Background/Purpose: Acoustic analysis is often used in speech evaluation but seldom for the evaluation of oral prostheses designed for reconstruction of surgical defect. This study aimed to introduce the application of acoustic analysis for patients with velopharyngeal insufficiency (VPI) due to oral surgery and rehabilitated with oral speech-aid prostheses.

Methods: The pre- and postprosthetic rehabilitation acoustic features of sustained vowel sounds from two patients with VPI were analyzed and compared with the acoustic analysis software Praat.

Results: There were significant differences in the octave spectrum of sustained vowel speech sound between the pre- and postprosthetic rehabilitation. Acoustic measurements of sustained vowels for patients before and after prosthetic treatment showed no significant differences for all parameters of fundamental frequency, jitter, shimmer, noise-to-harmonics ratio, formant frequency, F1 bandwidth, and band energy difference. The decrease in objective nasality perceptions correlated very well with the decrease in dips of the spectra for the male patient with a higher speech bulb height.
Introduction

Surgical treatments of the oral cavity and oropharynx are often performed to treat diseases such as cancers, infections, and congenital malformations. In circumstances when surgical resection leaves a defect in the oral cavity, especially in the palate region, the velopharyngeal (VP) valving mechanism is disrupted. Several types of prosthetic management for VP insufficiency (VPI) are described for maxillofacial prosthodontics.1-9 Whereas VP incompetence is traditionally managed by palatal lift prosthesis, maxillofacial prosthodontics use speech-aid prosthesis. The goal of these prostheses is to restore, as much as possible, the original VP function to achieve good swallowing and speech. Traditionally, after the device is applied, the prosthesis is evaluated according to clinical symptoms and under direct vision, as well as using lateral cephalometric images, nasal endoscopy, and video-fluoroscopic examinations.7,8,10,11 Speech functions are further evaluated through various assessment protocols, including the Sentence Intelligibility Test, measurements of appropriate separation of the nasal/nasopharyngeal and oral compartments, and scales of self-rated perceptions of communication effectiveness.12

The VP valving mechanism is well-known to regulate nasal resonance during speech. However, there is paucity of data regarding the evaluation of sound quality improvements for these prostheses despite obvious changes in the resonance of the speech sound. The pronunciation of a speaker with a defective soft palate is marked by hypernasality. Surgery may be necessary to repair the defective soft palate to reduce this hypernasality but an assessment is necessary to quantify the effectiveness of the surgery. Voice nasality is important in proper resonance and speech recognition. The evaluation of nasality is a complex procedure involving the measurement of the sound wave and airflow from the nose and oral cavity separately. Because of such complexity, acoustic analysis is seldom used in the evaluation of oral prostheses designed for surgical defect reconstructions.

In this study, a new quantitative method is proposed to evaluate hypernasality. The octave spectrum, which has sufficient spread in the low-frequency zone (<2000 Hz), was analyzed and spectral dips were used as indicators of nasality and compared before and after applying speech aid in two patients with palatal defects after cancer surgeries.

Materials and methods

Patients

One male and one female patient were analyzed. The 50-year-old male was a case of palate squamous cell carcinoma and the 48-year-old female was a case of palate adenoid cystic carcinoma. Both underwent radical excision surgery of the tumor with wide margins, leaving a large defect over the palatal area (Fig. 1).

Prosthesis

Prosthodontics specialists were consulted and prosthesis covering the defect over the palate was designed and applied to both patients (Fig. 2).

Sound recording

The patients were asked to pronounce/phonate the sustained vowels, including "/a:$/, "/e:/", "/i:/", "/o:$/", and "/u:/" with and without wearing the prosthesis, in a quiet room. The pronounced sound was recorded using a digital sound recorder (R-05, Roland, Osaka, Japan) for further analysis/data acquisition. The distance from the patient’s mouth to the microphone was set at 10 cm. The vowel sounds before and after the application of the speech-aid prosthesis were recorded two times for analysis for both patients.

