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Perturbation and Nonlinear Dynamic Analysis of Adult Male Smokers

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Abstract

Objective—Smoking results in a voice change and the perception by smokers of an abnormal voice may encourage quitting behavior. Moreover, a disordered voice is often the first sign of vocal pathology. Efforts to evaluate voice have focused on classical acoustic analysis; however, nonlinear dynamic analysis has been shown to be a reliable objective method for the evaluation of voice. We compare the discriminatory ability of these two methods when applied to normal and smokers' voices.

Study Design—Prospective study.

Methods—The study included 73 subjects, 36 nonsmokers and 37 smokers. A segment of sustain vowel production was obtained from each subject. Acoustic and correlation dimension (D2) analysis was applied to the data. Results were compared with a Mann Whitney rank sum test, logistic regression and ROC analysis.

Results—D2 values for smokers were significantly higher than for nonsmokers ($p < 0.001$). Jitter and shimmer analysis showed higher values for these parameters among smokers. Logistic regression indicated a higher predictive power with D2 and ROC analysis found no significant difference between the analysis methods.

Discussion—This study indicated that correlation dimension is highly sensitive to changes associated with smoking and has the potential to be implemented clinically as an indicator of abnormal voice. Further research could focus on using nonlinear dynamic analysis to create a normative database, producing standards for monitoring voice changes caused by cigarette smoking.

INTRODUCTION

Cigarette smoking is a major predisposing factor for an assortment of potentially fatal respiratory ailments.^{1–4} Within the upper airway, smoking is a risk factor for diseases including rhinitis, sinusitis and laryngitis.⁵ Chronic use of cigarettes often leads to laryngeal problems such as chronic inflammation, erythema, dryness, and itching laryngeal mucosa.⁶ Moreover, smoking increases rates of laryngeal reflux and Reinke's edema and is the most

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important factor associated with laryngeal carcinoma.⁶⁻⁷ Pathological changes in the larynx result in voice disruptions, and disordered voice is often the first symptom and chief complaint indicating laryngeal disease.⁸⁻⁹

Previous research indicated that smoking affects perceptual, acoustic and aerodynamic performance during phonation. Smoking results in a voice characterized as rough and breathy with a decreased pitch.⁷ Sorensen and Horii reported a lower fundamental frequency (F_0) for both running and spontaneous speech among male smokers compared to nonsmokers.¹⁰ Gonzalez observed elevated perturbation parameters (jitter, sPPQ) in early stage smokers of both genders and higher tremor parameters (ATRI, FTRI) in male smokers.¹¹ In studies examining aerodynamic aspects of phonation, lower vital capacities and maximum phonation times were noted. In addition, smokers were observed to produce greater peak and mean pressures during the voiceless stop-plosive task.¹²

Much of the previous research on voice in smokers has focused on fundamental frequencies and perturbation analysis. However, such analyses may not be appropriate for the smoker's voice. Titze recommended the classification of voices into three types prior to acoustic analysis. He defined a type 1 voice as nearly periodic and indicated that only this type of voice was suitable for acoustic analysis. Type 2 signals contained strong subharmonics or modulations, while type 3 signals are aperiodic. Titze recommended against applying perturbation analysis to type 2 and 3 signals due to difficulties associated with accurate extraction of F_0 .¹³ Normal voices are predominantly type 1 and are therefore easily analyzed with perturbation measures.¹³ Disordered voices can be characterized by any of Titze's three voice types.^{13,14} The decreased voice quality associated with smokers' voices may correspond with an increased likelihood of these voices being classified as type 2 or 3 and unsuitable for classic acoustic analysis.^{7,10-12}

Unlike perturbation analysis, nonlinear dynamic methods are capable of analyzing all three of Titze's voice types. Nonlinear analysis has been established as a viable means of measuring acoustic characteristics of phonation through computer modeling and excised larynx experiments.¹⁴⁻¹⁸ The method has been applied to both pathological and non-pathological voice samples in numerous studies to quantify the degree of aperiodicity and irregularity.^{16,19-21} Moreover, research has indicated that nonlinear measures require shorter samples, are more robust in response to noise and require a lower sampling rate than classical acoustic measures.¹⁶ These features increase the potential for applicability of nonlinear parameters in situations, such as the clinic, where the recording environment may not be ideal and computer storage may be limited.

