Chinese Journal of Physiology 52(6): 446-450, 2009
DOI: 10.4077/CJP.2009.AMH074

Changes of Rhythm of Vocal Fundamental Frequency in Sensorineural Hearing Loss and in Parkinson's Disease

Guo-She Lee[1] and Sheng-Huang Lin[2]

[1]*Department of Otolaryngology, Faculty of Medicine, School of Medicine, National Yang-Ming University, Taipei and Department of Otolaryngology, National Yang-Ming University Hospital, I-Lan and*
[2]*Department of Neurosurgery, Neurology, Buddhist Tzu Chi General Hospital and Tzu Chi University, Hualien and Department of Neurosurgery, Taipei Municipal Wan Fang Hospital and Taipei Medical University, Taipei, Taiwan, Republic of China*

Abstract

The neurological control of speech is a complex process that involves phonation organs, respiratory and auditory systems. In the instance of a steady-as-possible sustained phonation, the vocal fundamental frequency (F_0) is rhythmic and oscillating in varied degree. The present study examines the changes in the rhythm of F_0 in subjects with sensorineural hearing loss (SNHL) as well as in subjects with Parkinson's disease (PD) after being orally administered with dopamine. The sustained steady vocalizations of vowel [a:] from 19 subjects with SNHL and from 13 subjects with normal hearing were collected and statistically compared. In addition, the phonations of 14 subjects with PD before and after oral medication with oral dopamine were collected and statistically compared. The F_0 of a phonation was retrieved by digital signal processing of voice signals, and were then analyzed using Fourier transformation to acquire the amplitude of oscillation at different frequency components. Our study showed that subjects with SNHL had significantly larger fluctuation in the low frequency (< 3 Hz) than the subjects with normal hearing. In addition, dopamine medication significantly reduced the fluctuation in the mid-frequency (3-8 Hz) in subjects with PD. Our study indicates that power spectral analysis of F_0 may potentially be very useful in the evaluation or detection of SNHL and PD. The rhythms of F_0 are produced from neurological controls of phonation and may be used to access clinical diseases by a sustained phonation.

Key Words: voice, fundamental frequency, variability, power spectrum, rhythm

Introduction

In sound communication, humans use a very powerful language system to communicate with each other. The neuromuscular system usually plays the most important role on delicate control of vocalization for effective communication. Both open-loop and closed-loop neurological controls are involved in controlling phonation in loudness, intelligibility and speech pitch, in particular, the fundamental frequency (F_0). F_0 refers to the rate at which the vocal folds are vibrating during phonation and it is also the most fundamental pitch of voices. F_0 is important in speech intelligence especially in tonal language system (7). The control of F_0 has to be precise and requires operation of many control loops. For example, we first

Corresponding author: Dr. Guo-She Lee, Department of Otolaryngology, Faculty of Medicine, School of Medicine, National Yang-Ming University, No. 155, Sec. 2, Linong St., Taipei 11221, Taiwan, ROC. E-mail: guosheli@ms12.hinet.net; gslee@ym.edu.tw
Received: November 5, 2008; Revised: March 6, 2009; Accepted: March 16, 2009.
 ISSN : 0304-4920. http://www.cps.org.tw

use our neural memory to make a phonation at a preset level by introducing an open-loop control to maintain a steady F_0 in a sustained vowel vocalization. Then the sensory systems sense the error between the desired level and the actual level and send it to the integration centers that may be located in the central nerve system for processing. After processing, an action is relayed to the motor system to compensate for the error. Thus, a closed loop control is introduced to maintain the F_0 at the desire level and the repeats of the correction process of F_0 show a picture of getting up and down by centering the F_0 at the desired level. There may also be more than one closed loops involved in the control of phonation and the delay/latency of each control may be different. Loops with different delays will modulate the F_0, at different frequencies, and the analysis of the modulation of each frequency may provide a possibility to measure the control of each loop.

Parkinson's disease (PD) is a progressive neuromuscular disorder characterized by impaired motor functions such as resting tremor, bradykinesia and rigidity (5). There are also several impairments found in speech and phonation function of PD, such as dysarthria (5), monotonic speech, abnormal phonation intensity (17) and vocal tremor (14, 15). The vocal tremor is a perceived oscillation of pitch during phonation and is often associated with the fluctuation of F_0 in PD. There are also several speech abnormalities occurring in sensorineural hearing loss (SNHL) such as elevated F_0 (1, 6), impaired control of vocal intensity (8) and abnormal nasality (12). The oscillations of F_0 come from different control loops with different latencies and the impaired neurological controls of F_0 may exist in both the above two disorders. Analysis of the rhythm/oscillation of F_0 may provide a method for evaluation of the two disorders.

