Ability to Cough Can Be Evaluated through Cough Sounds:

An Experimental Investigation of Effects of Microphone Type on Accuracy*

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***Abstract*—To develop a novel cough ability evaluation system through cough sounds, this study verified the effects of three types of microphones (bone conduction mic, mini speech mic, and smartphone mic) on the estimated cough peak flow. From the results of the non-linear regression analysis, the determination coefficients showed high values (greater than 0.7) for the three types of microphones investigated. Furthermore, for the cough sounds recorded with the bone conduction mic and the smartphone mic, including the height variable in the revised prediction equation of the cough peak flow improved the accuracy of the estimated cough peak flow.**

I. Introduction

Cough is an important protective mechanism that causes the central airways to be cleared of foreign materials and excess secretions [1]. Objective analysis of cough may provide a noninvasive method to identify aspiration risk [2, 3], and it has been proposed that researchers should focus on techniques to improve coughing dysfunction, rather than develop new antibiotics, to decrease mortality due to aspiration pneumonia in the elderly [4]. To prevent aspiration pneumonia, the evaluation of the ability to cough is therefore as important as that of swallowing function.

The assessment of cough effectiveness includes measurements of cough peak expiratory flow (Q_{max}) [5-10]. Bach and Saporito concluded that the ability to generate Q_{max} of at least 160 L/min is necessary for a successful extubation or tracheostomy tube decannulation because an intercurrent upper respiratory tract infection and the inability to clear airway secretions trigger acute respiratory failure [6] [10]. Patients that can generate Q_{max} of more than 270 L/min have little risk of developing respiratory failure during upper respiratory tract infections [7].

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In the conventional Q_{max} measurement method, a face mask is attached to a spirometer or a peak flow meter to prevent infection, and subjects are required to cough voluntarily. However, the disadvantage of this method is that the measured Q_{max} changes depending on the type of face masks or bacterial filters. In addition, the mask, which is firmly attached to the patient's face to prevent air leakage, makes it difficult for the subject to perform natural and voluntary cough.

Therefore, this study has aimed to develop a simple evaluation system to assess the cough ability through cough sound without any face mask or bacterial filter. Several previous studies proposed methods to monitor cough frequency using a microphone in patients with asthma [11-18], but not for the cough ability. If the assessment of the cough ability through cough sound is feasible, it can be applied to patients in whom measurements of cough peak expiratory flow using the current method are difficult. In our previous studies, the relationship between Q_{max} and the peak cough sound pressure level (L_{max}) was assumed to be an exponential function. Using the proposed method, predicted cough peak expiratory flow $Q_{predicted}$ was calculated considering the effect of the subject height or gender [19]. However, the effects of the type of microphone on measured cough sounds and predicting $Q_{predicted}$ has not yet been verified. Therefore, this study aims to verify the effects of the type of microphone on $Q_{predicted}$ to develop a novel evaluation system.

II. Methods

This study was conducted in accordance with the amended declaration of Helsinki. The Hiroshima Cosmopolitan University Institutional Review Board (No. 2015031) approved the protocol, and written informed consent was obtained from all participants.

A. Subjects

A total of 25 young healthy subjects with no history of lung disease participated in the experiments. The mean ± standard deviation age of subjects was 21.0 ± 0.2 years (range: 21 - 22 years), the mean height of subjects was 165.5 ± 8.7 cm, and the mean weight of subjects was 61.1 ± 12.4 kg. The absence of pulmonary disease was ascertained in advance by inquiry and pulmonary function test.

B. Measurement method of cough flows

Measurement of cough was carried out in a sitting position. To measure cough flow, subjects wore a bag valve mask with a flow sensor (Mobile aero monitor AE-100i; Minato Medical

Figure 1. Types of microphones and measurement position: a) bone conduction microphone; b) mini speech microphone; c) smartphone microphone.

Science Co., Ltd., Osaka, Japan) attached. The maximum value of the obtained cough flow data was defined as Q_{max}. The measurement range of the flow sensor was 0 - 840 L/min, and the measurement accuracy was within 3% of the indicated value.