Nonlinear dynamic methods have not been previously applied to voices of smokers. In this study, we attempt to quantify the effect of smoking on voice with perturbation and nonlinear dynamic analysis. Next we compare the results of both methods in evaluating the voices of long-term Chinese male smokers as well as non-smokers using logistic regression and ROC analysis. We evaluate the potential to incorporate nonlinear measures into the typical acoustic analysis protocol.

METHODS

Subjects

The protocol used in the study was approved by the Ethics Committee of Shanghai EENT Hospital of Fudan University and the IRB of the University of Wisconsin. Female smokers are not common in China, therefore all subjects were male. Seventy three subjects were recruited from the EENT Hospital; 36 non-smokers and 37 smokers. All the subjects participated voluntarily and had no history of laryngeal disorder or trauma, nor were voice

complaints associated with their visit to the clinic. In accordance with routine clinical procedure, prior to acoustic analysis, all subjects received a rigid endoscopic examination. As we intended to employ acoustic analysis as a screening measure separate from endoscopic examination, these results did not influence inclusion in the study; however, significant endoscopic findings were noted. Exclusion criteria included: excessive use of voice, overexposure to noise, alcohol addiction, symptoms consistent with gastroesophageal reflux disease (GERD) and laryngopharyngeal reflux (LPR), symptoms of a cold within the previous two weeks and chronic rhinitis or post-nasal drip. Smokers were defined as subjects who smoked at least five cigarettes everyday for at least five consecutive years before the study. Nonsmokers were operationally defined as subjects who had never smoked. Subject information is provided in Table 1, including age, height, weight, number of cigarettes consumed per day, and number of years as a smoker. Smokers and nonsmokers were similar in age, height, weight and BMI.

Measurement

Subjects were seated in a sound proof room during data collection. A Shure PG48 microphone (Shure, Niles, IL) was used to record voice samples and was positioned 10 cm away from the subjects' mouths. Subjects were asked to produce an /a/ at a comfortable pitch. Each phonation lasted for at least 3 seconds and was monitored by a sound level meter (Radio Shack, Fort Worth, TX) to maintain intensity between 75 and 80 dB. Subjects were allowed to practice several times before recording. Voice samples were obtained using the Multi-Dimensional Voice Program (MDVP) model 5105, Version 3.1.4 at a sampling rate of 44.1 kHz (KayPENTAX, Lincoln, NJ). Three trials were recorded for each subject.

A one second segment was spliced from a central steady portion of each voice sample and analyzed by both perturbation and nonlinear dynamic methods. Voice onset and offset were excluded to avoid effects of speech intonations and interactions between the larynx and vocal tract on acoustic analyses. All voices were classified as type 1, type 2 or type 3 according to Titze's definitions using a narrowband spectrogram generated by PRAAT (Boersma & Weenink, <http://www.praat.org/>). Voices with clearly defined harmonics and without subharmonics, bifurcations or strong modulations in the fundamental frequency were classified as type 1, while the presence of any of these features resulted in a classification of type 2. Type 3 voices were defined by spectrograms where harmonics were not clearly defined (energy smeared across the frequencies). Figure 1 presents sample spectrograms of each voice type generated from voices included in the Disordered Voice Database 4337 (KayPENTAX, Lincoln Park, NJ).

Perturbation analysis

Perturbation analysis was performed with CSpeech software, version 4.0 (Milenkovic & Read, Madison, WI). Percent jitter, percent shimmer, and signal to noise ratio (SNR) were measured. Jitter measures the cycle-to-cycle frequency variation of the signal, while shimmer measures the cycle-to-cycle amplitude variation and SNR provides a measure of the amount of noise in the speech waveform.^{16,22}

The reliability of perturbation analysis was determined by a parameter called Error (ERR) calculated by the CSpeech program. ERR counts the number of times the calculated pitch period varies in excess of one sample position.²³ A high ERR indicates numerous pitch breaks which negatively affect the quality of the F_0 estimate. Data with a ERR greater than 10 are usually considered unreliable and the sample is deemed unsuitable for classical acoustic analysis.²³

