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Nonlinear Analyses of Elicited Modal, Raised, and Pressed Rabbit Phonation

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Abstract

Objectives/Hypothesis—The purpose of this study was to use nonlinear dynamic analysis methods such as phase space portraits and correlation dimension (D_2) as well as descriptive spectrographic analyses to characterize acoustic signals produced during evoked rabbit phonation.

Methods—Seventeen New Zealand white breeder rabbits were used to perform the study. A Grass S-88 stimulator (SA Instrumentation, Encinitas, CA) and constant current isolation unit (Grass Telefactor, model PSIU6; West Warwick, RI) were used to provide electrical stimulation to laryngeal musculature, and transglottal airflow rate and stimulation current (mA) were manipulated to elicit modal, raised intensity, and pressed phonations. Central 1 second portions of the most stable portion of the acoustic waveform for modal, raised intensity, and pressed phonations were edited, and then analyzed via phase space portraits, Poincaré sections, and the estimation of the correlation dimension (D_2). In an attempt to limit the effects of the highly variable and nonstationary characteristics of some of the signals being analyzed, D_2 analysis was also performed on the most stable central 200 ms portion of the acoustic waveform. Descriptive analysis of each phonation was also conducted using sound spectrograms.

Results—Results showed that the complexity of phonation and the subsequent acoustic waveform is increased as transglottal airflow rate and degree of glottal adduction is manipulated in the evoked rabbit phonation model. In particular, phonatory complexity, as quantified via correlation dimension analyses and demonstrated via spectrographic characteristics, increases from “modal” (i.e., phonation elicited at just above the phonation threshold pressure) to raised intensity (phonation elicited by increasing transglottal airflow rate) to pressed (phonation elicited by increasing the stimulation current delivered to the larynx). Variations in a single dynamic dimension (airflow rate or adductory force) resulted in significantly increased productions of

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nonlinear phenomenon, including bifurcations from periodicity to regions of subharmonic content, F_0 and harmonic jumps, and evidence of periodicity within aperiodic regions (“chaos”).

Conclusions—The evoked rabbit phonation model described in this study allows for the elicitation of various types of phonations under controlled conditions and therefore, has the potential to provide insight regarding important variables that may elicit examples of nonlinear phenomena such as subharmonics and deterministic chaos.

Keywords

nonlinear dynamic analysis; chaos; bifurcations; subharmonics; pressed phonation

Introduction

The use of animal models to investigate vocal anatomy, histology, and physiology has been a useful adjunct to the body of literature regarding vocal biology. Ex vivo and in vivo experimental designs provide an environment in which highly systematic manipulation of parameters that influence vocal function may be monitored and independently controlled. In addition, extreme phonation conditions that are difficult to achieve in human subjects can be investigated using these designs¹. In vivo preparations provide the added advantage of allowing for the study of cells and extracellular matrices in their native environment². Widely used animal models have included canine, porcine, ovine, and rabbit larynges^{1,3–11}.

Rousseau and colleagues¹² have developed a rabbit model to study phonation related molecular alterations. The rabbit phonation model allows for the investigation of vibration induced gene regulation, extracellular matrix deposition, and tissue remodeling in vivo. The rabbit model has advantages over other animal models because it is a naturally quiet animal, allowing for increased control over non-experimental vocalization. Perhaps of primary importance is that the histology of the rabbit lamina propria is quite similar to that of humans and, therefore, may be useful in experiments that alter the tissue properties of the vocal folds^{13,14}. The in vivo rabbit phonation model has been used to investigate gene expression changes following prolonged phonation¹², as well as the effects of systematic manipulation of transglottal airflow rate and electrical stimulation on glottal configuration^{2,15}. Though a key goal of these studies to date has been the investigation of the role of potentially injurious mechanical forces on expression and turnover of the vocal fold extracellular matrix, the in vivo rabbit model also provides an excellent preparation to investigate the phonatory parameters and their respective combinations that may result in irregular phonation and changes in the associated acoustic waveform. Irregular phonation types may be characterized by substantial variations from periodicity and may correspond to perceptually rough, “noisy” vocalization^{1,16}. Because these types of phonation produce acoustic waveforms that show considerable variability in signal profile and/or absence of apparent cyclic vibration, they may not be analyzed in a reliable and valid fashion using traditional time-based measures of acoustic perturbation such as jitter and shimmer. This is particularly the case with highly disturbed signals such as may be produced in raised subglottal pressure and pressed phonation conditions.

While severely perturbed acoustic signals may appear to represent random vibration (stochastic “noise”), these erratic looking signals may instead exemplify nonlinear phenomena, in which temporal behavior does not arise haphazardly but is deterministic (i.e., initial conditions or laws determine the end result). Studies of human and non-human vocalization have identified and described various types of nonlinear phenomena including the presence of frequency jumps (sudden, discontinuous changes in fundamental frequency); period-doubling and corresponding subharmonics (additional spectral components observed at integer divisors of the fundamental frequency); biphonation (the occurrence of two simultaneous but arbitrarily unrelated frequencies); and deterministic chaos (characterized by the observation of residual periodicity occurring in otherwise noisy segments)^{1,17–20}. Transitions between these vibratory conditions are referred to as bifurcations^{19,20}. The presence of nonlinear phenomena may increase the distinctiveness and auditory impact of individual vocalization or provide acoustic cues regarding vocal health^{18,19}.

