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The Impact of Nasalance on Cepstral Peak Prominence and Harmonics-to-Noise Ratio

Catherine Madill, PhD, CPSP; Duong Duy Nguyen, MD, PhD;
Kristie Yick-Ning Cham, BAppSc(SpPath) Hons, CPSP; Daniel Novakovic, FRACS, MBBS, MPH, BSc;
Patricia McCabe, PhD, CPSP

Objectives/Hypothesis: Cepstral peak prominence (CPP) has been reported as a reliable measure of dysphonia and a preferred alternative to harmonics-to-noise ratio (HNR). However, CPP has been observed to be sensitive to articulatory variation and vocal intensity. The aim of this study was to examine the impact of nasalance on CPP and HNR of voice signals. It was hypothesized that increased nasalance would be associated with decreased CPP.

Study Design: Within-subject correlation design.

Methods: Thirty vocally healthy female participants were recorded reading and producing a vowel in alternation with a nasal consonant while wearing a nasometer for calculation of nasalance. Recorded vowel, nasalized, and nasal segments of speech were used to calculate CPP using Analysis of Dysphonia in Speech and Voice software, and HNR and vocal intensity using Praat software.

Results: Significant main effects of conditions were observed for CPP. CPP values decreased significantly when phonation changed from vowel to nasalized vowel and to nasal. There was correlation between CPP and nasalance and between CPP and intensity. HNR was slightly higher in the nasal condition than in vowel. There was a weak correlation between HNR and nasalance. No correlation was found between HNR and intensity.

Conclusions: CPP is sensitive to changes in vocal tract configuration caused by nasalization as well as intensity, whereas HNR is not. Therefore, CPP may reflect the periodicity in source signal or the filtering effects of vocal tract. Further research is needed to clarify the application and interpretation of CPP in clinical practice.

Key Words: Acoustic analysis, cepstral analysis, cepstral peak prominence, harmonics-to-noise ratio, dysphonia, nasalance, nasalized vowel.

Level of Evidence: 4

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INTRODUCTION

The practice of voice clinicians often involves the assessment and treatment of patients with voice and resonance problems that can coexist.[1] It can thus be challenging to diagnose and quantify the characteristics of these disorders independently using perceptual judgment alone. Although perceptual analysis remains the gold standard, it is subjective in nature and prone to listener bias and unreliability.[2] More reliable and objective measures may theoretically be obtained using acoustic voice analysis. However, it is important to select robust acoustic outcome measures that accurately represent laryngeal function and are not affected by confounding factors such as the filtering effects of the vocal tract.

Pathological voices are characterized by the addition of noise in the voice spectrum[3] and aperiodicity.[4] Quantification of noise in voice signals has been implemented using the harmonics-to-noise ratio (HNR). Dysphonic voices have lower values of this measure than normal voices.[5] It has remained as a reliable acoustic measure and is correlated to auditory-perception of hoarseness,[6] and vocal clarity,[7] rendering it a useful clinical measure with good face validity. It has routinely been used to quantify the dysphonia in various pathological conditions of the larynx, especially where there are problems with periodicity and glottal noise.[5,8] It has also been reported that HNR is the best single predictor for breathiness and roughness.[8] HNR has been used extensively in the literature as an outcome measure of voice treatment.[9,10]

Cepstral analysis is obtained using a Fourier transform of the logarithm power spectrum.[11] From the voice cepstrum, a cepstral peak is identified corresponding to the fundamental period and is the dominant “rahmonic.” The cepstral peak prominence (CPP) is calculated as the difference in amplitude between the cepstral peak and the corresponding value on the regression line directly below the peak.[12] A highly periodic signal has a well-defined harmonic structure and a more prominent

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From the Voice Research Laboratory (C.M., D.D.N., K.Y.-N.C., P.M.); Faculty of Health Sciences and the Central Clinical School (D.N.), The University of Sydney, Sydney, New South Wales, Australia.

