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Computerized Analysis of Acoustic Characteristics of Patients with Internal Nasal Valve Collapse Before and After Functional Rhinoplasty

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ABSTRACT

Acoustic analysis of sounds produced during speech provides significant information about the physiology of larynx and vocal tract. The analysis of voice power spectrum is a fundamental sensitive method of acoustic assessment that provides valuable information about the voice source and characteristics of vocal tract resonance cavities. The changes in long-term average spectrum (LTAS) spectral tilt and harmony to noise ratio (HNR) were analyzed to assess the voice quality before and after functional rhinoplasty in patients with internal nasal valve collapse. Before and 3 months after functional rhinoplasty, 12 participants were evaluated and HNR and LTAS spectral tilt in /a/ and /i/ vowels were estimated. It was seen that an increase in HNR and a decrease in LTAS spectral tilt existed after surgery. Mean LTAS spectral tilt in vowel /a/ decreased from 2.37 ± 1.04 to 2.28 ± 1.17 ($P = 0.388$), and it was decreased from 4.16 ± 1.65 to 2.73 ± 0.69 in vowel /i/ ($P = 0.008$). Mean HNR in the vowel /a/ increased from 20.71 ± 3.93 to 25.06 ± 2.67 ($P = 0.002$), and it was increased from 21.28 ± 4.11 to 25.26 ± 3.94 in vowel /i/ ($P = 0.002$). Modification of the vocal tract caused the vocal cords to close sufficiently, and this showed that although rhinoplasty did not affect the larynx directly, it changes the structure of the vocal tract and consequently the resonance of voice production. The aim of this study was to investigate the changes in voice parameters after functional rhinoplasty in patients with internal nasal valve collapse by computerized analysis of acoustic characteristics.

Key words: *Acoustics, Rhinoplasty, Voice quality, Vocal cords, Speech, Noise, Larynx*

INTRODUCTION

An important hypothesis in the process of speech production is the source-filter theory that divides the speech production system into two major parts: Voice source (larynx) and filter (resonator).[1] Speech sounds are produced following the interaction of the filter and the voice source.[2] The voice signal produced by the source passes through the vocal tract that acts as a filter, some specific frequencies are enhanced, and eventually comes out of the mouth or nose.[3] The vocal tract influences the acoustic energy of the source as a resonator and filter. Some studies show that changes in the structure of any part of the resonators would alter speech characteristics.[4] This theory explains the hypernasality and the high pitch voice in children with tonsil hypertrophy.[5] Reports have shown that tonsillectomy or uvulopalatopharyngoplasty (UPPP) have modified the patients' speech with an increase in the level of nasal resonance and changes in the voice timbre following the increased space of the vocal tract.[6]

The source-filter theory also states that the characteristics of the vocal tract significantly affect the performance of the source.[7] In fact, source and filter are interdependent. This explains why mean fundamental frequencies are higher for high vowels such as /i/ compared to low vowels

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such as /a/.[7] This is due to the relation of the motion and status of the vocal tract to vocal cords and vice versa.

Previous studies on patients with velopharyngeal insufficiency and damaged vocal tract also reported the prevalence of vocal problems as 12–85%.[8] In actual, velopharyngeal insufficiency allows air to exit from the nose and decreases the intraoral pressure. These patients put more pressure on their larynx to compensate the velopharyngeal insufficiency decrease hypernasality, and consequently this would cause vocal problems. Therefore, changes in the vocal tract affect the performance of the source. Tahmasebifard showed that the modification of the vocal tract (mouth) in patients with velopharyngeal insufficiency through surgical operations improved the resonance and voice parameters and caused competent closure of vocal cords.[9]

Nasal airway also acts as a resonator and a filter on the acoustic energy of the source.[10] The internal nasal valve plays a key role in the adjustment of the air flow and formation of nasal resonances.[10] According to the role of nasal cavity as a resonator, obstruction of the nasal cavity may decrease or eliminate the nasal features in the production of a nasal sound (hypo-nasality)[11] and make pathological changes in the speech signal[12-14] based on the source-filter theory and regarding the interdependence of these two parts, such a problem in the vocal tract may change vocal characteristics.

