Published in final edited form as:

Int J Pediatr Otorhinolaryngol. 2008 December ; 72(12): 1829–1836. doi:10.1016/j.ijporl.2008.09.004.

Describing pediatric dysphonia with nonlinear dynamic parameters

Morgan L. Meredith, Shannon M. Theis, J. Scott McMurray, Yu Zhang, and Jack J. Jiang*

Department of Surgery, Division of Otolaryngology – Head and Neck Surgery, University of Wisconsin School of Medicine and Public Health, Madison, WI 53706

Abstract

Objective—Nonlinear dynamic analysis has emerged as a reliable and objective tool for assessing voice disorders. However, it has only been tested on adult populations. In the present study, nonlinear dynamic analysis was applied to normal and dysphonic pediatric populations with the goal of collecting normative data. Jitter analysis was also applied in order to compare nonlinear dynamic and perturbation measures. This study's findings will be useful in creating standards for the use of nonlinear dynamic analysis as a tool to describe dysphonia in the pediatric population.

Methods—The study included 38 pediatric subjects (23 children with dysphonia and 15 without). Recordings of sustained vowels were obtained from each subject and underwent nonlinear dynamic analysis and percent jitter analysis. The resulting correlation dimension (D_2) and percent jitter values were compared across the two groups using t -tests set at a significance level of $p = 0.05$.

Results—It was shown that D_2 values covary with the presence of pathology in children. D_2 values were significantly higher in dysphonic children than in normal children ($p = 0.002$). Standard deviations indicated a higher level of variation in normal children's D_2 values than in dysphonic children's D_2 values. Jitter analysis showed markedly higher percent jitter in dysphonic children than in normal children ($p = 0.025$) and large standard deviations for both groups.

Conclusion—This study indicates that nonlinear dynamic analysis could be a viable tool for the detection and assessment of dysphonia in children. Further investigations and more normative data are needed to create standards for using nonlinear dynamic parameters for the clinical evaluation of pediatric dysphonia.

Keywords

Voice; voice disorders; children; dysphonia; acoustic analysis

I. Introduction

Voice disorders affect approximately 6–9% of the pediatric population [1–4], or one million children nationwide [5]. Carding et al. report that incidence ranges from 6% to 23% [6]. Research has shown that children with voice disorders experience negative educational, social, and physical effects [7]. McMurray stated that childhood dysphonia negatively impacts social

*Correspondence should be addressed to: Jack J. Jiang, 5745 Medical Sciences Center, 1300 University Avenue, Madison, WI 53706, Tel: 608-265-7888, Fax: 608-265-2139, E-mail: jiang@surgey.wisc.edu .

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

development and academic performance [5], and research by Ruscello et al. and Lass et al. indicates that peer [8] and adult [9] opinions are negatively influenced when a child speaker is perceived to be dysphonic. A standard and objective measure of vocal function would benefit the pediatric population, given the aforementioned prevalence and consequences of childhood dysphonia. In fact, recent studies have stressed the need for such a tool [5,10–13]. Objective and quantitative data would be useful for the clinical diagnosis and assessment of voice disorders [14–15] and for the evaluation of treatment outcomes, which has become increasingly important for reasons related to medical liability [10].

It is common for clinicians to apply acoustic measures for the assessment of pediatric dysphonia, because they provide objective and quantitative data about a signal's behavior [16–18]. In a survey of 53 speech pathologists, over 75% reported that they were likely to use acoustic analysis for providing reinforcement to the patient and for evaluating treatment outcomes [14]. Since the 1960s, quantitative acoustic data has been obtained using perturbation measures such as jitter and shimmer [19–21], which quantify cycle-to-cycle variations in the fundamental frequency and amplitude of a signal, respectively [22].

Acoustic analysis research into the pediatric voice has produced findings of elevated jitter and shimmer values in normal children as compared to normal adults [23–26]. An investigation by Ferrand affirmed that this difference exists in both girls and boys [24]. When studying a group of 7–12 year olds, Dejonckere et al. showed that jitter values decrease with age, perhaps as a function of membranous vocal fold growth [27]. These findings imply that the pediatric voice requires special considerations when establishing baseline normal and dysphonic values and that care must be taken to differentiate the values from those of adults when necessary. Higher perturbation levels have been shown to correlate with dysphonia in children. Campisi et al. found a significant difference in jitter and shimmer values between dysphonic children aged 7–12 and age-matched controls [28].