In this study, the significant changes of F_0 in the phonation of subjects with SNHL and PD using power spectral analysis of F_0 were explored. The rhythm of F_0 was different in frequency and amplitude for the two diseases. The results of this study also indicated that the analysis of F_0 might become a useful tool for evaluation or detection of the two neurological diseases.

Materials and Methods

In the first part of the study, sustained 5-s vocalizations of vowel [a:] of 19 subjects with greater than 50 dB HL SNHL (13M, 6F; age 37~72 years, median 64 years) were collected using a dynamic microphone and an IBM-personal computer (PC) compatible sound adapter. The voice signals were digitally sampled at 44.1 kHz, and the intensity signals were sampled at 100 Hz with a sound level meter. The same vocalizations of 13 subjects (7M, 6F; age 36~76 years, median 54 years) with normal hearing were collected as the control group. In the second part of the study, the same vowel vocalizations of 14 subjects with Parkinson's disease (PD) (9M, 5F; age 39~76 years, median 62 years) were collected before and 1 h after taking L-Dopa (levodopa) orally. All subjects were instructed to vocalize at their comfort speech levels. Two voice recordings were taken and were averaged for each subject.

Fundamental frequencies of voice signals were obtained using the algorithm of auto-correlation function and were then converted to a sequence of cents after linear interpolation and re-sampling to the rate of 50 Hz. Because the F_0 of adult females are often twice that of adult males, the conversion of F_0 to cents is used to allow comparisons across subjects. This conversion has also been used to investigate the audio-vocal reflex utilizing the pitch-shift technique (3, 9). Here is the equation of cent conversion.

$$cent = 1200 \times \log_2 \left(\frac{f}{\bar{F}_0}\right)$$

where $\bar{F}_0$ is the mean of all F_0s of a 5-s voice sample and f is the frequency to be converted.

The power spectrum of F_0 was derived using fast Fourier transformation of the F_0 sequence (in cent), and was divided into a low frequency (0.2 Hz to 3 Hz), a middle frequency (3 Hz to 8 Hz) and a high frequency (8 Hz to 25 Hz). The intensity of each frequency component within each defined range was summed and eventually expressed in decibels (dB). A low-frequency power (LFP), a middle-frequency power (MFP) and a high-frequency power (HFP) were thus acquired for statistical comparison. The reason for division of spectral power into LFP, MFP and HFP and the corresponding frequency range had been cited in our previous work (10, 11).

Analysis software was developed using LabVIEW version 6.0 of National Instruments for Windows (National Instruments, Austin, TX, USA). Comparisons of F_0, vocal intensity, and spectral intensity between groups were assessed by two-sample *t*-test using SPSS for Windows, 10.0.1 (SPSS Inc., Chicago, IL, USA) at a confidence level of $P < 0.05$. Values are expressed as means ± SD.

Results

The F_0 of the SNHL subjects was not significantly different than the control subjects (Table 1). The vocal intensity, however, was higher for the SNHL subjects than the control subjects ($P = 0.02$, two-sample *t*-test). Fig. 1 shows the F_0 sequences

Table 1. Comparison of fundamental frequency and voice intensity of control subjects and subjects with SNHL

	Control	SNHL	*P* value*
F_0 (Hz)	158.2 ± 44.9	168.4 ± 65.0	0.55
Vocal Intensity (dB)	79.0 ± 7.7	84.5 ± 5.1	0.02

Values were expressed in means ± SD.

*Comparisons between control group and SNHL group was made using a two-sample *t*-test

F_0 = fundamental frequency; SNHL = sensorineural hearing loss

Table 2. Fundamental frequency, vocal intensity of the subjects with Parkinson's disease before and after taking L-Dopa

	Before L-Dopa	After L-Dopa	*P* value*
F_0 (Hz)	145.9 ± 34.4	81.0 ± 7.6	0.68
Vocal Intensity (dB)	151.6 ± 37.8	82.3 ± 5.5	0.60

Values were expressed in means ± SD.

