Chapter 6

Hearing Loss and the Voice

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Additional information is available at the end of the chapter

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Abstract

The voice varies according to the context of speech and to the physical and psychological conditions of the human being, and there is always a normal standard for the vocal output. Hearing loss can impair voce production, causing social, educational, and speech limitations, with specific deviation of the communication related to speech and voice. Usually, the voice is not the main focus of the speech-language pathology therapy with individuals with hearing loss, but its deviations can represent such a negative impact on this population that it can interfere on speech intelligibility and crucially compromise the social integration of the individual. The literature vastly explores acoustic and perceptual characteristics of children and adults with hearing loss. Voice problems in individuals with this impairment are directly related to its type and severity, age, gender, and type of hearing device used. While individuals with mild and moderate hearing loss can only present problems with resonance, severely impaired individuals may lack intensity and frequency control, among other alterations. The commonly found vocal deviations include strain, breathiness, roughness, monotone, absence of rhythm, unpleasant quality, hoarseness, vocal fatigue, high pitch, reduced volume, loudness with excessive variation, unbalanced resonance, altered breathing pattern, brusque vocal attack, and imprecise articulation. These characteristics are justified by the incapability of the deaf to control their vocal performance due to the lack of auditory monitoring of their own voice, caused by the hearing loss. Hence, the development of an intelligible speech with a good quality of voice on the hearing impaired is a challenge, despite the sophisticated technological advances of hearing aids, cochlear implants and other implantable devices. The purpose of this chapter is therefore to present an extensive review of the literature and describe our experience regarding the evaluation, diagnosis, and treatment of voice disorders in individuals with hearing loss.

Keywords: Hearing loss, voice, voice quality

1. Introduction

Didactically, the voice is described as the resulting sound of the vibration of the vocal folds, which is amplified by the vocal tract resonators. The vocal tract articulators modify this sound producing recognizable vowels and consonants. A pleasant and socially acceptable voice production is highly dependent on emotional, social, and physical conditions, the latter including auditory monitoring of the voice.

Hearing loss can impair oral communication, causing social, educational, and speech limitations, with specific deviation of the communication related to speech and voice. Usually, the rehabilitation process prioritizes auditory abilities, and therefore, the voice is not the main focus of the speech-language therapy with individuals with hearing loss. Its deviations, however, can represent such a negative impact on this population that it can interfere on speech intelligibility, cause a negative impact on the listener, and crucially compromise the social integration of the individual.

The challenges of voice production in individuals with hearing loss involve alterations in respiration, phonation, and articulation [1]. Also, voice problems in individuals with this impairment are directly related to its type and severity, age, gender, and type of hearing device used [2]. While individuals with mild and moderate hearing loss can only present problems with resonance, severely impaired individuals may lack intensity and frequency control, among other alterations [3]. Hence, the development of an intelligible speech with a good quality of voice in individuals with hearing loss is a challenge, despite the sophisticated technological advances of hearing aids, cochlear implants and other implantable devices.

2. The auditory system and voice production

Voice production (Figures 1A–1H) occurs by the integration of the respiratory, phonatory and articulatory systems, and also involves highly complex mechanisms of structures related to the central and peripheral nervous systems (Figure 1A) [4]. The airflow that is moved out of the lungs during expiration by the coordinated action of the diaphragm, abdominal muscles, chest muscles, and rib cage is directed toward the vocal folds (Figure 1B). Then to produce sound, the vocal folds are moved to midline by the action intrinsic muscles, nerves, and cartilages (Figures 1B–1D). The column of air from the lungs creates subglottic pleasure, causing the opening of the vocal folds. This is the beginning of a vibratory cycle that occurs repeatedly. In one vibratory cycle, the column of air pressure opens the bottom of the vocal folds. Then the air continues to move upward, now toward the top of the vocal folds, opening them entirely. The low pressure created behind the fast-moving air column produces the "Bernoulli effect", which causes the bottom to close, followed by the top. The closure of the vocal folds cuts off the air column and releases a pulse of air, and the cycle recommences (Figure 1E). The rapid pulses of air created in the repeated

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vibratory cycles produce "voiced sounds", which is then amplified and modified by the vocal tract resonators. The nose, pharynx, and mouth amplify and modify sound, allowing it to take on the distinctive qualities of voice. Finally, the articulators produce recognizable words [5] (Figures 1F–1G).

The neural component of the voice production generates two components for the voice: a propositional and an emotional one. The propositional vocalization is the expression of any idea that can be an abstract thought, an action, or an appreciation. Its content is not important if it has a communication proposal by means of the voice. The emotional vocalization expresses the emotional components of phonation. Both systems converge or integrate in the brainstem region where the retroambiguus nuclei are located. There, a new recording and a new result occur. This information goes to the nucleus ambiguus and retrofacial nucleus, which originate the vagal fibers of superior and inferior (recurrent) laryngeal nerves [6]. The peripheral nerves directly related the voice, providing sensory and motor innervation of the vocal tract include the glossopharyngeal nerve (IX cranial nerve), the trigeminal nerve (V cranial nerve), the facial nerve (VII cranial nerve), the vagus nerve (X cranial nerve), and the hypoglossal nerve (XII cranial nerve) [6].

Voice and speech production is therefore a complex process and involves numerous regulatory mechanisms [7]. In addition, during the whole process of maturation of the voice, people develop phonatory control and abilities to regulate and vary the voice use in different situations, which is directly related to a key component, which is the auditory feedback of the voice [8].

The auditory system is essential to regulate voice production by monitoring different voice parameters [9]. It provides two types of control over speech production: feedback control and feedforward control [10]. The feedback control monitors task performance during execution and also deviations from the desired performance, which are corrected according to sensory information. In the feedforward control, task performance is executed from previously learned commands, without reliance on incoming task-related sensory information. Speech and voice production involve both feedforward and feedback control, and auditory feedback impacts both control processes [11] (Figure 2).

Also, the auditory system has three roles: providing information regarding voice targets, which is important for corrections in pitch, volume, and other attributes that may affect intelligibility of speech; providing feedback about environmental conditions, which is important in noisy situations, for example, so that the speaker knows to enunciate more clearly, to increase amplitude, and to reduce speaking rate to increase intelligibility; and contributing to the generation of internal models for the motor plans for voice production, which is essential to the maintenance of a rapid speech rate through development of internal models, allowing for the vocal tract and related structures to be prepared before vocalization and for speech to continue without constant auditory feedback [10, 12]. These roles are responsible, therefore, for modeling voice quality, pitch, loudness, resonance, articulation, and speech rate.