Nonlinear dynamic analysis

Nonlinear dynamic methods, including correlation dimension (D2), are quantitative measurements that can be applied to normal as well as irregular or chaotic voice signals.^{13,16,17,19,20} D2 specifies the number of degrees of freedom necessary to describe a dynamic system. The more complex the system is, the greater number of degrees of freedom are needed to describe its dynamic state.^{17,20,24}

In this study, D2 was calculated using the nonlinear dynamic analysis software developed by the Laryngeal Physiology Laboratory at the University of Wisconsin. The program has been validated and described in numerous publications and therefore will not be extensively described in this study.^{15,16,20} By using the time delay technique the program creates a phase space with the equation: $\mathbf{X}_i = \{x(t_i), x(t_i - \tau), \dots, x(t_i - (m-1)\tau)\}$, where m is the embedding dimension and τ is the time delay.²⁵ According to Takens' embedding theorem m is defined so that when $m > 2D+1$ (where D is the Hausdorff dimension) the reconstructed phase space is topographically equivalent to the original phase space.²⁶ Fraser's mutual information method is used to generate a time delay and a correlation integral ($C(r)$) is calculated using the improved algorithm proposed by Theiler. The function exhibits power law behavior as described by: $C(r) \propto r^{D_2} e^{-m\tau K_2}$, which reveals the geometric scaling property of the attractor.²⁴ Using r to define the scaling region, curves of $\log_2 C(r)$ versus $\log_2 r$ are generated for each embedding dimension, m . The value of D_2 is calculated at the point where these curves converge. The reliability of the D_2 value is insured by maintaining a standard deviation less than 5% as determined by the software.

Statistical analysis

The Mann-Whitney rank sum test was employed to compare the smoking group with the nonsmoking group. Statistical significance was set at the level of 0.05. All calculations and graphics were completed using SigmaPlot 8.0 (Jandel Scientific, San Rafael, CA) and SigmaStat 3.0 (Jandel Scientific, San Rafael, CA). A receiver operating characteristics (ROC) analysis and logistic regression were used to evaluate the discrimination ability of the D2 and perturbation analyses.

RESULTS

Rigid endoscopic examination revealed two cases of vocal fold swelling and one case of vocal fold nodules in the group of nonsmokers. Smokers presented with one case of bilateral vocal fold polyps, one case of vocal fold hypertrophy, four cases of vocal fold swelling and erythema and one case of slight glottic insufficiency.

Signal typing characterized smokers' voices as type 2 more often than nonsmokers' voices. In all, 4 of the 36 nonsmokers' voices and 11 of the 37 smokers' voices were rated as type 2. All other voice samples were type 1; no voices included in this study were classified as type 3.

The results of perturbation analysis are summarized in Table 2. As the ERR value of one subject in non-smoking group was greater than acceptable value 10, the perturbation analysis with CSpeech of this subject was considered unreliable and is not included in the results.²³ Data from this subject are, however, included in the logistic regression and ROC analysis. Mean percent jitter and shimmer values for smokers were 0.364% and 4.569%, respectively. In contrast, mean percent jitter and shimmer values in nonsmokers were 0.283% and 2.497% (Figure 2A and 2B). A Mann-Whitney rank sum test indicated a significant difference between voices of smokers and nonsmokers for both jitter and shimmer ($p < 0.05$). Moreover, the SNR values for voices of smokers were significantly lower (18.076 dB) than for nonsmokers (21.863 dB, $p < 0.05$, Figure 2C).

Table 2 also includes the results of the nonlinear dynamic analysis. As shown in Figure 2D, mean D2 was significantly higher for the voices of smokers than for those of non-smokers (means of 2.205 and 1.681, respectively). A Mann-Whitney rank sum test indicated statistical significance ($p < 0.001$).

In order to compare D2 with the combined acoustic parameters, a logistic regression was performed. The utility of including D2 was determined by this regression. The results of an F test indicated that inclusion of D2 significantly improved the model ($p < 0.003$). Moreover, a model based solely on D2 was generated. The incorporation of the perturbation measures into this model did not result in a significant improvement ($p = 0.813$).

