Asymmetric spatiotemporal chaos induced by a polypoid mass in the excised larynx

Yu Zhang^{a)} and Jack J. Jiang

Department of Surgery, Division of Otolaryngology Head and Neck Surgery, University of Wisconsin Medical School, Madison, Wisconsin 53792-7375, USA

(Received 30 April 2008; accepted 23 August 2008; published online 7 October 2008)

In this paper, asymmetric spatiotemporal chaos induced by a polypoid mass simulating the laryngeal pathology of a vocal polyp is experimentally observed using high-speed imaging in an excised larynx. Spatiotemporal analysis reveals that the normal vocal folds show spatiotemporal correlation and symmetry. Normal vocal fold vibrations are dominated mainly by the first vibratory eigenmode. However, pathological vocal folds with a polypoid mass show broken symmetry and spatiotemporal irregularity. The spatial correlation is decreased. The pathological vocal folds spread vibratory energy across a large number of eigenmodes and induce asymmetric spatiotemporal chaos. High-order eigenmodes show complicated dynamics. Spatiotemporal analysis provides a valuable biomedical application for investigating the spatiotemporal chaotic dynamics of pathological vocal fold systems with a polypoid mass and may represent a valuable clinical tool for the detection of laryngeal mass lesion using high-speed imaging. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2988251]

Temporal chaos has recently been observed in pathological voices from patients with laryngeal diseases and excised larynx phonations. However, pathological vocal folds may exhibit spatial as well as temporal irregular dynamics; thus, the investigation of the spatiotemporal vibratory dynamics of pathological vocal folds is important. High-speed digital imaging offers a means of directly measuring the spatiotemporal vibratory dynamics of vocal folds, while excised larynx represents a physiological model to simulate laryngeal pathology. The purpose of this study is to investigate spatiotemporal vibratory dynamics of pathological excised larynx using high-speed imaging. The laryngeal pathology of vocal polyps can be simulated by suturing a mucosal tissue piece to the free margin of one side of the vocal folds. Normal vocal fold vibration shows spatiotemporal correlation and symmetry and is dominated by the first vibratory eigenmode. However, the pathological vocal folds with a polypoid mass show broken symmetry and spatiotemporal chaos. The pathological vocal folds spread vibratory energy across a large number of eigenmodes, and high-order eigenmodes show complicated dynamics. The laryngeal pathology of vocal polyps may induce asymmetric spatiotemporal chaos in high-speed imaging, which may provide valuable information to analyze and model disordered laryngeal activities.

I. INTRODUCTION

In recent years, spatiotemporal chaotic mechanisms of disordered behaviors in biomedical systems have been the target of considerable interest. Broken symmetry as well as spatiotemporal chaos have been observed in the fibrillating

heart,¹ the mammalian visual cortex,² and laryngeal systems.^{3,4} These investigations examine the potential contributions of spatiotemporal chaos to the understanding of physiologic disorders as well as pathophysiologic dysfunction.

Asymmetry in the biomechanical parameters and structures of the vocal folds due to laryngeal pathologies (such as vocal nodules, polyps, cysts, etc.) may induce complicated vibratory patterns. Temporal chaos has recently been studied in human pathological voices and in vocal fold model simulations.⁵⁻¹² Baken⁵ originally applied fractal analysis to quantify the irregularity in period and amplitude of normal voice time series. Titze *et al.*⁶ suggested methods of improving the understanding of pathological voice through nonlinear time series analysis. Herzel *et al.*^{8,9} applied an asymmetric two-mass vocal fold model to simulate vocal disorders in laryngeal paralysis. We recently proposed a nonlinear polyp model to study chaotic dynamics of vocal folds with a vocal mass lesion.¹² However, neither voice measurements, such as microphone voice recording and electroglottography, nor vocal fold models capture the spatial complexity of laryngeal activity.¹³

Vocal folds essentially exhibit spatial as well as temporal dynamics. High-speed digital imaging offers a means of directly measuring the spatiotemporal vibration of vocal folds.^{14,15} Our previous study³ using high-speed imaging showed that increasing subglottal pressure may induce spatiotemporal chaos in a normal canine larynx; however, it did not portray a direct clinical application of laryngeal disease. The spatiotemporal chaotic vibrations of asymmetric vocal folds in laryngeal pathologies have not been previously studied. Laryngeal diseases may cause abnormal spatial distribution, and a description of asymmetric spatiotemporal chaotic behaviors may be vital to understanding the overall dynam-

^{a)}Electronic mail: Zhang@surgery.wisc.edu.

ics of disordered voice production from laryngeal pathologies.