Sound analysis

The acoustic parameters were evaluated/performed by the Praat software (version 5.2.35, Paul Boersma and David Weenink, Phonetic Sciences Department, University of Amsterdam, The Netherlands) in a personal computer with a sampling rate of 44.1 kHz. The sound sampling parameters for the Praat software were set as follows: time steps, 1000; frequency steps, 250; window length, 0.005 seconds; window shape, Gaussian; algorithm, Fourier. To exclude irregularities associated with the onset and offset of phonation, the stable 3 seconds of the midvowel segment of the two voice samples was evaluated. The basic acoustic measurements data reported for each patient corresponded to the overall mean of all evaluated samples.

Basic acoustic measurements

The objective perception score before and after applying the prosthesis for both patients was judged independently by two different investigators who were blinded to the analysis data. The scores were given according the following criteria: No nasality, 0; mild nasality, 1; moderate nasality, 2; and severe nasality, 3. The final scores were obtained by averaging the scores of the two investigators after two rounds of evaluations.

The mean fundamental frequency, intensity, mean noise-to-harmonics ratio (NHR), jitter, shimmer, formant
frequency, F1 bandwidth, and band energy difference (BED) were also analyzed from the sound obtained from both patients.

Octave spectra analysis

The one-third octave spectral analysis was initially developed by Kataoka and colleagues as an alternative spectral approach for evaluating hypernasality. More recently, the one-third octave spectral analysis was expanded into more diverse clinical populations presenting with hypernasal speech (dysarthria, maxillectomy, cleft palate). Based on clinical observations, most classical singers with strong nasal resonance had significant spectral dips in the frequency zone between 500 Hz and 2000 Hz, which were observed in only one-fifth of untrained individuals. In a previous study (unpublished data, Wei-Chang Chen MD 2012, oral), 90% of patients with cleft palate and less than 20% of healthy controls had positive nasality under octave spectra. The nasal pole-zero pair pattern (a dip followed by an upward peak in the octave spectrum) was used, with 500–2000 Hz as the nasality parameter.

Statistical analysis

Data from each group in the basic acoustic analysis were compared using the Student t test. Statistical significance was set at \( p < 0.05 \).

Results

Basic acoustic measurements

In both patients, the objective nasality perception scores for all the five vowels were all reduced once the speech-aid prosthesis was applied (Table 1).

For the sustained vowels, there were no significant differences before and after prosthetic treatment for all parameters, including F0 (fundamental frequency), jitter, shimmer, NHR, formant frequency, F1 bandwidth, and BED, except for a slight decrease in F3 in the female patient (Table 2).

Octave spectral analysis

Results of the octave spectral analysis for the male patient (Fig. 3) were compared with the objective nasality...
perceptions (Table 1). When the vowels “/a:/” and “/o:/” were pronounced, the objective nasality perceptions and dip pattern in the spectra (arrow) did not decrease between the preprosthesis and postprosthesis application. When the vowels “/e:/”, “/i:/” and “/u:/” were pronounced, both the objective nasality perceptions and dip pattern decreased after prosthesis use. The decrease in objective nasality perceptions correlated well with the decrease in dips in the spectra (Table 3).

Results of the octave spectral analysis for the female patient (Fig. 4) were also compared with the objective nasality perceptions (Table 1). When the vowels “/e:/” and “/i:/” were pronounced, both the objective nasality perceptions and dip pattern (arrow) in the spectra decreased after the application of the prosthesis. When the vowels “/a:/” and “/o:/” were pronounced, the objective nasality perceptions did not improve significantly but the dip pattern decreased after prosthesis use. When the vowel “/u:/” was pronounced, the objective nasality perceptions improved significantly but the dip pattern did not decrease after prosthesis use. The decrease in objective nasality perceptions only partially correlated with the decrease in dips (Table 3).

