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Tidal Breathing Flow-Volume Curves with Impedance Pneumography During Expiratory Loading

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***Abstract*— Diagnosis of asthma in the preschoold children is difficult due to lack of objective lung function tests suitable for this age group. Impedance pneumography (IP) is a mode of measurement that may potentially enable ambulatory 24h recording of tidal breathing indices and respiratory dynamics that are known to relate to small airway obstruction. The aim of this research was to induce changes in breathing control and mechanics and study the ability of IP to reproduce TBFVC and track its changes under potentially difficult conditions. This was achieved by a comparison of direct mouth pneumotachograph (PNT) and IP tidal breathing flow-volume curves (TBFVC) during free breathing and expiratory loading obtained from 17 young lung-healthy subjects. The expiratory loading produced strong and significant changes in the respiratory pattern and mouth pressure. The agreement of PNT and IP normalized TBFVCs was found excellent having the highest distance between the normalized TBFVCs of (mean±SD) 7.4 %±3.6 % and 6.2 %±3.0 % during free and loaded breathing, respectively. The agreement was not affected by the presence of the expiratory load despite it poses multiple potential hazards for the IP measurements. We conclude that by using correct electrode placement and cardiac filtering, IP was able to accurately reproduce and track changes in normalized TBFVCs under normal and abnormal respiratory conditions in healthy adult subjects.**

I. INTRODUCTION

Diagnosis of asthma in preschool children is difficult because of unsuitability of the conventional lung function testing [1]. However, measurements during spontaneous tidal breathing (TB) require minimal co-operation, thus being suitable for small children and infants. There is a large body of research suggesting that parameters derived from TB flow curves or flow-volume curves (TBFVC) change in a deterministic way with obstructive respiratory diseases in young patients. The studies have shown for instance that TB parameters relate to forced expiratory volume in 1 second (FEV1) [2], airway resistance [3], bronchodilator response [4], [5], and methacholine challenge [6], [7] and that they can be used to discriminate between pathological respiratory conditions [8]. The current methods for assessing the TB pattern are hindered by the need of a direct access with the airways. Sedation can sometimes be used to overcome the psychological aspects of the measurement, but the physical face contact [9] and the increased dead space [10] still distort the respiratory pattern. Recently, we have presented highly accurate TB measurements in healthy adults and in adult patients with airway obstruction using a noninvasive mode of measurement, namely the impedance pneumography (IP) [11]–[13]. IP overcomes the presented shortcomings of the conventional measurements. In addition, through 24h TB pattern recording with ambulatory instrumentation [14], IP potentially enables assessing the temporal manifestations of asthma that are receiving increasing research interest [15]–[17].

It is a common misconception that the lung volume signal produced by the IP technique would stem solely, or at least mostly, from chest wall motion as in other noninvasive modes of respiration measurement. This would imply that abnormal respiratory mechanics could distort the IP measurement, and that IP would not be accurate enough to track subtle changes in the respiratory flow pattern. However, IP signal originates largely from the lung tissue [18], not only from the chest wall motion enabling making it potentially resistant to changes in breathing style.

The presented study serves two purposes: Firstly, to show that abnormal respiratory physics, mechanics and control, as induced by intense expiratory loading, do not degrade the IP measurement accuracy, and secondly, to show that IP can be used to accurately reproduce the TBFVC and track its changes in individual subjects.

II. MATERIALS AND METHODS

1) Subjects and Procedures: The subjects were 17 healthy young subjects (age 22-28, body mass index 19.2-26.9, 4 females) with no self-reported chronic respiratory diseases. The study was approved by the institutional review board and a written consent was obtained from all participants. Three-minute recordings of tidal breathing were acquired simultaneously with a pneumotachograph attached to the expiratory limb of the system and with an IP system (Figure 1). The measurements were conducted in supine position and the recording was repeated after attaching a flow resistor element on the expiratory limb. The current feeding IP electrodes were placed on the fifth intercostal space on the midaxillary line and the voltage measurement electrodes on the same level on the proximal side of the arm between the biceps and triceps brachii muscles. This electrode configuration has been previously reported to produce a highly linear impedance change to lung volume change ratio [19]. In addition, single channel ECG was measured to enable the use of a signal filtering algorithm that removes the cardiogenic part of the impedance signal (23).