In this paper, asymmetric spatiotemporal chaos will be observed in vocal folds with a polypoid mass using high-speed imaging. In order to simulate pathological vocal folds with a vocal polyp, a mucosal tissue piece will be sutured to the free margin of one side of the vocal folds. Spatiotemporal correlation and eigenmode analyses will be applied to describe the spatiotemporal dynamics of vocal fold vibrations, and nonlinear dynamic analysis will be employed to describe the temporal complexity of vibratory eigenmodes. The results suggest that the laryngeal pathology of vocal polyp may induce asymmetric spatiotemporal chaotic laryngeal activity.

II. EXPERIMENTAL MATERIALS

The laryngeal pathology of vocal polyp introduces additional mass to the vocal folds and causes an asymmetric biomechanical vocal fold structure, which may induce disordered voices and irregular vocal fold vibration.^{10,12,16} For patients with this laryngeal disease, the extreme conditions necessary for phonation (such as high subglottal pressure) may be difficult to achieve because of irreversible mechanical damage to the vocal folds. In addition, the biomechanical parameters of vocal folds are difficult to systematically monitor and independently control *in vivo*. Therefore, the use of an excised larynx to simulate the conditions of vocal polyp is most appropriate in this study. The stationarity and length of a signal can be easily ensured,¹⁷ since we can conveniently and steadily control laryngeal phonation conditions, such as subglottal pressure, for a long time.

The experimental system consisted of an excised larynx setup and a high-speed camera system, as shown in Fig. 1(a). A canine larynx harvested from a healthy laboratory dog was used. In order to simulate the vocal polyp, a piece of mucosal tissue with an approximate size of $4 \times 4 \times 4 \text{ mm}^3$ and similar biomechanical properties (such as density) to vocal fold tissue was harvested from the laryngo-pharyngeal region of the vocal folds. The polypoid mucosal tissue piece was then sutured under a surgical microscope (Carl Zeiss X25) on the free margin of the lower vocal fold. Using the procedure presented in our previous studies,^{3,17} the freshly excised larynx was stably mounted with a section of trachea on top of a pipe. The vocal fold length l_g from the anterior (thyroid cartilage) to posterior (arytenoid cartilage) sides was measured to be about 12 mm. Airflow was generated using an air compressor. Subglottal pressure (P_s) in the artificial lung was measured with a water manometer (Dwyer No. 1211). Vocal folds with certain biomechanical parameters have a threshold pressure to initiate vibration.¹⁸ When P_s was higher than the threshold pressure of 10 cm H₂O, the larynx began to vibrate. The phonation instability pressure^{11,17,19,20} of this larynx was measured as 50 cm H₂O. When P_s was increased above the phonation instability pressure, the larynx began to irregularly vibrate,^{11,17,19,20} which has been previously studied³ and will not be considered here. In this study, we set subglottal pressure as 40 cm H₂O; that is, close to phonation instability pressure. The normal larynx without the polypoid mass can regularly and symmetrically vibrate when P_s is

FIG. 1. (a) Diagram of the experimental system, which consists of an excised larynx with a polypoid mass and a high-speed camera. (b) High-speed images of vocal fold vibration, where the upper and lower images correspond to the normal and pathological vocal folds with a polypoid mass, respectively.

increased to 40 cm H₂O; however, the pathological vocal folds with the polypoid mass vibrate irregularly and asymmetrically at the same subglottal pressure P_s . The pressure measurement was repeated three times in order to ensure that its measurement was repeatable.

