter and Shimmer representation for a recorded voiced sound

Harmonics to Noise Ratio (HNR) is another essential parameter in the evaluation of voice production, and it is the ratio of the periodic components (harmonics) (generated by the vibration of the vocal folds) to the non-periodic components of a sound produced by the noise (generated by the air passing through the glottis). Both periodic and non-periodic components are expressed in dB. The higher the value of the Harmonic to Noise Ratio, the higher the quality and harmonicity of the voice.

Throughout the years, various types of research based on these parameters aim at comparing values of healthy speakers with voices affected by several pathologies or comparing values of the parameters from existing databases with values determined from vocal recordings and their extraction from different voice analysis programs.

The existence of normative values for fundamental frequency, Jitter, Shimmer, and HNR is essential in identifying different voice disorders. This is why most studies involve sustaining vowels for an extended period (several seconds for each vowel) so that frequency and variations in frequency and amplitude are more evident and easier to measure.

A great number of important studies included comparisons between groups of healthy subjects and groups of individuals with certain voice pathologies. Thus, in paper [6], voice parameters were determined for a group of patients with speech stuttering disorder and compared with a group of non-stutterers. The same type of comparison was made in the study [7], which involved groups of patients with voice disorders such as early-stage carcinoma, mutational falsetto and vocal cord polyp and one group of healthy voices.

Values for fundamental frequency, Jitter and Shimmer parameters were extracted from a voice analysis program. Results showed notable and clear differences regarding the voice parameters between the groups of subjects and emphasized the efficiency of voice analysis programs. For the groups of subjects with voice disorders, the values of most of the parameters were significantly higher than those for the group of healthy subjects.

In the present work, we investigate the vocal characteristics of patients diagnosed with malignant laryngeal tumors and compare the results with threshold levels found in previous studies of other researchers. The recording and analysis of the voices was made through a noninvasive method, that is through the voice analysis software named Praat.

2. MATERIALS AND METHODS

This paper is based on patient data collected within the Municipal Emergency Clinical Hospital of Timisoara. The voice recording of patients and data collection was only performed after each patient filled out and signed a freely consented agreement to participate in the medical didactic research in two wards of the hospital, otorhinolaryngology (ENT) and radiotherapy. The consent covered the respect of the use and processing of personal data, but also that the patients have been informed about the purpose and procedure used, duration, risks, etc.

2.1. Recording protocol and data collection

Voice evaluation with Praat software was performed by audio-recording a group of 22 patients (14 males and 8 females), all smokers, aged between 29 and 75 years, hospitalized either in the otorhinolaryngology or in the radiotherapy wards of the hospital.

The data of interest collected and used refer to patient age, diagnosis, gender (female/male), and smoking habits. Only 19 patients, 14 male and 5 female, out of the 22 were taken into consideration, as the others were either diagnosed with different disorders of the voice than laryngeal malignant tumors or the recordings were too short to be analyzed. Patients were asked to phonate and sustain the Romanian vowels [a], [e], [i], [o], and [u] as much as they could, one by one, at a comfortable pitch and intensity.

The voice recordings were made in the least noisy cubicles of the ENT and radiotherapy wards of the hospital, due to the impossibility of transporting the hospitalized patients to a completely soundproofed room. Each recording was made at a recording frequency of 44100 Hz, through a unidirectional microphone, directly into the voice analysis program Praat, and then saved as audio files. Patients were seated and instructed to position the microphone at about 10 cm from the mouth.

2.2. Voice analysis

In order to efficiently analyze the pathological voices using Praat, we chose to cut the beginning and ending portions of every recording, as they had additional noise (primarily overlapping voices) or did not contain any vocal signal. After the trimming of the irrelevant portions of the vocal sound, for the remaining section of the recorded vowels for each patient, the following features were extracted from Praat:

- Mean Pitch – the average value of the fundamental frequency (F_0) for the duration of the phonation;
- F_1 and F_2 – the first two formants, which are essential for vowel characterization and positioning;
- Jitter – measured in percent (in Praat Jitter(local));
- Shimmer – measured in percent (in Praat known as Shimmer(local));
- Harmonics-to-Noise Ratio – found as HNR in Praat.