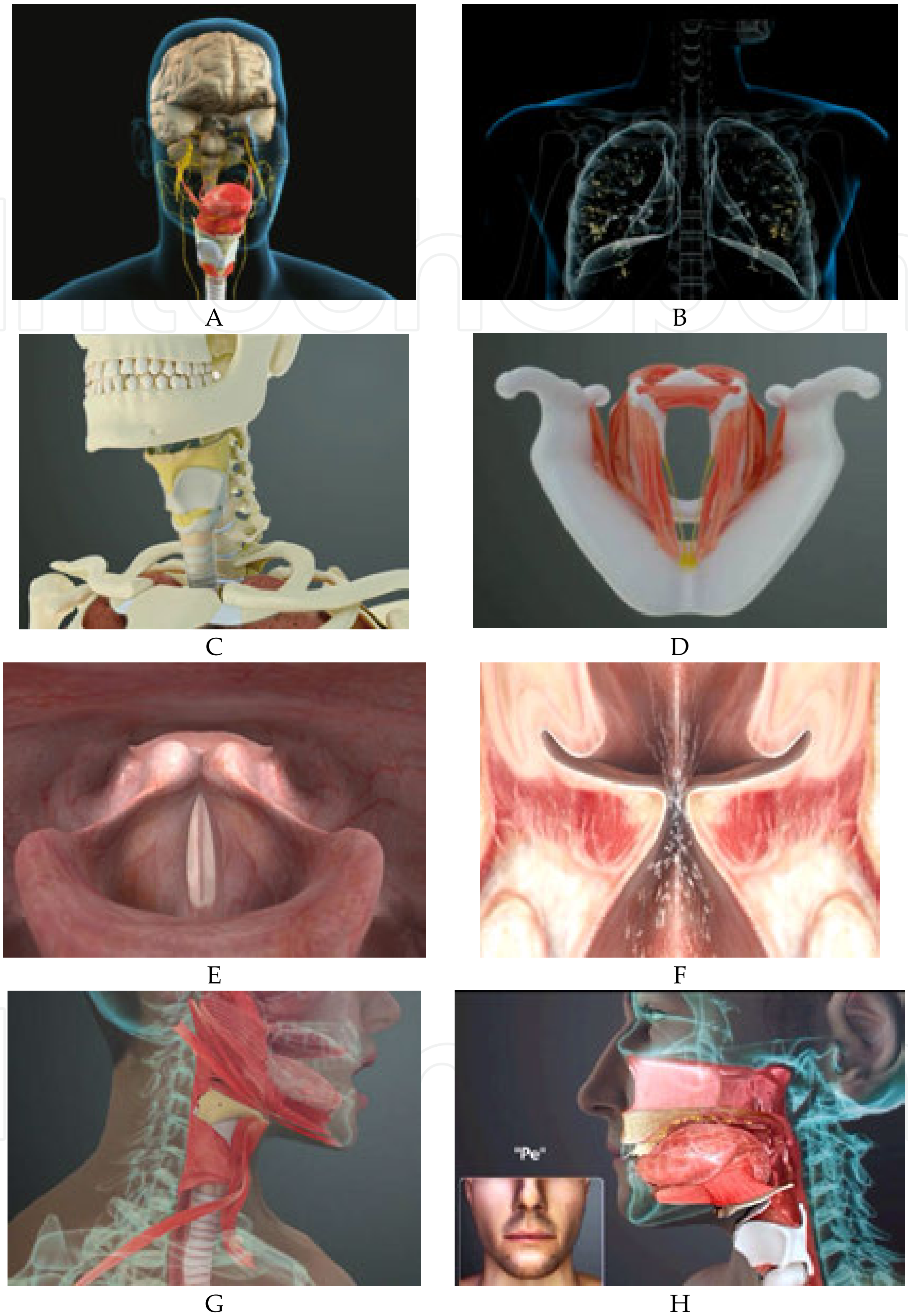

Figure 1. Voice production: (A) Peripheral innervation of the vocal tract; (B) respiration; (C) larynx; (D) intrinsic muscles of the larynx; (E) vibratory cycle; (F) vocal fold adduction; (G) extrinsic muscles of the larynx; (H) resonators and articulators. Source: Virtual Man Project [4].

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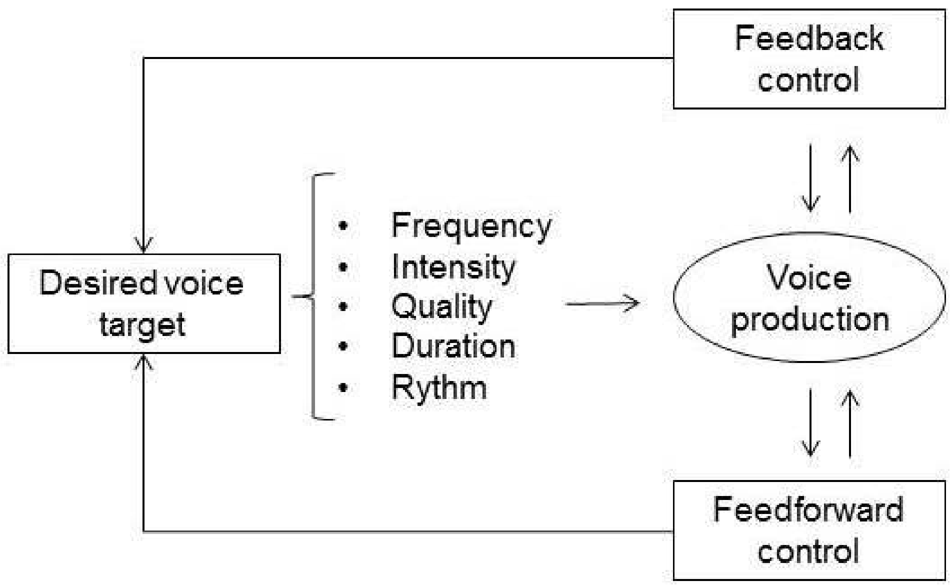

Figure 2. Auditory monitoring of voice production.

3. The voice of individuals with hearing loss

The overall product of a deaf speaker's vocal apparatus depends on the respiratory conditions, laryngeal state, resonators, articulators and prosodic aspects such as intensity, intonation, rhythm, and frequency.

Respiration aspects related to phonation can also be altered in this population. Laryngeal aerodynamics between children with bilateral profound sensorineural hearing loss using hearing aids and normal hearing children were compared by measuring vital capacity, peak flow, maximum sustained phonation, and fast abduction-adduction rate [13]. The authors found significant differences between vital capacity, maximum sustained phonation, and abduction-adduction rate, but not air flow, suggesting the presence of physiologically healthy and functional lungs for the airflow supply that will be required for speech production, but a limited use of the lung volume, poor management of the air supply, and poor laryngeal control during phonation.

Another potential factor that affects voice and speech intelligibility in individuals with hearing loss is the articulation accuracy of consonants and vowels. It is important to consider that voice and articulation are closely related since the sound that comes from the larynx is transformed into words by its combination with the dynamic and static structures of the upper vocal tract.

The phonetic inventory of the consonants in individuals with hearing loss can be compromised by distortions, substitutions, and omissions. Some phonological processes such as deletion of final consonants, cluster reduction, stopping, and devoicing may also occur [14], especially with voiced sounds and high frequency fricative consonants. The articulation of individuals with hearing loss has been reported to be characterized by the absence of some fricatives, the presence of distortions, and phonological disorders [15]. An adequate vowel production depends on the shape of the lips and position of the tongue and is also affected by the lack of auditory monitoring of the voice [16].