C. Measurement method of cough sounds

Fig. 1 shows the cough sound measurement method. Cough sound was measured using three types of microphones. To measure cough sound through bone conduction from the right external auditory canal, an electret condenser microphone (ECM-TL3; Sony Corporation, Japan) (bone conduction mic) was attached to the right ear canal (Fig. 1a). The sensitivity of the microphone was -35.0 dB (0 dB = 1 V/1 Pa, 1 kHz). A headset mini speech microphone (ECM-322BMP; Sony Corporation, Japan) (mini speech mic) was attached to the left ear (Fig. 1b). The sensitivity of the microphone was -42.0 dB (0 dB = 1 V/1 Pa, 1 kHz). The cough sound signal was digitized using a 16 bit analog-to-digital converter (PowerLab16/35, ADInstruments, Inc., Dunedin, New Zealand) at a 100 kHz sampling rate set by an analysis software (LabChart version 8, ADInstruments, Inc.). L_{max} was calculated from the maximal value of the cough sound pressure level obtained from the different types of microphone. The smartphone (iphone6 A1586; Apple Inc., United States of America) (smartphone mic) was held in the left hand while flexing the subject's elbow to 90° and the shoulder to 0°, and then internally rotating it to 45° (Fig. 1c).

To check the variation in the distance from the sound source to each microphone between subjects, we measured the distance from the edge of the lip to each microphone. In the case of the bone conduction mic, the distance from the microphone to the thyroid cartilage was measured.

D. Protocol

After giving sufficient cough method instruction to the subjects, maximal voluntary coughing was performed three times. Subjects had enough rest between each trial to reduce fatigue effects. Q_{max} and L_{max} were determined as the maximum value of each set of measured values.

E. Analysis

The rank correlation coefficient of Spearman evaluates the relationship of the distance from the sound source to each microphone and the height. The relationship between Q_{max} and L_{max} was assumed to be an exponential function[19] as in the following equation:

$$Q_{max} = a_1 \{\exp(a_2 L_{max}) - 1\}, \quad (1)$$

where a_1 and a_2 are constants. To establish a prediction formula for predicted Q_{max} ($Q_{\text{predicted}}$), the coefficients a_1 and a_2 in (1) were determined by non-linear regression analysis (Levenberg-Marquardt method) using Q_{max} and L_{max} obtained from each microphone. To verify the effect of the height (H) on $Q_{predicted}$, the expression in (2) was proposed by including the height variable in (1) as follows:

$$Q_{max} = (h_1 H + h_2)\{\exp(h_3 L_{max}) - 1\}, \quad (2)$$

where h_1, h_2, and h_3 are constants. To verify the prediction accuracy of $Q_{predicted}$, the relationship between $Q_{predicted}$ and Q_{max} was evaluated using the Spearman's rank correlation coefficient and regression analysis. In addition, the relative error was calculated from $Q_{predicted}$ and Q_{max}. Absolute reliability was investigated using the Bland-Altman analysis method to detect systematic errors, such as the fixed error and proportional error [20]. The Friedman test was used to compare the relative error between different microphone types. L_{max} and $Q_{predicted}$ obtained from the bone conduction mic were, respectively expressed as $L_{B\,max}$ and $Q_{B\,predicted}$, those obtained from the mini speech mic were expressed as $L_{M\,max}$ and $Q_{M\,predicted}$, and those obtained from the smartphone mic were expressed as $L_{S\,max}$ and $Q_{S\,predicted}$.

All statistical calculations were carried out using the IBM SPSS Statistics 24 for Windows. A value of $p < 0.05$ was considered to be statistically significant.

III. Results

A. Relationship between distance from sound source to each microphone and height

No significant correlation was found between the distance from the thyroid cartilage to the bone conduction mic, as well as the height ($r = 0.177$, $p = 0.398$). No significant correlation was found between the distance from the edge of the lip to the mini speech mic, as well as the height ($r = -0.046$, $p = 0.827$). A positive significant correlation was found between the distance from the lip to the smartphone mic, as well as the height ($r = 0.452$, $p = 0.023$).