Many studies have shown that nasal obstruction can impact pathophysiology of voice disorders.[5] Cecil *et al*. showed that the fundamental frequency of patients with chronic sinusitis was lower than that of normal people.[15] Meirelles also showed that 113 out of 208 people with vocal nodule experienced changes in their nasal cavity.[16]

The vocal changes arising from damages to the nasal airway can be diagnosed not only perceptually by a specialist but also through vocal, acoustic analysis.[17] In fact, the acoustic analysis of signals recorded by a microphone provides significant information about the physiology of the larynx and vocal tract.[18] The analysis of voice power spectrum is a fundamental sensitive method of acoustic assessment that provides valuable information about the voice source and characteristics of vocal tract resonance cavities. Lee *et al*. study showed that spectral components of voice signal had a close relationship with characteristics of the nasal airway.[17] The advantage of acoustic evaluation lies in that it analyzes exactly the same signals that are perceived by listeners.[19] Objective and quantitative measurement scales are required to analyze the voice quality parameters acoustically. LTAS and HNR are two parameters of spectral assessments and provide objective and quantitative values of the voice quality through acoustic assessments.[1,20-28] LTAS is the average power spectrum of acoustic signal frequencies and reflects the characteristics of the laryngeal source and vocal tract filter.[29] An LTAS of time-series data is essentially a spectrogram (three dimensional time-frequency-energy plot) where each frequency spectrum plotted along time is averaged over a much longer period than one windowed frame of a fast-Fourier transform, as for typical spectrograms. LTAS measures have been widely used in different studies because it is an effective, reliable, and accessible method for assessment of vocal characteristics.[20-28,30]

There are different measurement scales in LTAS. One of these scales is the alpha ratio, which is the ratio of energy between 0–1 and 1–5 kHz.[31] The level differences between frequency ranges in the LTAS reflect the slope of the source spectrum, which, in turn, is related to the glottal closing speed.[32]

Another acoustic parameter that can be a sensitive index of vocal performance is HNR.

Some methods have been proposed to quantify the presence of noise in speech. The HNR is described as the log ratio of the energies of periodic and aperiodic components.[33-36]

It seems that HNR is a parameter that can be used for the relationship between physiological aspects of voice production and perceptual characteristics of voice because the degree of spectral noise is associated with the output quality of voice.[37,38]

Techniques of septoplasty influence the speech and voice quality through modifying the resonant features of the vocal tract and speech production. Mora *et al*. showed the effectiveness of septoplasty,[11] UPPP,[39] and adenotonsillectomy[40] in modification of vocal features. Han *et al*.,[41] Kosztyła-Hojna *et al*.,[42] and Salami *et al*.[43] reported the positive changes following surgery. However, Foroughian *et al*. showed that cosmetic rhinoplasty is not always helpful, and the changes are problematic in general for most patients.[44]

Surgery is the primary treatment of nasal valve collapse.[14] One of the surgical techniques for nasal obstruction is the functional rhinoplasty that is performed to improve nasal performance.[45] The functional rhinoplasty is a treatment for all chronic nasal obstructions and has a potential effect on nasal resonance and vocal parameters through modifying the resonant features of the vocal tract.[11] There is a considerable evidence for the effectiveness of rhinoplasty techniques in treatment of nasal obstruction caused by nasal valve collapse.[46]

According to the source-filter theory, it is expected that the change in the status and function of the nasal cavity after the surgery results in a change in the performance of the voice source. The assessment of the effect of nasal obstruction surgeries on improvement of vocal signals of the source necessitates a review of speech signal parameters. Therefore, LTAS and HNR methods can be used in postoperative follow-ups due to their high sensitivity to changes and improvement of vocal parameters.[12]