ROC was used to compare the diagnostic utility of D2 and the combined acoustic measures (Figure 3). For D2 the area under the curve (AUC) was 0.739, while the combined measures generated an AUC of 0.689. Using the model combining all four parameters resulted in an AUC of 0.751. Based on the 95% confidence intervals for these values, the differences were not significant.

DISCUSSION

The present study demonstrates the existence of voice abnormalities in long term smokers. Moreover, these changes were detected by both perturbation and nonlinear analysis. Both types of analysis indicated significant differences between the smoker and nonsmoker groups and provided evidence for the presence of voice changes in the absence of patient reported pathology.

Overall, our acoustic results are in agreement with the literature. Several studies have noted a difference in perturbation measures among smokers, primarily jitter, though not all the reported results have been significant.^{11,27–29} As seen in this study, perturbation measures are highly variable when applied to disordered voices, which may contribute to the limited significance reported in previous literature.³⁰ Moreover, studies reporting acoustic analysis are relatively limited and the majority of these studies focus on decreased fundamental frequency.^{10,31,32} Variations in subject selection, analysis procedures and sample size have further contributed to uncertainty about smoking's effect on voice. Recent studies by Damborenea *et al.* focus on non-dysphonic smokers, while Gonzalez and Carpi selected only young and early stage smokers.^{11,28} In contrast, Guinaraes and Abberton chose subjects with reported voice problems, and Wan and Huang incorporated subjects with a history of both alcohol and cigarette abuse.^{27,29} In this investigation we limited our focus to long term smokers without a primary voice complaint and excluded extraneous factors such as vocal abuse, GERD, and alcohol addiction. We detected significant differences between the groups for all acoustic parameters.

The limitations of perturbation analysis have been widely discussed in the literature.¹³ Based on Titze's recommendations; only type 1 voices are eligible for perturbation analysis. These recommendations would eliminate 15 of the samples employed in this study.¹³ Despite these concerns, all but one of our samples met our qualifications for reliability in CSpeech (ERR value less than 10), suggesting Titze's requirements may be more stringent than necessary. Caution should continue to be employed when analyzing such data because of the increased difficulty associated with identifying and tracking the fundamental frequency. A cutoff ERR, as well as confirming that fundamental frequency and pitch period are within the range of expected values for the voice being analyzed will help to ensure that the results of classical acoustic analysis are reliable.

D2 is not limited in its application to any of Titze's voice types.^{14–18} This measure describes the geometrical scaling property of a voice in a state space and does not require the

definition of cycle period. It measures chaotic or aperiodic voice signals with great stability and reliability.¹⁶ Similar to the classical acoustic parameters, D2 was able to significantly differentiate between smokers and nonsmokers. Interestingly, D2 differentiated these voices with a lower p-value than the classic acoustic parameters. This result may be partially attributed to the higher level of variability observed in the classic acoustic parameters as can be observed in figure 2. While all parameters were significant by our defined cutoff of $p < 0.05$, the $p < 0.001$ achieved by D2 provides stronger evidence for separating these groups. Moreover, in our study, the inclusion of D2 in the linear regression significantly improved its predictive ability. Based on ROC analysis, perturbation measures and D2 had similar diagnostic utility. No previous literature has investigated the impact of smoking on correlation dimension; however, the present study suggests that this parameter may be incorporated with the classical acoustic parameters to improve differentiation. For noisy, short or otherwise low quality voice samples, D2 may allow analysis where perturbation parameters could not.

Both D2 and perturbation measures have particular disadvantages. As previously discussed, perturbation requires a periodic voice sample to generate valid measurements. The quality of recording also impacts perturbation analysis because this system requires a longer signal, higher sampling rate and lower level of noise.¹⁶ While D2 overcomes these limitations, these calculations are more computer-intensive and, therefore, have a longer processing time. Time required may vary based on the analysis program and computer system; however, in this study, it took about 4 minutes per voice sample. Both measures can be calculated from the same voice sample, suggesting the potential for combining these measures.