However, studies have indicated that perturbation measures may not validly analyze highly unstable, aperiodic voices [12,29–32], and that agreement among different perturbation analysis systems is low [11,33–34]. Variations in recording procedures have also been shown to affect the reliability of perturbation measures [35–36]. These findings have led researchers to seek a more reliable acoustic measure for the assessment of disordered voice.

Nonlinear dynamic parameters have recently emerged as an alternative to perturbation measures. Explanations of nonlinear dynamic parameters such as phase space reconstruction, correlation dimension, maximal Lyapunov exponents, Kolmogorov entropy, and second-order entropy are readily found in the literature [15,31–32,37–42]. Phase space reconstruction involves plotting an acoustic signal against itself at a time delay and the resultant phase space indicates the strength of a signal's periodicity; a periodic signal produces a closed trajectory whereas an aperiodic signal produces an irregular trajectory. The nonlinear dynamic measure of correlation dimension (D_2) relies upon this reconstructed phase space to quantify the number of degrees of freedom necessary to describe the signal. As a signal's complexity increases, an increasing number of degrees of freedom are required to describe it in the phase space, and thus D_2 increases. D_2 is commonly applied in research due to its simplicity and quick calculation time relative to other nonlinear dynamic parameters [37]. These reasons also indicate that it would lend itself to clinical use. D_2 was thus chosen as the parameter for analysis in this study.

Research has shown that nonlinear dynamic parameters effectively describe dysphonia [38–39,43] and differentiate between pathologic and normal subjects. Jiang et al., using subjects with vocal polyps, found a significant difference between correlation dimension values for pathologic subjects versus normal subjects [37]. It has also been shown to aid in the diagnosis

of laryngeal pathology [44–45] and vocal pathology in Parkinson's disease [46]. Alonso et al. have shown that using nonlinear parameters increases the effectiveness of an automatic detector of laryngeal pathology [47]. Unlike perturbation measures, nonlinear dynamic methods can analyze highly aperiodic signals [32,37] and are more robust in their measurement of speech contaminated by noise [19]. Additionally, analysis using nonlinear dynamic parameters allows a shorter minimal signal length in comparison to that required by perturbation measures [19], which is beneficial when working with young children who may have difficulty sustaining phonation.

To our knowledge, research on nonlinear dynamic methods has thus far been confined to the adult population. Acoustic analysis confers an advantage for the assessment of the pediatric voice, as it requires only a simple, quick, and non-invasive voice recording [1,18,48–49]. This is important because pediatric patient cooperation problems, as described by Smith et al., [49] would be avoided. Thus, nonlinear dynamic features may provide an expedient and reliable tool for the clinical diagnosis and evaluation of pediatric dysphonia.

II. Objectives

It is the purpose of this paper to collect preliminary normative data concerning the use of nonlinear dynamic parameters for assessing dysphonia in children. An assessment tool should be standardized [5,10–13], and this paper will work toward the creation of standards for describing pediatric voices with nonlinear dynamic parameters. D_2 analysis will be applied to audio samples of voices from normal and dysphonic children. Normal and dysphonic D_2 values will be compared to determine whether D_2 significantly differentiates normal from dysphonic pediatric voice. The samples will also undergo percent jitter analysis in order to compare results of a traditional perturbation measure and a nonlinear dynamic method.

III. Materials and Methods

A. Participants

The Institutional Review Board at the University of Wisconsin approved the protocol and consent procedures applied in this study. Twenty-three dysphonic children (17 males, 6 females) presenting to the Pediatric Voice Clinic at the University of Wisconsin provided recordings. Pediatric dysphonic subjects were examined by a pediatric otolaryngologist and speech-language pathologist to confirm the presence of dysphonia resultant to vocal pathology. Details of vocal pathologies represented in the group are summarized in Table 1. The mean age for the pediatric dysphonic group was 6.48 years (age range = 3–9 years).