Regarding all aspects of voice production, the voice of individuals with hearing loss has been widely described. Specifically, acoustic and perceptual findings (Tables 1 and 2) indicate alterations that go from minor loudness deviation to significant respiratory, phonatory, and articulatory disorders. However, these characteristics are inconsistent and not unanimous among authors. They are reported to depend on age of hearing loss onset, its type and severity, and on the treatment of choice (Table 1) and have been compared among groups of patients in different conditions: prelingually deafened and postlingually deafened, aided and unaided, pre and post cochlear implantation, and patients treated with either hearing aids or cochlear implants (Table 2).

Such a variety of vocal features and results (Tables 1 and 2) are possibly due different methodological approaches with different assessment conditions, such as different speech materials, different assessment techniques, different software, different perceptual protocols, number of participants, different age range, different hearing devices, different age at the activation of the hearing device, and presence or absence of a control group to establish normative data [17]. Therefore, the understanding of speech and voice production of individuals with hearing loss is still a challenge and is missing a standardized approach.

	HL characteristics	**Voice characteristics**
Type	Conductive	Reduced loudness [3]
	Sensorineural	High fundamental frequency (f_0) [18–21], f_0 within normal standards [15], normal jitter [15], normal shimmer [15], high variation of amplitude, and f_0 [22] instability [23,24]
	Mixed	Not reported
Severity	Mild to moderate	Resonance disorder [3]
	Severe to profound	High f_0 [18,25,26], instability [23,24,26,27]
Hearing loss onset	Prelingual	Hoarseness [28], breathiness [28], strain [26,28], high f_0 [20,25,26], high variability in f_0 [21,26], excessive intonation [21], monotone [20], excessive pitch variation [21], altered speech rate [21], increased loudness [21,29], loudness either to soft or too loud [20], resonance irregularity [17,21,30], instability [24,26]
	Postlingual	Abnormal intonation [21,28], high pitch/f_0 [21,31], altered speech rate [21,28], nasality [2,21], loudness deviation [2,21,28,31], roughness [1], strain [1], instability [1], high jitter [31], high shimmer [31] high noise to harmonic ratio [31]
Treatment	Hearing aid	High f_0 [19,32], high pitch [10], f_0 within normal standards [22], normal jitter [22], normal shimmer [22], high jitter [32], high shimmer [32], high variation of amplitude and f_0 [22], strain [17], instability [17, 30]

	HL characteristics	Voice characteristics
	Cochlear implant	High f_0 [19,26,33], normal f_0 [24,34], high pitch [17,26], variation of amplitude and fundamental frequency [22], high jitter and shimmer [32,33], instability [17,23,24,26], strain [10,19], significant overall severity of voice quality [26,35]

Table 1. Voice characteristic of individuals with hearing loss according to type and severity of hearing loss, hearing loss onset, and treatment of choice.

Comparison	Title	Results
Hearing loss onset	Acoustic analysis of the voice in pediatric cochlear implant recipients: a longitudinal study [19]	Normalization of the long-term amplitude control after cochlear implantation regardless of onset
	Acoustic analysis of voice in cochlear implant recipients with postmeningitic hearing loss [36]	No significant differences found regarding hearing loss onset
Unaided individuals × normal hearing adults	Acoustic features of voice in patients with severe hearing loss [31]	Deviated acoustic parameters for the unaided participants
Pre- to post cochlear implantation	Voice analysis of postlingually deaf adults pre- and post-cochlear implantation [1]	Improved overall severity, strain, loudness, and instability with cochlear implantation as well as reduction in fundamental frequency and its variability
	Change of phonation control after cochlear implantation [20]	Decrease of jitter, shimmer, fundamental frequency and amplitude variability in prelingually deafened children, and no significant differences in postlingually deafened adults. Even so, the children's voices were worse than the adults'
	Effect of cochlear implantation on nasality in children [27]	Significant reduction of nasality after cochlear implantation
Hearing aid × cochlear implant	Comparison of the overall intelligibility, articulation, resonance, and voice characteristics between children using cochlear implants and those using bilateral hearing aids: a pilot study [37]	Better intelligibility for users of cochlear implants and no differences in the remaining parameters
Cochlear implant × hearing aid × normal hearing	Objective voice quality in children using cochlear implants: a multiparameter approach [17]	Both groups with hearing loss presented with altered perceptual scores, with worse results for the

Comparison	Title	Results
		hearing aided children; no significant differences in acoustic measures were observed
	The influence of the auditory prosthesis type on deaf children's voice quality [32]	Better results for the participants with hearing aids
	Acoustic, aerodynamic, and perceptual analyses of the voice of cochlear-implanted children [35]	Better voice quality for children with cochlear implants
	Voice and pronunciation of cochlear implant speakers [38]	Better results for the participants with cochlear implants
Cochlear implant × normal hearing	Cochlear implanted children present voice parameters within normal standards [24]	Higher instability and frequency variation for cochlear implant users.
	An initial study of voice characteristics of children using two different sound coding strategies in comparison to normal hearing children [26]	Higher fundamental frequency, fundamental frequency variability, amplitude variability, overall severity, strain, loudness, instability, high pitch, and resonance deviation for the cochlear implanted participants
	Nasalance and nasality in children with cochlear implants and children with hearing aids [30]	Children with hearing aids and cochlear implants showed altered nasalance. Cul-de-sac resonance was observed on a significantly larger scale than in the normal hearing group, and children with were significantly more hypernasal in than normal hearing children
	Normal-like motor speech parameters measured in children with long-term cochlear implant experience using a novel objective analytic technique [39]	Cochlear implant users had poorer than normal intonation stimulability, particularly frequency variability
Hearing aid × normal hearing	Laryngeal aerodynamics in children with hearing impairment versus age- and height-matched normal hearing peers [13]	Significant difference in the vital capacity, maximum sustained phonation, and fast adduction abduction rate
	Variability in voice fundamental frequency of sustained vowels in	Significantly higher low frequency modulation for the individuals with hearing loss

Comparison	Title	Results
	speakers with sensorineural hearing loss [40]	
	Voice field measurements–a new method of examination: the influence of hearing on the human voice [41]	Voice field of the impaired person is significantly limited in regard to both frequency and dynamics, and it is narrower than that of intact persons.

Table 2. Overview of findings of voice characteristics when comparing hearing loss onset, treatment, and normal hearing.

3.1. Perceptual ratings of the voice of individuals with hearing loss

The auditory-perceptual evaluation of the voice is a key element to understand the voice production of individuals with hearing loss. When associated with acoustics, aerodynamics, laryngeal imaging, and quality of life, it gives a complete background to define the best treatment approach. Although it is subjective and depends on listener's experience, the auditory perception is the main upholder of voice therapy, and it can be correlated to all of the assessments cited.

The voice of the individuals with hearing loss has been perceptively characterized using several scales: the Voice Profile Analysis [42], the GRBAS scale [43], the GRBASI scale [44], the Prosody-Voice Screening Profile (PVSP) [45], the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V) [46], and visual analog scales of specific parameters [47]. Theses scales 14 can be used to characterize voice quality and quantify the vocal alteration.

