JOURNAL OF PHYSIOLOGY AND PHARMACOLOGY 2008, 59, Suppl 6, 331–340
www.jpp.krakow.pl

J. KNOCIKOVA[1], J. KORPAS[2], M. VRABEC[2], M. JAVORKA[3]

WAVELET ANALYSIS OF VOLUNTARY COUGH SOUND IN PATIENTS WITH RESPIRATORY DISEASES

[1]Institute of Medical Biophysics, [2]Institute of Pathological Physiology, and [3]Institute of Physiology, Jessenius Faculty of Medicine, Comenius University, Martin, Slovakia

Changes in the characteristics of the cough sound may refer to some specific pathological processes and their evolution. In this pilot study we analyzed voluntary cough sound properties in subjects with asthma bronchiale (AB) and chronic obstructive pulmonary disease (COPD) and discriminated them from the control cough sound in healthy subjects. The wavelet transform was used due to a nonstationarity of cough sound recordings. The duration of cough sound was longer during pathological conditions. The longest duration and the highest power of the cough sound were found in COPD. In AB patients, higher frequencies were detected compared with chronic bronchitis and the power of cough sound was shifted to a higher frequency range compared with control coughs. Cough sounds were classified using discriminant analysis with a correct classification rate of about 85-90 %. The method of cough analysis enables an objective quantification of voluntary cough sound with a useful diagnostic and prognostic value.

Key words: *asthma, chronic obstructive pulmonary disease, cough, sound analysis, wavelet transform*

INTRODUCTION

Cough is an important symptom of many respiratory and non-respiratory diseases accompanied by a characteristic acoustic phenomenon - cough sound. Changes in the characteristics of cough sound may refer to some specific pathological processes and their evolution. Therefore, information acquired from the cough sound is part of clinical practice (1). The patient's own subjective desription of cough frequency and properties usually does not help in identification of its cause. Smith *et al* (2) reported that health professionals are able to differentiate cough with mucus expectoration (productive cough) from those without mucus (nonproductive cough), but this differentiation is subjective, dependent on the clinician's skill and experience, and sometimes may lead to wrong diagnosis. Such subjective evaluation does not allow storing the cough sound data either. These problems have led to designing new methods of objective analysis of the acoustic properties of cough sound. Recently, several algorithms for detection of cough sounds in continuous sound monitoring have been developed to enable objective quantification of cough frequency and timing (3-5) or differentiation of cough sounds among healthy subjects and patients with various diseases (6-7). Several possible methods of cough sound analysis have been proposed, including tussiphonogram analysis (7), frequency domain (spectral) analysis (6, 8), or comparison between spectrogram and time-expanded waveforms (9-11). However, the major limitation of these methods is that an obvious nonstationarity of the cough sound is usually ignored.

In this study we propose a method of quantification of acoustic properties using time-frequency analysis by wavelet transform. Our major aim was to find the parameters of cough sound records that would enable to discriminate voluntary cough sounds obtained from healthy subjects and patients with common chronic respiratory diseases - asthma bronchiale (AB) and chronic obstructive pulmonary disease (COPD).

MATERIAL AND METHODS

Subjects

The study was approved by a local Ethics Committee and was performed in accordance with the Helsinki Declaration of 1975 for Human Research. We analyzed a total of 65 voluntary cough sound recordings from healthy subjects (control group) and patients with AB and COPD. The set included 26 recordings from the control subjects (11 males, 15 females, median age 22 years), 17 related to AB patients (8 males, 9 females, median age 32 years) and 22 obtained from patients with COPD (16 males, 6 females, median age 67 years). The asthmatic and COPD patients were in stable phases of disease without any detectable acute symptoms (*e.g.*, dyspnea, wheezing), and patients received their regular pharmacological treatment.

Cough sound recording and analysis

Recordings of the cough sound were obtained in a quiet echo-free room by a condenser microphone placed in a constant distance from the patient´s mouth, out of the main stream of exspired air to eliminate artifacts. Subjects were asked to perform three voluntary coughs with maximal effort following maximal inspiration. The sound with maximal intensity from three attempts was chosen for further analysis. Cough sounds were sampled at a frequency of 11025 Hz. Cough sound analysis was implemented and performed by a self-developed computer program written in MATLAB programming environment (HUMUSOFT, v.7.3.0.267).