A high-speed digital camera was mounted vertically above the larynx to record the vocal fold vibrations. The high-speed camera system acquired images at a sampling rate $f_s = 1/T_s$ of 4000 frames per second with a resolution of 256×512 pixels. Figure 1(b) shows ten successive high-speed image frames of normal (upper) and pathological (lower) vocal folds. The normal vocal folds show the regular shapes, differing from the irregular shapes of the pathological vocal folds with a polypoid mass. The vocal fold edges were manually extracted using image edge detection on a frame-by-frame basis. In order to study the asymmetric vocal fold vibrations, we applied a reference line from the anterior to the posterior side of the vocal folds, which denoted the midline at the rest state, to separate the upper and lower glottal edges. The displacements of two sides of the vocal folds can be derived from the distances between the glottal edges and the reference line. For different spatial positions, or index j , the glottal edge movements can be described using the spatiotemporal series $u^{(\alpha)}(j, t)$, where the indices $\alpha = 1, 2, 3$, and 4 correspond to the upper edge of the normal vocal folds, the lower edge of the normal vocal folds, the upper edge of the pathological vocal folds, and the lower edge of the pathological vocal folds, respectively.

FIG. 2. (Color) The spatiotemporal plots of (a) the normal vocal folds and (b) the pathological vocal folds with a polypoid mass, where the color-coded value of $u^{(\alpha)}(j, t)$ with respect to the spatial index j and time t displays the spatiotemporal evolution of vocal fold vibrations.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the spatiotemporal plots of $u^{(\alpha)}(j, t)$ with and without the polypoid mass. It is readily noticeable that $u^{(1)}(j, t)$ and $u^{(2)}(j, t)$ of the normal vocal folds show highly symmetric and regular patterns [Fig. 2(a)]. Alternatively, asymmetric and irregular spatiotemporal vibratory patterns can be observed in $u^{(3)}(j, t)$ and $u^{(4)}(j, t)$ of the pathological vocal folds [Fig. 2(b)]. The sufficiently decreased amplitude of $u^{(4)}(j, t)$ shows the spatial region ($40 < j < 80$) of the polypoid mass. The pathological vocal folds display very complex vibratory dynamics.

Low spatiotemporal correlations can be observed in spatiotemporally chaotic systems. To describe the spatiotemporal correlation characteristics of the vocal folds, we calculate the correlation function $C^{(\alpha)}(i, j, \tau)$ as^{3,21}

$$C^{(\alpha)}(i, j, \tau) = \frac{\langle \Delta u^{(\alpha)}(i, t) \Delta u^{(\alpha)}(j, t + \tau) \rangle_T}{\sqrt{\langle \Delta u^{(\alpha)}(i, t)^2 \rangle_T \langle \Delta u^{(\alpha)}(j, t + \tau)^2 \rangle_T}} \quad (\alpha = 1, 2, 3, \text{ and } 4), \quad (1)$$

where $\Delta u^{(\alpha)}(i, t) = u^{(\alpha)}(i, t) - \langle u^{(\alpha)}(i, t) \rangle_T$ and $\langle \bullet \rangle_T$ denotes the average with respect to t . We apply the maximal value $C_{\max}^{(\alpha)}(i, j)$ of $C^{(\alpha)}(i, j, \tau)$ with respect to the delay time τ , and then set the center of the glottis as the reference point. Figure 3 shows the graph of $C_{\max}^{(\alpha)}(i)$ versus i , where the curves from top to bottom correspond to the upper edge $u^{(1)}(j, t)$ of the normal vocal folds, the lower edge $u^{(2)}(j, t)$ of the normal

FIG. 3. Spatial correlation function $C_{\max}^{(\alpha)}(i)$ vs spatial index i , where the curves from top to bottom correspond to the spatiotemporal series $u^{(1)}(j, t)$, $u^{(2)}(j, t)$, $u^{(3)}(j, t)$, and $u^{(4)}(j, t)$, respectively. The indices 1, 2, 3, and 4 correspond to the upper edge of the normal vocal folds, the lower edge of the normal vocal folds, the upper edge of the pathological vocal folds, and the lower edge of the pathological vocal folds, respectively.