To investigate the acoustic characteristics and positioning of the Romanian language vowels, in relation to each other, we extracted the first two formants of every recorded vowel. The extracted data was used to plot a graph, namely a vowel chart, that illustrates the changes that may occur in the case of a malignant tumor in terms of place of articulation, degree of opening of the mouth, or the rounding degree of the lips, in comparison to the vowel schematization for a normal voice.

For a normal voice, the first formant, F_1, is inversely related to the vowel height (for example, the vowel [a] has a high F_1, and the vowel [i] has a low F_1 [8]), and F_2, the second formant, is directly proportional to the degree of anteriority (frontness) of the vowel ([i] has a higher F_2 and is considered a front vowel, whereas a back vowel such as [u] has a lower F_2). Threshold values (Table 1) for the frequencies of the formant were considered from [9].

Table 1. Average frequencies for the first two formants for a normal voice [9]

Vowel	F_1 [Hz]	F_2 [Hz]
a	850	1610
e	390	2300
i	240	2400
o	360	640
u	250	595

As far as the articulation process of the vowels is concerned, during the phonation of vowel [a], the jaw and the lingual muscle (tongue) are in the lowest position and the opening of the mouth is maximal, for the phonations [e] and [o], the tongue is in an intermediate position; and for [i] and [u], in relation to the palate, the lingual muscle is in a very high position.

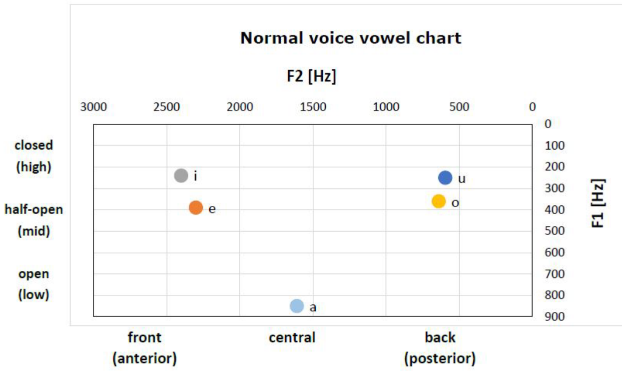

Figure 3. Vowel chart for normal voice. Vowel position in relation to the average frequencies of F_1 and F_2 for a healthy voice

Laryngeal malignancies, or laryngeal tumors, are the most common type of tumor localization in the area of the head and neck [10] is much more common in men than women. In cases of these types of tumors (regardless of the section of the larynx it affects: supraglottic, glottic, or subglottic), the position of the vowels is affected, as the frequencies of the first two formants change substantially compared to those for a healthy voice (Figure 3). This change in the position of the vowels appears due to the lesions and additional mass appearing on the anatomical structures of the voice box, causing their irregular movement as the flow of air passes through them.

For a patient diagnosed with laryngeal cancer at the glottic floor, an increase in both formant frequencies can be observed for the vowels [o] and [u], Table 2. This causes the degree of mouth opening to change, from a normal, closed degree to a semi-closed one. For the other three vowels, [a], [e], and [u], the differences in formant frequencies are not as noticeable as in the other two vowels.