Reported characteristics in the last 10 years include significant overall severity of dysphonia [17, 26, 35, 48], roughness [17], strain [17, 16, 48], resonance deviations [26, 48], high pitch [1, 26], and instability [24, 26].

One particular study [21], described the voice characteristics of 40 profoundly hearing-impaired young adults using the Voice Profile Analysis (VPA), which includes articulatory (supralaryngeal) settings, laryngeal settings, strain, and prosodic settings of the voice tract. The comparison with a control group showed some interesting data for the individuals with hearing loss:

- Range of movements: minimized tongue movements, both minimized and extensive jaw movement, and both minimized and extensive lip movements
- Pitch and loudness: narrow pitch range, low pitch variability, low loudness mean, narrow loudness range, and low loudness variability
- Tension: pharyngeal constriction, both laryngeal tension and looseness
- Laryngeal factors: harshness, use of falsetto, raised larynx

Considering these findings, the positioning, movement, and strain of the articulatory organs seem worthy of further study as they shape the voice tract and determine some aspects of voice quality.

In terms of resonance, the most reported characteristic in individuals with hearing loss is nasality. The abnormal nasalization of vowels and nasal consonants significantly contributes to the abnormal voicing of children and adults with hearing loss, which is related to poor control of the velopharyngeal valve due to the lack of auditory feedback–oral/nasal distinctions [28] and is related to the duration if the hearing impairment [2] and speech rate [27]. The velopharyngeal valve lack rhythm and strength in this population, despite normal structure and muscle activity [49].

A mixed resonance, however, is not an uncommon feature. A pharyngeal resonance also known as cul-de-sac [30, 50] can also be found and is associated with elevation of the hyoid and retraction of the tongue [51]. Hyponasality is also reported [52]. Thirty profoundly deaf children [42] had significantly higher nasalance values compared with a normal hearing control group when nasal consonants were absent (reflecting hypernasality) and significantly lower when an utterance was loaded heavily with nasal consonants (reflecting hyponasality).

The suprasegmental features of speech that are conveyed by the parameters of fundamental frequency, intensity, and duration can directly affect the voice production and speech intelligibility. These features constitute prosody, which is considered the "melody and rhythm of spoken language" [53]. During the development of oral communication, how children acquire target appropriate prosodic structure is important because it plays a role in many aspects of linguistic function, from lexical stress to grammatical structure to emotional effect. It is therefore important for the transmission of meaning and thus for intelligibility. These aspects of the oral communication can be problematic for individuals with hearing loss since auditory monitoring is critical for listeners' recognition of prosodic contrasts of speech [54]. An investigation of the production of speech intonation in cochlear implanted children in comparison with their age-matched peers with normal hearing [54] found inappropriate intonation contours for the implanted participants. Another study found that cochlear implanted children present restriction of intonation, particularly in interrogative sentences [55].

3.2. Acoustic characteristics

The acoustic analysis is an instrumental assessment that complements the auditory perceptive evaluation and provides quantitative and qualitative information about voice behavior from the analysis of the sound signal. By using computerized software, it is possible to obtain measures of fundamental frequency, perturbation and noise indexes, temporal changes in speech, and also visual graphic interpretation. This assessment magnifies the understanding of voice behavior and allows the documentation of treatment outcome.

The voice characteristics of the individual with hearing loss can be visually measured or numerically evidenced in the acoustic analysis and depend on the anatomy and physiology of the entire vocal tract. For example, the fundamental frequency can be influenced by the length, elongation, mass, and tension of the vocal folds and is integrated with the subglottic pressure. The higher fundamental frequency observed in individuals with hearing loss is related to greater tension during voice production as a result of the search for kinesthetic monitoring [41].

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with the subglottic pressure. The higher fundamental frequency observed in individuals with hearing loss is related to greater tension during voice production as a result of the search for kinesthetic monitoring [41]. Also, individuals with hearing loss have difficulties in maintaining the stability of the fundamental frequency [56], during the extension of a vowel and during connected speech.

In Figure 3, the emissions of the sustained /a/ vowel by two men with 27 years of age, one with hearing loss and one with normal hearing, are presented. It is possible to visualize the greater instability in frequency (blue) and intensity (gray) and also higher fundamental frequency (203 Hz) produced by the individual with hearing loss in comparison to the individual with normal hearing (87Hz).

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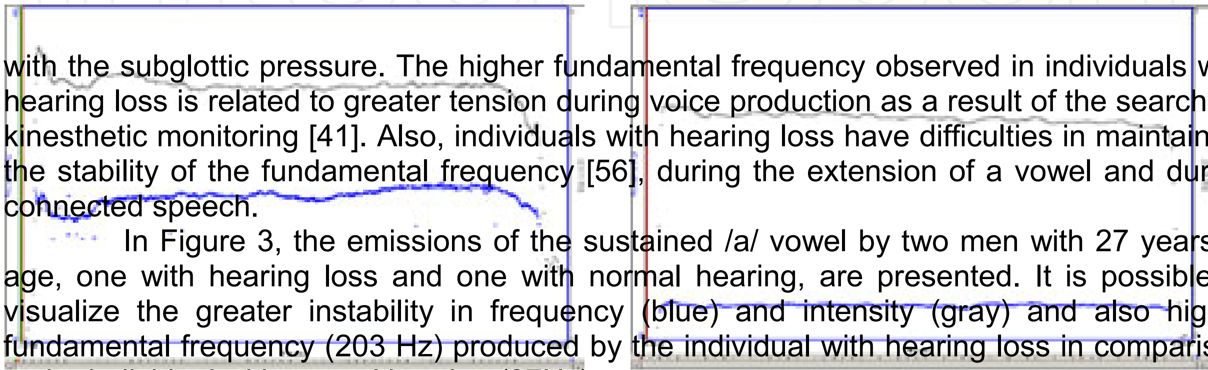

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A B

Figure 3. Graphs with fundamental frequency (blue) and intensity (gray) of the voices of an individual with hearing loss (A) and an individual with normal hearing (B) during the emission of a sustained vowel, obtained with the program Real Time Pitch from KayPentax.

Figure 4 shows the excessive variation of frequency of a child with 4 years of age with hearing loss in comparison to a child with the same age and with normal hearing while counting numbers.