vocal folds, the upper edge $u^{(3)}(j, t)$ of the pathological vocal folds, and the lower edge $u^{(4)}(j, t)$ of the pathological vocal folds, respectively. The normal vocal folds show high spatial correlation from the anterior to the posterior sides of the glottis, and $C_{\max}^{(\alpha)}(i)$ shows upper-lower symmetry. However, for the pathological vocal folds, $C_{\max}^{(\alpha)}(i)$ of both glottal edges decreases sufficiently. Traditional lumped parameter models of vocal folds such as asymmetric two-mass models^{8,9,11,12} require high spatial correlation from the anterior to posterior sides of the glottis and therefore cannot be applied to reveal the weak spatiotemporal correlation of the pathological vocal folds in this study. The two sides of the glottal edges show different spatial correlations. $C_{\max}^{(\alpha)}(i)$ of $u^{(4)}(j, t)$ rapidly decreases at the region of the polypoid mass. Therefore, the polypoid mass may break down the spatial correlation of the vocal fold vibrations and destroy the spatiotemporally ordered and symmetric state.

In order to determine the spatiotemporal degrees of freedom of the vocal fold vibrations, we apply a Karhunen-Loeve decomposition to $u^{(\alpha)}(j, t)$. The spatial covariance matrices $C_{ij}^{(\alpha)} = \langle \Delta u^{(\alpha)}(i, t) \Delta u^{(\alpha)}(j, t) \rangle_T$ can be calculated,^{3,4,7,21,23} where $i, j = 1, 2, \dots, M$ ($M = 128$) is the spatial index. $C_{ij}^{(\alpha)}$ is a symmetric matrix whose eigenvalues $\lambda_j^{(\alpha)}$ and eigenmodes $\mathbf{Q}_j^{(\alpha)}$ satisfy $C_{ij}^{(\alpha)} \mathbf{Q}_j^{(\alpha)} = \lambda_j^{(\alpha)} \mathbf{Q}_j^{(\alpha)}$. $\lambda_j^{(\alpha)}$ measure the energies of $\mathbf{Q}_j^{(\alpha)}$. $\mathbf{Q}_j^{(\alpha)}$ form a complete orthonormal set $\sum_{k=1}^M \mathbf{Q}_i^{(\alpha)}(k) \mathbf{Q}_i^{(\alpha)}(k) = \delta_{ij}$, so $u^{(\alpha)}(j, t)$ can be expanded as

$$u^{(\alpha)}(k, t) = \langle u^{(\alpha)}(k, t) \rangle_T + \sum_{j=1}^M a_j^{(\alpha)}(t) \mathbf{Q}_j^{(\alpha)}(k), \quad (2)$$

where $a_j^{(\alpha)}(t) = \sum_{k=1}^M \mathbf{Q}_j^{(\alpha)}(k) \Delta u^{(\alpha)}(k, t)$ and denotes the temporal expansion coefficients. For the normal vocal folds, the spatial distributions of the first two eigenmodes of the upper edge $u^{(1)}(j, t)$ and the lower edge $u^{(2)}(j, t)$ are sufficiently close, and their corresponding temporal expansion coefficients show periodically oscillatory behaviors (see Fig. 4). The first two eigenvalues of $u^{(1)}(j, t)$ and $u^{(2)}(j, t)$ are esti-

FIG. 4. (Color online) The first and second eigenmodes and the corresponding temporal expansion coefficients of the normal vocal folds, where the indices 1 and 2 correspond to the upper and lower edge of the normal vocal folds, respectively.

mated as ($\lambda_1^{(1)}=98.1\%$, $\lambda_2^{(1)}=1.0\%$) and ($\lambda_1^{(2)}=96.9\%$, $\lambda_2^{(2)}=2.1\%$), respectively. The first eigenmodes of the upper and lower glottal edges capture more than 90% of the vibratory energy, and, thus, the normal vocal fold vibrations are dominated mainly by the first eigenmodes $Q_1^{(1)}$ and $Q_1^{(2)}$.⁷ However, for the pathological vocal folds, broken symmetries in the first two eigenmodes $Q_1^{(4)}$ and $Q_2^{(4)}$ of the lower edge $u^{(4)}(j, t)$ can be observed around the polypoid mass area, and aperiodic time series can be found in their corresponding temporal expansion coefficients $a_1^{(4)}(t)$ and $a_2^{(4)}(t)$ (see Fig. 5). Aperiodic time series can also be observed in $a_1^{(3)}(t)$ and $a_2^{(3)}(t)$ of the upper edge $u^{(3)}(j, t)$. To capture more than 90% of the vibratory energy of the pathological vocal folds, the eigenmode numbers of $u^{(3)}(j, t)$ and $u^{(4)}(j, t)$ should be increased to 2 and 7, respectively, and their corresponding eigenvalues are estimated as ($\lambda_1^{(3)}=75.4\%$, $\lambda_2^{(3)}=18.2\%$), and ($\lambda_1^{(4)}=43.2\%$, $\lambda_2^{(4)}=26.9\%$, $\lambda_3^{(4)}=6.9\%$, $\lambda_4^{(4)}=5.2\%$, $\lambda_5^{(4)}=3.5\%$, $\lambda_6^{(4)}=2.2\%$, $\lambda_7^{(4)}=1.9\%$), respectively. $u^{(4)}(j, t)$ shows a more complex spatiotemporal behavior than $u^{(3)}(j, t)$. The