Global properties of cough sound

At first, we studied the acoustic pressure changes over time, so called tussiphonogram. The start and end of cough sound was detected when the sound signal standard deviation (in a window of 200 samples) exceeded the empirically ascertained threshold level (ten times the level of background noise measured during cough-free periods). After detection of the start and end of cough sound, the length of cough sound was measured.

For further analysis, time-frequency analysis using wavelet transform was applied. Wavelet analysis was performed using Daubechies 3 as a mother wavelet. The results of the continuous wavelet transform were expressed in the form of a scalogram (*Fig. 1*). Wavelet coefficients are a function of wave translation (time) and its scale. Fast changes of the signal amplitude (high frequency oscillations) were expressed on lower scales, slow changes on higher scales. Scale values could be approximately transformed to pseudo-frequency units F_a (in Hz).

For each cough sound, we found a maximum of all wavelet coefficients (for all times and scales). Time of the occurence of cough sound ($TIME_{max}$), corresponding wavelet scale ($SCALE_{max}$), and a value of the maximum wavelet coefficient (MAX) were quantified. Power at given time instant of a cough sound was calculated by integration (as an area under the wavelet coefficients curve) for each sample of time ("vertical integration of scalogram"). We measured the maximum value of power ($MAXPOWER_{time}$) during individual cough sounds. Next, we explored

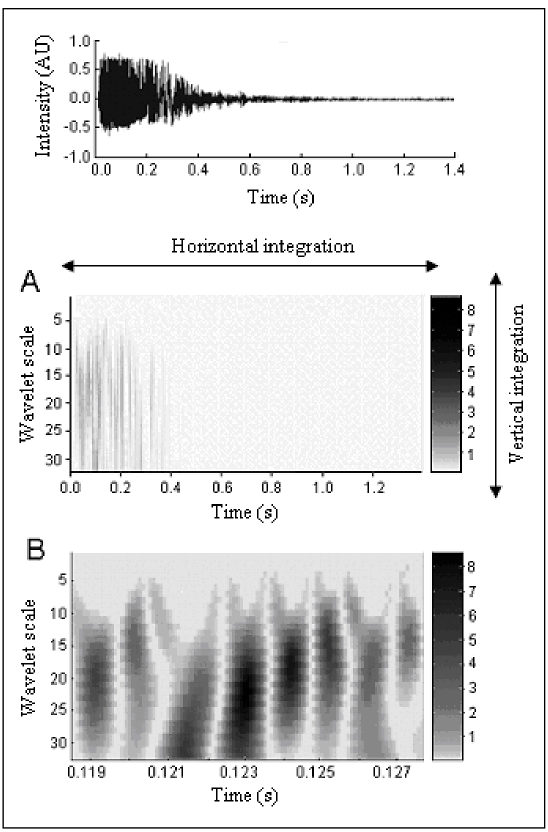

Fig. 1. Voluntary cough sound is presented in the form of acoustic pressure changes over time and in the form of a wavelet scalogram for the whole cough sound (A) and for a short interval of cough sound as the maximum of wavelet coefficients (B). The value of each wavelet coefficient is illustrated on the scalogram by a shade chosen from the grayscale (on the right-hand side of the figure) as a combination of scale (y-axis, reciprocal function of frequency) and translation (x-axis, time) values. Fast changes of the signal amplitude (high frequency oscillations) are expressed in low scales, slow changes in high scales. Vertical and horizontal integrations are indicated: vertical integration refers to the computing of sound power at a given time instant. Horizontal integration enables to estimate the contribution of given scale (and corresponding frequency) to the whole cough sound record. Vertical integration was performed for each time instant (each sample), horizontal integration was performed for each value of scale (each frequency). AU - arbitray units. Wavelet scale is a dimensionless value.