Two commonly used methods to describe nonlinear phonatory behavior include phase space portraits and the subsequent computation of the correlation dimension. Typically, voice waveform data are embedded in phase space and then reconstructed as an attractor using the method of lag variables/delay coordinates²⁰. A periodic signal will show a closed trajectory in phase space (a limit cycle), with increasing perturbation resulting in irregular/chaotic trajectories (a strange attractor)^{20–22}. While vocal fold vibration may be graphically portrayed as a trajectory in phase space with time evolution²³, further computation is required to objectively describe the complexity of the signal in space or time. The correlation dimension (D_2) is a quantitative measure that may specify the number of degrees of freedom (i.e., dimensions) needed to describe a dynamic system^{1,21}. If the dynamics of a system can be determined to be low dimensional, then a complex determinism may exist which is responsible for the observed signal profile²⁴. Alternatively, the more complex the system, the greater the number of degrees of freedom needed to describe its dynamic state, and the higher the correlation dimension.

While many types of nonlinear phonatory behavior may be quantified using the correlation dimension, vocalizations that are characterized by highly irregular phonation or increased levels of turbulent noise (as in severe breathy phonations) may not be analyzed in a reliable fashion using D_2 alone because there may be no convergence of the correlation dimension with increasing stochastic behavior in the waveform^{24–26}. In addition, while D_2 may be used to objectively characterize the degree of complexity (i.e., the number of degrees of freedom/dimensions needed to describe the system), it does not specify the particular type of nonlinear phenomena being produced. Therefore, multiple studies have used descriptive spectrographic analyses to further elucidate objective nonlinear analyses using methods such as the correlation dimension^{1,18,19,23}.

The purpose of this study was to use nonlinear dynamic analysis methods such as phase space portraits and correlation dimension (D_2) as well as descriptive spectrographic analyses to characterize acoustic signals in an evoked rabbit phonation model. In particular, the goals of this study were to investigate the following:

1. Are nonlinear acoustic phenomenon observed in rabbit phonations?

2. What are the conditions that may elicit nonlinear phenomenon in rabbit phonations?

Methodology

In Vivo Preparation

Seventeen New Zealand white breeder rabbits weighing 3 to 5 kg were used to perform the study. The animals were anesthetized with intramuscular injections of ketamine (35 mg/kg), xylazine (5 mg/kg), and acepromazine (0.75 mg/kg). To assess general well-being, heart rate, oxygen saturation levels, and temperature were monitored throughout the procedure. To maintain anesthetic effects, additional administrations of ketamine (17.5 mg/kg) and acepromazine (0.375 mg/kg) were administered as needed. To prepare the rabbits for surgery, the neck was shaved from the submentum down to the chest and the rabbits were placed on an operating platform in the supine position. As described previously²⁷, a vertical midline neck incision from the hyoid bone to sternal notch was used to expose the larynx and trachea. The trachea was transected proximal to the sternum and a tracheostomy was performed. A 3.5 cuffed endotracheal tube (RUSCh, Kern, Germany) was inserted into the upper portion of the bisected trachea and placed approximately 2 cm below the glottal aperture. The cuffed endotracheal tube was inflated to seal off the trachea and to deliver airflow to the glottis.

To serve as cathodes for electrical stimulation, a stainless-steel hooked electrode was inserted into the belly of each cricothyroid muscle in the direction perpendicular to the muscle fibers. To serve as anodes for electrical stimulation, two hooked electrodes were placed into the cricothyroid membrane. One electrode was also inserted into the membrane on each side at the intersection of a longitudinal line 1 mm lateral to midline and a transverse line 1 mm inferior to the thyroid cartilage. A Gilmont Instruments flowmeter (GF-8522-1700, Barrington, IL) and Conch Therm III humidifier (Hudson, RCI, Temecula, CA) were used to deliver compressed humidified airflow to the glottis. A Grass S-88 stimulator (SA Instrumentation, Encinitas, CA) and constant current isolation unit (Grass Telefactor, model PSIU6; West Warwick, RI) were used to provide electrical stimulation to the laryngeal apparatus, while manipulating transglottal airflow rate and stimulation current (mA) to elicit modal, raised intensity, and pressed phonation.

