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Discrimination of “Hot Potato Voice” Caused by Upper Airway Obstruction Utilizing a Support Vector Machine

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**Objectives/Hypothesis:** “Hot potato voice” (HPV) is a thick, muffled voice caused by pharyngeal or laryngeal diseases characterized by severe upper airway obstruction, including acute epiglottitis and peritonsillitis. To develop a method for determining upper-airway emergency based on this important vocal feature, we investigated the acoustic characteristics of HPV using a physical, articulatory speech synthesis model. The results of the simulation were then applied to design a computerized recognition framework using a mel-frequency cepstral coefficient domain support vector machine (SVM).

**Study Design:** Quasi-experimental research design.

**Methods:** Changes in the voice spectral envelope caused by upper airway obstructions were analyzed using a hybrid time-frequency model of articulatory speech synthesis. We evaluated variations in the formant structure and thresholds of critical vocal tract area functions that triggered HPV. The SVMs were trained using a dataset of 2,200 synthetic voice samples generated by an articulatory synthesizer. Voice classification experiments on test datasets of real patient voices were then performed.

**Results:** On phonation of the Japanese vowel /e/, the frequency of the second formant fell and coalesced with that of the first formant as the area function of the oropharynx decreased. Changes in higher-order formants varied according to constriction location. The highest accuracy afforded by the SVM classifier trained with synthetic data was 88.3%.

**Conclusions:** HPV caused by upper airway obstruction has a highly characteristic spectral envelope. Based on this distinctive voice feature, our SVM classifier, who was trained using synthetic data, was able to diagnose upper-airway obstructions with a high degree of accuracy.

**Key Words:** Hot potato voice, upper airway obstruction, articulatory speech synthesis, support vector machine.

**Level of Evidence:** 2c

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**INTRODUCTION**

Certain pharyngeal or laryngeal diseases such as peritonsillitis or acute epiglottitis cause pathognomonic voice changes. The voice is described as thick or muffled, and is termed a “hot potato voice” (HPV), as if the patient was struggling with a mouthful of hot food. Emergency physicians and otolaryngologists are alert for this peculiar voice change because it implies that the patient has severe pharyngeal or laryngeal problems and is in danger of airway obstruction or suffocation. We have also encountered this change in patients suffering from upper airway obstruction caused by a large tumor or severe edema. Although HPV is well recognized as an important sign of an upper airway emergency, very few studies have focused on this unique symptom, and its acoustic characteristics remain unclear.1

The source-filter model is a simplified speech production mechanism. In this model, speech is viewed as the passage of a glottal excitation signal (a source) through a time-varying linear filter that models the resonant characteristics of the vocal tract. Hence, it should be possible to represent the acoustic characteristics of HPV as distinct resonance characteristics caused by vocal tract constriction. We initially identified the common resonance characteristics, or spectrum envelope, of the voice, rendering it possible to identify patients with peritonsillitis or acute epiglottitis via voice assessment alone. We then used computerized HPV recognition to establish a method for the diagnosis of dangerous upper airway obstructions. This is regarded as a classification problem, in which the classifier assigns input vectors (patient voices) to finite discrete categories (e.g., presence or absence of vocal tract constriction point). The classifier can be trained with previously categorized (voice) samples and labeled based on the corresponding vocal tract shapes. We used a supervised machine-learning technique (support vector machine (SVM)) to this end.

However, the voice spectrum envelope reflects pronounced interindividual variation in the phrase and morphology of the vocal tract. Such common variation may conceal subtle changes caused by pathological airway
obstruction; thus, it was necessary to accumulate and analyze numerous HPVs to reveal their common features. Supervised learning by SVMs requires a large training dataset. In practice, opportunities to examine and treat patients with severe upper airway obstructions are limited; thus, it has been difficult to define the features of HPV.

To resolve this problem, we used a model of physical, articulatory speech synthesis (Fig. 1). Changes in the voice spectrum envelope caused by upper airway obstructions were calculated using this model and compared to those of affected patients; this revealed specific spectrum envelope characteristics of the unusual voice. Synthesized voices made by highly constricted vocal tracts were thick and muffled, thus typical HPVs, and allowed effective analyses of acoustic characteristics. Finally, we used large amounts of synthetic data to train SVMs to classify clinical HPVs of real patients with upper airway obstructions.