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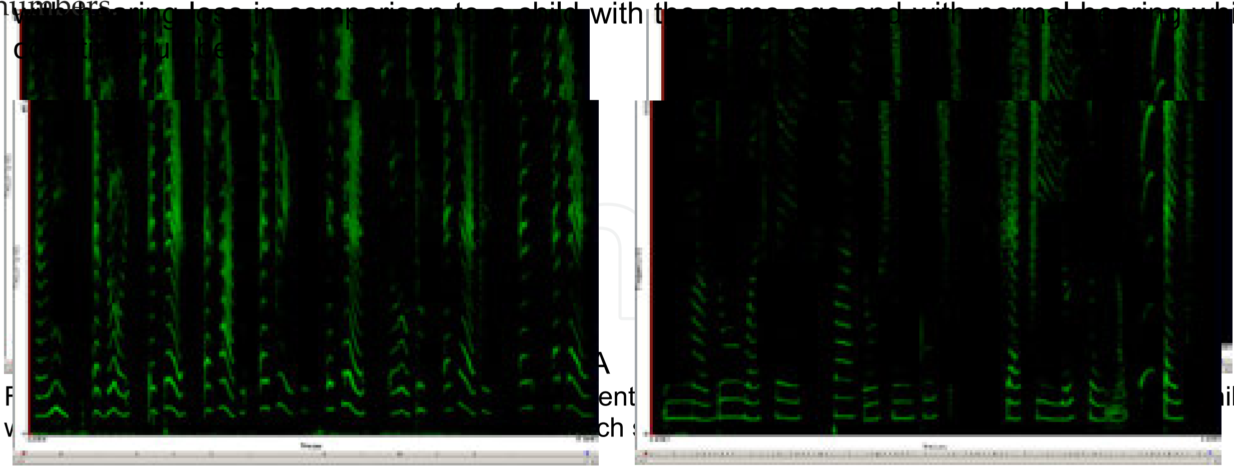

A B

Figure 4. Graphs with frequency spectrogram of the speech of a child with hearing loss and a child with normal hearing, obtained with the Multi Speech software from KayPentax.

The acoustic evaluation can be performed visually by describing the spectrogram, a tridimensional graph the present the following information obtained by the Fourier transformation: the frequency in the ordinate axis, measured in Hertz; the time in the abscissa axis, measured in seconds; and the intensity, according to the degree of darkening or coloration of the spectrum, measured in decibel [57].

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Figure 5 shows the spectrograms of a woman with 32 years of age with hearing loss and of another with the same age and normal hearing evidence, the irregularity of the sustentation of the emission, greater presence of noise, greater spacing between the harmonics, intensity, and effort in the voice of the woman with hearing loss.

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Figure 4 shows the excessive variation of frequency of a child with 4 years of age with hearing loss in comparison to a child with the same age and with normal hearing while counting numbers.

Figure 4. Graphs with spectrograms of the sequential speech of a child with hearing loss and a child with normal hearing, obtained with the Multi Speech software from KayPentax.

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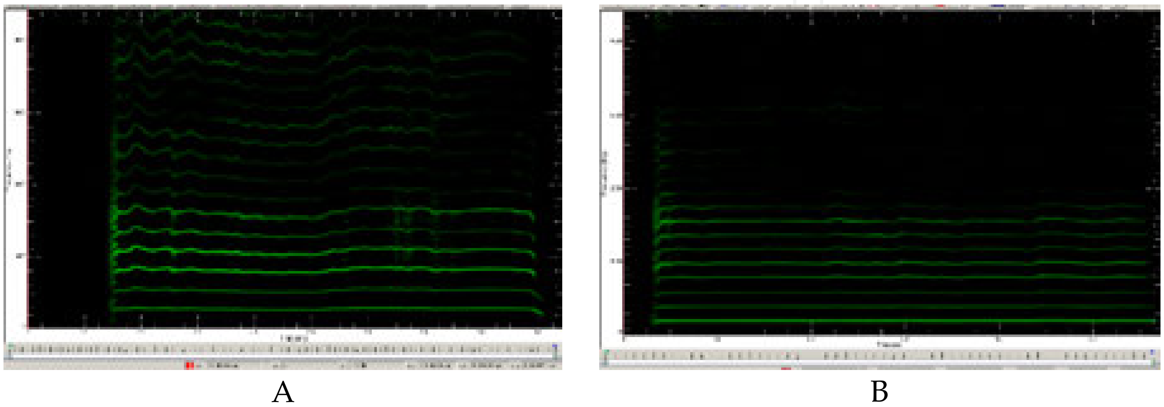

Figure 5. Graphs with spectrograms of the sustained vowel of a woman with hearing loss (A) and a woman with normal hearing (B) obtained with the Multi Speech program from KayPentax.

Some perturbations of the sound wave and of the ratio of noise in relation to the harmonics were used by some authors to characterize the voice of individuals with hearing loss. These characteristics can be related to the perception of roughness and strain in the voice. Generally, the voices of individuals with hearing loss show more perturbation of the sound wave and greater quantity of noise in relation to individuals with normal hearing [58]. Among the measures of perturbation, the jitter indicates short-term variability of the fundamental frequency. These values can represent a small variation in mass or tension of the vocal folds, on the distribution of mucus on them, on the symmetry of the structures, or even in the muscular or neural activity involved; the shimmer indicates short-term variability of the amplitude of the sound wave, and it is a measure of phonatory stability. Its values increase as the amount of noise in the emission increases [59]. The noise-to-harmonic ratio measures the relative quantity of additional noise in the voice signal, which can be generated by the turbulence of the airflow in the glottis in cases of incomplete closure during phonation or also result from aperiodic vibration of the vocal folds [60], being associated with the presence of roughness. One of the limitations of this form of acoustic analysis is that, to perform a reliable analysis of jitter, shimmer, and noise measures, the sound signal cannot be too altered. This analysis is only reliable in normal or slightly altered voices, which prevents the evaluation of voices with more severe alterations.

3.3. Laryngeal features

Based on perceptual and acoustic data, many authors [3, 17, 33, 35, 61] state that individuals with hearing loss have difficulties in controlling the laryngeal function. To this date, however, laryngeal characteristics of individuals with hearing loss have not been thoroughly studied.

It has been stated that the larynx of a hearing-impaired child usually shows no anatomic or physiological abnormalities in the first years of life, but lack of auditory feedback can result in discoordination of intrinsic and extrinsic laryngeal muscles and disturbed contraction and relaxation of antagonistic muscles [13].

Inadequate laryngeal activity of four normally hearing and four hearing-impaired persons was found during productions of word-initial voiced and voiceless consonants with a flexible fiber-optic laryngoscope [62]. Three of the hearing-impaired subjects exhibited greater variability than their normally hearing peers in terms of the degree and duration of vocal fold abduction during voiceless consonant productions, but only one exhibited excessively wide glottal openings, suggesting that deaf persons waste air during speech production.

A study [63] was conducted with two normal hearing adults and four adults with profound hearing loss using high speed laryngeal film and acoustic data. The authors used the vowel-consonant-vowel segment “aha.” The study found that two of the hearing-impaired subjects did not exhibit glottal waveforms in vowel production, which differed substantially from those of the normally hearing subjects. However, one subject with hearing loss exhibited maximal glottal openings approximately double those of the other subjects and large cycle-to-cycle variability. The most dramatic differences observed between the normally hearing and hearing-impaired subjects were the duration and the magnitude of the abductory gestures associated with devoicing. The vocal fold abductory-adductory movements associated with the devoiced segments appeared to be discontinuous in nature, which was characterized by abrupt abductory movement following the first vowel, which frequently reached a plateau before adductory movement associated with the second vowel. Such laryngeal features can result in abnormal voice production; however, these laryngeal findings were not correlated to voice quality.