Transglottal airflow was delivered at 85 cm³/sec while the stimulation current was increased in 0.2 mA steps until arriving at the phonation threshold. Modal phonation was produced using stimulation currents of 0.2 – 0.6 mA above the phonation threshold on average. This represented the current level necessary for producing sustained audible phonation. For raised intensity phonation, transglottal airflow rate was increased to 144 cm³/sec, while keeping stimulation current at levels required for modal phonation. Although continuous sweeps of airflow and adduction parameters similar to those performed in excised larynx experiments such as conducted by Herbst et al.²⁸ are possible using the in vivo rabbit preparation, a fixed airflow parameter of 144 cm³/sec was used to elicit raised intensity phonation based on our previous experiments, which have demonstrated that this airflow setting (in combination with the aforementioned 0.2-0.6 mA stimulation currents) can produce reliable phonations that are 5dB to 10 dB louder than modal intensity phonations. These raised

intensity levels have been associated with changes to inflammatory mediator gene expression and compromised vocal fold epithelial barrier integrity^{27,29}. For pressed phonation, transglottal airflow was delivered at 85 cm³/sec, while increasing stimulation current to produce a characteristically pressed phonation type.

Acoustic Analyses

Acoustic signals were recorded using a Shure SM48 unidirectional dynamic microphone (Shure Inc., Niles, IL) that was placed 10 cm from the opening of the laryngoscope and digitized using the Computerized Speech Lab (CSL Model 4500) (Kay Elemetrics Corp., Lincoln Park, NJ) at 44.1 kHz, 16 bits and later downsampled to 22.05 kHz for further analyses. Central 1 second portions of the most stable portion of the acoustic waveform for modal, raised intensity, and pressed phonations were edited, and then analyzed via phase space portraits and the estimation of the correlation dimension (D_2). In an attempt to limit the effects of the highly variable and nonstationary characteristics of some of the signals being analyzed, correlation dimension analysis was also performed on the most stable central 200 ms portion of the phonation waveform.

Nonlinear Analyses

Nonlinear analysis procedures were computed using Visual Recurrence Analysis (VRA) v. 4.9 software³⁰, TISEAN 3.0 Nonlinear Time Series Analysis software³¹, and SciLab v. 5.3.3 (Scilab Enterprises, Versailles, France). Three-dimensional (3D) phase space portraits and Poincaré sections were computed to visualize the spatial structure of the dynamical system. A Poincaré section may be used to reduce the dimension of a dynamical system by slicing it with a surface of a lower dimension. As an example, a three-dimensional phase space may be intersected with a transversely oriented plane such that the attractor is now viewed in two-dimensions periodically whenever its trajectory moves through the plane³². When the Poincaré section is made through the entire phase portrait³³, simple highly periodic limit cycles will show two small, tightly clustered regions as point trajectories pass into and out of the Poincaré plane. Quasiperiodic and chaotic signals with increased complexity will show a greater number of clustered regions; overlapping regions; and/or increased scattering (indicative of increased periods). Noise will result in highly scattered regions with no obvious order or clustering. For the purposes of this study, the Poincaré section was placed at 45 degrees above the horizontal plane (the equation of the plane: $-x-y+z=0$) and the points in the Poincare section were plotted using an orthonormal basis for the plane.

The time-series of each vocalization was embedded in a phase space using the method of delay-coordinates:

$$X_i = \{x(t_i), x(t_i - \tau), \dots, x(t_i - (m - 1)\tau)\},$$

where m is the embedding dimension and τ is the time delay^{1,20,23}. The choice of an appropriate time delay τ and embedding dimension m (computed using the VRA software) are important for the success of the phase space reconstruction and for subsequent

correlation dimension calculations. One of the suggested methods of estimating the proper τ is via the mutual information method of Fraser and Swinney³⁴. Mutual information is a parameter applied to measure the general dependence of two variables. In the curve of the mutual information function versus τ , the first minimum value of the mutual information function provides an effective criterion for choosing the proper time delay. The minimal optimal embedding dimension can be obtained using the false nearest neighbor method³⁵, in which the percentage of false nearest neighbors (i.e., points in the dataset that are neighbors solely because we are viewing the attractor in too small of an embedding space) should drop to a minimum when the appropriate embedding dimension has been reached.

The appropriate time delay τ is also important for computing an important measure of the dimensionality of the attractor, referred to as the correlation dimension (D_2). The correlation dimension quantifies the complexity or irregularity of the reconstructed system. Using correlation dimension, the dynamic characteristics of chaotic systems can be distinguished from those of white noise, since the estimate of D_2 of stochastic white noise does not converge with increasing m , whereas D_2 of a chaotic system converges to a finite value with the increase of m . For the purposes of this study, D_2 was computed using the TISEAN software with $m = 1$ to 20 evaluated. In chaotic states, the D_2 usually takes on noninteger values, and the larger the D_2 of the attractor, the more complicated the behavior of the nonlinear system³⁶. The estimated value of the correlation dimension is equal to the plateaued region of the slope where the D_2 value is stabilized for increased embedding dimensions. The stabilized values from successive embeddings have been referred to as saturation²⁴ or convergence³⁷. Figure 1 provides examples of TISEAN correlation dimensional analyses for rabbit phonations in which convergence of D_2 in the scaling region is observed vs. nonconvergence of D_2 . In a manner similar to DiBona and Jones³⁸, the value of D_2 was calculated by averaging across all embeddings in which the D_2 value in the scaling region deviated by $< 5\%$ from embedding to embedding.