B. Non-linear regression

Fig. 2 and Table I show the results of the non-linear regression analysis of the experimental data measured using each microphone. The determination coefficients of the bone conduction mic by (1) or (2) were: $R^2 = 0.827$ and $R^2 = 0.829$. The determination coefficients of the mini speech mic by (1) or (2) were $R^2 = 0.835$ and $R^2 = 0.837$. The determination coefficients of the smartphone mic by (1) or (2) were $R^2 = 0.713$ and $R^2 = 0.737$. In all cases, the determination coefficients were slightly higher in (2) with respect to the height variable.

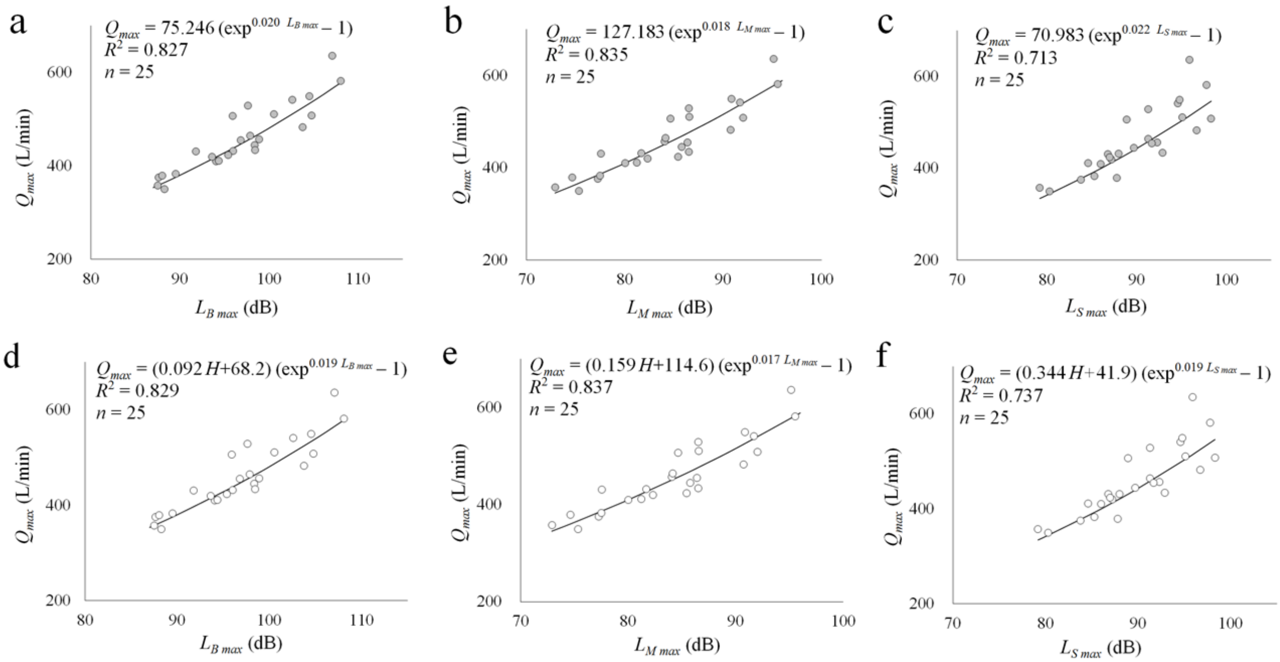

Figure 2. Results of non–linear regression analysis. (a) Bone conduction mic. Non-linear regression using (1). (b) Mini speech mic. Non-linear regression using (1). (c) Smartphone mic. Non-linear regression using (1). (d) Bone conduction mic. Non-linear regression using (2). (e) Mini speech mic. Non-linear regression using (2). (f) Smartphone mic. Non-linear regression using (2).