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Send correspondence to Catherine Madill, Voice Research Laboratory (Speech Pathology), The University of Sydney, PO Box 170, Lidcombe, NSW 1825, Australia. E-mail: cate.madill@sydney.edu.au

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cepstral peak than a less periodic signal.[12] Unlike HNR, which is measured from prolonged vowel only, CPP can be measured from both prolonged vowel and connected speech. Although the accurate calculation of HNR depends on the periodicity of the signal, hence signal type, CPP does not depend on signal types and can be reliably used to analyze type 3 and type 4 voice signals, as they do not depend on pitch identification and tracking.[12–14] The CPP and its smoothed measure (CPPS) [12,15] have emerged as a robust method of acoustic voice analysis.[16–18] For both vowels and connected speech, CPP had the strongest weighted correlations with overall voice quality compared to other measures.[19] There is a strong correlation between CPP and breathiness,[12] and CPP is a significant predictor of dysphonic severity.[18] The CPP and CPPS have also been used to evaluate outcome after voice therapy[20] and laryngeal surgeries.[21,22]

However, there is consistent evidence that CPP may be sensitive to individual vocal tasks, intensity,[14] and vocal tract configuration, in which different vowels have demonstrated different CPPS values,[14] and a nasal sentence has a high CPP.[23] Conversely, lower CPP values have been observed in patients with velopharyngeal insufficiency (VPI).[24] Resonant voice productions have been associated with higher CPP values than habitual voice quality.[25] It has been assumed that CPP can be used as a measure of periodicity of vocal fold vibration.[12] However, the correlation between this measure and other voice qualities, such as vocal roughness, has been questioned.[16] The inconclusive nature of these results raises the question of how CPP relates to the underlying physiological processes of the vocal tract during phonation.[26]

The perceptual evaluation of the resonance component of the voice is difficult.[27] Nasalance is used as an acoustic measure to complement perceptual ratings of nasality in the assessment of resonance disorders.[28,29] It represents the ratio between nasal and nasal-plus-oral acoustic energy in speech production[30] and varies proportionally to the degree of nasal resonance.[31] Nasalance correlates strongly with perceived nasality[31,32] and has high test–retest reliability.[29] It has been utilized in broad clinical and research applications in speakers with cleft lip and palate and other velopharyngeal impairments.[33,34] Thus, nasalance is considered a robust instrumental measurement in the assessment of resonance disorders.[35,36]

If CPP is to be used to report outcome after voice therapy and laryngeal surgeries, it is important to know how different vocal tract configurations would affect it. It is therefore necessary to quantify the extent to which CPP is affected by nasality. Comparison with a time-based measure (i.e., HNR) in the same experimental conditions would yield important information about whether these two measures respond differently to changes in nasalance. The aims of this study were to: 1) examine the effect of changes in nasalance on CPP and HNR and 2) identify the correlation between CPP and HNR and nasalance.

MATERIALS AND METHODS

Permission for the study was approved by the University of Sydney's Human Research Ethics Committee (2016/120).

Participants

The participants in this study comprised of 30 vocally healthy female speakers (mean age = 22 years, standard deviation [SD] = 3.9, range = 19–41 years). Inclusion criteria were: 1) fluent English speakers, with English as their primary language; 2) no existing or reported history of laryngeal, nasal, or respiratory disorders; 3) no history of laryngeal injury or trauma; and 4) current nonsmokers who had not smoked within the previous 10 years. On the day of the recording, all participants reported they were in general good health with no reported significant conditions that would alter voice production. All participants passed the screening protocol for normal voice on the day of data collection, designed to model previous studies that addressed participants with healthy voices.[30,37]

Speech Samples

Participants were required to read a constantly voiced alternating vowel and nasal task /a - ŋ - a - ŋ - a - ŋ - a/ in one single breath to control for variations in relative vocal intensity.[14] The vowel /a/ was used, as this is a low back vowel, and it is believed that it has lower level of acoustic transmission via the palate compared with high vowels[38]; therefore, any nasal acoustic energy would stem from velopharyngeal activities. They were also required to produce this sequence as similarly to natural connected speech as possible without any stress or prolongation of any segments. No instruction for duration was provided to participants. The researcher produced the task as a model and participants were required to imitate so that the production was consistent across participants to minimize variability. Before recording, participants were required to practice reading the task at their comfortable rate with no audible breaks or inspiratory pauses when connecting the vowels and the nasals together. Once the participants indicated familiarity with the task, they were instructed to read the speaking task at a comfortable pitch and loudness, and natural rate, as if conversing with the researcher.