*Comparison between before L-Dopa and after L-Dopa was made using a two-sample *t*-test

L-Dopa = levodopa

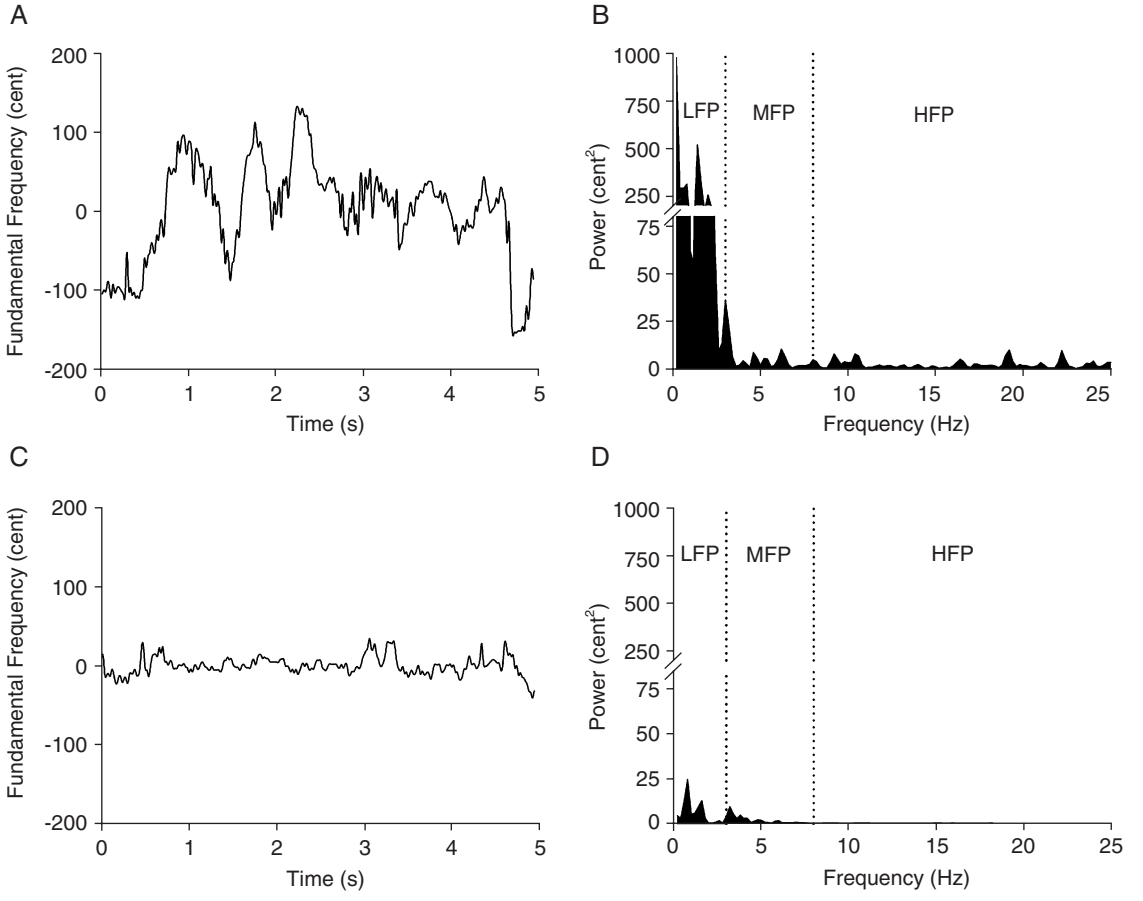

Fig. 1. Fundamental frequency (F_0) and its power spectral analysis of sustained 5-s vocalizations of vowel [a:] recorded from a subject with sensorineural hearing loss (SNHL) and a subject with normal-hearing. Frequency analysis (A) and power spectrum (B) of F_0 of vowel [a:] recorded from a subject with SNHL. Frequency analysis (C) and power spectrum (D) of F_0 of vowel [a:] recorded from the subject without SNHL. LF, low-frequency power (0.2~3 Hz). MFP, middle-frequency power (3~8 Hz). HFP, high-frequency power (8~25 Hz).

and the calculated power spectra of a SNHL subject (Fig. 1, A and B) and a control subject (Fig. 1, C and D). The F_0s of the SNHL subject fluctuated in a slow (6 cycles in 5 s, *i.e.* 1.2 Hz) but larger amplitude than the F_0s of the control subject. The power spectra of the F_0 of the two groups of subjects are shown in Fig. 3A. The LFP of the spectrum was significantly greater for the SNHL subjects than for the control subjects ($P < 0.001$, two-sample *t*-test).