Spectrographic Analysis

In addition to correlation dimension analyses, a descriptive analysis of each phonation was conducted using sound spectrograms. Consensus judgments from two trained judges blinded to rabbit phonation type (i.e., modal, raised, or pressed) were obtained for each rabbit phonation for the presence or absence of the following key spectrographic features (from Riede Owren, & Arcadi¹⁸):

- Strong, distinctive harmonic content throughout
- Harmonic smearing
- Frequency variation characterized by continuous, smooth modulation
- Frequency jumps – sudden F_0 and/or harmonic changes in which vibration rate moves up or down discontinuously
- Subharmonics – additional spectral components that can suddenly appear at integer values of an identifiable F_0

- Deterministic chaos – episodes of “nonrandom noise”; may be characterized by harmonic “windows” that occur in otherwise noisy segments
- Biphonation – the occurrence of two simultaneous but independent fundamental frequencies
- Isolated episodes of aperiodicity/noise
- Consistent aperiodicity/noise

Spectrograms of rabbit phonation were presented to each judge in a randomized fashion using Cool Edit Pro v. 2.1 (Syntrillium Software, Phoenix, AZ, 2003). Spectrographic analysis was computed using 1024 pt. frames with 75% overlap and Blackman-Harris windowing. Judges were asked to rate the presence of each of the aforementioned spectrographic features. At a later time, the ratings of the two judges were compared and only spectrographic features in which there was agreement between the two judges were tabulated. Figure 2 provides an example of a sustained rabbit phonation in which several of the aforementioned examples of Riede et al.'s¹⁸ spectrographic features were observed.

Results

Correlation Dimension (D_2)

Using central 1 sec. phonation samples, only 11 of the 17 rabbits evaluated were able to produce phonations in which D_2 was observed to reliably saturate/converge for all three phonatory conditions (modal, raised, and pressed; 33 phonations analyzed). Analysis of variance (ANOVA; 3 levels of Phonation Type) was computed using SPSS 16.0 for Windows (Chicago, SPSS Inc., 2006) to assess whether there was a significant difference in mean D_2 for the various phonation types. Results ($F(2, 20) = 3.69, p < .05$) indicated a significant effect of phonation type with an increase in mean correlation dimension from modal (Mean $D_2 = 2.13$; $SD = 0.67$), to raised intensity ($D_2 = 2.61$; $SD = 1.39$), and finally to pressed phonation ($D_2 = 3.59$; $SD = 1.59$) observed (see Figure 3). Post-hoc analyses using Bonferroni adjusted t-tests indicated that the difference in D_2 was significant between modal and pressed conditions ($p < .05$).

Similar results were observed for the analysis of central 200 ms phonation samples (see Figure 3), with the added benefit of reduced signal variability within the shorter time frame resulting in 15 of 17 rabbit phonations in which satisfactory D_2 convergence was observed for all three phonatory conditions (45 phonations analyzed). As with the central 1 sec. samples, One-Way ANOVA results ($F(2, 28) = 9.79, p = .001$) showed an increase in mean correlation dimension from modal (Mean $D_2 = 2.14$; $SD = 0.92$), to raised intensity ($D_2 = 3.05$; $SD = 1.53$), and finally to pressed phonation ($D_2 = 4.22$; $SD = 1.66$), though overall p level and mean D_2 differences between phonation types were more substantial when analyzing with the shorter time frame. Post-hoc analyses using Bonferroni adjusted T-tests again indicated that the difference in D_2 was significant between modal and pressed conditions ($p < .001$).

Spectrographic Analyses

The consensus ratings for the spectrograms of the various phonations of all 17 rabbits (51 in total) were categorized as indicative of (a) the presence of periodic, controlled phonation (strong harmonics; smooth F_0 variations), (b) continuous aperiodicity, or (c) nonlinear phenomenon (F_0 and/or harmonic jumps; subharmonics; biphonation; deterministic chaos). A series of Chi-Square analyses indicated significant associations between Phonation Type and (1) the presence/absence of Strong Harmonics ($p = .0007$), (2) the presence/absence of Nonlinear Phenomena ($p = .002$), and (3) the presence/absence of Continuous Aperiodicity ($p = .015$). A review of Figure 4 shows that the vast majority of modal phonations were characterized by strong harmonics (82.3%) and relatively few episodes of nonlinear phenomena or continuous aperiodicity (19.6% and 11.8%). In contrast, raised intensity and pressed phonations resulted in increased harmonic smearing and irregularity and, particularly in pressed phonation, increased episodes of nonlinear phenomena (47.1%). Biphonation was the least frequently occurring nonlinear phenomenon. Subharmonics were common in both raised intensity and pressed phonations, while F_0 /harmonic jumps and chaotic vibration were observed primarily in pressed phonation.