The spectrum plot for Figs. 3 and 4 was focused on the frequency range (250–2000 Hz) that is most likely to be affected by palatal defects. The data represent the sound pressure level (y axis) according to a specific frequency (x axis). The frequency axis was transformed to a logarithm scale for better interpretation.

Discussion

This study demonstrates that acoustic analysis, especially the octave spectral analysis, has good potential for revealing certain acoustic characteristics of the objective hypernasality and may be used for evaluating the acoustic functions of the oral speech-aid prosthesis.

Table 1 The pre- and postprosthesis objective perception scores of the two patients.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>Male</th>
<th>Objective perception</th>
<th>Female</th>
<th>Objective perception</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preprosthesis</td>
<td>Postprosthesis</td>
<td>Preprosthesis</td>
<td>Postprosthesis</td>
</tr>
<tr>
<td>a</td>
<td>0.00</td>
<td>0.00</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>e</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
<td>0.33</td>
</tr>
<tr>
<td>i</td>
<td>0.50</td>
<td>0.00</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>o</td>
<td>2.50</td>
<td>0.33</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>u</td>
<td>1.00</td>
<td>1.00</td>
<td>0.67</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Score 0 = none; Score 1 = mild; Score 2 = moderate; Score 3 = severe.

Table 2 The pre- and postprosthesis basic acoustic measurements of the two patients.

<table>
<thead>
<tr>
<th></th>
<th>F0 (Hz)</th>
<th>F1 bandwidth (Hz)</th>
<th>F1 (Hz)</th>
<th>F2 (Hz)</th>
<th>F2 (Hz)</th>
<th>F3 (Hz)</th>
<th>F4 (Hz)</th>
<th>BED dB</th>
<th>Jitter (%)</th>
<th>Shimmer (%)</th>
<th>NHR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preprosthesis Male</td>
<td>117.62</td>
<td>1.16</td>
<td>339.24</td>
<td>1.16</td>
<td>466.16</td>
<td>339.24</td>
<td>415.82</td>
<td>415.82</td>
<td>2668.43</td>
<td>3.74</td>
<td>0.08</td>
</tr>
<tr>
<td>Postprosthesis Male</td>
<td>118.04</td>
<td>1.76</td>
<td>325.66</td>
<td>1.76</td>
<td>466.16</td>
<td>325.66</td>
<td>415.82</td>
<td>415.82</td>
<td>2783.92</td>
<td>3.74</td>
<td>0.08</td>
</tr>
<tr>
<td>Preprosthesis Female</td>
<td>184.50</td>
<td>8.88</td>
<td>258.15</td>
<td>8.88</td>
<td>466.16</td>
<td>8.88</td>
<td>415.82</td>
<td>415.82</td>
<td>2557.58</td>
<td>3.74</td>
<td>0.08</td>
</tr>
<tr>
<td>Postprosthesis Female</td>
<td>184.50</td>
<td>3.77</td>
<td>192.11</td>
<td>3.77</td>
<td>466.16</td>
<td>3.77</td>
<td>415.82</td>
<td>415.82</td>
<td>2654.57</td>
<td>3.74</td>
<td>0.08</td>
</tr>
</tbody>
</table>

BED = band energy difference; F0 = fundamental frequency; f1–f4 = formant frequency; NHR = noise-to-harmonics ratio.

*p < 0.05.
Acoustic analysis usually investigates properties such as the mean-squared amplitude of a waveform and its duration, fundamental frequency, or other properties of its frequency spectrum. Since the invention of the Edison phonograph in the late 19th century, the study of acoustic phonetics has been greatly enhanced as technology has allowed the speech signal to be recorded and then later processed and analyzed.\textsuperscript{15–17}

Furthermore, acoustic analysis of speech is the study of the acoustic characteristics of speech, both normal and abnormal. It involves the physical aspects of spoken language such as waveform analysis, voice onset time measurements, and formant frequency measurements.\textsuperscript{18} In the beginning, acoustic analyses have been heavily used in the field of speech therapy and speech rehabilitation to monitor treatment responses.\textsuperscript{19–24} Acoustic analyses have also been frequently