TABLE I. RESULTS OF EACH NON-LINEAR REGRESSION

Type of microphone	**Coefficient**	**Estimate**	**95% confidence interval**		R^2
			Lower bound	***Upper bound***	
Bone conduction mic	a_1	75.246	25.037	125.456	0.827
	a_2	0.020	0.014	0.026	
	h_1	0.092	-0.309	0.493	0.829
	h_2	68.236	10.964	125.509	
	h_3	0.019	0.012	0.026	
Mini speech mic	a_1	127.183	44.069	210.296	0.835
	a_2	0.018	0.012	0.024	
	h_1	0.159	-0.507	0.826	0.837
	h_2	114.603	18.905	210.301	
	h_3	0.017	0.010	0.024	
Smartphone mic	a_1	70.983	3.377	138.590	0.713
	a_2	0.022	0.013	0.031	
	h_1	0.344	-0.415	1.102	0.737
	h_2	41.907	-33.079	116.893	
	h_3	0.019	0.009	0.030	

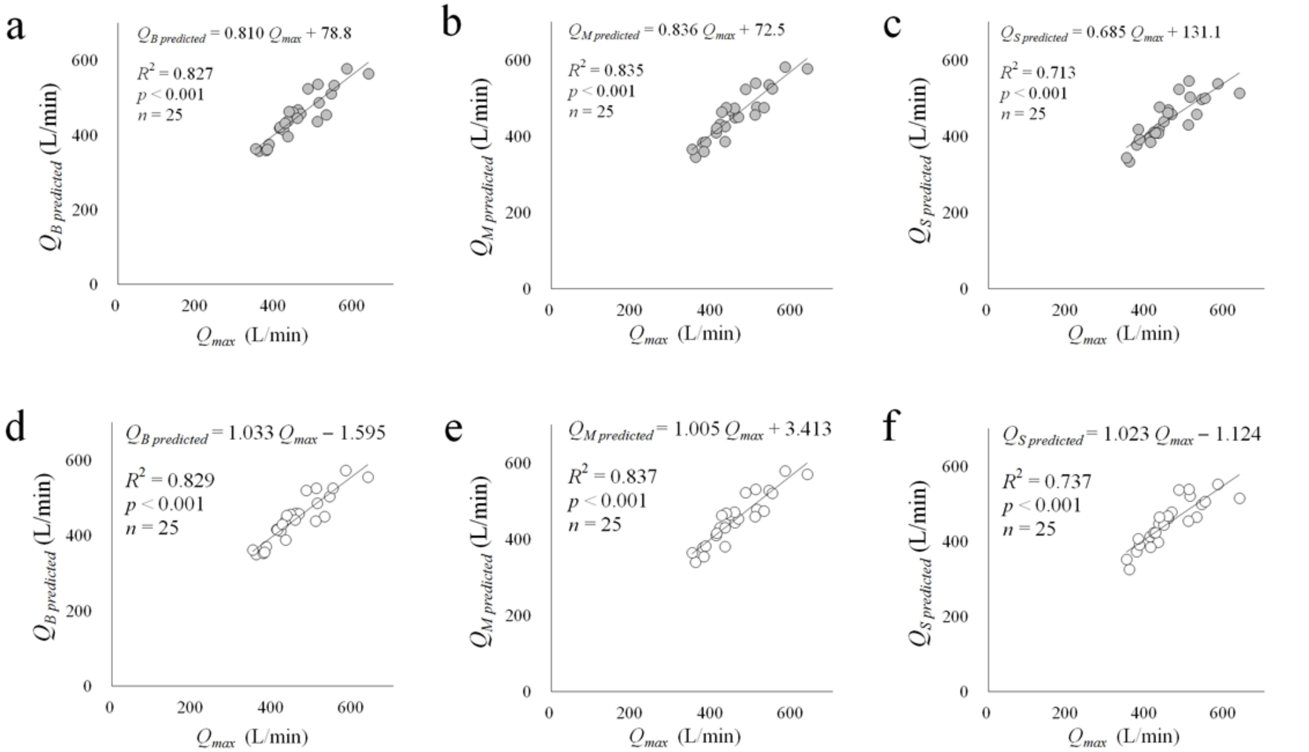

Figure 3. Results of the rank correlation coefficient of the Speaman analysis. (a) Bone conduction mic. $Q_{B\,predicted}$ was calculated using (1). (b) Mini speech mic. $Q_{M\,predicted}$ was calculated using (1). (c) Smartphone mic. $Q_{S\,predicted}$ was calculated using (1). (d) Bone conduction mic. $Q_{B\,predicted}$ was calculated using (2). (f) Mini speech mic. $Q_{M\,predicted}$ was calculated using (2). (f) Smartphone mic. $Q_{S\,predicted}$ was calculated using (2).

TABLE II. RESULTS OF THE RANK CORRELATION COEFFICIENT OF SPEARMAN

		Eq. (1)			Eq. (2)		
		$Q_{B\,predicted}$	$Q_{M\,predicted}$	$Q_{S\,predicted}$	$Q_{B\,predicted}$	$Q_{M\,predicted}$	$Q_{S\,predicted}$