3.4. Voice-related quality of life

The instruments used to measure quality of life in health sciences allow the understanding of the impact of a condition through patient perception. These materials have been used to obtain a multidimensional assessment of the human being. Patient-based assessment can be used to compose the evaluation process, helps clinicians to select strategies for rehabilitation based on specifics indentified, and monitors treatment outcomes [64].

With the inclusion of quality of life analysis in the health sciences, voice-related quality of life protocols were created since protocols about general health are not ideal to assess patients with voice disorders. Due to the importance of human communication in the several domains that contribute to quality of life, these instruments investigate if there are physical, emotional, and social limitations related to voice disorders, including the use of professional voice [65].

These instruments, therefore, contribute to the knowledge of the impact of the communication disorders manifested by the voice alteration. The extensive list of voice problems the individuals with hearing loss can affect their quality of life. However, the protocols of voice-related quality of life already developed are not entirely adequate to the voice problems frequently presented by individuals with hearing loss, and voice-related quality of life in individuals with hearing loss has not yet been thoroughly studied.

A single study [4] investigated voice-related quality of life in this population by comparing the scores of the Voice Handicap Index [66] between adults with moderate to profound hearing loss and their normal peers. There were significant differences in the total score and in the score of all three domains: functional, physical, and emotional. However, there was a major variability of responses obtained in the group of patients with hearing loss (a variation of 94 points) so the authors were not able to define a VHI score range.

Also, the several protocols of quality of life related to the presence of hearing loss or use of hearing aids [67–69] approach communication aspects regarding sound reception and not regarding the difficulties of voice and speech production, even though it is common knowledge that hearing interferes also in the emission stage of the communicative process.

4. Voice training in individuals with hearing loss

The auditory rehabilitation aims to allow deaf individuals using devices such as heading aids and cochlear implants to develop auditory abilities and oral communication. However, since voice characteristics commonly found in individuals with hearing loss can greatly compromise oral communication, voice training in addition to hearing, language, and speech rehabilitation is essential to restore normal physiology. For both prelingually deafened children and postlingually deafened adults, intervention can improve voice quality and prevent the development of abnormal voice production. Depending on the findings of the voice assessment, the treatment can include techniques for respiration, posture, movement of the articulators, vertical laryngeal excursion, loudness, and resonance [70].

The speech and language rehabilitation program of the Brasilia Teaching Hospital (Hospital Universitário de Brasília [HUB]) provides treatment for children, adolescents, and adults with moderate to profound hearing loss who are users of hearing aids and/or cochlear implants. The purpose of the therapy goes beyond speech perception. In the therapeutic plan, voice training is considered an element just as important as auditory training, being considered therefore a part of the extensive process of rehabilitation of individuals with hearing loss.

Voice training comprises many approaches: the universal methods that change voice quality as a whole and the specific techniques that rely on laryngeal imaging and aim to work with specific groups of muscles. With the use of different techniques and exercises, it is possible to modify the voice by acting on the muscle activity of the vocal tract, to enhance the relationship of the three subsystems of voice production (respiration, phonation, and resonance), and to demonstrate to the patient the many possibilities of motor adjustments of voice production

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[57]. Based on the findings of the voice assessment and on laryngeal imaging whenever possible, the clinician can select a number of voice exercises that are thoroughly described in the literature [50, 71] to improve the abnormalities found. Some of the exercises suggested for hearing-impaired individuals are the prolonged /b/ exercise, manual circumlaryngeal massage associated with the emission of vowels and words, emissions of the closed vowels /o/ and /u/ while flexing the head to fix the larynx in a lower position, chewing, and lip vibration [72, 73]. In Table 3, some exercises for voice treatment [50, 71] are suggested based on findings of voice characteristics of individuals with hearing loss reported in the literature.

Voice feature	Purpose	Exercise
High fundamental frequency (f_0)	Reduce f_0, lower the larynx	Manual circumlaryngeal massage, yawn-sigh exercise, descendent pitch glide
High amplitude and frequency variation	Reduce amplitude and frequency variation	Visual monitoring of speech with computerized software
Nasality/resonance alterations	Increase intraoral air pressure, dissipate energy in the voice tract	Visual monitoring of nasal airflow with mirror or scape-scope, chewing exercises associated with vibratory sensations in nasal and facial bones, humming, mouth opening
Roughness, breathiness, harshness, strain	Balance aerodynamic and myoelastic forces, mobilize vocal fold mucosa	Manual circumlaryngeal massage, humming, chewing exercises, yawn-sigh exercise, tongue vibration, vocal fry
Instability	Improve phonatory stability	Exercises with long sustained tones
Monotone	Vary rate, pitch, and loudness	Musical scales, pitch glides, *messa di voce*, cards with arrows going up and down in a sentence
Excessive intonation	Promote control over pitch and loudness, reduce excessive vertical excursion of the larynx	Visual monitoring of speech using frequency and amplitude displays
Altered speech rate	Control speech rate	Monitor speech rate with metronome

Table 3. Common voice alterations in individuals with hearing loss and the respective techniques and exercises suggested in the voice rehabilitation.

Naturally, adapting the conventional voice therapy is very helpful, especially for people with severe to profound hearing loss since the training should not rely exclusively in auditory monitoring. Among the methods used for hearing rehabilitation is the multisensory method that uses the auditory channel, the visual channel, and tactile/kinesthetic cues [74, 75]. In the voice clinic, the use of visual, kinesthetic, and proprioceptive cues is extremely useful to develop parameters such as frequency and intensity [71], which is due to the fact that visual and tactile/kinetic feedbacks of the vocal apparatus are preserved in this population and should be explored in addition to the auditory training [70]. Abilities such as lip reading exemplify the use of visual cues for the development of speech and voice [72].