Most previous studies have analyzed the effects of classical surgical techniques on the improvement of vocal parameters and resonant features. So far, few studies have assessed the acoustic aspects of voice production after rhinoplasty and the studies in this regard mostly focus on the fundamental frequency and oral-nasal resonance. In some studies, participants experienced surgeries of the nasal passages more than once, so these studies are not reliable in finding a direct relationship between a specific surgery and acoustic changes. Nasal cavity acts as a part of voice production system, and so it is very important to evaluate quantitatively the effects of surgical interventions on voice quality. Acoustic spectrum analysis uses LTAS spectral tilt and HNR variables and provides valuable information about the involvement of the voice source and filter function of the vocal tract and their effect on one another. However, these two parameters have not been assessed in previous studies, and no study on the effect of this type of surgery on preoperative and postoperative characteristics of voice has been performed in Persian-speaking people before. This is the first study to conduct and develop a computerized analysis for quantification of acoustic characteristics using filter-source theory in functional rhinoplasty patients. This is a noninvasive, reliable, and fast method to compare voice quality before and after functional rhinoplasty in patients with internal nasal valve collapse.

MATERIALS AND METHODS

In this study, the number of participants was selected as 12 people based on statistics analysis by GPower Software[47,48] GPower 3.1.0 (Franz Faul,University of Kiel, Germany) retrieved from http://www.gpower.hhu.de/. Chart 1 shows the flow diagram of the progress through the phases of trial (i.e., enrollment, intervention, follow-up, data analysis) with $\alpha = 0.05$ and $1-\beta = 0.95$. These participants included patients with internal nasal valve collapse, nine males and three females with a mean age of 24.75 years. They attended Otorhinolaryngology Clinic of Alzahra Hospital in Isfahan, Iran. Once the participants received some information about the study and declared their consent, they underwent an ear-nose-throat (ENT) specialist examination including registering their personal health record, nasoendoscopy, and computed tomography scan. The participants were candidates for functional rhinoplasty who agreed to participate in the study. The inclusion criteria of the study were the moderate to severe collapse of the internal nasal valve and a time gap of 2 years from the beginning of the problem, according to the patients' medical records. The patients with the following criteria were excluded from the study: Craniofacial abnormalities, neurological problems, allergic rhinitis proven by the medical records, nasal pathological findings, lower respiratory diseases (asthma), any history of previous nasal operations, hearing impairment based on pure tone audiometry test, use of drugs to treat the collapse during the study, upper airway infections or allergies, and smoking. All procedures of the study were approved by Research Ethics Committee of Isfahan University of Medical Sciences.

Signal Recording

The initial voice samples were collected 1–15 days before the surgical operation. Once the lack of cold, hoarseness in all participants and menstruation in females was confirmed on the voice recording day, the demographic questionnaire was completed by the participants. The participants were familiarized with the method of the test, and they were asked to produce the voice sample before the test. To minimize the environmental noise,[49] participants were transferred to an acoustic room (with noise of 28 dB based on sound level meter [TES-1351]). The voice samples were recorded separately for each. The participants were seated in a comfortable condition and a Microphone (Somic SENIC ST-818 3.5 mm On-Ear Stereo Headphones with Adjustable Microphone and 2.5 m Cable) was placed 5 cm from the center of their lips[50] on the right corner of mouth. The stability of this distance was checked when recording the voice samples. The participants were asked to produce the vowels /a/ and /i/ within three tests at least for 5 s. The reason for choosing the vowels was their different place of articulation in the vocal tract. /i/ is the highest front vowel, and /a/ is the lowest back vowel.[51]

Vocal intensity during vowel prolongation was kept at 75 ± 2 dB[52] (measured with sound level meter) by guiding patients manually. Because the vocal intensity should be consistent for different subjects, we can compare the results. The patients' voice sample was recorded concurrently using Praat (version 5.0.23) software[53] (Boersma, Paul &Weenink, David (2015). Praat: doing phonetics by computer [Computer program]. Version 5.0.23, retrieved from http://www.praat.org/) at a sampling frequency of 44.1 KHz using a laptop equipped with a sound card. The surgical operation in all participants was performed by the same surgery team.