Q_{max}	r	0.915	0.926	0.891	0.923	0.919	0.915
	p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	n	25	25	25	25	25	25

C. Accuracy of each predicted equation

Fig. 3 and Table II show the results of the correlation and regression analysis between $Q_{predicted}$ and Q_{max}. A strong positive significant correlation was found between each $Q_{predicted}$ and Q_{max} ($r = 0.896 – 0.926$). Specifically, the results of $Q_{predicted}$ predicted by (2) using the bone conduction mic and the smartphone mic strongly correlated with Q_{max} (Table II). Fig. 4 shows the results of the Bland-Altman method for assessing the agreement between $Q_{predicted}$ and Q_{max}. In all cases, the Bland-Altman analysis showed no systematic error between $Q_{predicted}$ and Q_{max}.

D. Comparison results of the relative errors

Fig. 5 shows results of the comparison of the relative errors between each $Q_{predicted}$ and Q_{max}. The relative errors were 4.6 ± 3.8% by the bone conduction mic in (1), 4.9 ± 3.5% by the mini speech mic in (1), 5.9 ± 4.9% by the smartphone mic in (1), 4.8 ± 4.0% by the bone conduction mic in (2), 4.8 ± 3.6% by the mini speech mic in (2), and 5.4 ± 4.7% by the smartphone mic in (2). The Friedman test showed that there was no significant difference between the relative errors (p = 0.315).