Figure 3  The octave spectra comparisons for the male patient before and after the application of the speech-aid prosthesis. When the vowels "/a:/$ and "/o:/$ were pronounced, the objective nasality perceptions and the dip pattern in the spectra (arrow) did not decrease between preprosthesis and postprosthesis. When the vowels "/e:/", "/i:/" and "/u:/" were pronounced, both the objective nasality perceptions and the dip pattern in the spectra decreased after the application of the prosthesis.
used to evaluate patients with different kinds of dysphonia in the field of laryngology, as well as the speech performances of patients with a cochlear implant. Recently, the technique has been applied in the evaluation of thyroideectomy-related changes. 

Traditionally, oral prosthesis, especially speech aids, is evaluated through direct visual observations, cephalometric radiographs, and nasal endoscopies. Endoscopy is often accompanied by video recordings for better speech and swallowing evaluations. In a study carried out by Bohle et al, speech-aid and obturator prostheses attribute to a higher percentage of intelligible speech. However, they also concluded that the position for optimal speech cannot be specifically located mathematically and objective ratings of the efficacy of the obturator-speech bulbs by the clinicians do not correspond to intelligibility. It is obvious that final intelligibility requires evaluation by a speech specialist. Nevertheless, a speech specialist is not always readily available during the design, fitting, or modification of speech-aid prosthesis. Thus, objective acoustic analysis may serve as a useful tool for prosthodontics specialists for real-time functional acoustic evaluation that is possible through a simple computer program on a laptop.

There are several remarkable characteristics in the octave spectrum analysis for the nasality. First, the nasal pole-zero pairs (a dip followed by an upward peak in the octave spectrum) appear more frequently between the frequencies of 500 Hz and 2000 Hz. Second, increased numbers of spectral dips are related to perceptual nasality. A pole in the spectrum is regarded as a relatively strong sound intensity area, whereas a dip in the spectrum is regarded as a relatively weak sound intensity area. Although the mechanisms for the formation of the pole and the dip remained unclear, it is believed that it is generated through the disturbance of sound oral–nasal coupling by the palatal defect. It is also possible that the sound travels easily through the palatal defect to the nasal cavity, and thus forms multiple additional high-intensity areas (poles and dips between poles) shown on the spectrum. The advantage of using the octave spectrogram is that this transformation allows the region between the 500 Hz and 2000 Hz to be presented in greater detail. This frequency range lies between the frequency of the first formant (F1) and the second formant (F2), and is closely related to the position of the tongue and the palate in pronunciation.

The spectrum is also affected by the size and shape of the vocal tract. Because the mechanics of pronunciation as well as the size and shape of the vocal tract varies significantly for every individual, the octave spectrogram for an individual speech appears untidy and difficult to interpret. However, for every individual, a more consistent pattern can be observed or identified in the spectrogram for vowels. Therefore, it is more feasible to compare the octave spectrogram for vowels from the same individual to evaluate the acoustic outcomes of a certain procedure or treatment objectively.

Nonetheless, this potential is limited by the inconsistency between the objective perception and the octave spectrogram. In this study, the consistency of the male patient appears to be much better than that of the female patient. More cases and data were needed to show whether sex differences may result in this different spectrogram characteristics. Moreover, although similar, the shapes of the speech-aid oral prosthesis for the two patients are different. The most different part appears to be the posterior attached speech bulb, which is regarded as a very important functional part of the prosthesis. Recently, Kwon et al reported that low-bulb obturators function similar with high-bulb obturators in terms of articulation of speech, but they had difficulty in controlling hypernasality in maxillectomy patients. The bulb height for the female patient is lower, and thus contributes to the less satisfactory results. In the present study, the palatal defect seems to have little influence on objective nasality perceptions in the pronunciation of the vowels ”/a:/” and ”/o:/”. As such, it can be recommended that the percentage for vowels ”/a:/” and ”/o:/” in the speech content evaluation of the speech-aid prosthesis function be modified and reduced as much as possible.