Voice signals were collected again 3 months after the surgery under the same conditions. Prior to recording the second voice samples, the participants underwent examinations by an ENT specialist and also were examined again in terms of inclusion and exclusion criteria of the study. The collected voice samples were encoded by a person who was not involved in the analysis of voice signals and were randomly studied.

Feature Extraction

The LTAS spectra for each subject, as well as HNR acoustic measure, was both obtained automatically by Praat Program (version 5.0.23) (Boersma, Paul &Weenink, David (2015). Praat: doing phonetics by computer [Computer program]. Version 5.0.23, retrieved from http://www.praat.org/).[53] The frequency range used in the acoustic analysis was 0–8 kHz, with Hanning Window with a time resolution of 40 ms and bandwidth of 160 Hz.

In this way, the *LTAS* as a function of frequency can be calculated as:

$$LTAS(f)=\frac{1}{L}\sum_{i=1}^{L}PSD_i(f)$$

Where PSD_i (f) is a power spectral density for the i^{th} windowed frame of signal.

Due to the definition of sound pressure level we have:

$$SPL(dB)=10\log_{10}\left(\frac{p}{p_0}\right)$$

Where P_0 = 0.0002 mbar and is the threshold of hearing. Consequently, in acoustics, PSD measure is usually related to $P_0 = 2.10^{-5}$ P, which is defined as a threshold of human hearing at the frequency of 1 kHz.[54] Hence, *LTAS* that is calculated in regards to this threshold can be formulated as follows:

$$LTAS_{dB}(f)=10\log_{10}(LTAS(f)/P_{thr}{}^{2})$$

Such a normalized *LTAS* of speech signal is measured in dB/Hz units.[53]

Figures 1 and 2 showed *LTAS* (*dB*) versus frequency for /i/ for one of the subjects before and after surgery.

HNR was calculated with Boersma's algorithm for periodicity calculation.[55]

$$HNR(dB)=10\log_{10}\frac{r'_x(\tau_{\max})}{1-r'_x(\tau_{\max})}$$

Where $r'_x(\tau)=\frac{r_x(\tau)}{r_x(0)}$ and the autocorrelation $r_x(\tau)$ as a function of the lag τ is defined as:

$$r_x(\tau)=\int x(t)x(t+\tau)dt$$

The autocorrelation of a signal at zero lag equals the power in the signal, the normalized autocorrelation at $\tau_{\max}$ represents the relative power of the periodic (or harmonic) component of the signal, and its complement represents the relative power of the noise component.

The short-term autocorrelation at a time t is estimated from a short windowed segment of the signal centered around t. Appendix A includes all steps of the algorithm for HNR calculation.[55] the parameters of this algorithm were considered as follows:

- Time step parameter: 0.01 s
- Minimum pitch: 75 Hz
- Silence threshold: 0.1
- Number of candidates per frame: 4.5.

Statistical Assessment

The data were analyzed using nonparametric statistics including Wilcoxon test for comparing the HNR and LTAS variables of the vowels /a/ and /i/ before and 3 months after the surgery. The significance level in all tests was 0.05. The

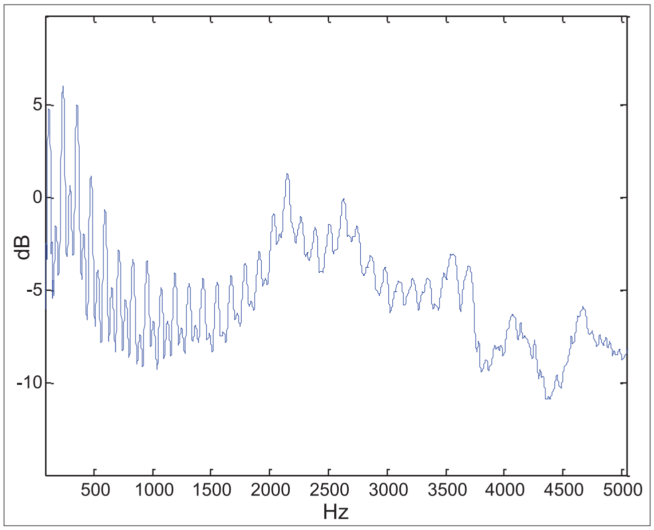

Figure 1: Long-term average spectrum (dB) versus frequency for /i/ for one of subjects before surgery