MATERIALS AND METHODS

Analyses of the Acoustic Characteristics of the HPV

The Physical, Articulatory Speech Synthesis Model. The foundations for speech synthesis based on articulatory modeling were built by Fant (1960), Holmes et al. (1964), Planagan (1972), Klatt (1976), and Allen et al. (1987). In the classic approach, wave propagation in the vocal tract is approximated by a digital ladder, or waveguide, filter operating in a discrete time domain. The celebrated Kelly-Lochbaum model approximates the vocal tube as a set of cylindrical elements of overall length $L_a = c/F_s$, where $c$ is the velocity of sound and $F_s$ the audio sampling rate. However, differences in vocal tract shape or length cannot be easily accommodated using this model. We employed the hybrid time-frequency system proposed by Sondhi and Schroeter in which a chain-matrix approach is used to compute the transfer function of the vocal tract in the frequency domain (Fig. 1). This allows incorporation of realistic frequency-dependent losses as well as variations in vocal tract length and the number of tubes that describe the vocal tract, independent of sampling frequency.

A chain matrix relates the pressure and volume velocity at the output side of a tube $[P_{out} U_{out}]$ to those at the input side $[P_{in} U_{in}]$, capitalized to denote variables in the frequency domain obtained by performing Laplace transforms:

$$
\begin{bmatrix}
P_{in} \\
U_{in}
\end{bmatrix}
= 
\begin{bmatrix}
k_{11} & k_{12} \\
k_{21} & k_{22}
\end{bmatrix}
\begin{bmatrix}
P_{out} \\
U_{out}
\end{bmatrix} = K
\begin{bmatrix}
P_{out} \\
U_{out}
\end{bmatrix}
$$

The elements of this matrix are easy to compute for a tube of uniform area, being specified to include wall vibration and viscous friction. In this study, an arbitrary tube was represented as a concatenation of elementary uniform sections. Considering non-nasal sounds for simplicity, the overall vocal tract chain matrix is the product of a sequence of elementary $2 \times 2$ matrices: $K = K_1K_2 \cdots K_N$.

Assuming that the tract is terminated by the radiation impedance $Z_R$ of the lips, the transfer function of the entire vocal tract is:

$$
\frac{U_{out}}{U_{in}} = \frac{1}{k_{21}Z_R + k_{22}}
$$

This transfer function relates the volume velocity at the output and input sides of the vocal tract. The input impedance of the vocal tract, as seen at the glottis, is:

$$
\frac{P_{in}}{U_{in}} = \frac{k_{11}Z_R + k_{12}}{k_{21}Z_R + k_{22}}
$$

The frequency response of this model is obtained by substituting $s = io\omega$ for the transfer function. To calculate the transfer function of the entire vocal tract, we used the vocal tract variables of Sondhi and the area function data of Story and...
Acoustic Characteristics of the Synthesized HPV and its Auditory Impressions. The primary aim of this study was to investigate the relationship between the change in voice spectral envelope caused by vocal tract constriction and any association with HPV. First, we used the above-described physical simulation model to analyze gradual variations of the spectral envelope caused by vocal tract constriction. Next, we generated five test datasets consisting of around 400 synthetic vowel sounds each; we gradually decreased the vocal tract area function of 11 elementary uniform sections of the oropharynx, from the top of the epiglottis to the velum, beginning with the normal values and decreasing to a minimum of 0.01 cm². We varied the area function, decreasing intervals slightly and randomly by every voice sample production, to uniformly distribute the sampling points of the vocal tract shape. The number of voice samples, therefore, differed in each dataset. Five otolaryngologists evaluated each sound and noted whether it sounded such like an HPV. The labeled voice samples were scatter-plotted in terms of their formant-frequency space (the first $F_1$ to fourth $F_4$ formants), and then the threshold of the critical area function triggering the HPV was obtained.

Classification of Clinical HPV Using a SVM. SVM is a powerful discriminative classifier pioneered by Cortes and Vapnik. It SVM maps an input onto a high-dimensional space and then defines a maximum-margin hyperplane that optimally separates the data with high generalizing capability and performance. We employed a C-SVM algorithm with a radial basis function kernel.