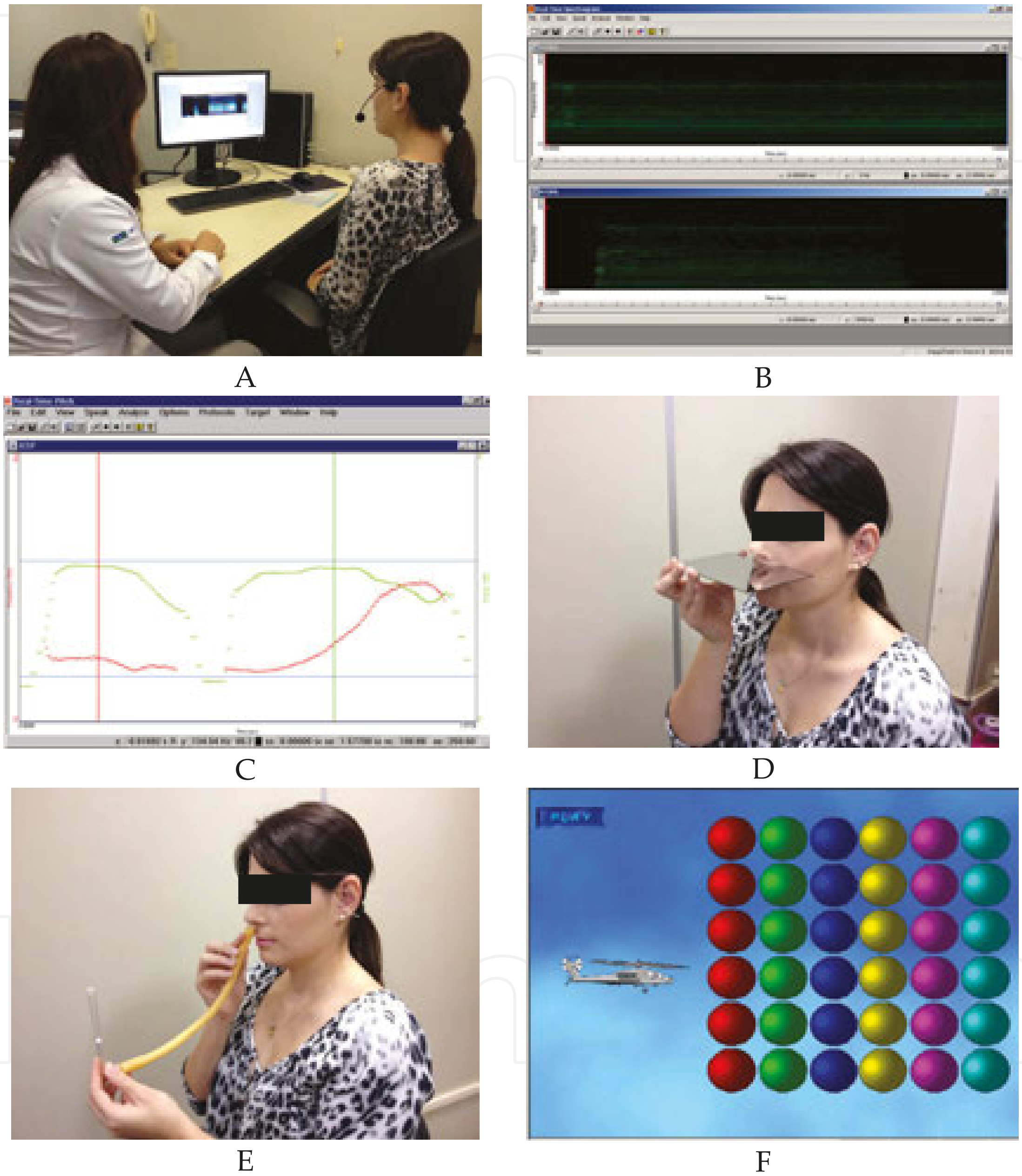

Figure 6. Examples of visual feedback in voice training. (A) Real-time spectrogram (GRAM 5.1.6). (B) Real-time monitoring of voice signal following a model provided in the upper window (Real Time Pitch, KayPentax). (C) Real-time monitoring of frequency and intensity. (D) Nasal mirror and for monitoring nasal airflow. (E) Scape-scope for monitoring nasal airflow. (F) Visual monitoring of intensity (Voice Games, KayPentax).

Using visual cues, it is possible to monitor adequate frequency and intensity with established thresholds, noise, voice attacks, strain, instability, formants, and voicing. Such methods are

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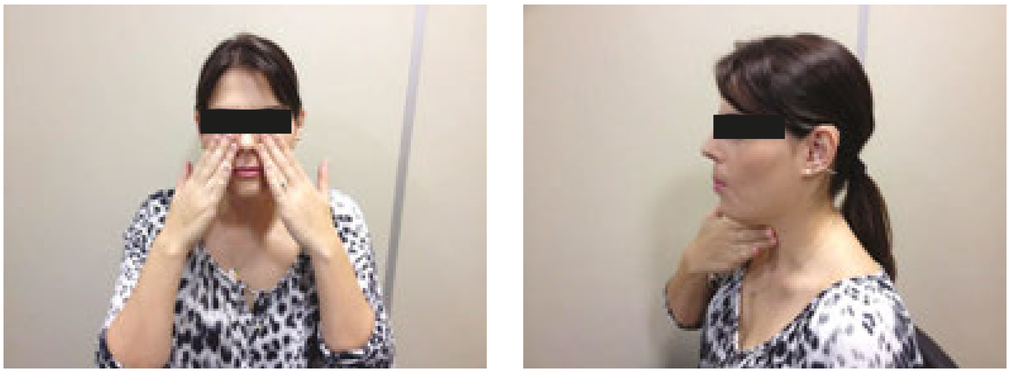
considered effective in the voice rehabilitation of deaf individuals [76, 77]. Studies found improved frequency control, respiratory support, intelligibility, jitter and shimmer after voice therapy with computerized visual feedback [72, 78], and reduced nasality using visual cues to monitor nasal airflow [79, 80]. These cues include spectrograms, diagrams, nasal mirror, scape-scope, and even computerized software for children to promote a playful environment while training voice production (Figures 6A–6F).

The tactile/kinesthetic monitoring is harder to develop. Patients must identify proprioceptive symptoms and sensations that indicate abnormal voice production such as tightness, presence of secretion, pain, dryness, discomfort, etc. The procedure for using these cues include emission while touching the head, forehead, face, and resonance cavities, including the nose, neck, and thorax [71] (Figures 7A–7B).



A B

Figure 7. Examples of kinesthetic feedback in voice training. (A) Hands feeling resonators for resonance control. (B) Monitoring larynx decent for normalizing pitch.

A structured voice therapy program for individual with hearing loss was described [78] and consisted of 16 therapy sessions, conducted twice a week with the duration of 1h. In the first half of the therapy session, the participants performed specific vocal exercises, which consisted of tongue snapping, tongue or lip vibration, humming, fricative sounds, prolonged /b/ exercise, vocal fry, overarticulation, chewing exercise, chanting, and visual/proprioceptive monitoring. In the second half, computerized games were used to provide visual feedback for monitoring frequency and intensity during speech tasks. The program showed promising results in speech and voice using these techniques and exercises. A similar approach was later suggested [72] using mainly visual feedback with computerized games and also finding improvement in speech and voice production.

A case study is presented to illustrate the immediate results of voice training during a therapy session of a young adult with profound hearing loss that use a unilateral cochlear implant. The patient is a 26-year-old male, with bilateral profound hearing loss due to bacterial meningitis at the age of 23 years.

To compare the results of the voice exercises, the prolonged /a/ vowel and a sample of sequential speech (counting from 1 to 10) were recorded pre- and post-therapy session. The perceptive analysis of the /a/ vowel pre-therapy evidenced brusque vocal attack, roughness, nasality, and instability. The sequential speech evidenced roughness, nasality, and imprecise articulation. The purpose of the voice exercises was to reduce laryngeal strain, to reduce nasality and cul-de-sac resonance improving relationship between glottal source and resonance, and to enhance articulation.