the distribution of the signal power in the frequency domain. After calculation of the power for each band of a wavelet scale (corresponding to the appropriate frequency), as an area under the appropriate wavelet coefficients during the whole cough sound ("horizontal integration of scalogram"), we detected the frequency related to the maximum power ($FREQUENCY_{maxpower}$). Based on the power values computed for each measured scale, we calculated the energy distribution of the whole cough sound in four frequency bands: over 1764 Hz (FB1), from 882 to 1764 Hz (FB2), from 490 to 882 Hz (FB3), and below 490 Hz (FB4). We determined a percentage of power corresponding to these frequency bands (PFB1, PFB2, PFB3, PFB4) related to the total energy E of a cough sound recording. Another parameter computed after "horizontal integration" was the cutoff frequency (cut-off) - maximum frequency (minimum scale), where the sound power decreased below 10% of the maximum total power (corresponding to the scale of $FREQUENCY_{maxpower}$) - it is a measure of the upper limit of frequencies contributing to cough sound.

Decomposition of the signal up to 5^{th} level was realized by a discrete wavelet transform. In this way, 5 vectors of detail coefficients and 5 vectors of aproximate coefficients were computed. Each of them was decribed by its energy - it was quantified as a sum of squares of vector values (ED1-5 (energy of detail coefficients 1-5), EA1-5 (energy of approximate coefficients 1-5). We computed also proportion of ED1-5 and EA1-5 to the total energy (PED1-5, PEA1-5).

Detailed cough sound properties related to the sample with the maximum of wavelet coefficients

We depicted the curve of wavelet coefficients (spectrum) related to the sample, when their maximum occurred (time instant $TIME_{max}$). This spectrum was divided into 5 bands (V1-5) according to the scale values. The lowest frequencies under 352 Hz correspond to the V5 band, frequency range 352-490 Hz represents the V4 band, the range 490-801 Hz represents the V3 part. A frequency band from 801 to 2205 Hz was expressed in the V2 band. The highest frequencies over 2205 Hz were included in the V1 band. Powers of all these bands (PV1 - PV5) were computed and subsequently related to the total power corresponding to this instant of time (ratios PV1Ratio-PV5Ratio). In addition, we found a frequency band with maximum power (PV_{max}Band) and computed its power (PV_{max}).

Statistics

Due to nongaussian distribution of variables (confirmed using the Lilliefors test), we used the Mann-Whitney U test to evaluate between group differences in the cough sound characteristics. Pearson Chi-square test was used to test the relationship between different diseases and the number of band with the maximum power (parameter PV_{max}Band). Differences were considered significant if $P< 0.05$.

Subsequently, we performed a discriminant analysis considering the parameters of the cough sound. Variables that mostly and independently contributed to the discrimination of the groups assessed were selected by a stepwise backward selection algorithm to minimize cross-correlations between variables. The performance of linear discrimination function was evaluated using a leave-one-out strategy to reduce in-sample error and Jacknifed classification matrix values were presented.

RESULTS

Global properties of the cough sound

The analysis of cough sound duration revealed that under pathological conditions the cough sound lasted longer. In COPD, the length of sound was greater compared with both the control group (P=0.001) and the AB group (P=0.001). There also was a significant difference in the duration of cough sound in the AB patients compared with the controls (P=0.037).

The maximum of wavelet coefficients for COPD occurred later (parameter $TIME_{max}$) compared with the control (P=0.002) and AB groups (P=0.001) and was found at a higher scale (corresponding to lower frequencies) in COPD compared with asthma (parameter $SCALE_{max}$, P=0.012). The value of this maximum (parameter MAX) was highest in the COPD group (COPD *vs*. control: P=0.001, COPD *vs*. AB: P=0.001). A significant difference also was found in the MAX value between the AB and control groups; it was lower in the AB group (P=0.025).