Recording Instrumentation

Acoustic recordings took place in a soundproof booth with ambient noise below 45 dB SPL. All participants wore a head-mounted C420^{III} cardioid microphone (AKG Acoustics, Vienna, Austria),[39] with a constant microphone-to-mouth distance of 5 cm. The microphone was calibrated with a sound pressure level meter prior to data collection. All recordings were made using a Layla 24/96 Multitrack Recording System (Echo Audio Corporation, Santa Barbara, CA) and Adobe Audition software version 1.5 (Adobe, San Jose, CA)[40] at 44.1 kHz. The acoustic signal was recorded simultaneously with nasalance data collection. Nasalance scores were obtained using a Nasometer II 6400 (PENTAX Medical, Montvale, NJ),[41] which was calibrated to the manufacturer's instructions prior to use.[42]

Acoustic Analyses

The voice samples were edited using Praat version 5.4.20.[43] From the productions, three segments were prepared for acoustic analyses: 1) the whole vowel segment of /a/, 2) the whole nasalized segment of /a/, and 3) the whole nasal /ŋ/. These were identified by examining acoustic waveform to detect changes in amplitude and narrow band spectrogram to identify changes in formants and harmonic structures across segments. The first formant was used to detect the nasalized vowel and nasal as the change in this formant is the major cue of nasalization and nasal.[44] The Nasometer Contour display mode of the Nasometer II program[41] was also used to identify the segments. The nasalance contour had three clearly distinct parts, that is the

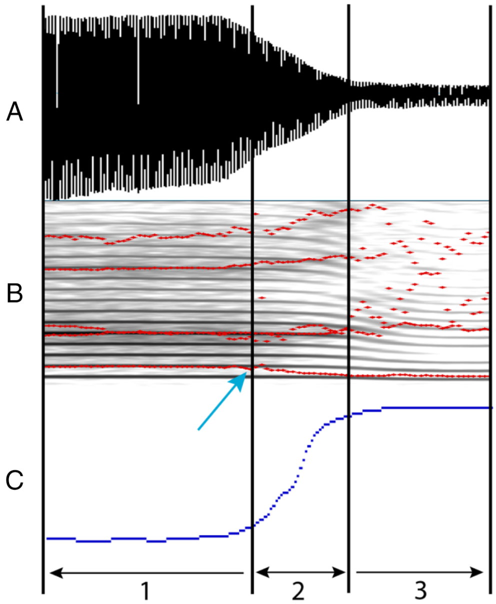

Fig. 1. Diagram of three measurement segments. (A) Acoustic waveform. (B) Narrow-band spectrogram with formant tracks. Arrow shows the changes in the first formant, indicating start of nasalization. (C) Nasometer contour indicating the three segments: 1 = vowel, 2 = nasalized vowel, and 3 = nasal.

horizontal, rising, and plateau, corresponding to the vowel, nasalized vowel, and nasal, respectively (Fig. 1). The samples were edited to include the acoustic signal from the moment of voice onset and offset, where silence and inspiratory pauses were removed.

Analysis of Dysphonia in Speech and Voice (ADSV) software[45] was used to calculate CPP values in the vowel, nasalized, and nasal samples. CPP was obtained from each segment by visual confirmation of the waveform indicating the onset and offset of each speaking task. The onsets and offsets of >200 ms of the samples were removed for reliability of acoustic analysis.[46] Each sample then underwent automatic analysis by the ADSV software.

Praat was used to calculate HNR in decibels in the vowel, nasalized, and nasal samples. Narrow-band spectrograms in Praat were used to check whether voice samples were either type 1 or type 2 signals before HNR measurement.[47] HNR was measured, as it can effectively act as a benchmark for CPP to further assess its clinical potential, especially to delineate the relationship between cepstral measures and resonance. Relative vocal intensity in decibels was also obtained from Praat for all segments. This variable was used as a covariate in statistical analyses, as vocal intensity can affect cepstral/spectral-based measurements.[14]

The Nasometer II program was used to estimate the percentage nasalance of each of the voice samples. It is the ratio of nasal acoustic energy over oral and nasal acoustic energy combined.[48]

As each task included four vowel segments, three nasalized vowel segments, and three nasals, measurements were made on all of these segments. Vowel data were averaged from all four vowel segments, nasalized data were averaged from all three nasalized segments, and nasal data were averaged from all three nasal segments.