Table 2. Average frequencies of the first two formants for a pathological male voice (glottic section cancer)

Vowel	F_1 [Hz]	F_2 [Hz]
a	836.38	1347.75
e	474.78	2335.16
i	337.93	2406.77
o	451.39	921.31
u	405.34	958.07

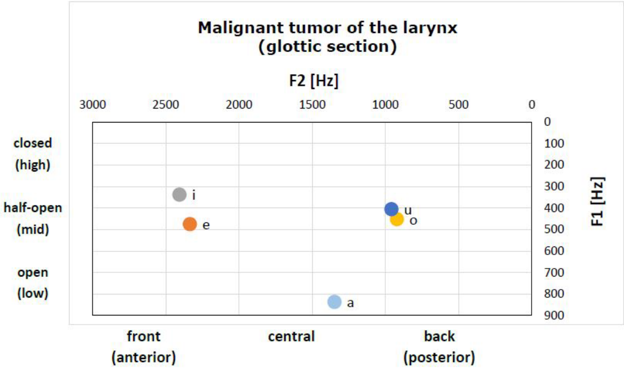

Figure 4. Vowel chart in malignant tumor of the glottic section of the larynx in a male subject

In the first stage of laryngeal cancer at the glottic level, the tumor affects just one vocal fold. In this particular case, the articulation of the sounds is altered due to the changes in the oscillations of the vocal fold. Its movement is affected by the extra mass (tumor) on the vocal fold. Figure 4 and Figure 5 show the vowel diagram (chart) for a case of a left vocal cord malignant tumor for a female subject and a case of a left vocal fold tumor for a male subject, respectively. Values of the formant frequencies used are presented in Table 3 and Table 4.

Table 3. Values of F_1 and F_2 for a female subject diagnosed with left vocal fold malignant tumor

Vowel	F_1 [Hz]	F_2 [Hz]
a	809.81	1240.50
e	537.11	2539.42
i	360.08	2964.05
o	424.94	889.36
u	370.90	769.57

As it can be observed in Figure 4, for a female patient, for vowel [a], the frequency of F_2 decreases in comparison to the one for the normal voice, which makes the vowel change position in articulation, from a normal, central position, to a back position. The same decrease of the second formant of the vowel [a] makes its phonation require rounding of the lips, but the degree of mouth opening remains maximal.

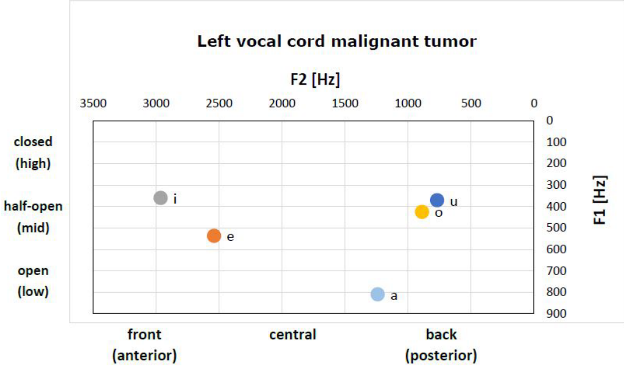

Figure 5. Vowel chart in malignant tumor of a single vocal fold (female patient)

Articulation of vowel [i] remains in a front position, but the increase of F_1 determines an intermediate position of the tongue and limits the opening of the mouth to a certain extent (semi-open). As far as vowels [o] and [u] are concerned, due to the increase in F_2, they slightly approach the values specific for central vowels, and the increase in F_1 makes them higher. Vowel [e] shows minor changes by having a higher value for the first formant. For the male patient, the localization of vowel [a] remains normal, but the vowels [o] and [u] become more central due to the increase of the frequency for the second formant for both vowels. An increase in F_1 for vowel [i] causes an increase in vowel height and makes it be closer to the same degree of mouth opening as for the vowel [e].