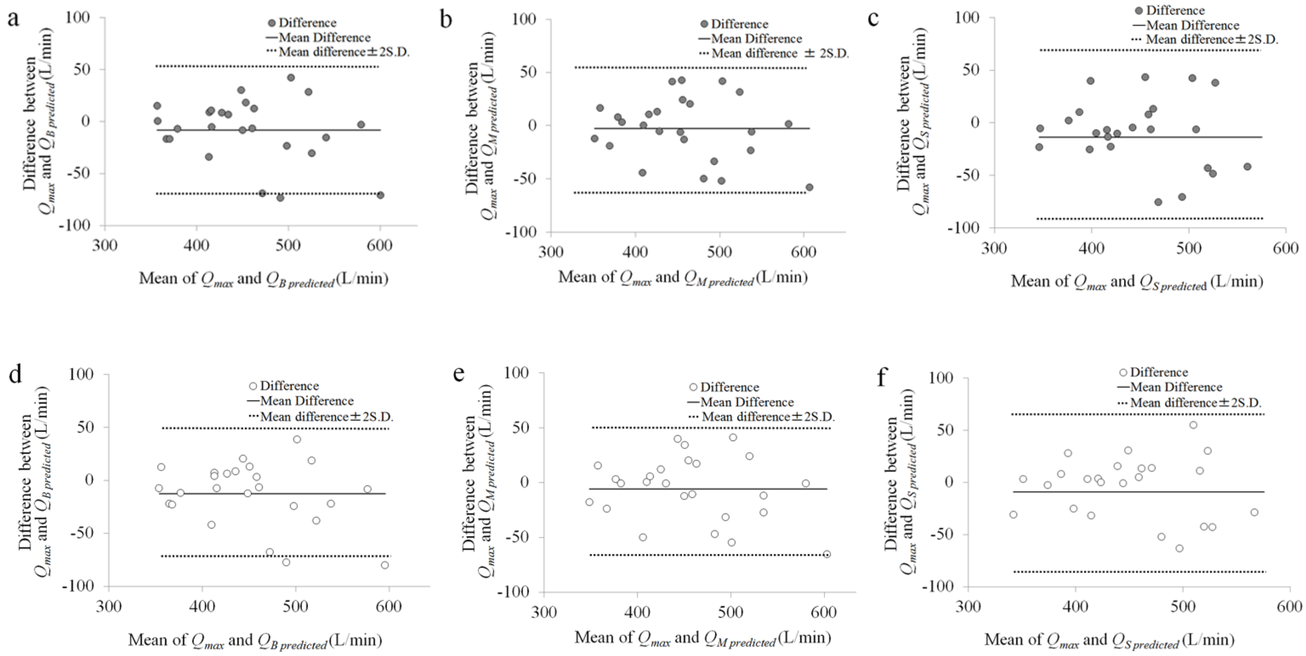

Figure 5. Results of the Bland-Altman method for assessing agreement between $Q_{predicted}$ and Q_{max} (solid line: mean difference; dashed line: 95% confidence interval of difference): a) bone conduction microphone; b) mini speech microphone; c) smartphone microphone; d) bone conduction microphone; e) mini speech microphone; f) smartphone microphone).

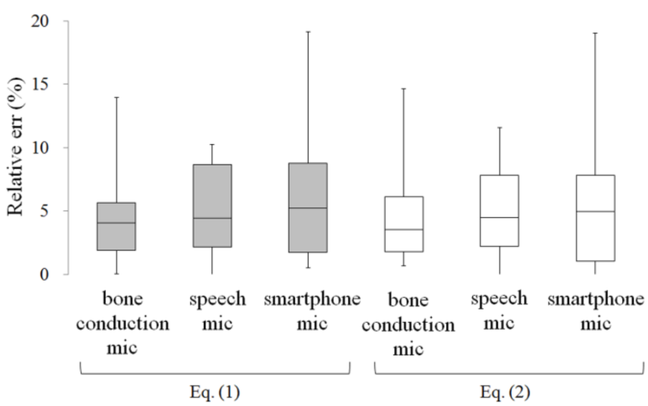

Figure 4. Graph comparing the relative errors between different microphone types: Friedman test showed that there was no significant difference between the relative errors (p = 0.315) .

IV. Discussion

This study predicted cough peak expiratory flow Q_{max} through cough sound based on the knowledge that the respiratory flow rate is related to the breathing sound [21-23], and the relationship between Q_{max} and L_{max} can be expressed by an exponential function [19]. The results of the non-linear regression analysis confirmed high determination coefficients for the mini speech mic, bone conduction mic, and smartphone mic. To accurately measure cough sounds, it was necessary to keep a constant distance between the sound source and the microphones without changing the distance by coughing-induced body motion [19]. This is because cough sound decreases with distance from the sound source, and body motion causes artifacts, thereby reducing prediction accuracy. The decrease in sound level L_p can be calculated by the distance from the sound source r_1, r_2 using the following equation:

$$L_p = 20 \log (r_2/r_1). \qquad (3)$$

The distance from the sound source to the mini speech mic fixed to the ear was closest and this distance was kept nearly constant, even when coughing-induced body motion occurred; this was the reason the highest determination coefficient was obtained. In the case of the bone conduction mic and the smartphone mic, the distance from the sound source to these microphones may be changed depending on the subject's height. In particular, results of the correlation analysis showed the relationship between the distance from the lip to the smartphone and the height. Therefore, including the height variable in (2) improved the accuracy of $Q_{predicted}$ for the conduction mic and the smartphone mic.