Statistical Analyses

Data were analyzed using IBM SPSS Statistics 22 (IBM, Armonk, NY).[49] The effects of three speaking conditions were examined using one-way repeated-measures analysis of variance (ANOVA), in which sphericity of data was checked using the Mauchly test. The Pearson product-moment correlation coefficient was used to examine the relationship between CPP and nasalance, CPP and vocal intensity, nasalance and vocal intensity, HNR and nasalance, HNR and CPP, and HNR and intensity. Acoustic analyses in this study were performed by the second and third authors. Interrater reliability of measurement was checked using the intraclass correlation coefficient (ICC) (two-way mixed, absolute agreement) on the nasalance, CPP, and HNR data for 10% of samples. The nasalance, CPP, and HNR were also remeasured a second time in 10% of samples by the second author to check intrarater reliability using a paired t test. All voice samples were tested for normality using the Shapiro-Wilk test. Significance level was $P = .05$.

RESULTS

ICC calculation showed excellent agreement between the two raters in the measurement of nasalance (ICC = 0.998, $P < .001$), CPP (ICC = 0.985, $P < .001$), and HNR (ICC = 0.953, $P < .001$). For intrarater reliability, the paired t test showed no statistically significant differences in nasalance ($t = -0.088$, $P = .931$), CPP ($t = -1.06$, $P = .298$), and HNR ($t = -0.824$, $P = .417$) between the first and second measurements.

A small amount of variability in measurements was attributed to the measurers analyzing slightly different onset and offset points from bracketing the acoustic signal with the cursor.

Effects of Nasality on CPP

One-way repeated-measures ANOVA was used to analyze data in three speaking conditions (vowel, nasalization, nasal). The Mauchly test of sphericity was nonsignificant for CPP ($\chi^2[2] = 1.033$, $P = .597$), nasalance ($\chi^2[2] = 5.835$, $P = .054$), HNR ($\chi^2[2] = 5.189$, $P = .075$) and intensity ($\chi^2[2] = 5.017$, $P = .081$). Bonferroni-adjusted post hoc tests were conducted on all significant effects.

Table I shows mean and standard deviation (SD) of each acoustic measure in the three segments. Significant main effect of tasks on nasalance was observed: $F(2,58) = 463.242$, $P < .001$, partial $\eta^2 = 0.941$. Nasalance increased by 15.4% when vocal task changed from vowel to nasalized ($P < .001$), 43.2% from nasalized to nasal ($P < .001$), and 58.6% from vowel to nasal ($P < .001$).

A statistically significant main effect was observed for CPP: $F(2,58) = 88.676$, $P < .001$, partial $\eta^2 = 0.754$. Post hoc tests showed that CPP decreased by 2.1 dB when the task changed from vowel to nasalized ($P < .01$), 0.9 dB from nasalized to nasal ($P < .05$), and 3 dB from vowel to nasal ($P < .01$).

A significant main effect of task was observed on HNR: $F(2,58) = 7.861$, $P = .001$, partial $\eta^2 = 0.213$. HNR did not change significantly when the task changed from vowel to nasalized ($P = .591$) but increased by 2.1 dB when the task changed from nasalized to nasal ($P = .009$). On average, HNR in the nasal segment was 1.5 dB higher than that in the vowel ($P = .018$).

TABLE I.
Mean CPP, Nasalance, HNR, and Vocal Intensity for the Three Speaking Conditions: Vowel /a/, Nasalization, and Nasal /ŋ/.