Examples of Three-dimensional Phase Space Portraits and Poincaré Sections

Figures 5-7 provide 3-D phase space portraits and Poincaré sections, two-dimensional (2-D) Poincaré plots, and associated 1024 pt. spectral slices for representative modal, raised, and pressed phonations. In the modal phonation example (Fig. 5), the phase space portrait approximates a limit cycle and the 2-D Poincaré plot shows two tightly clustered regions as point trajectories pass into (blue colored points) and out of (red colored points) the Poincaré plane. The spectral slice shows distinct harmonics (particularly in the 1000-4000 Hz range), with a dominant spectral harmonic in the 1000 Hz region. The correlation dimension (D_2) for this sample = 1.2. In the raised phonation example (Fig. 6), the 3-D phase space portrait shows a loop characteristic of period-doubling, and the 2-D Poincaré plot shows four clustered regions as point trajectories pass into and out of the Poincaré plane. The spectral slice shows the presence of subharmonics, with the correlation dimension (D_2) for this sample = 1.95. For the pressed phonation example (Fig. 7), the 3-D phase space portrait and 2-D Poincaré plot both show a highly irregular and complex set of trajectories. However, the observation of convergence in the correlation dimension estimate (D_2 for this sample = 4.11) indicates that this waveform may actually be chaotic vs. stochastic noise. In addition, the spectral slice shows a possible “fundamental” peak in the 1000 Hz region amongst broad band random frequency content.

Discussion

The results of this study showed that the complexity of phonation is increased as transglottal airflow rate and degree of glottal adduction is manipulated in the evoked rabbit phonation model. In particular, phonatory complexity, as demonstrated via spectrographic characteristics and quantified via correlation dimension analyses, increases from “modal” (i.e., phonation elicited at just above the phonation threshold pressure) to raised intensity (phonation elicited by increasing transglottal airflow rate) to pressed (phonation elicited by increasing the stimulation current delivered to the larynx). While modal rabbit phonation

was characterized as low dimensional, with strong harmonic content and smooth F_0 and harmonic variation, variations in a single dynamic dimension (airflow rate or adductory force) resulted in significantly increased production of nonlinear phenomena, including bifurcation from periodicity to regions of subharmonic content, F_0 and harmonic jumps, and evidence of periodicity within aperiodic regions (“chaos”). The progression of increased signal complexity from modal-to-raised-to-pressed phonation observed in this study is similar to the progression from quasi-periodic to torus doubled quasi-periodic to chaotic motion (as well as additional nonlinear and chaotic behavior such as hysteresis and chaotic transients) with accompanying increases in correlation dimension observed in string vibration with increased forcing amplitudes by Molteno and Truffillaro³⁹. While the presence of nonlinear acoustic phenomenon has been previously described in both animal and human phonations (in both disordered and alarm states), the results of this study demonstrate that nonlinear acoustic phenomena can be elicited under controlled, experimental conditions.

A significant increase in D_2 was observed from modal to pressed phonation, with the mean D_2 for raised phonation observed to lie between these other modes of phonation. D_2 refers to the number of degrees of freedom needed to describe a system. The increased complexity of vibration observed in pressed rabbit phonation reflects a higher dimensional system that requires more state variables to describe it. Therefore, the D_2 values for such systems will be substantially higher as compared to those values of systems that are responsible for the modal phonations elicited in this study. The use of D_2 was able to track increased vibratory complexity in many of these modal-to-raised-to-pressed phonations that, due to considerable variability in signal profile and/or the absence of apparent cyclic vibration, would not have been possible using traditional measures of phonatory aperiodicity such as jitter and shimmer. As an example, the highly irregular pressed phonation example in Figure 7 did show a convergence in the correlation dimension (thereby revealing the essential degrees of freedom and an underlying organization in the acoustic data) that would not have been quantifiable via standard perturbation methods. This potential benefit of correlation dimension vs. traditional measures of phonatory disturbance has been previously demonstrated by Zhang and colleagues²¹. However, as reported by Behrman and Baken²⁴, Awan et al.²⁵, and Sprecher et al.²⁶, highly nonstationary and/or stochastic signals may not be measured effectively using D_2 due to a lack of convergence in the D_2 estimates with increased embeddings. In some phonations, stochastic characteristics override low-dimensional patterns, obscuring periodicities and preventing analysis²⁶. Though not quantitative, the additional use of methods such as the spectrographic analyses utilized in this study can be effective in describing nonlinear acoustic phenomena. The use of shorter duration acoustic samples may also result in improved D_2 analyses for highly nonstationary signals as observed in this study though, ideally, short duration D_2 estimates would be computed at multiple points throughout the duration of the sample. Though not possible with the software used in this study, computation of D_2 using moving window analysis⁴⁰ may be more effective in quantifying D_2 and its variation in highly nonstationary signals than the isolated samples used in the present study. In addition, a method of visualizing changes in phase space portraits and associated Poincaré sections over time described by Herbst et al.³³ may also be applicable to the types of nonstationary animal vocalizations described in this study.