Table 4. Values of F_1 and F_2 for a male subject diagnosed with right vocal fold malignant tumor

Vowel	F_1 [Hz]	F_2 [Hz]
a	751.92	1658.60
e	358.58	1863.55
i	332.57	2218.30
o	437.36	1120.00
u	328.65	1052.85

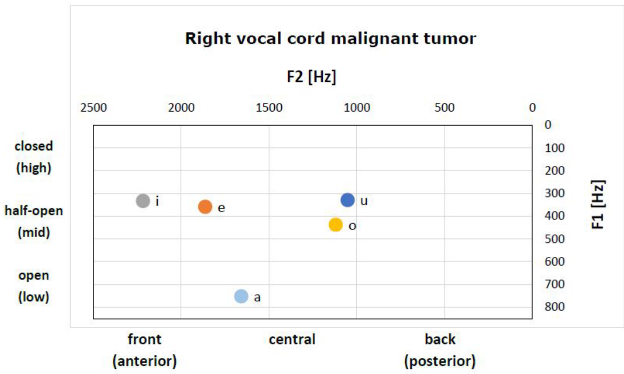

Figure 6. Vowel chart in malignant tumor of a single vocal fold (male patient)

2.3. Determination of characteristic parameters

Other than analyzing a human voice by means of the resonance frequencies of the vocal tract, an analysis performed in the previous section, there are several other parameters that can lead to quicker identification of human phono articulatory disorders. This is a perspective that is in continuous growth, for which a great number of studies, such as [2], [11], [12], [13], [14], have been developed.

In this study, the determination of the main characteristics of a human voice was performed on the same audio recordings of the patients diagnosed with laryngeal malignant tumors.

The extraction of the parameters was done directly from the voice report generated by Praat software and was processed (separated based on gender) so that we could determine their mean values and compare them to threshold levels from the literature.

Fundamental frequency is one of the most widely used characteristics in voice analysis since it provides essential information about gender, articulation of sounds, and so on. For the comparison of the determined mean values of F_0 for the pathologic voices with threshold values for healthy voices, the fundamental frequency ranges proposed by Palumbo in [15] were chosen. The adult female F_0 ranges from 175 to 245 Hz, and for an adult male it is between 105 and 160 Hz. These ranges differ by gender as the length of the vocal tract is individual, and in general, the vocal tract of men is longer than that of women. The average fundamental frequencies are 128 Hz for male subjects and 225 Hz for women, according to [16].

Table 5 shows the mean values for F_0 extracted for the 14 male and 5 male patients with laryngeal cancer. Figures 6 and 7 show the values presented in table 5 and the average fundamental frequencies for normal voices of men and women.

Table 5. Mean fundamental frequencies for patients with laryngeal cancer

Vowel	Fundamental frequency	
	Women F_0 [Hz] (mean value)	Male F_0 [Hz] (mean value)
a	147.07	118.05
e	134.37	136.31
i	153.43	179.64
o	167.56	137.26
u	176.63	171.12

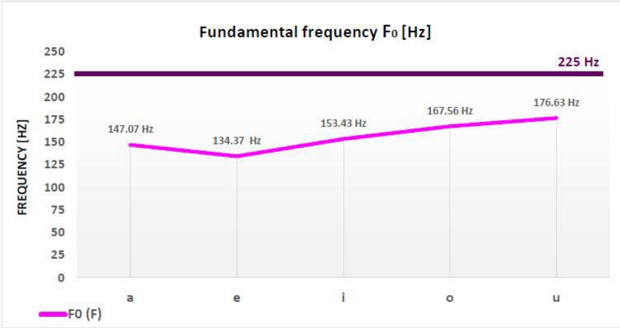

Figure 7. Mean fundamental frequency values for female subjects

Larger variations in fundamental frequency are much more pronounced in women than in men. For women diagnosed with laryngeal cancer, the frequency values of all recorded vowels fall below the average fundamental frequency for a healthy voice (Figure 6), with the lowest fundamental frequency observed for the vowel [e].