However, we did not consider the effect of age because all the participants were young volunteers. A relationship between Q_{max} and age has been reported [24-26]. In addition, previous studies suggested that breath sound can be affected by sound frequency [21-23]. Therefore, the effects of age and cough sound frequency should be investigated in future studies. Moreover, previous studies have proposed methods to extract cough sounds from daily utterances, and clinical application is progressing [27-29]. Incorporating these methods to the proposed system may improve accuracy. For clinical application, it is necessary to incorporate such methods into our system to increase prediction accuracy.

V. Conclusion

In this study, we proposed a novel cough ability evaluation system through cough sound, and conducted experiments to verify the effects of three types of microphones (bone conduction mic, mini speech mic, and smartphone mic) on estimated values of cough peak flow. The results of the non-linear regression analysis confirmed high determination coefficients for the three types of microphones investigated. Furthermore, including the height variable in the prediction equation improved the accuracy of $Q_{predicted}$ for the conduction mic and the smartphone mic. However, we did not consider the effects of age and cough sound frequency on $Q_{predicted}$. These effects should be investigated in the future. Based on experimental results, we also plan to develop a simple cough ability evaluation system using smartphones that can be used for in-home care.

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References

[1] R. W. Fuller and D. M. Jackson, "Physiology and treatment of cough," *Thorax,* vol. 45, pp. 425-30, Jun 1990.

[2] K. W. Hegland, M. S. Okun, and M. S. Troche, "Sequential voluntary cough and aspiration or aspiration risk in Parkinson's disease," *Lung,* vol. 192, pp. 601-8, Aug 2014.

[3] C. A. Smith Hammond, L. B. Goldstein, D. J. Zajac, L. Gray, P. W. Davenport, and D. C. Bolser, "Assessment of aspiration risk in stroke patients with quantification of voluntary cough," *Neurology,* vol. 56, pp. 502-6, Feb 27 2001.

[4] S. Ebihara, H. Sekiya, M. Miyagi, T. Ebihara, and T. Okazaki, "Dysphagia, dystussia, and aspiration pneumonia in elderly people," *J Thorac Dis,* vol. 8, pp. 632-9, Mar 2016.

[5] J. D. Finder, D. Birnkrant, J. Carl, H. J. Farber, D. Gozal, S. T. Iannaccone, *et al.*, "Respiratory care of the patient with Duchenne muscular dystrophy: ATS consensus statement," *Am J Respir Crit Care Med,* vol. 170, pp. 456-65, Aug 15 2004.

[6] J. R. Bach and L. R. Saporito, "Criteria for extubation and tracheostomy tube removal for patients with ventilatory failure. A different approach to weaning," *Chest,* vol. 110, pp. 1566-71, Dec 1996.

[7] J. R. Bach, Y. Ishikawa, and H. Kim, "Prevention of pulmonary morbidity for patients with Duchenne muscular dystrophy," *Chest,* vol. 112, pp. 1024-8, Oct 1997.

[8] J. R. Bach, "Update and perspective on noninvasive respiratory muscle aids. Part 2: The expiratory aids," *Chest,* vol. 105, pp. 1538-44, May 1994.

[9] J. R. Bach, "Update and perspectives on noninvasive respiratory muscle aids. Part 1: The inspiratory aids," *Chest,* vol. 105, pp. 1230-40, Apr 1994.

[10] J. R. Bach, "Amyotrophic lateral sclerosis: predictors for prolongation of life by noninvasive respiratory aids," *Arch Phys Med Rehabil,* vol. 76, pp. 828-32, Sep 1995.

[11] A. Spinou and S. S. Birring, "An update on measurement and monitoring of cough: what are the important study endpoints?," *J Thorac Dis,* vol. 6, pp. S728-34, Oct 2014.

[12] L. J. Toop, K. P. Dawson, and C. W. Thorpe, "A portable system for the spectral analysis of cough sounds in asthma," *J Asthma,* vol. 27, pp. 393-7, 1990.