As stated by Herzel et al.²⁰, a variety of laryngeal/phonatory conditions can result in bifurcation to nonlinear modes of vibration such as desynchronization of vocal fold vibration, interaction of vocal fold vibration with subglottal or supraglottal resonances, and (as in the current study) pressed phonation. Herzel et al.²⁰ have stated that the nonlinear forms of vibration observed in pressed phonations may be the result of interactions between the ventricular and true vocal folds. While this may be the case for the presence of subharmonics⁴¹, the F_0 /harmonic jumps frequently observed during pressed phonation in this study may be somewhat similar to nonlinear jumps in amplitude tremor frequency that have been associated with points of critical change in muscle fatigue in humans⁴². It may be that, in addition to the possible contribution of supraglottal constrictions and vibration, the observation of increased vibrational complexity and nonlinear vibratory phenomena observed in the pressed phonations in this study were due to experimentally increased electrical stimulation to the laryngeal musculature (i.e., cricothyroid muscle) and increased muscle fatigue as compared to modal and raised phonation. In addition, as in human voice, pressed phonation often produces high frequency spectral noise that may be perceived as harshness⁴³. Excessive levels of noise will also be expected to increase the vibrational complexity of the acoustic waveform and reflect a transition from nonlinear, deterministic to stochastic forms of vibration.

Of course, as in humans, not all rabbits followed the trends observed in this study, with some rabbits able to produce relatively periodic phonation even under conditions of high transglottal airflow rates and hyperadduction. It may be possible in future experimental designs to apply finer manipulations of transglottal airflow rate and adductory forces to determine the conditions that result in the production of nonlinear and/or aperiodic phonation. Although modal phonation demonstrated the least amount of phonatory complexity in this study, future investigations may be warranted to determine if prolonged modal phonation (i.e., increased time-doses) results in more frequent occurrences of nonlinear phenomenon. Such information would provide additional insight into the relationship between possible injurious mechanical forces and irregular phonations.

Conclusion

Our analysis has provided an improved understanding of the complexity of vibration in the different modes of phonation elicited in a previously described in vivo rabbit phonation model.^{2, 12, 13, 25} These results also provide insight into the conditions that may result in the development of nonlinear vocal phenomena that are often observed in disordered human voice productions. The types of nonlinear phenomena observed in this study have also been observed in rough quality in human voices and cases of vocal fold asymmetry. In addition, these types of vibrational irregularities may reflect the effects of disease on phonatory function as well as overall health status. Unlike many studies on nonlinear phenomena in which investigators may only speculate on the underlying conditions that may have resulted in these types of vibration, the evoked rabbit preparation described here allows for the elicitation of these types of phonations under controlled conditions and therefore, has the potential to provide insight into important variables (such as transglottal airflow rates and degree of laryngeal muscle stimulation) that may contribute to nonlinear phenomena such as subharmonics and deterministic chaos.