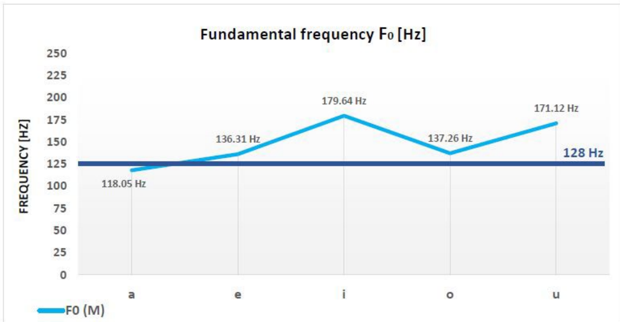

Figure 8. Mean fundamental frequency values for male subjects

As far as the group of male patients is concerned (Figure 7), an increase in fundamental frequency can be observed for 4 out of the 5 recorded vowels. In men, the high vowels [i] and [u] have the highest fundamental frequency, while the lowest frequency is found in the vowel [a].

The changes in fundamental frequency occur due to various reasons that affect both the mechanical properties and the structure of the tissue of the vocal folds.

The relationship between vocal cord length, tissue tension, and fundamental frequency is emphasized in paper [17], in which the authors state the fact that if the vocal cord is longer, this causes a reduction in fundamental frequency. On the other hand, a greater tension of the vocal folds causes an increase in fundamental frequency.

Tissue elasticity is one of the most important properties in determining the vibrational frequency. In laryngeal malignant tumors, especially those affecting the glottic section, stiffening of the vocal fold and narrowing of the Reinke`s space are specific, which may be a primary reason for the decrease in F_0 and occurrence of the dysphonia.

Moreover, deformation of the vocal folds due to different shapes and sizes of the tumors can cause variations in fundamental frequency. This is because the thickness and length of the vocal cord are affected.

For example, an increase in the mass of the vocal cords, due to the mass of the tumor, can lead to a slower movement of the vocal cord, which causes a decrease in fundamental frequency. Additionally, they may cause modifications in the tension of the vocal folds if the tumors affect the muscles that regulate this tension, leading to a lowering of the fundamental frequency.

As far as Jitter, Shimmer, and HNR parameters are concerned, they are of the utmost importance in the characterization of a pathological voice.

These parameters were also determined for the same type of pathology, and the standard ranges of variation, for a healthy speaker, were considered between 0.5-1% for Jitter, less than 3% for Shimmer [18], and for HNR, a value below 20 dB is considered to be specific for a pathological voice, according to [19].

The values for each parameter, Jitter, Shimmer and HNR are presented in Tables 6, 7, and 8, for the group of patients diagnosed with malignant laryngeal tumors.

Table 6. Vocal parameters for voices affected by laryngeal cancer - Jitter

Vowel	Jitter [%]	
	Gender	
	F	M
a	1.40	1.70
e	2.45	2.16
i	1.93	2.22
o	1.15	1.90
u	1.62	3.07

Table 7. Vocal parameters for voices affected by laryngeal cancer - Shimmer

Vowel	Shimmer [%]	
	Gender	
	F	M
a	11.13	6.39
e	8.43	5.50
i	9.17	5.38
o	10.40	4.47
u	14.63	10.64

Table 8. Vocal parameters for voices affected by laryngeal cancer - HNR

Vowel	HNR [dB]	
	Gender	
	F	M
a	13.81	10.52
e	16.26	13.45
i	22.77	15.66
o	22.34	14.08
u	19.22	10.39

Values for the perturbations in the fundamental frequency, namely Jitter, in both female and male patients reveal the presence of a disorder of the voices. Figures 8 and 9 show the variations by gender of Jitter in relation to F_0 (M-male, F-female).