The F_0 and vocal intensity of the PD subjects before L-Dopa were not significantly changed with the medication of L-Dopa (Table 2). Fig. 2 shows the F_0 sequences and the calculated power spectra of a PD subject before and after dopamine medication. There were apparent fluctuations of 4~6 Hz in the F_0 sequence before medication as evident by marked

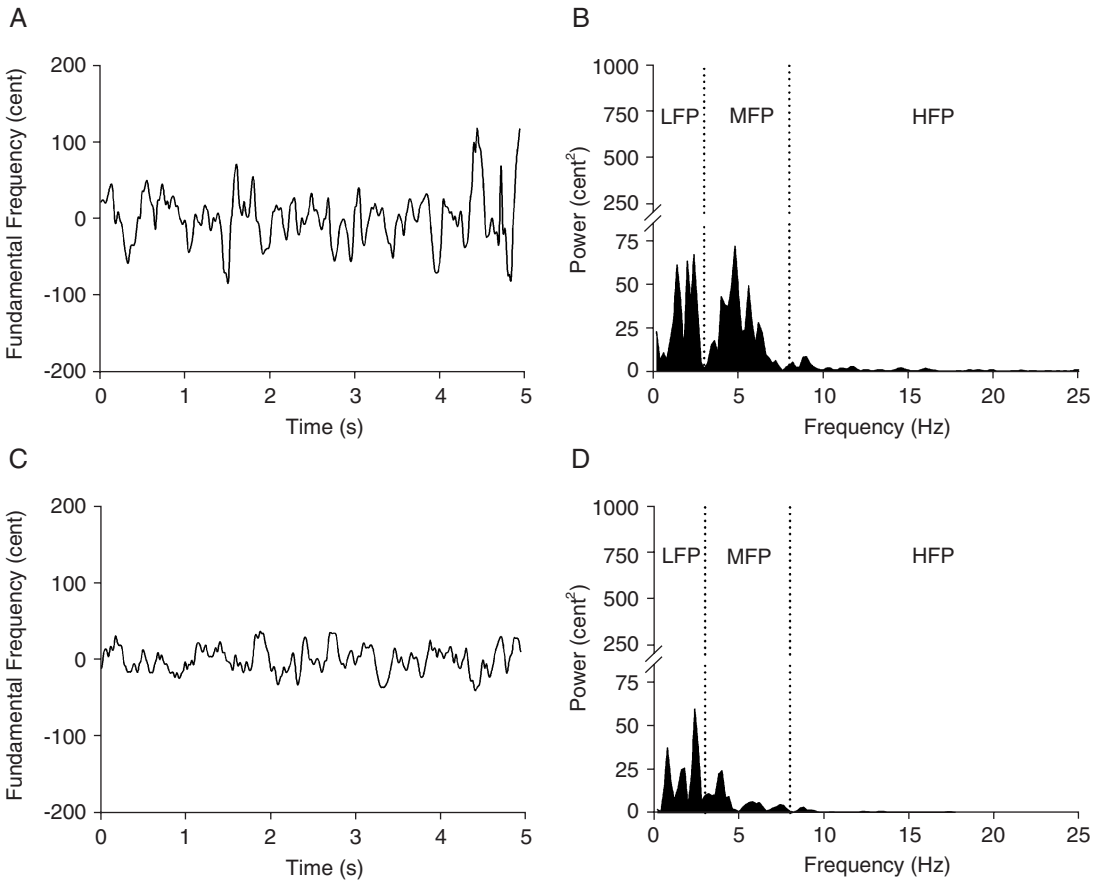

Fig. 2. Fundamental frequency (F_0) and its power spectral analysis of sustained 5-s vocalizations of vowel [a:] recorded from a subject with Parkinson's disease (PD) before and after L-Dopa medication. Frequency analysis and power spectrum of F_0 of vowel [a:] recorded from the PD subject before (A & B) and after (C & D) L-Dopa medication. (See Fig. 1 for legends).