pathological polypoid mass spreads the vibratory energy across a large number of eigenmodes and induces asymmetric spatiotemporal chaos in vocal fold vibrations.

Our previous study using the normal larynx showed that extremely high subglottal pressure may induce spatiotemporal chaos in normal vocal folds,^{3,23} which may not have direct clinical relevance to laryngeal diseases. This study simulating the pathological larynx with a vocal fold polyp shows that subglottal pressure is not the only factor that can produce irregular vocal fold vibrations, and the laryngeal pathology of vocal polyp represents another important factor in inducing asymmetric spatiotemporal chaos below the phonation instability pressure of the normal vocal folds. This may explain why vocal disorders are more often observed in patients with laryngeal diseases than in normal subjects. Clinically, laryngeal pathologies such as vocal nodules and cysts can produce additional vocal masses, including vocal polyps. Thus, the spatiotemporal dynamics of pathological vocal folds in this study is clinically important and generally ap-

FIG. 5. (Color online) The first and second eigenmodes and the corresponding temporal expansion coefficients of the pathological vocal folds, where the indices 3 and 4 correspond to the upper and lower edge of the pathological vocal folds, respectively.

plicable for these laryngeal diseases. In addition, based on lumped mass models, Herzel *et al.*^{8,9} suggested that left-right vocal fold asymmetry represents an important mechanism for inducing temporal instability in laryngeal paralysis. Other mechanisms for inducing temporal instability are excessively high subglottal pressure,¹¹ sound-tract interaction,²⁴ additional vibrating tissue such as vocal membranes²⁵ and polyp,¹² or register transition.²⁶ However, these studies focused on voice temporal instability and cannot capture the spatial complexity of laryngeal activity. This study using high-speed imaging in excised larynx experiments further shows that polypoid mass is an important factor in producing spatiotemporal complexity in vocal fold systems. This finding has not been reported in previous studies. Polypoid mass affects the mechanical properties of the vocal folds by imparting vocal mass. Extra mass at the midpoint of the vibrating vocal folds interferes with the glottal closure and causes structure asymmetry. The interaction between polypoid mass and vocal folds may induce asymmetric spatiotemporal chaos in excised larynges. Physical similarity between canine and human larynges means that the asymmetric spatiotemporal chaos observed in the excised canine larynx with polypoid mass may also occur in human larynx with laryngeal mass lesions, such as vocal nodules, polyps, cysts, etc. Knowledge of these asymmetric spatiotemporal chaos patterns might lead to the development of new tools for early detection of laryngeal pathologies using high-speed imaging.

The eigenmode analysis shows that vocal fold vibrations can be mostly described by a small number of vibratory eigenmodes. With and without the polypoid mass, temporal expansion coefficients $a_j^{(\alpha)}(t)$ of these eigenmodes show quite different temporal characteristics, as shown in Figs. 4 and 5. In order to further describe the dynamics of the temporal expansion coefficients $a_j^{(\alpha)}(t)$ of normal and pathological vocal folds, nonlinear dynamic methods need to be applied. We reconstruct the phase space of the time series $a_j^{(\alpha)}(t)$ with a 1 s length ($N=4000$) as $\mathbf{X}_j^{(\alpha)}(t_i) = \{a_j^{(\alpha)}(t_i), a_j^{(\alpha)}(t_i - \tau), \dots, a_j^{(\alpha)}(t_i - (m-1)\tau)\}$,²⁷ where m is the embedding dimension and τ is the time delay that can be determined using the mutual information method.²⁸ When $m > 2D + 1$,²⁹ (D is the Hausdorff dimension), the embedding is a diffeomorphism from the original phase space to the reconstructed delay space. To quantify the dimension of the reconstructed phase space, we consider the correlation dimension of $a_j^{(\alpha)}(t)$ as³⁰