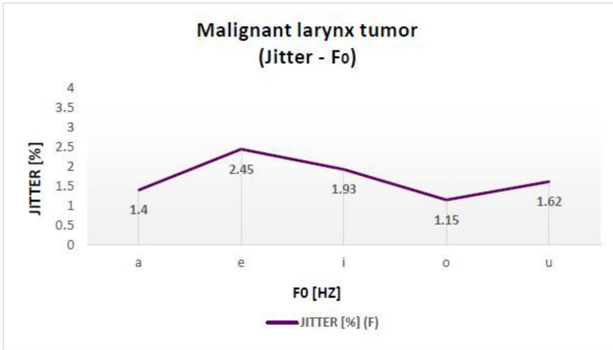

Figure 9. Jitter variations in relation to fundamental frequency for female patients

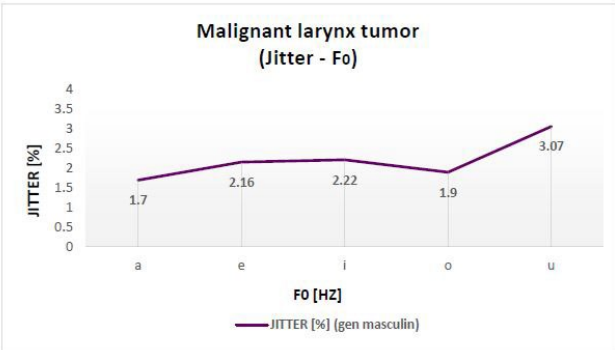

Figure 10. Fundamental frequency variations in relation to jitter for male patients

Figure 8 shows a significant variation of the Jitter parameter in relation to the average fundamental frequencies for the group of female subjects. For each vowel, the values of Jitter exceed the normative range for this parameter, which clearly shows the presence of a pathology of the larynx.

The highest values of Jitter are found for the vowels [e] and [i], which have among the lowest values in fundamental frequency. In contrast, vowels [a], [o], and [u] present small variations in Jitter but have increased values for the fundamental frequency.

Male subjects show smaller variations of the Jitter parameter than female subjects, as depicted in Figure 9. Here, the highest values of Jitter can be seen for vowels [e], [i], and [u], for which the largest increases in the fundamental frequency can also be observed. Vowels [a] and [o] have a lower value for Jitter, but that still exceeds the normative range for a healthy speaker.

The alterations can be caused by the tumors of the larynx, which either introduce extra mass to the anatomical structures or cause a loss of elasticity, leading to the stiffening of the vocal cords.

The stiffening of the cords is caused by the narrowing of the glottic gap and is characteristic of the so-called blown voice. This narrowing may, in turn, cause the inability to breathe, thus necessitating an operation to insert a tracheal cannula to facilitate breathing.

Figure 10 presents a bar graph showing the differences in the mean values of the Jitter parameter by gender for each vowel and the superior limit of the normative range (1%). Here it can be clearly seen that the highest value for Jitter is for males, with a mean value of 3.07% for the sustained [u] vowel.

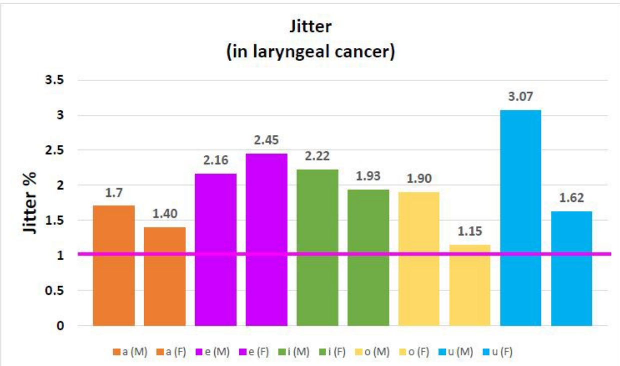

Figure 11. Jitter [%] by gender in malignant laryngeal tumor

In terms of variation in signal amplitude, respectively, the Shimmer parameter, the mean values for the five vowels exceed the threshold value of 3% for a normal voice. This parameter depends and varies according to lesions on the vocal folds, reduced glottal resistance, and is correlated to a hissing voice and the presence of additional noise in the phonation process.

Table 7 reveals the significant difference between genders as far as the Shimmer parameter is concerned. The highest percentage of Shimmer can be seen (Figure 11) for vowel [u], with a value of 14.63% for women, compared to the mean value of 10.64% for the vowel, and also for the vowel [u].