Fifteen healthy children with normal voices (3 males, 12 females) were recruited at the Pediatric Voice Clinic as accompanying siblings of the pediatric dysphonic subjects or patients and siblings presenting in the clinic for other non-voice related otolaryngological concerns. No signs of dysphonia were noted. The mean age for the pediatric normal group was 7.8 years (age range = 2–15 years).

B. Procedure

i. Recording—Recordings of pediatric voices were made at the Pediatric Voice Clinic. Subjects were asked to sustain the vowel /a/ ('ah') and/or /i/ ('ee') at a comfortable pitch and intensity. Recordings were made in a soundproof room with the recording microphone (AKG Acoustics, Vienna, Austria) positioned 4–6 cm away from the subject's mouth. A Kay Elemetrics attenuator, model 7177–8000 (KayPENTAX, Lincoln Park, NJ) was employed. The samples were recorded and digitized using Kay Elemetrics Computerized Speech Lab hardware and software, model 4500 (KayPENTAX) at a sampling rate of $f_s = 44.1$ kHz. Prior to nonlinear dynamic analysis, signals were resampled to $f_s = 25$ kHz using Goldwave software,

version 5.1 (Goldwave Inc., St. John's, NL, Canada). To avoid effects of speech intonation or interactions between the larynx and vocal tract on analysis, a middle stationary segment $x(t_i)$, $t_i = i\Delta t$, $\Delta t = 1/f_s$, $i = 1, 2, \dots, L$, with a length of 1 second was selected for analysis from each subject's recording.

ii. Nonlinear dynamic analysis—The voice segments underwent nonlinear dynamic analysis using software developed at the laryngeal physiology laboratory at the University of Wisconsin. Calculations made by this software were based upon the algorithms previously employed in studies of phonation in excised larynges [31] and human vocal pathologies [15, 32, 40]. In this study, D_2 was calculated for each sample to allow for quantitative comparison across groups. D_2 analysis required approximately two minutes per sample. The reliability of each D_2 value was determined using a standard deviation measure provided by the software program. To ensure the reliability of a given D_2 value, its standard deviation should not exceed 5%. Any sample in this study producing a standard deviation above 5% would be discarded.

iii. Perturbation analysis—Perturbation analysis was completed using the Multi Dimensional Voice Program (MDVP) (KayPENTAX). The percent jitter mean and standard deviation values were calculated for each pediatric normal and dysphonic sample. Percent jitter could not be calculated for two samples from the pediatric normal group due to low signal amplitude. Those samples were not included in percent jitter analysis.

iv. Statistical analysis—Statistical analysis was completed using SigmaStat 3.0 and SigmaPlot 8.0 software (Jandel Scientific, San Rafael, CA). Paired t -tests were administered to compare normal versus dysphonic pediatric voices. Both D_2 and percent jitter values underwent statistical analysis. Statistical significance was set at the level of 0.05.

IV. Results

A summary of nonlinear dynamic analysis results can be found in Table 2. These results are represented graphically in Figure 1. The standard deviation of each sample was below 5%, so all samples were considered reliable. The pediatric dysphonic group demonstrated significantly higher D_2 values than the pediatric normal group ($p = 0.002$). The D_2 values of the pediatric dysphonic group showed a low standard deviation. Pediatric normal voices exhibited a slightly higher standard deviation than pediatric dysphonic voices.

Figure 2 and Figure 3 depict phase space reconstructions from subjects in this study. Figure 2 shows a normal subject's phase space reconstruction, and Figure 3 shows the phase space reconstruction of a dysphonic subject. The phase space reconstructions were created by plotting the subjects' voice signals against themselves at some time delay. A periodic signal, as seen in Figure 2, creates a closed trajectory, representing the regular waveforms produced by normal voice. An aperiodic signal, as seen in Figure 3, shows marked irregularity in the phase space reconstruction, representing the aperiodicity of dysphonic voice [50–51]. The phase space reconstructions derived from subjects in this study show a closed trajectory for the normal subject and an irregular trajectory for the dysphonic subject.

Percent jitter results are represented numerically and graphically in Table 3 and Figure 2, respectively. The pediatric dysphonic group showed a significantly higher mean percent jitter than the pediatric normal group ($p = 0.025$). Standard deviations were high for both pediatric normal ($SD = 1.117$) and pediatric dysphonic ($SD = 1.150$) groups.