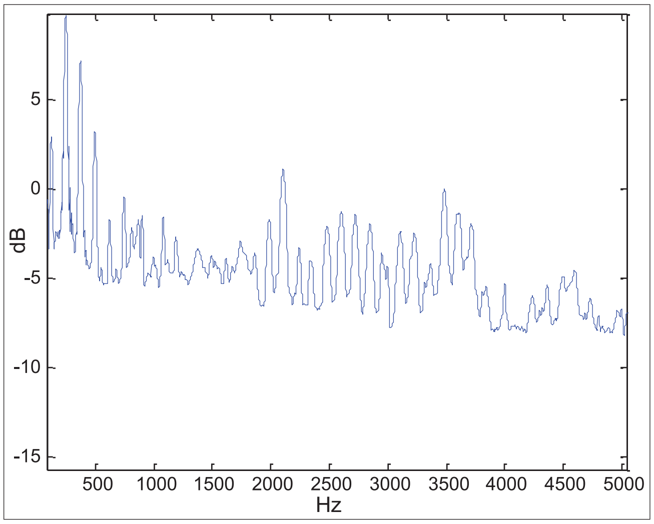

Figure 2: Long-term average spectrum (dB) versus frequency for /i/ for the same subject after surgery

statistical analysis was performed using SPSS18 (version 18, PASW, Chicago, IL, USA).

RESULTS

In this study, each participant underwent acoustic analysis before surgery and then 3 months after the surgery. Table 1 shows the demographics of the participants.

Chart 2 shows that mean HNR in vowel /a/ significantly increased 3 months after surgery from 20.71 ± 3.93 to 25.06 ± 2.67 ($P = 0.002$). Chart 3 illustrates mean HNR in vowel /i/ significantly increased 3 months after the surgery from 21.28 ± 4.11 to 25.26 ± 3.94 ($P = 0.002$).

Chart 4 shows mean LTAS spectral tilt significantly decreased 3 months after surgery in vowel /i/ from 4.16 ± 1.65 to 2.73 ± 0.69 ($P = 0.008$). Chart 5 illustrates mean LTAS spectral tilt decreased 3 months after surgery in vowel /a/ from 2.37 ± 1.04 to 2.28 ± 1.17; however, these changes were not statistically significant ($P = 0.388$).

DISCUSSIONS

The results of this study showed a decrease in the acoustic parameter, LTAS spectral tilt. Considering that LTAS spectral

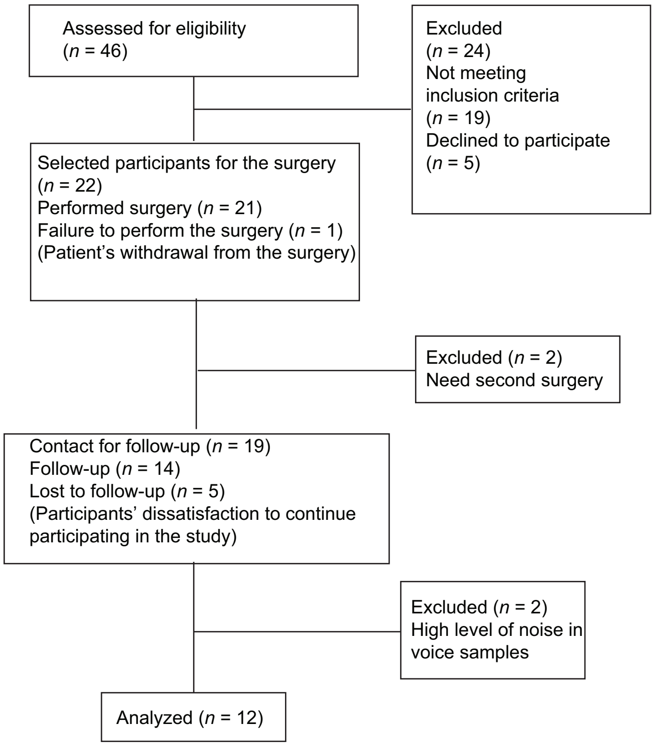

Chart 1: Flow diagram of the progress through the phases of trial (i.e., enrollment, intervention, follow-up, data analysis)