$$D_{2,j}^{(\alpha)} = \lim_{r \rightarrow 0} \frac{\log_{10} \tilde{C}_j^{(\alpha)}(r)}{\log_{10} r}, \quad (3)$$

where r is the radius around $\mathbf{X}_j^{(\alpha)}(t)$, and $\tilde{C}_j^{(\alpha)}(r)$ is the correlation integral given by³¹

$$\tilde{C}_j^{(\alpha)}(r) = \frac{2}{(N+1-W)(N-W)} \times \sum_{n=W}^{N-1} \sum_{i=0}^{N-1-n} \theta(r - \|\mathbf{X}_j^{(\alpha)}(t_i) - \mathbf{X}_j^{(\alpha)}(t_{i+n})\|), \quad (4)$$

where

FIG. 6. (a) Correlation integral $\log_{10} \tilde{C}_j^{(\alpha)}(r)$ vs $\log_{10} r$ of $a_1^{(1)}$, where the curves from bottom to top correspond to the embedding dimension $m = 1, 2, \dots, 12$, respectively. (b) The estimated dimensions vs m , where the curves from bottom to top correspond to the temporal expansion coefficients $a_1^{(1)}, a_1^{(2)}, a_1^{(3)}, a_1^{(4)}$, and white Gaussian noise, respectively. The indices 1, 2, 3, and 4 correspond to the upper edge of the normal vocal folds, the lower edge of the normal vocal folds, the upper edge of the pathological vocal folds, and the lower edge of the pathological vocal folds, respectively. (c) The estimated dimensions of $a_j^{(\alpha)}(t)$ vs the eigenmode number j , where N.C. means “nonconvergent.”

$$\theta(x) = \begin{cases} 1, & x > 0 \\ 0, & x \leq 0 \end{cases}$$

is the Heaviside step function and W is set to be the time delay τ . In Fig. 6(a), for sufficiently large m , the converged slopes of the curves of $\log_{10} \tilde{C}_j^{(\alpha)}(r)$ versus $\log_{10} r$ in the scaling region ($2^{7.1} < r < 2^{11.5}$) give the dimension estimate (1.03 ± 0.01) of $a_1^{(1)}$, where the time delay is $3T_s$ and the curves from bottom to top correspond to $m = 1, 2, \dots, 12$, respectively. For the image resolution of 256×512 pixels, the digitized error ($< 0.4\%$) is sufficiently less than the scale of the scaling region and will not affect the dimension estimate. Recent studies have shown that the dimension estimate can be obtained when the digitized noise of a voice signal is as high as 2%.³² Thus, nonlinear dynamic analyses can be applicable for high-speed image data with a high image resolution. Figure 6(b) shows the dependences of the estimated dimensions on m , where the curves from bottom to top correspond to $a_1^{(1)}(t), a_1^{(2)}(t), a_1^{(3)}(t), a_1^{(4)}(t)$, and white Gaussian noise, respectively. The indices 1, 2, 3, and 4 correspond to the upper edge of the normal vocal folds, the lower edge of the normal vocal folds, the upper edge of the pathological vocal folds, and the lower edge of the pathological vocal folds, respectively. With the increase of m , the estimated dimension of white noise does not exhibit a saturation tendency; however, the estimated dimensions of $a_1^{(3)}(t)$ and $a_1^{(4)}(t)$ approach 2.68 ± 0.02 and 3.07 ± 0.02 , respectively. $a_1^{(3)}(t)$ and $a_1^{(4)}(t)$ of the pathological vocal folds have higher dimensions than $a_1^{(1)}(t)$ and $a_1^{(2)}(t)$ of the normal vocal folds, suggesting more complex dynamics in the laryngeal pathology. Figure 6(c) shows the relationship between the estimated dimensions of $a_j^{(\alpha)}(t)$ and the eigenmode number j . For the normal vocal folds, the correlation dimensions of $a_j^{(\alpha)}(t)$ remain low even when the eigenmode number is as high as 6, and then the normal vocal folds are dominated by