Figure 5 and Figure 6 depict MDVP radial diagram results from subjects in this study. Figure 5 shows a normal subject's radial diagram, and Figure 6 shows that of a dysphonic subject. The radial diagram plots analysis results in a circular fashion, with the axis of each parameter

starting at the center of the circle and extending radially outward. The sole parameter included in this analysis was percent jitter. The normative values are contained within the circle, as seen in Figure 5, and the values extending beyond the circle are of a magnitude that exceeds the normative threshold, as seen in Figure 6 [52]. The radial graphs representing subjects in this study show percent jitter values within the normative threshold for the pediatric normal subject, and extending beyond the normative threshold for the pediatric dysphonic subject.

V. Discussion

Traditional perturbation measures such as jitter and shimmer have been shown to differentiate between normal and dysphonic pediatric voices by Campisi et al. [28]. However, the potential drawbacks of using perturbation methods for describing dysphonic voice have been widely discussed in the literature. These drawbacks include a lack of reliability when analyzing highly aperiodic voices [12,29–32], low agreement among different perturbation analysis systems [11,33–34], longer minimal signal length [19], and sensitivity to variations in recording systems [35–36]. This paper aimed to determine whether the nonlinear dynamic parameter of correlation dimension (D_2) successfully differentiated between normal and dysphonic pediatric phonations. Additionally, this paper compared nonlinear dynamic analysis to perturbation measures by applying percent jitter analysis to the data and comparing the results with D_2 analysis results.

In our evaluation of correlation dimension as a tool for describing pediatric dysphonia, we found that D_2 successfully correlated with dysphonia in children. This finding suggests that D_2 could potentially detect dysphonia in children, pending the establishment of normative values. Considerable overlap was observed between normal and dysphonic populations. This overlap indicates that a primary application of D_2 may be assessing intrasubject change rather than predicting pathology. Jiang et al. demonstrated the successful evaluation of treatment outcomes using correlation dimension and second-order entropy in subjects with vocal polyps [32]. A study assessing pre- and post- treatment values in pediatric populations is recommended. Further studies involving larger subject groups matched for age, pathology type and severity would also be useful to establish baseline values for differentiating between normal and dysphonic pediatric voices.

Large intersubject D_2 variability was observed in the pediatric normal and dysphonic groups. Variability among pediatric normal subjects may relate to a relatively large age range in that group. Dejonckere et al. have shown that jitter levels decrease with age [27] due to changes in vocal fold physiology. Moreover, the large proportion of females in the pediatric normal group (4:1) as compared to the pediatric dysphonic group (1:2.8) may have contributed to D_2 variability. Although a gender difference has not been demonstrated when using perturbation measures in children [24], this finding suggests that further studies concerning gender differences when assessing children's voice using nonlinear dynamic parameters may prove helpful.

Results of percent jitter analysis showed a significant difference between normal and dysphonic pediatric speakers ($p = 0.025$). Sample size in the pediatric normal group was reduced from 23 to 21 due to low amplitude in two samples, which may indicate another disadvantage of perturbation measures. The larger standard deviations and higher p -values resulting from perturbation analysis indicated lower reliability as compared to nonlinear dynamic analysis. This finding suggests that nonlinear dynamic analysis could be a more reliable alternative to perturbation measures when assessing disordered voice.

A worthwhile extension of this study could employ a different nonlinear dynamic parameter to analyze pediatric normal and dysphonic voices. Correlation dimension is one of several

nonlinear dynamic parameters that can be used to analyze dysphonia; other parameters include maximal Lyapunov exponents, Kolmogorov entropy, and second-order entropy [15,31–32, 37–42]. The literature has shown significant differences between normal and pathologic phonations using maximal Lyapunov exponents in excised larynges [31] and in subjects with unilateral laryngeal paralysis [45], and when using second-order entropy in subjects following surgical excision of vocal polyps [32].