[13] C. Thorpe, L. Toop, and K. Dawson, "Towards a quantitative description of asthmatic cough sounds," *European Respiratory Journal,* vol. 5, pp. 685-692, 1992.

[14] S. S. Birring, T. Fleming, S. Matos, A. A. Raj, D. H. Evans, and I. D. Pavord, "The Leicester Cough Monitor: preliminary validation of an automated cough detection system in chronic cough," *Eur Respir J,* vol. 31, pp. 1013-8, May 2008.

[15] C. William Thorpe, W. Richard Fright, L. J. Toop, and K. P. Dawson, "A microcomputer-based interactive cough sound analysis system," *Computer Methods and Programs in Biomedicine,* vol. 36, pp. 33-43, 1991/09/01/ 1991.

[16] H. Sumner, A. Woodcock, U. Kolsum, R. Dockry, A. L. Lazaar, D. Singh, *et al.*, "Predictors of objective cough frequency in chronic obstructive pulmonary disease," *Am J Respir Crit Care Med,* vol. 187, pp. 943-9, May 01 2013.

[17] K. K. Lee, S. Matos, D. H. Evans, P. White, I. D. Pavord, and S. S. Birring, "A longitudinal assessment of acute cough," *Am J Respir Crit Care Med,* vol. 187, pp. 991-7, May 01 2013.

[18] A. J. Ing, M. C. Ngu, and A. B. Breslin, "Pathogenesis of chronic persistent cough associated with gastroesophageal reflux," *Am J Respir Crit Care Med,* vol. 149, pp. 160-7, Jan 1994.

[19] Y. Umayahara, Z. Soh, K. Sekikawa, T. Kawae, A. Otsuka, and T. Tsuji, "Cough peak flow can be predicted via cough sounds," *(submitted to Scientific Reports)*.

[20] J. M. Bland and D. G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement," *Lancet,* vol. 1, pp. 307-10, Feb 08 1986.

[21] B. Shykoff, Y. Ploysongsang, and H. Chang, "Airflow and normal lung sounds," *Am Rev Respir Dis,* vol. 137, pp. 872-6, Apr 1988.

[22] S. S. Kraman, "The relationship between airflow and lung sound amplitude in normal subjects," *Chest,* vol. 86, pp. 225-9, Aug 1984.

[23] R. Dosani and S. S. Kraman, "Lung sound intensity variability in normal men. A contour phonopneumographic study," *Chest,* vol. 83, pp. 628-31, Apr 1983.

[24] C. S. Beardsmore, S. P. Wimpress, A. H. Thomson, H. R. Patel, P. Goodenough, and H. Simpson, "Maximum voluntary cough: an indication of airway function," *Bull Eur Physiopathol Respir,* vol. 23, pp. 465-72, Sep-Oct 1987.

[25] C. S. Beardsmore, A. Park, S. P. Wimpress, A. H. Thomson, and H. Simpson, "Cough flow-volume relationships in normal and asthmatic children," *Pediatr Pulmonol,* vol. 6, pp. 223-31, 1989.

[26] C. Bianchi and P. Baiardi, "Cough peak flows: standard values for children and adolescents," *Am J Phys Med Rehabil,* vol. 87, pp. 461-7, Jun 2008.

[27] A. H. Morice, G. A. Fontana, M. G. Belvisi, S. S. Birring, K. F. Chung, P. V. Dicpinigaitis, *et al.*, "ERS guidelines on the assessment of cough," *Eur Respir J,* vol. 29, pp. 1256-76, Jun 2007.

[28] S. Matos, S. S. Birring, I. D. Pavord, and D. H. Evans, "Detection of cough signals in continuous audio recordings using hidden Markov models," *IEEE Trans Biomed Eng,* vol. 53, pp. 1078-83, Jun 2006.

[29] S. Matos, S. S. Birring, I. D. Pavord, and D. H. Evans, "An automated system for 24-h monitoring of cough frequency: the leicester cough monitor," *IEEE Trans Biomed Eng,* vol. 54, pp. 1472-9, Aug 2007.