periodic and regular vibrations. For the pathological vocal folds, $a_j^{(a)}(t)$ of the low-order eigenmodes ($j \leq 3$) show low-dimensional characteristics; however, the estimated dimensions of the higher-order eigenmodes are not convergent. In this study, under high driving pressure, the laryngeal pathology of vocal polyp produced extremely complex spatiotemporal vibratory patterns of vocal folds, and, thus, high temporal and spatial variables might be needed to reconstruct pathological vocal fold vibrations. Such complex spatiotemporal chaotic vibratory patterns have not been found in previous vocal fold models^{7-9,11,12,18} using nonlinear oscillators to study temporal chaos. In many physical systems, such as hydrodynamic and magnetoplasmas systems, temporal chaos with spatial order may represent a middle state from spatiotemporal order to spatiotemporal chaos. When a certain system parameter changes, system behaviors may start from a highly ordered spatiotemporal state, develop into a temporal chaotic state with spatial order, and settle within a spatiotemporal chaotic state. The transition among these three patterns in laryngeal systems has not been studied and should be further investigated. High-speed imaging represents an important tool to record these vocal fold vibratory patterns.

IV. CONCLUSION

In this paper, using high-speed imaging in an excised larynx, we experimentally observed asymmetric spatiotemporal chaos induced by a polypoid mass simulating the laryngeal pathology of vocal polyps. The normal vocal folds showed spatiotemporal correlation and symmetry in vibratory patterns, and the first eigenmodes of normal vocal folds captured more than 90% of the vibratory energy, while the corresponding temporal expansion coefficient displayed low-dimensional characteristics. However, the pathological vocal folds with a polypoid mass showed broken symmetry. The polypoid mass spreads the vibratory energy across a large number of eigenmodes and induces asymmetric spatiotemporal chaos in vocal fold vibrations. The estimated dimensions of the temporal expansion coefficient of sufficiently high-order eigenmodes are not convergent, indicating their complicated dynamic characteristics. Spatiotemporal chaos is an important physical phenomenon which can be widely observed in physical systems, including Taylor–Coquette flow, the atmosphere, lasers, and coupled-map lattices. However, asymmetric spatiotemporal chaos in biomedical systems has not received considerable investigation because of the complexity of biomedical systems and the limitation of measurement techniques. In the last decade, laryngeal pathology has been studied extensively from temporal perspectives.⁵⁻¹³ There is a lack of understanding of the asymmetric spatiotemporal aspect of disordered voice production from laryngeal pathologies. In this study, we applied measurement techniques of high-speed imaging and analysis based on spatiotemporal perspectives that were important for the investigation of complex spatiotemporal behaviors in laryngeal pathologies. The results showed that asymmetric

spatiotemporal chaos of pathological vocal folds may play an important role in understanding the mechanisms of vocal disorders from the laryngeal pathologies of vocal mass lesion and asymmetries. This study examines the potential contributions of spatiotemporal chaos to the understanding of pathological disorders, which may be clinically important to developing new methods for the further assessment and diagnosis of laryngeal diseases from high-speed imaging.

ACKNOWLEDGMENTS

This study was supported by NIH Grant Nos. 1-RO1DC006019 and 1-RO1DC05522 from the National Institute of Deafness and other Communication Disorders.