Correlation dimension appears to be a valuable parameter for the clinical assessment of pediatric dysphonia. Findings indicated that on average, correlation dimension differentiates between normal and dysphonic voice in children. However, the considerable overlap between pediatric normal and dysphonic populations leads us to qualify our recommendation for the use of nonlinear dynamic analysis in children; currently, its application should be limited to intraspeaker rather than interspeaker assessment. This study has demonstrated the possible benefits of using the nonlinear dynamic parameter of correlation dimension to evaluate dysphonia in children, and possible extensions of this study have been suggested to encourage further investigation into this area.

VI. Conclusion

In this paper, we used the nonlinear dynamic parameter of correlation dimension (D_2) to compare normal and dysphonic pediatric speakers. The results of this investigation showed that D_2 is significantly higher in dysphonic children than in normal children. Percent jitter analysis of the data demonstrated a correlation with dysphonia, but results showed markedly larger standard deviations and a lower p -value than D_2 results. These findings indicate that in addition to being a child-friendly procedure, nonlinear dynamic analysis may be more reliable than traditional perturbation measures when differentiating between pediatric normal and dysphonic voices. However, several unexpected findings, including large overlap between groups, indicate that this area requires further investigation. More studies are needed to collect normative data on the use of nonlinear dynamic analysis as an objective, quick, and easily administered tool for describing pediatric dysphonia.

Acknowledgment

This work was supported by the NIH Grant RO1 DC006019 from the National Institute on Deafness and Other Communication Disorders. The authors are indebted to Julia MacCallum for her guidance in writing this manuscript.

References

1. Hirschberg J, Dejonckere PH, Hirano M, Mori K, Shultz-Coulon HJ, Vrticka K. Voice disorders in children. *Int J Pediatr Otorhinolaryngol* 1995;32:S109–S125. [PubMed: 7665280]
2. Hooper CR. Treatment of Voice Disorders in Children. *Lang Speech Hear Serv in Sch* 2004;35:320–326.
3. Dejonckere PH. Voice problems in children: pathogenesis and diagnosis. *Int J Pediatr Otorhinolaryngol* 1999;49:S311–S314. [PubMed: 10577828]
4. Trani M, Ghidini A, Bergamini G, Presutti L. Voice therapy in pediatric functional dysphonia: a prospective study. *Int J Pediatr Otorhinolaryngol* 2007;71:379–384. [PubMed: 17137639]
5. McMurray JS. Disorders of phonation in children. *Pediatr Clin North Am* 2003;50:363–380. [PubMed: 12809328]
6. Carding PN, Roulstone S, Northstone K. ALSPAC Study Team. The prevalence of childhood dysphonia: a cross-sectional study. *J Voice* 2006;20:623–630. [PubMed: 16360302]
7. Conner NP, Cohen SP, Theis SM, Thibeault SL, Heatley DG, Bless DM. Attitudes of children with dysphonia. *J Voice* 2008;22:197–209. [PubMed: 17512168]
8. Ruscello DM, Lass NJ, Podbesek J. Listener's perceptions of normal and voice-disordered children. *Folia Phoniatr (Basel)* 1998;40:290–296. [PubMed: 3243521]