Using the above physical simulation model, we created the training dataset for SVMs, containing 2,200 synthetic voice samples with different vocal tract area functions for 11 elementary uniform sections of the oropharynx, from the top of the epiglottis to the velum, from the normal values to a minimum of 0.01 cm². The sustained Japanese vowel /e/ was chosen for the analyses because its normal phonation requires a relatively large oropharyngeal space. It was therefore assumed that constrictive changes in the oropharynx would more extensively affect phonation of this vowel than other vowels. Prior to the SVM training phase, synthetic voice samples of the training dataset were classified and labeled in terms of vocal tract constriction at an arbitrary minimum area function threshold value in the sections of the whole oropharynx, not by any auditory impression of an HPV. To explore the effects of the various extents of vocal tract constriction, the SVMs were trained using several training datasets with different area function thresholds (from 0.15 cm² to 0.30 cm²). Consequently, the SVMs were able to discriminate the voices of patients with vocal tract constriction in some part of the oropharynx based on arbitrarily set thresholds.

The test dataset included 12 HPV samples from real patients with upper airway obstructions (Table I) and six voice samples from patients with no constrictive upper airway disease. To reduce analytical inaccuracies caused by the low amount of available test data, we created five test datasets, in which the offset points of the cropping analyses were randomly changed; the average of the values from the five datasets served as the final result.

The SVM hyperparameters were tuned via eight-fold cross-validation with the training datasets, and then fine-tuned using the test dataset. Next, we performed voice classification experiments on the test datasets employing the trained SVMs. All training, tuning, and classification experiments employed the R package e1071 (Dimitriadou et al., 2014), which wrapped LIBSVM (Chang and Lin, 2011).

RESULTS

Acoustic Characteristics of the HPV

Figure 2 depicts the trajectory of the simulated spectrum envelope when articulating the Japanese vowel /i/, caused by gradual decreases in the area functions of elements corresponding to three different parts of the pharynx: the top of the arytenoid, the top of the epiglottis, and around the palatine tonsil. The volumes range from the normal values (blue) to 0.01 cm² (red). Below, we focus on formant variation representative of changes in the spectral envelope. In general, the $F_2$ frequency gradually fell as the area function decreased, to initially approach and finally coalesce with $F_1$ at about 1,000 Hz. However, changes in the higher-order formants varied by the location of the constriction, which at the top of the arytenoid was associated with relatively good preservation of higher-order formant structure (Fig. 2a); the resonance characteristic resembled that of a single cylindrical pipe. Constriction at the top of the epiglottis decreased the $F_3$ frequency, which ultimately became integrated with $F_4$...
Constriction around the palatine tonsil decreased the frequency of $F_6$, which ultimately became integrated with $F_5$, and also reduced the $F_4$ frequency (Fig. 2c). Such variation in higher-order formants subtly affected the timbre of the HPV.

We found that the variation in formant structures associated with the different vocal tract constriction patterns were very complicated; we do not present the details for all vowels or constriction patterns. We show typical changes in formant structure associated with phonation of other Japanese vowels in Figure 3.

Figure 4 shows the threshold values of the area functions at which simulated voices were perceived as HPVs for 11 elementary uniform sections corresponding to the oropharynx, ranging from the top of the epiglottis to the velum. The average threshold (all sections) was 0.15 cm$^2$.

**DISCUSSION**

HPV is a well-known symptom of a peritonsillar abscess or acute epiglottitis and is a recognized warning sign of upper airway obstruction. However, both the details of the voice and the mechanism of its generation remain unclear. Finkelstein et al. found that peritonsillar infection immobilized the palatopharyngeal, superior constrictor, and levator veli palatini muscles of the affected side, and that HPV reflected an underlying, transient velopharyngeal insufficiency combined with muffled oral resonance. However, we sometimes encounter patients with HPV or similarly altered voices who have upper airway obstructions caused by conditions other than a peritonsillar abscess, such as acute epiglottitis, large epiglottic cyst, laryngopharyngeal edema, or a large pharyngeal tumor. Therefore, we consider that changes in vocal tract shape or wall surface properties per se, rather than velopharyngeal insufficiency, alter the resonance characteristics of the vocal tract to generate the HPV; our simulation results showed that the sound generated by a simple vocal tract, part of which was heavily constricted, was actually perceived as a thick and muffled HPV. The average threshold required to change a plain