- ¹F. X. Witkowski, L. J. Leon, P. A. Penkoske, W. R. Giles, M. L. Spano, W. L. Ditto, and A. T. Winfree, *Nature* **392**, 78 (1998).
- ²L. Sirovich, R. Everson, E. Kaplan, B. Knight, E. O'Brien, and D. Orbach, *Physica D* **96**, 355 (1996).
- ³Y. Zhang and J. J. Jiang, *Phys. Rev. E* **72**, 035201(R) (2005).
- ⁴J. Neubauer, P. Mergell, U. Eysholdt, and H. Herzel, *J. Acoust. Soc. Am.* **110**, 3179 (2001).
- ⁵R. J. Baken, *J. Voice* **4**, 185 (1990).
- ⁶I. R. Titze, R. Baken, and H. Herzel, in *Vocal Fold Physiology: New Frontier in Basic Science*, edited by I. R. Titze (Singular, San Diego, 1993), pp. 143–188.
- ⁷D. A. Berry, H. Herzel, I. R. Titze, and K. Krischer, *J. Acoust. Soc. Am.* **95**, 3595 (1994).
- ⁸H. Herzel, D. Berry, I. R. Titze, and I. Steinecke, *Chaos* **5**, 30 (1995).
- ⁹I. Steinecke and H. Herzel, *J. Acoust. Soc. Am.* **97**, 1874 (1995).
- ¹⁰Y. Zhang, C. McGilligan, L. Zhou, M. Vig, and J. J. Jiang, *J. Acoust. Soc. Am.* **115**, 2270 (2004).
- ¹¹J. J. Jiang, Y. Zhang, and J. Stern, *J. Acoust. Soc. Am.* **110**, 2120 (2001).
- ¹²Y. Zhang and J. J. Jiang, *J. Acoust. Soc. Am.* **115**, 1266 (2004).
- ¹³R. J. Baken and R. F. Orlikoff, *Clinical Measurement of Speech and Voice* (Singular, New York, 1999).
- ¹⁴J. J. Jiang, E. Yumoto, S. J. Lin, Y. Kadota, H. Kurokawa, and D. G. Hanson, *Ann. Otol. Rhinol. Laryngol.* **107**, 98 (1998).
- ¹⁵T. Wittenberg, M. Moser, M. Tigges, and U. Eysholdt, *Mach. Vision Appl.* **8**, 399 (1995).
- ¹⁶F. Chagnon and R. E. Stone, in *Organic Voice Disorders Assessment and Treatment*, edited by W. S. Brown, B. P. Vinson, and M. A. Crary (Singular, San Diego, 2000), p. 219.
- ¹⁷J. J. Jiang, Y. Zhang, and C. N. Ford, *J. Acoust. Soc. Am.* **114**, 2198 (2003).
- ¹⁸I. R. Titze, *J. Acoust. Soc. Am.* **83**, 1536 (1988).
- ¹⁹Y. Zhang, W. J. Reynders, J. J. Jiang, and I. Tateya, *J. Speech Lang. Hear. Res.* **50**, 611 (2007).
- ²⁰J. J. Jiang and I. R. Titze, *Laryngoscope* **103**, 872 (1993).
- ²¹J. Loenardy, F. Kaiser, M. R. Belic, and O. Hess, *Phys. Rev. A* **53**, 4519 (1996).
- ²²D. Merbach, O. Hess, H. Herzel, and E. Scholl, *Phys. Rev. E* **52**, 1571 (1995).
- ²³Y. Zhang, J. J. Jiang, C. Tao, E. Bieging, and J. K. MacCallum, *Chaos* **17**, 043114 (2007).
- ²⁴H. Hatzikirou, W. T. Fitch, and H. Herzel, *Acta Acust.* **92**, 468 (2006).
- ²⁵P. Mergell, W. T. Fitch, and H. Herzel, *J. Acoust. Soc. Am.* **105**, 2020 (1999).
- ²⁶I. T. Tokuda, J. Horacek, J. G. Svec, and H. Herzel, *Chaos* **18**, 013102 (2008).
- ²⁷N. H. Packard, J. P. Crutchfield, J. D. Farmer, and R. S. Shaw, *Phys. Rev. Lett.* **45**, 712 (1980).
- ²⁸A. M. Fraser and H. L. Swinney, *Phys. Rev. A* **33**, 1134 (1986).
- ²⁹F. Takens, *Lect. Notes Math.* **898**, 366 (1981).
- ³⁰P. Grassberger and I. Procaccia, *Phys. Rev. Lett.* **50**, 346 (1983).
- ³¹J. Theiler, *Phys. Rev. A* **34**, 2427 (1986).
- ³²Y. Zhang, J. J. Jiang, and S. M. Wallace, *J. Acoust. Soc. Am.* **118**, 2551 (2005).