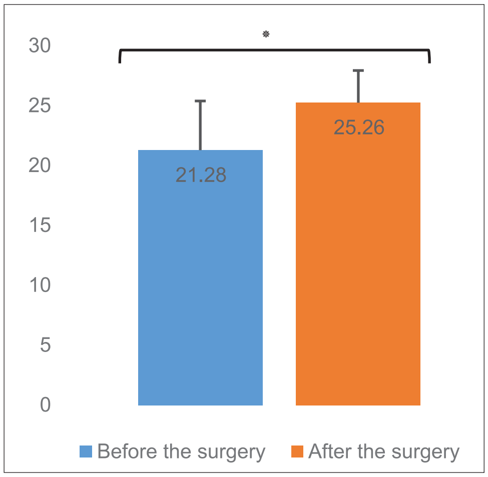

Chart 3: Harmony to noise ratio in the vowel /i/ before and 3 months after the surgery

Table 1: Demographics of the participants

Sex	Number	Mean age
Male	9	25.22±5.28
Female	3	23.33±4.04

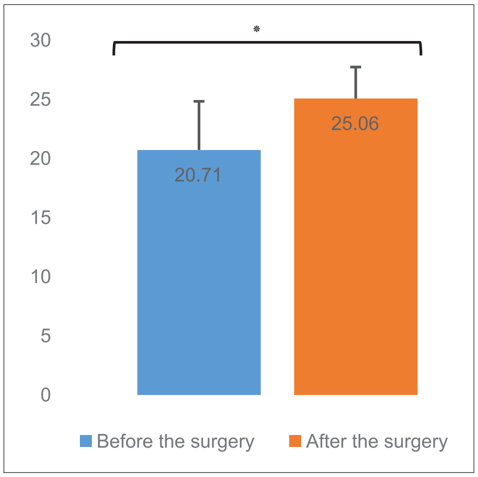

Chart 2: Harmony to noise ratio in the vowel /a/ before and 3 months after the surgery

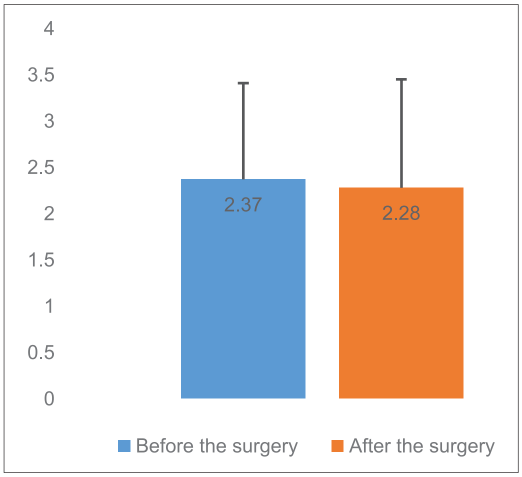

Chart 4: Long-term average spectrum spectral tilt in the vowel /a/ before and 3 months after the surgery

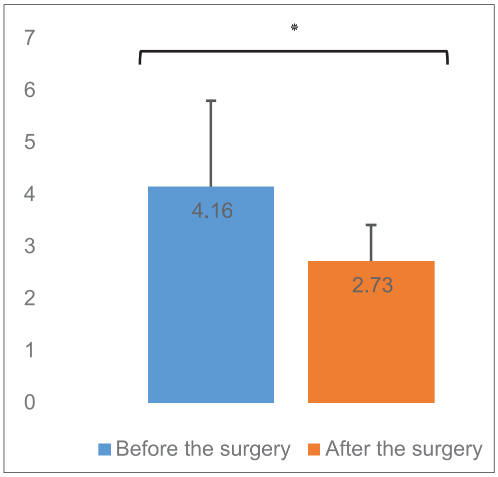

Chart 5: Long-term average spectrum spectral tilt in the vowel /i/ before and 3 months after the surgery (*Represents the significant statistical analysis by comparing mean values of each preoperative and postoperative parameters)