The maximum power of cough sound ($MAXPOWER_{time}$) was significantly higher in the COPD group compared with the other two groups (P=0.001 for each comparison). This value was lower in the AB group (P=0.035) if compared with the controls. There was no significant difference related to the frequency at which the power value reached the maximum ($FREQUENCY_{maxpower}$) between the COPD and control groups. These frequencies were predominantly found in a range from 275 Hz up to 600 Hz, although they could reach up to 800 Hz in the COPD group. This parameter was higher in the AB than in the control group (P=0.007). For the cutoff frequency (cut-off), significant differences occurred only between COPD and AB; this measure was higher in the AB group (P=0.023).

Differences also were found considering the sound power distribution in the four frequency bands studied. Although no significant differences between the groups were found in the percentage of power in the highest frequencies (over 1764 Hz - parameter PFB1), the second and fourth bands` contributions (PFB2, PFB4) to the total sound power were significantly different between the AB and control groups: in the AB group, PFB2 parameter was higher (P=0.017), and *PFB4* was lower (P=0.005) when compared with the controls (*Fig. 2*).

According to the discrete wavelet transform results, the energies of all detailed and approximate coefficients were higher in COPD compared with the other two groups. In addition, the parameter ED3 was higher (P=0.018), while *ED5* (P=0.031) and PED5 were lower (P=0.003) in the AB compared with control subjects.

Cough sound properties related to the sample with maximum wavelet coefficients

In the instant when the sample with maximum of wavelet coefficients occurred, powers in the two frequency bands related to the frequency range 352-801 Hz (V3 and V4) were significantly higher in the COPD group compared with the other two groups (P= 0.001). Marked differences were also found in PV5 (power at the lowest frequencies): COPD caused its increase (P=0.001) if compared with the other two groups; asthma caused its decrease (P=0.021) in comparison with the control group.

The contribution of frequency bands expressed as the percentage of the total power was significantly different, especially when COPD was compared with the AB group; the proportion of the second (PV2Ratio, P=0.002) and third frequency bands (PV3Ratio, P=0.008) was lower in COPD. The presence of COPD resulted in an increase in the contribution of V5 (the parameter PV5Ratio, P=0.008). The proportion of the third band (PV3Ratio) was higher (P=0.033) and of the fifth band PV5Ratio was lower (P=0.033) in asthma compared with the controls. COPD differed from the controls only by a decrease in the high frequency contribution - the parameters PV1Ratio (P=0.01) and PV2Ratio (P=0.027). Although we found several clear differences between the COPD and the other two groups, differentiation between asthma and control subjects remained inadequate, which brough it into the focus of our further analysis.