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References

1. Jiang JJ, Zhang Y, Ford CN. Nonlinear dynamics of phonations in excised larynx experiments. *J Acoust Soc Am*. 2003; 114(4):2198. [PubMed: 14587617]
2. Ge PJ, French LC, Ohno T, Zeale DL, Rousseau B. Model of evoked rabbit phonation. *Ann Otol Rhinol Laryngol*. 2009; 118(1):51–55. [PubMed: 19244964]
3. Koyama T, Kawasaki M, Ogura JH. Mechanics of voice production. I. Regulation of vocal intensity. *Laryngoscope*. 1969; 79(3):337–54. [PubMed: 5776731]
4. Koyama T, Harvey JE, Ogura JH. Mechanics of voice production. II. Regulation of pitch. *Laryngoscope*. 1971; 81(1):45–65. [PubMed: 5091313]
5. Berke GS, Moore DM, Gerratt BR, Hanson DG, Bell TS, Natividad M. The effect of recurrent laryngeal nerve stimulation on phonation in an in vivo canine model. *Laryngoscope*. 1989; 99(9): 977–82. [PubMed: 2770387]
6. Berke GS, Moore DM, Gerratt BR, Hanson DG, Natividad M. Effect of superior laryngeal nerve stimulation on phonation in an in vivo canine model. *Am J Otolaryngol*. 1989; 10(3):181–7. [PubMed: 2742054]
7. Slavitt DH, Lipton RJ, McCaffrey TV. Glottographic analysis of phonation in the excised canine larynx. *Ann Otol Rhinol Laryngol*. 1990; 99(5 Pt 1):396–402. [PubMed: 2337319]
8. Alipour F, Scherer RC, Finnegan E. Pressure-flow relationships during phonation as a function of adduction. *J Voice*. 1997; 11(2):187–94. [PubMed: 9181542]
9. Jiang JJ, Raviv JR, Hanson DG. Comparison of the phonation-related structures among pig, dog, white-tailed deer, and human larynges. *Ann Otol Rhinol Laryngol*. 2001; 110(12):1120–5. [PubMed: 11768701]
10. Regner M, Robitaille M, Jiang J. Interspecies comparison of mucosal wave properties using high-speed digital imaging. *Laryngoscope*. 2010; 120(6):1188–1194. [PubMed: 20513038]
11. Alipour F, Jaiswal S. Phonatory characteristics of excised pig, sheep, and cow larynges. *J Acoust Soc Am*. 2008; 123(6):4572–81. [PubMed: 18537405]
12. Rousseau B, Ge P, French LC, Zeale DL, Thibeault SL, Ossoff RH. Experimentally induced phonation increases matrix metalloproteinase-1 gene expression in normal rabbit vocal fold. *Otolaryngol Head Neck Surg*. 2008; 138(1):62–8. [PubMed: 18164995]
13. Thibeault SL, Gray SD, Bless DM, Chan RW, Ford CN. Histologic and rheologic characterization of vocal fold scarring. *J Voice*. 2002; 16(1):96–104. [PubMed: 12002893]
14. Maytag AL, Robitaille MJ, Rieves AL, Madsen J, Smith BL, Jiang JJ. Use of the rabbit larynx in an excised larynx setup. *J Voice*. 2013; 27(1):24–8. [PubMed: 23159025]
15. Swanson ER, Abdollahian D, Ohno T, Ge P, Zeale DL, Rousseau B. Characterization of raised phonation in an evoked rabbit phonation model. *Laryngoscope*. 2009; 119(7):1439–43. [PubMed: 19422027]
16. Jiang JJ, Titze IR. A methodological study of hemilaryngeal phonation. *Laryngoscope*. 1993; 103(8):872–82. [PubMed: 8361290]
17. Gerratt BR, Kreiman J. Toward a taxonomy of nonmodal phonation. *J Phon*. 2001; 29(4):365–381.
18. Riede T, Owren MJ, Arcadi AC. Nonlinear acoustics in pant hoots of common chimpanzees (*Pan troglodytes*): frequency jumps, subharmonics, biphonation, and deterministic chaos. *Am J Primatol*. 2004; 64(3):277–91. [PubMed: 15538766]
19. Fitch W. Calls out of chaos: the adaptive significance of nonlinear phenomena in mammalian vocal production. *Anim Behav*. 2002; 63(3):407–418.
20. Herzel H, Berry D, Titze IR, Saleh M. Analysis of vocal disorders with methods from nonlinear dynamics. *J Speech Hear Res*. 1994; 37(5):1008–19. [PubMed: 7823547]