The selected exercises were as follows:

- Humming
- Humming associated with vowels
- Chanting the sequence "mananha, menenhe, mininhi, mononho, mununhu"
- Chewing exercise
- Chewing exercise associated with sequential speech (numbers from 1 to 10, months of the year, days of the week)

After the therapy session, there was a significant reduction of the brusque voice attack, roughness, and nasality in both emissions. In Table 4, some acoustics parameters of the /a/ vowel are presented pre- and post-therapy session using the Multi Dimensional Voice Program (MDVP, KayPentax). There was a slight reduction in fundamental frequency, although it is within normal standards for men at this age. There was also reduction of short- term variation (jitter) and long-term variation of frequency (jitter), short-term (shimmer) and long-term variation of amplitude (vAm), and reduction of the noise to harmonic ratio (NHR).

Parameter	Pre-therapy	Post-therapy
Average fundamental frequency (f_0)	127.052	123.322
Jitter (%)	3.966	3.337
Fundamental frequency variation (vF_0)	3.652	3.247
Shimmer (%)	5.590	4.176
Peak to peak amplitude variation (vAm)	14.535	9.725
Noise to harmonic ratio (NHR)	0.214	0.147

Table 4. Acoustic parameters of the /a/ vowel pre- and post-therapy session.

In Figure 8, the narrowband spectrogram of the pre-therapy /a/ vowel shows brusque voice attack, presence of subharmonics, low high-frequency harmonics, and instability. In the post-therapy spectrogram, increase in high-frequency harmonics, reduction of brusque voice attack, reduction of subharmonics, and reduction of instability are observed.

Figure 9 shows the narrowband spectrogram of the sequential speech using the Multi Speech Main Program (KayPentax), on which a significant increase of harmonics can be observed, although there is presence of subharmonics in both emissions.

In Figure 8, the narrowband spectrogram of the pre-therapy /a/ vowel s... brusque voice attack, presence of subharmonics, low high-frequency harmonics ... instability. In the post-therapy spectrogram, increase in high-frequency harmonics, reduction of brusque voice attack, reduction of subharmonics, and reduction of instability observed.

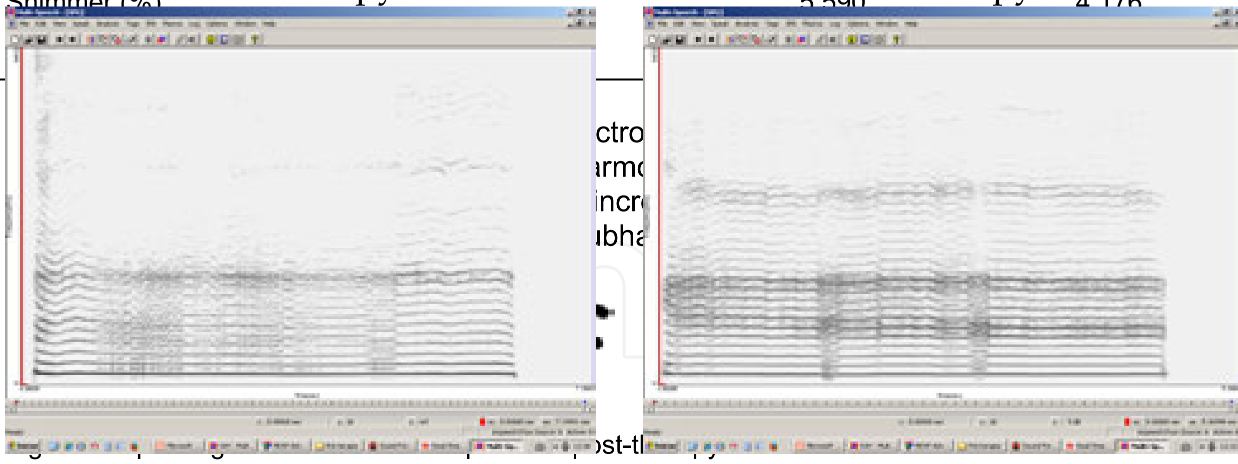
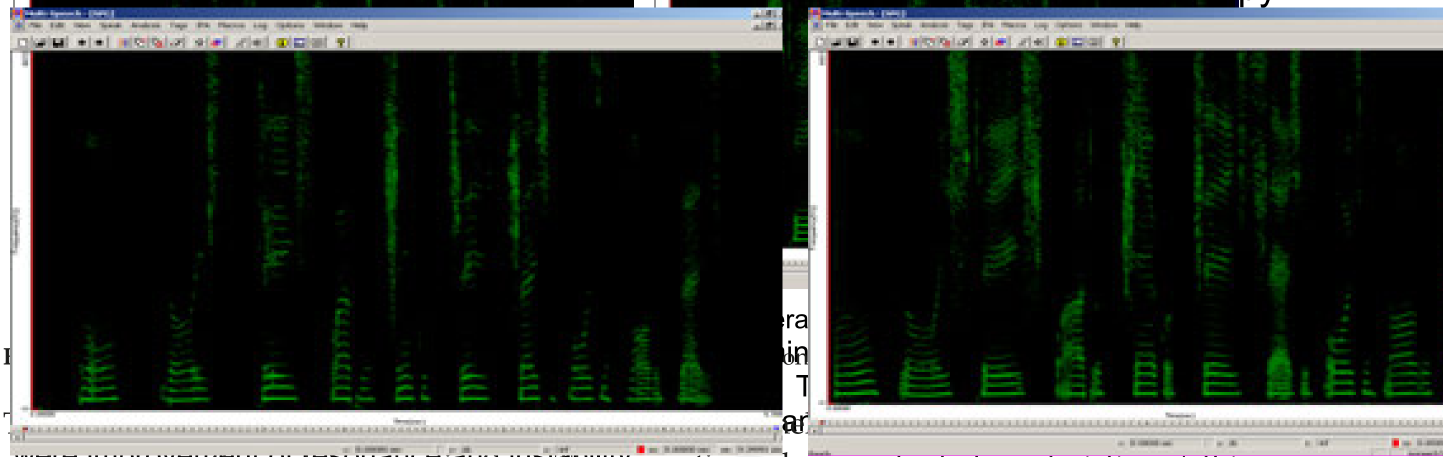


Figure 8. Spectrogram of the /a/ vowel pre- and post-therapy session.

Figure 9 shows the narrowband spectrogram of the sequential speech using the Multi Speech Main Program (KayPentax), on which a significant increase of harmonics can be observed, although there is presence of subharmonics in both emissions.



and consequently oral communication. The acoustic and perceptual characteristics of this individual improved significantly, and the most prominent features were improvement of resonance and instability.

5. Conclusions

The primary difficulties of children and adults with hearing loss are related to auditory abilities and language development, and with reason, they become the primary center of attention in the rehabilitation process. However, voice abnormalities should not be overlooked since they can greatly compromise voice quality and speech intelligibility. There is still much to be done in this area of expertise. The understanding of laryngeal behavior, acoustic and perceptual characteristics, voice-related quality of life, and an effective implementation of voice training in the process of rehabilitation is crucial. In adequate proportions, vocal rehabilitation should take place along with the auditory training and oral language development since the very beginning of treatment so that individuals with hearing loss can achieve intelligible, pleasant, and socially acceptable oral communication, maintaining correct function of respiration, phonation, articulation, and resonance.

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