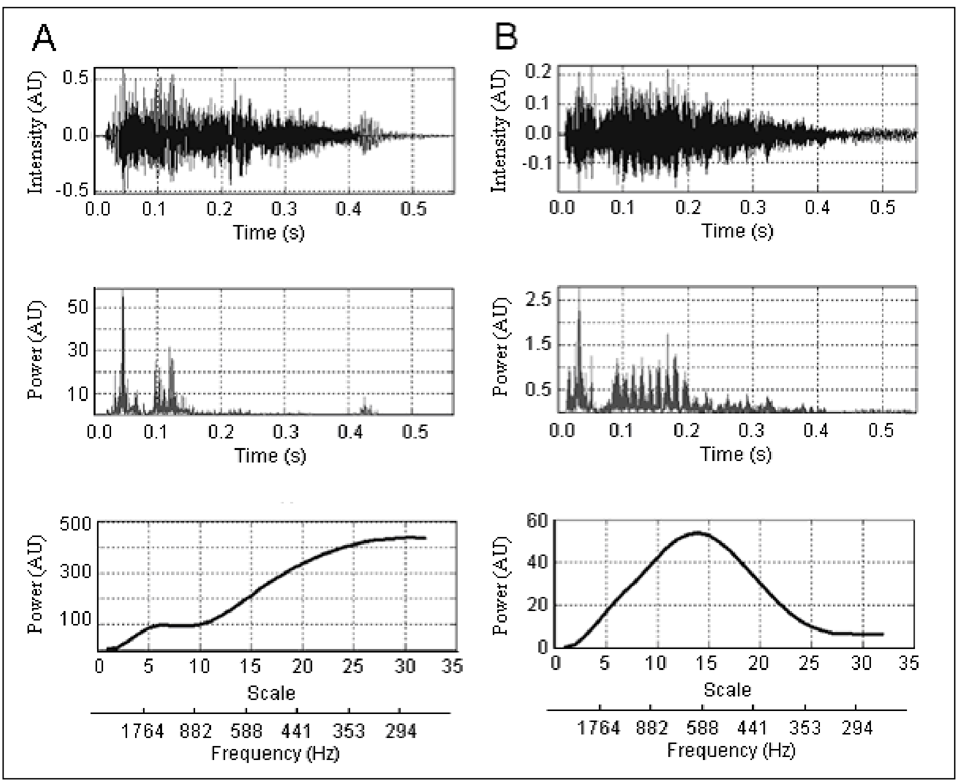

Fig. 2. Time-expanded waveforms and cough sound powers - results of vertical (sound power as a function of time) and horizontal (sound power as a function of wavelet scale) integration: A - control group, B - asthma bronchiale. In the asthma patient, the power of cough sound is shifted to a higher frequency range compared with the control coughs. Different scales correspond to the appropriate frequency values according to the frequency scale shown in the bottom panels. A marked sound non-stationarity can be seen in the middle graphs - sound power oscillates with time in a very complex manner. AU - arbitrary units.

Based on the previous frequency bands division (V1-V5), the frequency band with the maximal power contribution to the signal at a sample with maximum of wavelet coefficients was chosen (the parameter PV_{max}Band). A relation between the PV_{max}Band and group was found (*Fig. 3A*): maximum occurred in the V5 band mostly in the COPD and control groups. In contrast, this situation occurred in only one case in the AB group (1 of the 17 records). The maximum in the V3 and V4 bands occurred in all three groups. The maximum in the V4 band was typical for asthmatic coughs, its occurrence in the V3 band had the same probability for asthma as was that for the controls.

Classification

Two linear functions (Factor 1 and 2, see *Fig. 3B*) were required to discriminate the three groups studied - these two functions were found by a

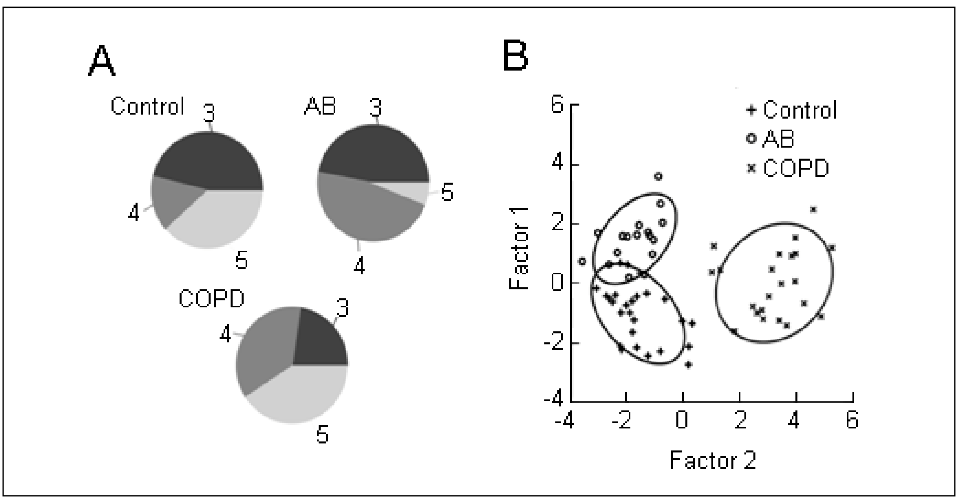

Fig. 3. Discrimination between the analyzed groups. A - Differences in the number of bands with maximum contribution to the sound power (parameter PV_{max}Band) at the time when a sample with the maximum of wavelet coefficients occurs. In the asthma (AB) group, the maximum power in this time instant can be found mostly in the third and fourth bands and rarely occurs in the fifth band. In contrast, in control subjects the fifth frequency band contributes to power at this time instant very often. No significant differences in this parameter were found between the COPD and control groups. Coughs in the AB group differed significantly when compared with the COPD and control groups in this qualitative measure. Power (PV_{max}) of frequency band PV_{max}Band is lower in asthma cough when compared with the control group (Pearson Chi^2, $P<0.05$). B - Final discrimination based on the variables Factor 1 and Factor 2 that are linear combinations of selected cough sound parameters. Variables that contributed the most to the discrimination between the groups assessed were selected by a stepwise backward selection algorithm to minimize cross-correlations between the variables. COPD coughs differed from the other two groups, AB and control cough sounds were more similar in the parameters assessed.