21. 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(4):2551. [PubMed: 16266175]
22. Giovanni A, Ouaknine M, Guelfucci R, Yu T, Zanaret M, Triglia JM. Nonlinear behavior of vocal fold vibration: the role of coupling between the vocal folds. *J Voice*. 1999; 13(4):465–76. [PubMed: 10622513]
23. Jiang JJ, Zhang Y, McGilligan C. Chaos in voice, from modeling to measurement. *J Voice*. 2006; 20(1):2–17. [PubMed: 15964740]
24. Behrman A, Baken RJ. Correlation dimension of electroglottographic data from healthy and pathologic subjects. *J Acoust Soc Am*. 1997; 102(4):2371–9. [PubMed: 9348696]
25. Awan S, Roy N, Jiang J. Nonlinear dynamic analysis of disordered voice: the relationship between the correlation dimension (D2) and pre-/post-treatment change in perceived dysphonia severity. *J Voice*. 2010; 24(3):285–93. [PubMed: 19502002]
26. Sprecher A, Olszewski A, Jiang JJ, Zhang Y. Updating signal typing in voice: addition of type 4 signals. *J Acoust Soc Am*. 2010; 127(6):3710–16. [PubMed: 20550269]
27. Rousseau B, Suehiro A, Echemendia N, Sivasankar M. Raised intensity phonation compromises vocal fold epithelial barrier integrity. *Laryngoscope*. 2011; 121(2):346–51. [PubMed: 21271586]
28. Herbst CT, Stoeger AS, Frey R, et al. How low can you go? Physical production mechanism of elephant infrasonic vocalizations. *Science*. 2012; 337(6094):595–9. [PubMed: 22859490]
29. Swanson ER, Ohno T, Abdollahian D, Garrett CG, Rousseau B. Effects of raised-intensity phonation on inflammatory mediator gene expression in normal rabbit vocal fold. *Otolaryngol Head Neck Surg*. 2010; 143(4):567–572. [PubMed: 20879195]
30. Kononov E. Visual Recurrence Analysis (VRA). 2005; 4.9
31. Hegger R, Kantz H, Schreiber T. Practical implementation of nonlinear time series methods: The TISEAN package. *Chaos*. 1999; 9(2):413–435. [PubMed: 12779839]
32. Morse, D.; Perry, J.; Smith, R. A Glossary of Terms Used in Nonlinear Dynamics. In: Perry, J.; Smith, R.; Woivod, I.; Morse, D., editors. *Chaos in real data: analysis of non-linear dynamics from short ecological time series*. Dordrecht: Kluwer Academic; 2000.
33. Herbst CT, Herzel H, Svec JG, Wyman MT, Fitch WT, Jan GS. Visualization of system dynamics using phasegrams. *J R Soc Interface*. 2013 May; 10:1–14.
34. Fraser A, Swinney H. Independent coordinates for strange attractors from mutual information. *Phys Rev A*. 1986; 33(2):1134–1140. [PubMed: 9896728]
35. Kennel M, Brown R, Abarbanel HDI. Determining embedding dimension for phase-space reconstruction using a geometrical construction. *Phys Rev A*. 1992; 45(6):3403. [PubMed: 9907388]
36. Jeong J. Nonlinear dynamics of EEG in Alzheimer's disease. *Drug Dev Res*. 2002; 56(2):57–66.
37. Chai L, Sprecher AJ, Zhang Y, Liang Y, Chen H, Jiang JJ. Perturbation and nonlinear dynamic analysis of adult male smokers. *J Voice*. 2011; 25(3):342–7. [PubMed: 20472394]
38. DiBona G, Jones S. Dynamic analysis of renal nerve activity responses to baroreceptor denervation in hypertensive rats. *Hypertension*. 2001; 37:1153–1163. [PubMed: 11304518]
39. Molteno TC, Tufillaro NB. Torus doubling and chaotic string vibrations: Experimental results. *J Sound Vib*. 1990; 137(2):327–330.
40. Olszewski AE, Shen L, Jiang JJ. Objective Methods of Sample Selection in Acoustic Analysis of Voice. *Ann Otol Rhinol Laryngol*. 2011; 120(3):155–161. [PubMed: 21510140]
41. Lindestad PA, Blixt V, Pahlberg-Olsson J, Hammarberg B. Ventricular fold vibration in voice production: a high-speed imaging study with kymographic, acoustic and perceptual analyses of a voice patient and a vocally healthy subject. *Logoped Phoniatr Vocol*. 2004; 29(4):162–70. [PubMed: 15764210]
42. Boucher V. Acoustic correlates of fatigue in laryngeal muscles: findings for a criterion-based prevention of acquired voice pathologies. *J Speech, Lang Hear Res*. 2008; 51:1161–1170. [PubMed: 18664703]
43. Askenfelt A, Hammarberg B. Speech waveform perturbation analysis: A perceptual-acoustical comparison of seven measures. *J Speech Hear Res*. 1986 Mar; 29:50–64. [PubMed: 3702379]

Figure 1.

Examples of correlation dimension (D_2) vs. log radius (r) plots. D_2 is observed to converge for successive embeddings in the upper plot (A: $D_2 = 1.56 \pm 0.23$), whereas D_2 does not converge in a definitive scaling region in the lower plot (B).

Figure 2.

Example of a rabbit vocalization showing multiple instances of nonlinear phonatory behavior, including the presence of subharmonics, fundamental frequency (F_0) jumps, and “chaos.” Transitions to and from varying types of vibratory condition are representative of bifurcations.

Figure 3. Mean correlation dimension (D_2) and standard deviations for modal, raised intensity, and pressed phonation types.

Figure 4.

Relative distribution of key spectrographic characteristics across modal, raised intensity, and pressed phonation types.

Figure 5.

3-D Phase space portrait and Poincaré section (A), 2-D Poincaré plot (B), and associated spectral slice (C) for a representative modal phonation sample. The phase space portrait approximates a limit cycle and the 2-D Poincaré plot shows two tightly clustered regions as point trajectories pass into (blue points) and out of (red points) the Poincaré plane. The spectral slice shows distinct harmonics (particularly in the 1000-4000 Hz range), with a dominant spectral harmonic in the 1000 Hz region. The correlation dimension (D_2) for this sample = 1.2.

Figure 6.

3-D Phase space portrait and Poincaré section (A), 2-D Poincaré plot (B), and associated spectral slice (C) for a 200 ms representative raised phonation sample. The 3-D phase space portrait shows a loop characteristic of period-doubling, and the 2-D Poincaré plot shows four clustered regions as point trajectories pass into (blue points) and out of (red points) the Poincaré plane. The spectral slice shows the presence of subharmonics. The correlation dimension (D_2) for this sample = 1.95.

Figure 7.

3-D Phase space portrait and Poincaré section (A), 2-D Poincaré plot (B), and associated spectral slice (C) for a 200 ms representative pressed phonation sample. While the 3-D phase space portrait and 2-D Poincaré plot both show a highly irregular and complex set of trajectories, the observation of convergence in the correlation dimension estimate indicates that this waveform may actually be chaotic vs. stochastic noise (D_2 for this sample = 4.11). In addition, the spectral slice shows a possible “fundamental” peak in the 1000 Hz region amongst broad band random frequency content.