Measures	Conditions	Mean	SD	Range	Minimum	Maximum	No.
Nasalance, %	Vowel	36.4	12.7	51.0	6.5	57.5	30
	Nasalization	51.8	11.4	53.1	20.0	73.1	
	Nasal	94.9	4.0	17.8	80.5	98.3	
CPP, dB	Vowel	11.6	1.6	6.7	7.8	14.5	30
	Nasalization	9.5	1.7	6.0	7.0	13.0	
	Nasal	8.6	1.3	5.0	6.2	11.2	
HNR, dB	Vowel	26.1	2.5	10.8	22.4	33.2	30
	Nasalization	25.4	3.2	19.1	15.1	34.2	
	Nasal	27.6	2.9	11.1	22.0	33.1	
Intensity, dB	Vowel	61.5	2.8	9.3	56.2	65.5	30
	Nasalization	55.9	3.3	11.9	49.6	61.5	
	Nasal	46.9	3.2	12.4	39.5	51.9	

CPP = cepstral peak prominence; HNR = harmonics-to-noise ratio; SD = standard deviation.

A significant main effect for vocal intensity was also found: $F(2,58) = 493.191$, $P < .001$, partial $\eta^2 = 0.944$. Intensity dropped by 5.5 dB when the task changed from vowel to nasalized ($P < .01$), 9.1 dB from nasalized to nasal ($P < .01$), and 14.6 dB from vowel to nasal ($P < .01$).

Correlation Between Nasalance, CPP, HNR, and Vocal Intensity

The Pearson r correlation coefficient was calculated to examine the relationship between CPP and HNR, and between these two acoustic measures and nasalance using data of all three tasks combined in all participants (n = 90). CPP had a weak negative correlation with HNR ($r = -0.293$, $P = .005$). These two measures showed different trends of relationship with nasalance. Although CPP showed statistically significant negative correlation with nasalance ($r = -0.533$, $P < .01$), HNR had a weak positive correlation with nasalance ($r = 0.228$, $P = .031$). These results further clarified the opposite effects of nasalance on these two measures.

There was also statistically significant correlation between CPP and vocal intensity ($r = 0.618$, $P < .01$). CPP increased as intensity was elevated and vice versa. However, no significant correlation was observed between HNR and intensity ($r = -0.051$, $P = .635$).

Nasalance showed a strong correlation with intensity ($r = -0.875$, $P < .01$), that is, as nasalance increased, vocal intensity decreased.

DISCUSSION

This study confirmed the hypotheses in which CPP decreased from vowel to nasalization and to nasal phonation by 2.1 and 3 dB, respectively. This finding confirmed previous findings that CPP measure is affected by task-specific factors. The CPP has also been found to change across vowel and connected speech,[50] across different sentence types,[23] and across different vowel types.[14] To explain the findings in this study, it is important to note that CPP is affected by the overall spectral energy.[12] When a vowel stands close to a nasal consonant (e.g., /ng/), there is a coupling effect between the oral and nasal resonance, and this results in dampening of vocal intensity.[51] In nasal sounds, high-frequency energy traveling through the nasal cavity is significantly dampened from acoustic energy absorption resulting in lower resonant frequencies.[52] As a result, the following acoustic phenomena occur: 1) occurrence of extra poles and zeros, 2) a reduction in the first formant amplitude, 3) spectral flatness in the low-frequency range, and 4) a reduction in the overall intensity of the vowel.[53] In the production of nasalized and nasal sound, the excitation of the vocal tract is also attenuated as a result of a decrease in the oral cavity area.[54] Using the decrease in spectral energy to explain for the decrease in CPP seems reasonable, as we found positive correlation between CPP and vocal intensity. The dependence of CPP on vocal intensity has also been observed previously.[14]

The CPP of the /a/ vowel in this study was consistent with previous studies using the same vowel at comfortable pitch and loudness (Table II). The change in CPP in

TABLE II.
CPP Values of /a/ Vowel in Normal Voices.

Studies	Pitch and Intensity	Acoustic Program	Mean CPP (SD)
Watts and Awan, 2011[57]	Comfortable pitch and loudness	Awan's Windows-based software	11.08 (1.91)
Awan and colleagues, 2012[14]	Comfortable pitch and loudness	Hillenbrand's cepstral analysis program	CPPS: 7.56 (1.05) (comfortable voice)
Madill and colleagues, 2018[50]	Comfortable pitch and loudness	Analysis of Dysphonia in Speech and Voice	10.92 (1.36) (cohort 1, 78 speakers); 11.09 (1.90) (cohort 2, 33 speakers)

CPP = cepstral peak prominence; CPPS = smoothed cepstral peak prominence; SD = standard deviation.

nasality was also expected, as it has been shown to vary in nasal phrases[23] and in VPI.[24] However, a decrease of 3 dB (equivalent to 25.9%) as phonation changes from vowel to nasal may be clinically significant, particularly if the CPPS is used, given that the mean cutoff threshold of CPPS for connected speech obtained from a similar analyzing program (i.e., ADSV) has been found to be 4.15 dB (SD = 1.73, range = 0.4–7.12) [55] or below 4 dB[56] for pathological voices.