9. Lass NJ, Ruscello DM, Stout LL, Hoffmann PM. Peer perceptions of normal and voice-disordered children. *Folia Phoniatr (Basel)* 1999;43:29–35. [PubMed: 2071074]
10. Bhuta T, Patrick L, Garnett JD. Perceptual evaluation of voice quality and its correlation with acoustic measurements. *J Voice* 2004;18:299–304. [PubMed: 15331102]
11. Hicks DM. Functional voice assessment: what to measure and why. NIDCD Monograph 1991;1:204–209.
12. Titze IR. The G. Paul Moore Lecture. Toward standards in acoustic analysis of voice. *J Voice* 1991;8:1–7. [PubMed: 8167782]
13. Bough ID, Heuer RJ, Sataloff RT, Hills JR, Cater JR. Intrasubject variability of objective voice measures. *J Voice* 1996;10:166–174. [PubMed: 8734392]
14. Behrman A. Common practices of voice therapists in the evaluation of patients. *J Voice* 2005;19:454–469. [PubMed: 16102671]
15. Jiang JJ, Zhang Y. Nonlinear dynamic analysis of speech from pathologic subjects. *Electron Lett* 2002;38:294–295.
16. Niedzielska G. Acoustic analysis in the diagnosis of voice disorders in children. *Int J Ped Otorhinolaryngol* 2001;57:189–193.
17. Cohen SR, Thompson JW, Geller KA, Birns JW. Voice change in the pediatric patient: a differential diagnosis. *Ann Otol Rhinol Laryngol* 1983;92:437–443. [PubMed: 6625440]
18. Dejonckere PH, Remacle M, Fresnel-Elbaz E, Woisard V, Crevier L, Millet B. Reliability and clinical relevance of perceptual evaluation of pathological voices. *Rev Larngol Otol Rhinol (Bord)* 1998;119:247–248.
19. Zhang Y, Jiang JJ, Wallace SM, Zhou L. Comparison of nonlinear dynamic methods and perturbation methods for voice analysis. *J Acoust Soc Am* 2005;118:2551–2560. [PubMed: 16266175]
20. Lieberman P. Perturbations in vocal pitch. *J Acoust Soc Am* 1961;33:597–603.
21. Lieberman P. Some acoustic measures of the fundamental periodicity of normal and pathological larynges. *J Acoust Soc Am* 1963;35:344–353.
22. Titze, IR. Principles of Voice Production. Upper Saddle River, NJ: Prentice Hall; 1994. p. 281
23. Oates JM, Kirkby RJ. An acoustic investigation of voice quality disorders in children with vocal nodules. *Aust J Hum Commun Disord* 1980;8:28–39.
24. Ferrand CT. Harmonics-to-noise ratios in normally speaking prepubescent girls and boys. *J Voice* 2000;14:17–21. [PubMed: 10764113]
25. Glaze LE, Bless DM, Milenkovic P, Susser RD. Acoustic characteristics of children's voice. *J Voice* 1998;2:312–319.
26. Steinsapir, CD.; Forner, LL.; Stemple, JC. Voice characteristics among black and white children: do differences exist?; Paper presented at American Speech-Language-Hearing Association Annual Convention; Detroit, Mich. 1986.
27. Dejonckere PH, Wieneke GH, Bloemenkamp D, Lebacq J. F0-perturbation and F0/loudness dynamics in voices of normal children, with and without education in singing. *Int J Pediatr Otorhinolaryngol* 1996;35:107–115. [PubMed: 8735407]
28. Campisi P, Tewfik TL, Pelland-Blais E, Husein M, Sadeghi N. MultiDimensional Voice Program analysis in children with vocal cord nodules. *J Otolaryngol* 2000;29:2000.
29. Titze, IR. Workshop on acoustic voice analysis: summary statement. Denver, CO: National Center for Voice and Speech; 1995. p. 1-36.
30. Karnell MP, Chang A, Smith A, Hoffman H. Impact of signal type on validity of voice perturbation measures. *NCVS Status Prog Rep* 1997;11:91–94.
31. Jiang JJ, Zhang Y, Ford CN. Nonlinear dynamics of phonations in excised larynx experiments. *J Acoust Soc Am* 2003;114:2198–2205. [PubMed: 14587617]
32. Zhang Y, McGilligan C, Zhou L, Vig M, Jiang JJ. Nonlinear dynamic analysis of voices before and after surgical excision of vocal polyps. *J Acoust Soc Am* 2004;115:2270–2277. [PubMed: 15139638]
33. Karnell MP, Hall KD, Landahl KL. Comparison of fundamental frequency and perturbation measurements among three analysis systems. *J Voice* 1995;9:383–393. [PubMed: 8574304]
34. Bielamowicz S, Kreiman J, Gerratt BR, Dauer MS, Berke GS. Comparison of voice analysis systems for perturbation measurements. *J Speech Hear Res* 1996;39:126–134. [PubMed: 8820704]