**Computational Recognition of the HPV**

Figure 5 shows the testing dataset classification results and the efficiencies of interpretation by trained SVMs; the different threshold values of area function used to assess the synthesized voice samples of the training datasets are depicted. The highest efficiency was 88.3% at a threshold of 0.23 cm$^2$. As the threshold increased, the false-positive rate rose, and as the threshold decreased, the false-negative rate rose, as expected given the classification framework employed.
voice to a HPV was 0.15 cm² in our simulation, representing an extremely severe airway constriction, substantiating the pathological significance of such a voice, which constitutes a clinical emergency. In terms of velopharyngeal insufficiency, in another simulation of narrow-conjunction nasal tract coupling achieved by tapping two special matrices at the velum in a chain matrix, imitating velopharyngeal insufficiency, we found that it introduces zero above $F_1$ and formed a distinctive envelope shape around 1,000 Hz, resembling the changes caused by oropharyngeal constriction (Fig. 6). This shape change appeared to accentuate the HPV caused by oropharyngeal constriction.

Our articulatory synthesis model has several limitations. For simplicity, we did not seek to emulate the surface properties of the vocal tract wall, and we ignored the transient dynamics of linguistic activity. We assumed that these did not contribute to the acoustic characteristics of the HPV because our simplified model well represented the perceptual auditory features of that voice; refinements can be made if the simulation objectives of other implementations differ.

Our approach allows evaluation of the resonance characteristics of HPV using formant frequencies, which is an easily comprehensible method to evaluate the voice spectral envelope. As is evident from the above discussion,
when simply combined with a linear classifier, the formant frequencies can be used to construct a machine-learning model enabling HPV discrimination. However, several problems with this design must be resolved before the method can be put into practice. First, the characteristics of the voice spectral envelope are represented not only by the formant frequencies but also by the bandwidth or energy of each formant. Second, as previously explained, some of the formant frequencies were close to each other and finally coalesced into a single spectral peak as constriction of the vocal tract became severe. Therefore, even if a sequence of formant frequencies is calculated using real voice data, it will be difficult to ensure one-to-one correspondences between the components of this formant sequence and those of other real or synthetic data. For these reasons, the characteristic features used for a machine-learning classifier should be representative of the entire structure of the voice spectral envelope. MFCC is a reasonable feature that is able to describe the overall shape of the spectral envelope in a small set of coefficients.

In addition, and importantly, we utilized synthetic data generated by an articulatory synthesizer to train the HPV classifier and supervise learning. Obviously, even the best machine-learning model is useless if high-quality data are lacking. Too few clinical HPV samples are available to allow supervised machine learning. However, the articulatory speech synthesizer generated a very large number of voice samples labeled with arbitrary thresholds. The use of only virtually synthetic data to train machine-learning models may initially appear to be inappropriate, although synthesized and real HPVs sound very similar. On careful consideration, however, supervised learning using synthetic data affords several advantages. Synthetic data can be labeled with perfect accuracy as long as the model precisely represents the required phenomena, even when such data are very difficult to capture or assess in real life.

The excellent classification results that we obtained may imply that our simulation of articulatory synthesis well mimics the real HPV phonation phenomenon. In the current study, the different constriction positions in the oropharynx could not be discriminated because too few test data were available. Our framework of machine-learning models trained by synthetic data can also be applied to several other clinical issues in pathological voice diagnosis, such as a nasal voice or dysarthria. Constructing a high-quality dataset with abundant real voice data will enable improved diagnostic capability.
CONCLUSION
Using a physical, articulatory speech synthesis model, we showed that HPV caused by upper airway obstruction has a highly characteristic spectral envelope. On the basis of the distinctive voice features of HPV, the SVM classifier, trained using synthetic data, afforded excellent efficiency in terms of the diagnosis of upper airway obstruction during examination of the patient’s voice.

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