discriminant analysis. Several variables that contributed most significantly to the discrimination of these groups were chosen by an automatic procedure of stepwise backward selection. These parameters included: length of the cough sound, PV_{max}Band, PV4, PV5, PFB1, PFB4, cut-off, total energy, and PED1. Other parameters were excluded from the discriminant functions due to a high correlation with other included variables, which made little suitable for addition new information concerning the group discrimination. About 85-90% of cough sounds were correctly classified into the appropriate groups (*Fig. 3B*).

DISCUSSION

This study demonstrates that it is possible to successfully tell control, asthmatic, and COPD subjects apart, based on the parameters of wavelet analysis of voluntary cough sounds recordings.

The background of the cough sound creation is so far obscure. It is assumed that the cough sound is created by vibration of the lungs and airways structures. The process is accompanied by a change of the laminary air flow into a turbulent one (7), mostly when narrowing of the airways occurs due to bronchoconstriction or hypersecretion. In addition, changes in airway compliance may affect the ability of airway structures to resound, which has an important effect on the cough sound (6), and which motivated us to perform the cough sound analysis during common pathological conditions in the respiratory tract.

Several papers have dealt with a spectral analysis of cough sound by Fourier transform. However, this kind of analysis is suitable only for the processing of stationary signals and the cough sound is non-stationary in its nature (12). Time-frequency methods, including wavelet analysis, enable spectral analysis of non-stationary signals with improved time and frequency resolution.

In the present study we confirmed previous findings that duration of the cough sound is longer in pathological conditions (6, 7). The longest duration highest power of the sound were typical for COPD compared with other groups. In addition, the length of cough sound in AB was greater compared with the controls. According to the visual inspection of a scalogram, we found that lower frequencies (under 1500 Hz) contributed substantially to the overall energy of the cough sound. When the sound intensity during an individual cough decreases (especially at the end of cough), higher frequencies are accented. This finding is in accordance with the findings of Piirila (13). In addition, we tried to objectively ascertain the upper limit of cough sound frequencies. Significant differences in this limit were found between the COPD and asthma patients; in the latter group the frequency limit shifted upward, which is likely caused by airway narrowing.

In the present study we described the pattern of distribution of the signal power in the frequency domain. Pavesi *et al* (3) quantified the energy expended in a cough by measuring the area under the power spectral curve. We quantified the sound energy in a similar manner by considering the area under the wavelet coefficients curve. We found that COPD differs from the other groups by a significantly higher amount of energy in the frequency range under 800 Hz. Sound energy related to the lowest frequencies under 500 Hz contributes to the total energy of cough sound less in the asthma than in the control group. On the other side, frequency band between 882 Hz and 1764 Hz is enhanced in patients suffering from asthma. These findings confirm the observation that higher frequencies are accented in the sound spectrum of cough during airway obstruction (14).

Many of the cough sound characteristics assessed in this study were different between the COPD and the other two (AB, control) groups, including the time of the occurence of wavelet coefficients maximum ($TIME_{max}$; higher in COPD), the scale of this maximum ($SCALE_{max}$; higher in COPD), the parameter *cut-off* (lower in COPD), and all the parameters quantifying cough sound intensity ($MAXPOWER_{time}$, the energies of all detailed and approximate coefficients, total power; all of which were higher in the COPD group).