The major limitation of this study is the very limited number of case studies evaluated (n = 2). As previously mentioned, the octave spectra gathered from different individuals may differ greatly. Thus, it is impractical to compare and analyze the octave spectra from many different individuals. It is clear that the octave spectra analysis has shown some potential in the nonperceptual acoustic functional evaluation of the speech-aid prosthesis, but it is far from ideal and may only be regarded as the closest to date. Human speech is complex and is regulated

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**Table 3** Correlations of decreased objective nasality perceptions and decreased dip patterns in the octave spectra after the use of speech-aid oral prosthesis.

<table>
<thead>
<tr>
<th>Vowel</th>
<th>Objective nasality perceptions</th>
<th>Dip pattern (arrow) in the octave spectra</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>No change</td>
<td>No change</td>
<td>Yes</td>
</tr>
<tr>
<td>e</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Yes</td>
</tr>
<tr>
<td>i</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Yes</td>
</tr>
<tr>
<td>o</td>
<td>No change</td>
<td>No change</td>
<td>Yes</td>
</tr>
<tr>
<td>u</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Yes</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>No change</td>
<td>Decreased</td>
<td>No</td>
</tr>
<tr>
<td>e</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Yes</td>
</tr>
<tr>
<td>i</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Yes</td>
</tr>
<tr>
<td>o</td>
<td>No change</td>
<td>Decreased</td>
<td>No</td>
</tr>
<tr>
<td>u</td>
<td>Decreased</td>
<td>No change</td>
<td>No</td>
</tr>
</tbody>
</table>
by various complex factors. The human vocal tract extends from the vocal fold upward to the lips. A complete palate is needed to separate the oral and nasal cavities. However, a complete palate is only one of the critical factors in the control of the nasality. The VP orifice regulated by the soft palate also has a significant influence on voice quality and resonance. High-quality postprosthesis voice rehabilitation is necessary to achieve satisfactory functional results.

To date, the well-trained ears of a speech expert remain the golden standard in acoustic evaluation. The findings of this study may only be the beginning of a new field in maxillofacial prosthodontics. As shown in our study, the acoustic analysis is performed through sound recording followed by computer program analysis. Currently, it is difficult to obtain a real-time feedback which appears to be useful to improve the prosthesis. However, if the acoustic

Figure 4  The octave spectra comparisons for the female patient before and after the application of the speech-aid prosthesis. When the vowels "/e:/" and "/i:/" were pronounced, both the objective nasality perceptions and the dip pattern (arrow) in the spectra decreased after the prosthesis. When the vowels "/a:/" and "/o:/" were pronounced, the objective nasality perceptions did not improve significantly but the dip pattern decreased after the prosthesis. When the vowel "/u:/" was pronounced, the objective nasality perceptions improved significantly but the dip pattern in the spectra did not decrease after the prosthesis.
analysis hardware and software can be further improved, the real-time feedback potentially can provide immediate prosthesis functional evaluations and help the prosthodontists easily and quickly adjust the shape or thickness of the prosthesis for a better fit and function. Although much work still needs to be done and more studies are warranted, based on the octave spectral analysis, acoustic analysis may become a very useful and powerful tool in the functional evaluation of prosthetic treatments.

In conclusion, acoustic analysis appears to be a potential technique in the evaluation of the functions of oral speech-aid prostheses. These prostheses significantly eliminate dysfunctions caused by surgical defects and contribute to a high percentage of intelligible speech. Octave spectrum analysis may be valuable for detecting changes in the nasality characteristics of the voice during prosthetic treatment for VPI.

Financial disclosure

None.

References