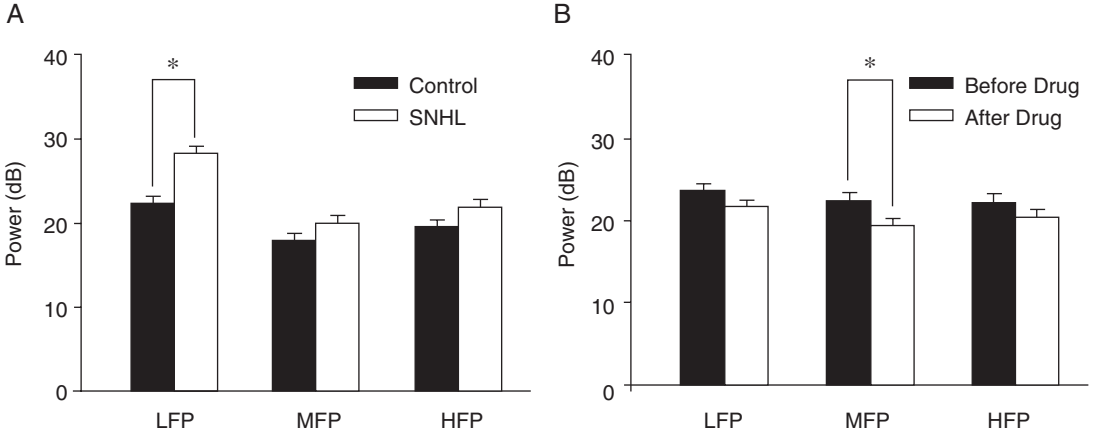

Fig. 3. Comparisons of low-frequency power (LFP), middle-frequency power (MFP) and high-frequency power (HFP) of sustained 5-s vocalizations of vowel [a:] recorded from subjects with (A, unfilled bars) or without (A, filled bars) sensorineural hearing loss (SNHL) and Parkinson's disease (PD) before (B, filled bars) and after (B, unfilled bars) L-Dopa medication. *$P < 0.05$, two-sample *t*-test.

peaks in the middle frequency range of the calculated power spectrum (Fig. 2, A and B). However, the fluctuations and marked peaks of the F_0 sequence and the power spectrum became noticeably smaller after medication (Fig. 2, C and D). Fig. 3B shows the LFP, MFP and HFP of all the PD subjects before

and after medication. Clearly, the MFP was significantly reduced by medication ($P < 0.05$, two-sample *t*-test).

Discussion

In this study, the F_0 rhythms related with two neuropathological disorders (SNHL and PD) were examined using the power spectral analysis of F_0 of sustained vocalization of a single vowel /a:/. The low-frequency oscillations (< 3 Hz) of F_0 were significantly greater in the subjects with SNHL while the middle-frequency oscillations (3~8 Hz) were significantly reduced in PD after medication.

Human phonation is a complex process involving various systems to maintain F_0 at a desired level under a negative feedback control mechanism. This negative feedback mechanism increases or decreases the F_0 relative to a preset level to ensure a sustained steady phonation. However, the sensitivity, power and response reaction latency for each feedback control mechanism of F_0 are different. For example, response reaction latency for F_0 change is typically long (310-680 ms) for neural pathway underlying audio-vocal reflex (2). The modulation of F_0 using this kind of mechanism is deduced to be low-frequency (< 3.3 Hz). The loss of such feedback using the model of binaural noise masking showed a large but slow F_0 oscillation (11). In agreement with all these reports, the present study of the SNHL subjects also revealed a significant increase of low-frequency F_0 modulation (Figs. 1 and 3, Table 1).

Parkinson's disease is a documented disorder of impaired neuromuscular controls, and the impaired control loops involving the rest tremors were speculated from central and/or peripheral mechanisms at around 3~6 Hz (13). In addition to limb tremors, the vocal tremors were also observed in PD, and the modulation of vocal F_0 was observed between 4 Hz and 8 Hz (4, 15). In one study, the PD subjects showed a decrease in frequency tremor intensity index of vocalization after medication with L-Dopa (16). In this study, the power spectral analysis of F_0 contour demonstrated a significant decrease of middle-frequency power (3~8 Hz) after medication. This provided the evidence that the middle frequency power of F_0 spectrum reflects the ability of the neuromuscular controls in human phonation mechanisms.