With regard to the comparison of cough between healthy control subjects and patients with AB, we found differences in the value of wavelet coefficients maximum (MAX, lower in AB), in frequency contributing maximally to the whole cough sound energy ($FREQUENCY_{maxpower}$, higher in AB group), in the contribution of frequencies from 882 to 1764 Hz (parameter PFB2, higher in AB) and frequencies below 490 Hz (PFB4, lower in AB group), and in the parameters derived by discrete wavelet transform (ED3, higher in AB; ED5, PED5, lower in AB group compared with control subjects).

The analysis we perfored enabled to correctly classify about 85-90% of records. Differences in the quality of cough sound can be objectified with the use of methods suitable for non-stationary signal analysis. Acoustic properties of the cough sound can provide auxiliary, rapidly and non-invasively obtainable measures with potentially useful diagnostic and prognostic values. We suggest that after futher research the acoustic parameters could be used for an automatic classification of cough sounds to aid the assessment of disease progression and to monitor therapy.

Acknowledgements: We thank Prof. Milos Tatar for his valuable comments and suggestions. This study was supported by grants VEGA (No. 1/2274/05, 1/2265/05) and by European Social Fund Project N. SOP LZ 2005/NP1-027.

Conflicts of interest: The authors had no conflicts of interest to declare in realtion to this article.

REFERENCES

1. Korpas J, Anand A, Paintal AS. Cough: From Lab to Clinic. New Delhi, Ane Books India; 2006.
2. Smith JA, Ashurst HL, Jack S, Woodcock AA, Earis JE. The description of cough sounds by healthcare professionals. *Cough* 2006; 2: 1.

3. Pavesi L, Subburaj S, Porter-Shaw K. Application and validation of a computerized cough acquisition system for objective monitoring of acute cough: a meta-analysis. *Chest* 2001; 120: 1121-1128.
4. Coyle MA, Keenan DB, Henderson LS *et al*. Evaluation of an ambulatory system for the quantification of cough frequency in patients with chronic obstructive pulmonary disease. *Cough* 2005; 1: 3.
5. Murata A, Ohota N, Shibuya A, Ono H, Kudoh S. New non-invasive automatic cough counting program based on 6 types of classified cough sounds. *Intern Med* 2006; 45: 391-397.
6. Piirila P. Differences in acoustic and dynamic characteristics of spontaneous cough in pulmonary diseases. *Chest* 1989; 96: 46-53.
7. Korpas J, Sadlonova J, Vrabec M. Analysis of the Cough Sound: an overview. *Pulm Pharmacol* 1996; 9: 261-268.
8. Doherty MJ, Wang LJ, Donague S *et al*. The acoustic properties of capsaicin-indeced cough in healthy subjects. *Eur Respir J* 997; 10: 202-207.
9. Subburaj S, Parvez L, Rajagopalan TG. Methods of recording and analysing cough sounds. *Pulm Pharmacol* 1996; 9: 269-279.
10. Murata A, Taniguchi Y, Hashimoto Y, Kaneko Y, Takasaki Y, Kudoh S. Discrimination of productive and non-productive cough by sound analysis. *Intern Med* 1998; 37: 732-735.
11. Olia PM, Sestini P, Vagliasindi M. Acoustic parameters of voluntary cough in healthy non-smoking subjects. *Respirology* 2000; 5: 271-275.
12. Korpas J, Vrabec M, Sadlonova J, Javorka M, Javorkova N. Single, double and multi cough sound differentiation. *Acta Physiol Hung* 2005; 92: 203-209.
13. Piirila P. Acoustic properties of cough and crackling lung sounds in patients with pulmonary diseases. PhD Thesis, Helsinki University, Helsinki; 1992.
14. Debreczeni LA, Korpas J, Salat D. Spectral analysis of cough sound recorded with and without a nose clip. *Bull Eur Physiopathol Respir* 1987; 23 Suppl 10: 57-61.

Received: May 15, 2008
Accepted: August 29, 2008

Author's address: Juliana Knociková, Institute of Medical Biophysics, Comenius University, Jessenius Faculty of Medicine, Mala Hora 4, 037 54 Martin, Slovakia; phone: +421 43 4221422, fax: +421 43 4131426; e-mail: knocikova@chello.sk