There are some implications of our findings. Firstly, if connected speech CPP is an outcome measure for within-subject effects after voice therapy or laryngeal surgeries, nasalance should be considered as a confounder, and standardized speech tasks with the least effects of nasalance should be used. It would not be suitable to report CPP from tasks with strong nasal contents (e.g., the Consensus Auditory-Perceptual Evaluation of Voice nasal phrase), as the effects of treatment may not be isolated from those of nasalance. Secondly, if connected speech CPP is used to compare two patient populations,[57] it would be necessary also to use standardized speech tasks and control for nasalance in both groups. In cases where there is VPI, the effects of nasalance on CPP as an outcome measure would be more profound, and it may be necessary to measure nasalance in association with CPP. Thirdly, in patients with resonance disorders, the use of CPP in voice assessment may not accurately reflect the phonatory function of the larynx.

We also found that HNR increased by 1.5 dB (5.7%) when phonation changed from vowel to nasal. As vocal tract and velopharyngeal port adjustments appear to play an important role in determining voice quality,[58] it may be likely that periodicity improved as a result of the impedance effect of the vocal tract on laryngeal configuration when phonation changed from vowel to nasal. Ogawa and colleagues[59] demonstrated that nasal resonance has significantly lower perturbation and F0 standard deviation, implying more stable phonation. This magnitude of increase in HNR in nasal phonation may not have clinical significance because of the wider range of HNR values compared with CPP. Furthermore, given that it is always measured from sustained vowels, the chance for HNR to be affected by nasalance in speakers without resonance disorders would be limited. This implies that HNR may be more reliable than CPP in documenting dysphonia caused by aperiodicity of the vocal signal. However, it is important to note that the effects of resonance disorders on HNR are yet to be confirmed and should be clarified in future studies.

The present study observed more variation in nasalance data in the vowel and nasalized segments than in nasal (Table I). This may be related to the inherent variability in normal speech that may be more pronounced in vowel and nasalized vowel than in nasal. Previous research has also found nasalance score variability[60] and within- and between-speaker[61,62] naturally occurring variations in voice and speech production. In addition, in this study, the participants was required to produce the vowel–nasal sequence in a way that was as similar to natural speech as possible without controlling for duration. Between-segment and between-speaker variability in duration may also be another source of the variation in nasalance findings. Although this variability may not prevent the opposite effects of nasalance on CPP and HNR, it may affect the extent of those effects. This variability and the extent to which nasal coupling occurred in a nondisordered voice may be different from that in VPI. Future studies are warranted to examine more varied etiologies and severities of voice and resonance disorders to determine whether CPP measurements respond differently to nasalance changes. Further research is also recommended to clarify the application and interpretation of what CPP actually measures, especially its algorithms and calculations in relation to the source-filter theory of speech production.[63] Current practices using CPP to indicate presence, absence, or severity of dysphonia should also be explored.

CONCLUSION

This study found that CPP is sensitive to changes in vocal tract configuration during phonation, in which it is decreased by 3 dB when phonation changed from vowel to nasal. This suggests that although CPP is a measure of periodicity of vocal fold vibration, it cannot be discrete from the resonant function of the vocal tract. This implies that in applying CPP in clinical voice analyses, the effects of the vocal tract need to be taken into account. Conversely, HNR appears to be less affected by the resonatory conditions of the vocal tract. In practice, HNR is calculated from prolonged vowels of type 1 and type 2 signal and not from connected speech. Therefore, it should be selected as a measure of laryngeal function and vocal fold vibration in these conditions. The CPP would be used as a measure of overall voice quality, but its result may contain information of the voice source, resonance, and intensity.

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