As demonstrated here, voice changes may occur without being perceived by the patient. In many studies, subjects reported no voice changes associated with their smoking habit.^{11,28} In a study by Glas *et al.*, smokers scored similarly to nonsmokers on a voice handicap index, suggesting that any pathology remained undetected by these subjects.³³ While all the smokers in our study interpreted their voices as normal, objective analysis was able to detect decreased voice quality. Such evidence of decreased vocal quality may provide the impetus for long-term smokers to quit smoking by confirming physiological damage. As seen in this study, rigid scope examination did find underlying pathology in some of the subjects included in this study; however, few patients are willing to undergo this procedure in the absence of perceived voice or throat problems. As voice analysis is non-invasive, more smokers would be willing to undergo testing that could produce early evidence of voice changes and possibly predict the development of more serious upper airway disorders. Many of the visually observed pathologies may have been associated with smoking as this habit is known to increase occurrences of hyperplasia, Reinke's edema, vocal fold swelling and thickening of the laryngeal mucosa and predis.³⁴⁻³⁶ Hoarseness is often the first symptom of early stage glottic carcinoma and early diagnosis and treatment improves prognosis and voice preservation. A noninvasive system for monitoring a smoker's laryngeal health is of great benefit.

Future studies may endeavor to determine the impact of smoking duration on voice. We also plan to generate a reference range for voice quality, using both D2 and perturbation measures, in order to provide convincing evidence of decreased voice quality among smokers.

CONCLUSION

Perturbation and nonlinear dynamic analysis were used to analyze the voice signals of both smoking and nonsmoking subjects. Differences between two groups were observed in jitter,

shimmer, SNR and D2. Based on the results of a logistic regression, D2 showed higher predictive power than the combined acoustic parameters. With further research, D2 may be used as a clinical parameter individually or in combination with acoustic parameters to evaluate voice quality. More studies are needed to create a normative database to acoustic or nonlinear dynamic analysis for monitoring smokers' voices.

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Figure 1.

Sample spectrograms of (from left to right), type 1, type 2 and type 3 voices. Spectrograms were generated using PRAAT software from voices included in the Disordered Voice Database supplied by KayPENTAX. The type one voice shows clearly defined harmonics with limited energy between these harmonics. The type two voice shows readily apparent subharmonics with energy levels near that of the fundamental frequency. The type 3 voice has harmonics that are more obscured; there is evidence of bifurcations and a spread of energy across the lower frequencies.

Figure 2.

Box plots of percent jitter (A), percent shimmer (B), SNR (C) and D2 (D) in the voices of nonsmoker and smokers. The top and bottom of the box represent the 75th and 25th percentiles, respectively. The middle line indicates the mean; the whiskers correspond to the minimum and maximum values, excluding outliers (indicated by dots).

ROC for 3 Acoustics vs. D2

Figure 3.

Receiver operating characteristics (ROC) analysis of D2 and perturbation analysis. Curves represent D2, the combined acoustic parameters (acoustic GLM) and a regression with all study parameters (all GLM). AUC values for D2, acoustic GLM and all GLM are 0.739, 0.689 and 0.751, respectively.

Table 1

Subject information. Mean (Standard deviation).

	Non-smokers(n=36)	Smokers(n=37)	p value
Age (yrs)	42.47 (8.48)	44.59 (6.80)	0.477
Height (m)	1.71 (0.05)	1.72 (0.06)	0.240
Weight (kg)	68.44 (8.00)	70.23 (9.28)	0.340
Body Mass Index	23.48 (2.04)	23.79 (2.70)	0.778
Cigarettes Smoked per Day		17.68 (7.33)	
Total Years Smoked		20.32 (6.82)	

Table 2

Results of acoustic and D2 analysis. Reported are the means with standard deviation given in parentheses.

	Non-smokers(n=36)	Smokers(n=37)	p value
Jitter	0.283(0.109)	0.364(0.169)	0.038 *
Shimmer	2.497(2.009)	4.569(4.290)	0.003 *
SNR	21.863(4.763)	18.076(5.542)	0.004 *
Err	0.03(0.169)	0.324(0.915)	0.425
D2	1.681(0.0026)	2.205(0.0038)	<0.001 *

* Denotes significance at the p=0.05 level