The rhythms of voice result from many control mechanisms during vocalization. A longer control pathway produces a slower rhythm, and a shorter control pathway produces a faster rhythm. The control theory, such as the open-loop control and closed-loop control in physics or mechanics, can be applied for biological functions. More importantly, the power spectral analysis of F_0 contour may be used for evaluation or detection of clinical neuropathological diseases such as SNHL and PD.

Acknowledgments

This work was supported by the grant of National Science Council, Taiwan, ROC (NSC 97-2314-B-010-021).

References

1. Campisi, P., Low, A., Papsin, B., Mount, R., Cohen-Kerem, R. and Harrison, R. Acoustic analysis of the voice in pediatric cochlear implant recipients: a longitudinal study. *Laryngoscope* 115: 1046-1050, 2005.
2. Hain, T.C., Burnett, T.A., Kiran, S., Larson, C.R., Singh, S. and Kenney, M.K. Instructing subjects to make a voluntary response reveals the presence of two components to the audio-vocal reflex. *Exp. Brain Res*. 130: 133-141, 2000.
3. Hain, T.C., Burnett, T.A., Larson, C.R. and Kiran, S. Effects of delayed auditory feedback (DAF) on the pitch-shift reflex. *J. Acoust. Soc. Am.* 109: 2146-2152, 2001.
4. Hanson, D.G., Gerratt, B.R. and Ward, P.H. Cinegraphic observations of laryngeal function in Parkinson's disease. *Laryngoscope* 94: 348-353, 1984.
5. Jankovic, J. Parkinson's disease: clinical features and diagnosis. *J. Neurol. Neurosurg. Psychiatry* 79: 368-376, 2008.
6. Kishon-Rabin, L., Taitelbaum, R., Tobin, Y. and Hildesheimer, M. The effect of partially restored hearing on speech production of postlingually deafened adults with multichannel cochlear implants. *J. Acoust. Soc. Am.* 106: 2843-2857, 1999.
7. Kuo, Y.C., Rosen, S. and Faulkner, A. Acoustic cues to tonal contrasts in Mandarin: implications for cochlear implants. *J. Acoust. Soc. Am*. 123: 2815, 2008.
8. Langereis, M.C., Bosman, A.J., Van Olphen, A.F. and Smoorenburg, G.F. Effect of cochlear implantation on voice fundamental frequency in post-lingually deafened adults. *Audiology* 37: 219-230, 1998.
9. Larson, C.R., Burnett, T.A., Kiran, S. and Hain, T.C. Effects of pitch-shift velocity on voice F_0 responses. *J. Acoust. Soc. Am.* 107: 559-564, 2000.
10. Lee, G.-S., Hsiao, T.-Y. and Kuo, T.B. Relationship between fundamental frequency system and audio-vocal reflex: Illustration by power spectral analysis of vocal fundamental frequency. *J. Taiwan Otolaryngol. Head Neck Surg*. 39: 145-152, 2004.
11. Lee, G.S., Hsiao, T.Y., Yang, C.C.H. and Kuo, T.B.J. Effects of speech noise on vocal fundamental frequency using power spectral analysis. *Ear Hear*. 28: 343-350, 2007.
12. Lock, R.B. and Seaver, E.J., 3rd. Nasality and velopharyngeal function in five hearing impaired adults. *J. Commun. Disord*. 17: 47-64, 1984.
13. McAuley, J.H. and Marsden, C.D. Physiological and pathological tremors and rhythmic central motor control. *Brain* 123: 1545-1567, 2000.
14. Moore, G.P., Ding, L. and Bronte-Stewart, H.M. Concurrent Parkinson tremors. *J. Physiol.* 529: 273-281, 2000.
15. Perez, K.S., Ramig, L.O., Smith, M.E. and Dromey, C. The Parkinson larynx: tremor and videostroboscopic findings. *J. Voice* 10: 354-361, 1996.
16. Sanabria, J., Ruiz, P.G., Gutierrez, R., Marquez, F., Escobar, P., Gentil, M. and Cenjor, C. The effect of levodopa on vocal function in Parkinson's disease. *Clin. Neuropharmacol.* 24: 99-102, 2001.
17. Sapir, S., Ramig, L. and Fox, C. Speech and swallowing disorders in Parkinson disease. *Curr. Opin. Otolaryngol. Head Neck Surg*. 16: 205-210, 2008.