tilt shows the difference between the energy level of frequency range 0–1 kHz and 1–5 kHz, the decrease in the above parameter indicates an increase in the energy level in the range of high formants compared to that before the surgery. Given that the form of the transglottal airflow during the closure phase determines the range of higher harmonies of the voice source, if the glottis closes slowly or incompletely during phonation, the closure phase of vocal cords would change, and the spectral level in the range of higher formants would decrease. Taking into account that the LTAS spectral tilt reflects the speed at which vocal cords close[31,56] higher LTAS before the surgery indicated the slow and incomplete closure of the vocal cords, and its decrease after the surgery indicated the faster and competent closure of the vocal cords. The insignificance of the changes in /a/ rather than that in /i/ after the surgery might be due to the higher sensitivity of /i/ as a high vowel to changes.[57] Meanwhile, it should be noted that high vowels acoustically tend to be nasal compared to other vowels. The strong nasal acoustic energy in high vowels is likely to have a close relationship with acoustic features of the vowel nasalization.[58]

Because LTAS spectral tilt parameter was not calculated in similar studies, it is not possible to compare the results. However, our results are consistent with the results of Tahmasebifard study that investigated change of this parameter before and after re-repair surgery in children with velopharyngeal insufficiency.[9]

This study also showed an increase in HNR. The HNR is an index of voice quality and shows the integrity of the voice mechanism. It is a potent and very sensitive index in assessments and can indicate the vocal performance because HNR reflects the voice quality.[37] The increasing noise increases the turbulence of the airflow produced in glottis during phonation. The incomplete closure of vocal cords increases the glottal airflow, and consequently, the turbulence increases. The resultant frictional noise is reflected in the spectrum at a higher noise level, and thus, HNR decreases.[37,38] In this respect, it can be concluded that an increase in HNR after the surgery indicated the improved closure of vocal cords.

HNR Improvement after surgery has been reported in some studies such as Mora[11,39,40] Kosztyła-Hojna *et al*.,[42] Salami *et al*.,[43] and Tahmasebifard.[9] Results of Mora studies showed that NHR postoperative normalization represents altered dynamics in the structures of the resonator, which implies postoperative changes of vocal tract structures and a greater acoustical quality of the voice with less nasalized vowels. Kosztyła-Hojna *et al*.,[42] Salami *et al*.[43] also with regard to the improvement of this parameter and others relating to the vocal tract surgery in their studies mentioned positive effects of surgery on voice quality.

The changes in the two parameters after the surgery showed the regulation of supraglottic flow along with a decrease in the resistance of vocal tract and a decrease in laryngeal adductor force required for phonation.[11]

Based on the source-filter theory which is a successful framework for explaining the acoustic structure, the acoustic energy produced by the voice source (larynx) is modified by a filtering system (vocal tract) and is eventually released.[3] In fact, certain modifications and changes in vocal output are the results of transmission in supraglottal cavities. The shape and size of acoustic spaces of the vocal tract and the interconnection of these spaces play a major role in the regulation of resonant characteristics.[39] The nasal valve as a part of vocal tract constitutes the narrowest part of the nose and so applies maximum resistance to airflow.[10] The resistance primarily depends on the shape and size of the internal nasal cavity.[11] The internal nasal valve collapse is an important cause of nasal obstruction,[14] and this can add acoustic aspects to the speech signal.[11] Regarding the interaction between source and filter (source-filter theory), speakers with nasal obstruction need subglottal pressure to make the intraoral pressure to produce voices and increase the amplitude of voice due to the acoustic damping in the nasal passage. These speakers put more pressure on the larynx when using compensatory mechanisms. According to the source-filter theory, these pressures damage the larynx and consequently damage the vocal signs. This study using filter-source theory showed that the functional rhinoplasty had the potential to influence the voice quality through modifying the resonant features of the nasal passage. In fact, the change in the structure of nasal tract after the surgery, which leads to a decrease in resistance of the nasal airway and an increase in the nasal space, is the cause of changes in acoustic characteristics of the voice.[11]

It is very important to consider the impact of vocal tract problems as a reason for voice disorders. Because without resolving the problems of the vocal tract, voice therapy might be ineffective.