35. Titze IR, Winholtz WS. Effect of microphone type and placement on voice perturbation measurements. *J Speech Hear Res* 1993;36:1177–1190. [PubMed: 8114484]
36. Titze IR, Horii Y, Scherer RC. Some technical considerations in voice perturbation measurements. *J Speech Hear Res* 1987;30:252–260. [PubMed: 3599957]
37. Jiang JJ, Zhang Y, McGilligan C. Chaos in voice, from modeling to measurement. *J Voice* 2006;20:2–17. [PubMed: 15964740]
38. Herzel H, Berry D. Analysis of vocal disorders with methods from nonlinear dynamics. *J Speech Hear Res* 1994;37:1008–1019. [PubMed: 7823547]
39. Titze, IR.; Baken, R.; Herzel, H. Evidence of chaos in vocal fold vibration. In: Titze, IR., editor. *Vocal Fold Physiology: New Frontiers in Basic Science*. San Diego: Singular; 1993. p. 143-188.
40. Zhang Y, Jiang JJ, Biazzo L, Jorgensen M. Perturbation and nonlinear dynamic analysis of voices from patients with unilateral laryngeal paralysis. *J Voice* 2005;19:519–528. [PubMed: 16301098]
41. Herzel H. Bifurcations and chaos in voice signals. *Appl Mech Rev* 1993;46:399–413.
42. Kumar A, Mullick SK. Nonlinear dynamical analysis of speech. *J Acoust Soc Am* 1996;100:615–629.
43. Behrman A, Baken RJ. Correlation dimension of electroglottographic data from healthy and pathologic subjects. *J Acoust Soc Am* 1997;102:2371–2379. [PubMed: 9348696]
44. Zhang Y, Jiang JJ. Nonlinear dynamic analysis of signal typing of pathological human voices. *Electron Lett* 2003;39:1021–1023.
45. Giovanni A, Ouaknine M, Triglia J-M. Determination of largest Lyapunov exponents of vocal signal: application to unilateral laryngeal paralysis. *J Voice* 1998;13:341. [PubMed: 10498051]
46. Rahn DA 3rd, Chou M, Jiang JJ, Zhang Y. Phonatory impairment in Parkinson's disease: evidence from nonlinear dynamic analysis and perturbation analysis. *J Voice* 2007;21:64–71. [PubMed: 16377130]
47. Alonso JB, Fernando D, Carlos TM, Ferrer MA. Using nonlinear features for voice disorder detection. *NOLISP* 2005:94–106.
48. Dejonckere PH, Lebacqz J. Acoustic, perceptual, aerodynamic and anatomical correlations in voice pathology. *J Otorhinolaryngol Relat Spec* 1996;58:326–332.
49. Smith ME, Marsh JH, Cotton RT, Myer CM. Voice problems after pediatric laryngotracheal reconstruction: videolaryngoscopic, acoustic, and perceptual assessment. *Int J Pediatr Otorhinolaryngol* 1993;25:173–181. [PubMed: 8436462]
50. Packard NH, Crutchfield JP, Farmer JD, Shaw RS. Geometry from a time series. *Phys Rev Lett* 1980;45:712.
51. Zhang Y, MacCallum JK, Zhou L, Jiang JJ. Objective Acoustic Analysis of Pathological Voices From Patients with Vocal Nodules and Polyps. *Folia Phoniatri*. 2008In press
52. KayPENTAX. Lincoln Park, NJ: 2007. Multi-Dimensional Voice Program (MDVP) Model 5105 Software Instruction Manual.

Figure 1.
 D_2 distribution by group

Figure 2.
Phase space reconstruction: pediatric normal subject

Figure 3.
Phase space reconstruction: pediatric dysphonic subject

Figure 4.
Percent jitter by group

Figure 5.
MDVP radial diagram: pediatric normal subject

Figure 6.
MDVP radial diagram: pediatric dysphonic subject

Table 1

Etiology of dysphonia for pediatric dysphonic subjects

Diagnosis	Number of Subjects
Costal cartilage graft for subglottic stenosis	2
Nodules	15
Papilloma removal	1
Prenodular edema	1
Unspecified dysphonia	2
Vocal fold paralysis	1
Vocal fold scarring	1
Total	23

Table 2Mean and standard deviation D_2 by group

Group	D_2
Pediatric dysphonic	M = 1.633 SD = 0.387
Pediatric normal	M = 1.195 SD = 0.413

Table 3

Mean and standard deviation percent jitter by group

Group	<i>Percent Jitter</i>
Pediatric dysphonic	M = 1.906 SD = 1.150
Pediatric normal	M = 1.261 SD = 1.117