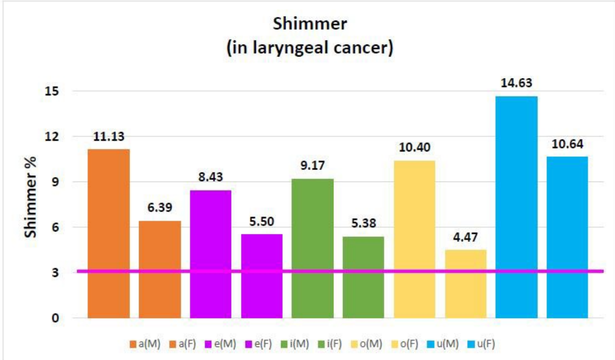

Figure 12. Shimmer [%] by gender in malignant laryngeal tumor

Another essential characteristic in the analysis of the human voice is the HNR parameter (the ratio between the acoustic energy of harmonics and non-harmonics [20]). It is influenced by F_0, Jitter, and Shimmer. For this parameter, values were obtained from Praat and further processed to further analyze the sounds.

The graphical representation of the harmonic-to-noise ratio in patients diagnosed with laryngeal tumors and its threshold value is shown in Figure 12.

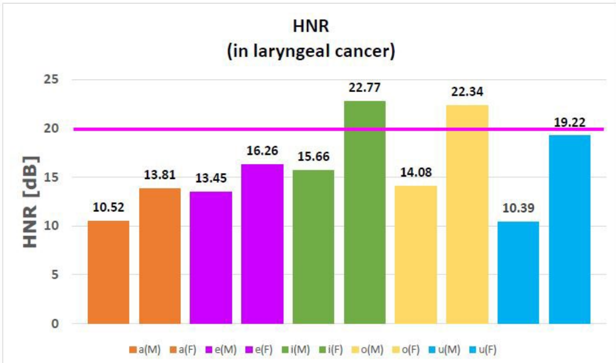

Figure 13. HNR [dB] by gender in malignant laryngeal tumor

Females, in general, have a higher harmonics-to-noise ratio compared to males, according to [21], which can be explained by the fact that during phonation males have a smaller narrowing in the glottal space than females, resulting in a lower harmonic level and a louder noise.

Figure 12 shows that even in the case of the studied type of pathology in this paper, HNR is higher for females than males for each vowel. In comparison to the standard value chosen, an HNR ‹20 dB, with only two exceptions in the case of the female subject (vowel [i] with an HNR of 22.77 dB and vowel [o] with an HNR of 22.34 dB), all fall into the category of pathological vowel in terms of HNR.

3. CONCLUSIONS

The movement of the anatomical structures of the larynx is of considerable importance in sound and speech generation. Any change in the organs involved in the process of phonation can lead to voice disorders, respectively, to the change of the vibrational pattern of the human vocal folds.

The determination of the essential characteristics of the human voice by using vocal analysis programs can be a non-invasive technique of great utility and effectiveness in identifying pathologies that may affect the phonatory system and the process of speech.

The use of the audio recording of patients with a pathology of the larynx and using the program Praat to analyze and extract the targeted characteristics and parameters of voice (fundamental frequency, formants, Jitter, Shimmer, harmonics-to-noise ratio) led to the creation of the vowel charts (diagrams). These charts reveal the differences in the phonation and articulation processes of the pathologic voiced sounds compared to a chart constructed for a healthy voice. The graphical results showed that the existence of a disorder in the larynx affects both processes, resulting in changes in terms of opening or closing of the mouth, position of the lingual muscle, etc.

To emphasize the utility of a vocal analysis program in the identification of voice pathologies, after the extraction of the parameters, we performed their comparison to normative data taken from previous studies conducted by different researchers. The results of the comparisons show that for a given pathology, the value of the parameters changes significantly from those of a healthy voice.

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