CONCLUSION

The internal nasal valve collapse causes more resistance to the airflow and acoustic damping in the nasal passage. When the vocal tract is modified in these patients, they do not have to use compensatory mechanisms and apply more pressure on the larynx any longer. After the surgery and modification of the vocal tract, the vocal cords closed sufficiently. This is also confirmed by computerized analysis of acoustic parameters.

The various methods of perceptual analysis show a considerable amount of subjectivity. However, computerized acoustic analysis helps to find an objective way for evaluating voice quality. When acoustic parameters are quantified, it would be easier to compare different voices.

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Conflicts of Interest

There are no conflicts of interest.

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APPENDIX

Appendix A: Boersma's algorithm for harmony to noise ratio measurement.

A summary of the complete 9-parameter algorithm, as it is implemented into the speech analysis and synthesis program Praat, is given here:

Step 1: Preprocessing - To remove the side lobe of the Fourier transform of the Hanning window for signal components near the Nyquist frequency, we perform a soft up sampling as follows: Do an fast-Fourier transform on the whole signal; filter by multiplication in the frequency domain linearly to zero from 95% of the Nyquist frequency to 100% of the Nyquist frequency; do an inverse fast-Fourier transform of order one higher than the first fast-Fourier transform.

Step 2: Compute the global absolute peak value of the signal (see Step 3.3).

Step 3: Because our method is a short-term analysis method, the analysis is performed for a number of small segments (frames) that are taken from the signal in steps given by the time step parameter (default is 0.01 s). For every frame, we look at most maximum number of candidates per frame (default is 4) lag-height pairs that are good candidates for the periodicity of this frame. This number includes the unvoiced candidate, which is always present. The following steps are taken for each frame:

Step 3.1: Take a segment from the signal. The length of this segment (the window length) is determined by the minimum pitch parameter, which stands for the lowest fundamental frequency that you want to detect. The window should be just long enough to contain three periods (for pitch detection) or six periods (for harmony to noise ratio measurements) of minimum pitch. Example, if minimum pitch is 75 Hz, the window length is 40 ms for pitch detection and 80 ms for harmony to noise ratio measurements.

Step 3.2: Subtract the local average.

Step 3.3: The first candidate is the unvoiced candidate, which is always present. The strength of this candidate is computed with two soft threshold parameters. Example, if voicing threshold is 0.4 and silence threshold is 0.05, this frame bears a good chance of being analyzed as voiceless (in Step 4) if there are no autocorrelation peaks above approximately 0.4 or if the local absolute peak value is less than approximately 0.05 times the global absolute peak value, which was computed in Step 2.

Step 3.4: Multiply by the window function (Eq. 5).

Step 3.5: Append half a window length of zeroes (because we need autocorrelation values up to half a window length for interpolation).

Step 3.6: Append zeroes until the number of samples is a power of two.

Step 3.7: Perform a fast Fourier transform (discrete version of Eq. 15), example, with the algorithm realft from Press *et al*. (1989)

Step 3.8: Square the samples in the frequency domain.

Step 3.9: Perform a fast Fourier transform (discrete version of Eq. 16). This gives a sampled version of ra (τ).

Step 3.10: Divide by the autocorrelation of the window, which was computed once with steps 3.5 through 3.9 (Eq. 9). This gives a sampled version of rx (τ).

Step 3.11: Find the places and heights of the maxima of the continuous version of rx (τ), which is given by Eq. 22, example, with the algorithm Brent from Press *et al*. (1989). The only places considered for the maxima are those that yield a pitch between minimum pitch and maximum pitch. The maximum pitch parameter should be between minimum pitch and the Nyquist frequency.