2) Equipment: The subjects wore a face mask (7900 Series, Hans Rudolph, Shawnee, KS 66227, USA) of the

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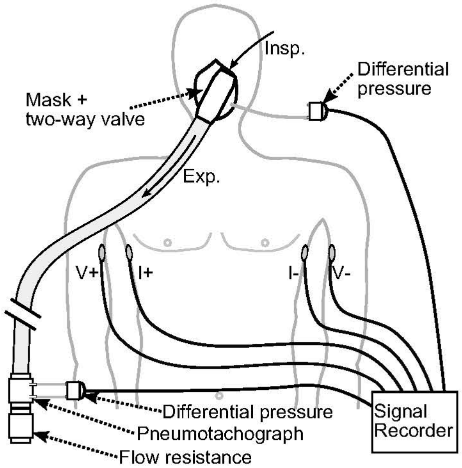

Fig. 1. The measurement setup used for simultaneous pneumotachograph and impedance pneumography tidal breathing recording. The current feeding electrodes of the impedance measurement (I+, I-) were placed on the fifth intercostal space on the midaxillary line and the voltage electrodes (V+, V-) on the arms in a matching position in the proximal side. The flow resistance was attached when indicated. An additional differential pressure sensor was attached to the mask to monitor mouth pressure for post-measurement detection of possible mask leaking.

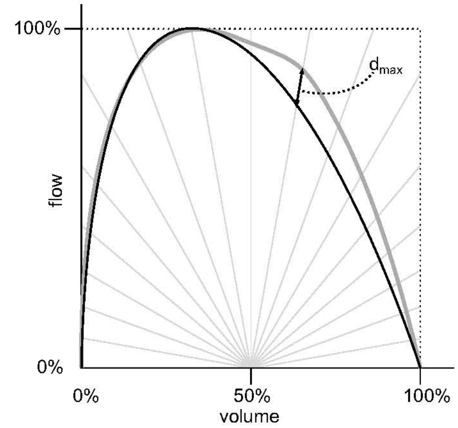

Fig. 2. The difference between the normalized expiratory tidal breathing flow volume curves obtained with pneumotachograph and impedance pneumograph was calculated along each of the radial grey lines in steps of 10 degrees. The largest found difference, d_{max}, was reported.

best fitting size (XS, S, M, L). The mask was connected to a two-way valve system (Series 2700 Large, Hans Rudolph) where the inspiratory limb was free and the expiratory limb was connected to the PNT and the 15 $cm_{H_2O}s/l$ resistor element (7100R, Hans Rudolph) with a three meter tube. For a post-measurement detection of mask leaks, the mouth pressure was continuously recorded inside the mask with a pressure sensor (SS42L, Biopac Systems). The heated PNT (A. Fleisch No. 3, Lausanne, Switzerland) was connected to a differential pressure transducer (SS40L, Biopac Systems, Goleta, CA 93117, USA) with a declared combined linearity and hysteresis error of ± 0.05 %. The flow measurement system was calibrated before each subject using a three-litre calibration syringe (PCS-3000, Piston Medical, Budapest, Hungary). IP signal was recorded with a bioimpedance measurement device (EBI100C, Biopac Systems) using a 100 kHz, 400 μA excitation current. All the transducers were connected to a Biopac MP35 unit that digitized and stored the signals at 500 Hz sampling frequency.

3) Signal Processing and Statistical Analysis: In addition to the respiratory component, the thoracic impedance signal also contains a cardiogenic component that originates from the pulsatile blood movement in the thorax. This distortive part of the signal was attenuated using a slightly modified version of the filtering algorithm presented by Seppä et al (23). For producing a representative TBFVC a number of breaths were averaged as instructed by the official guidelines on tidal breathing analysis [20]. The most similar respiratory cycles were discovered from the IP signal by an algorithm based on comparing the correlations of the flow signals of the cycles. If less than four similar cycles were found due to slow and irregular breathing, the measurement was excluded from the analysis. Each TBFVC was normalized in volume and flow for range 0...100 % and the chosen individual TBFVCs were averaged in 100 angle segments in a manner resembling the one illustrated in Figure 2 to produce a single representative TBFVC. Then the corresponding cycles in the PNT recording were normalized and averaged in the same way. The difference between IP and PNT for each pair of averaged TBFVCs was assessed by calculating their difference along radial lines with 10 degree separation and choosing the highest of those values to represent the difference d_{max} as illustrated in Figure 2. The statistical difference between measurements during the free and loaded breathing was assessed by the paired Wilcoxon signed rank test.

III. RESULTS

Two successful recordings of TBFVC were obtained from all but one subjects simultaneously with PNT and IP yielding a total of 33 measurements. For one subject the loaded respiration was too irregular to produce four similar TBFVCs as required for the analysis. The amount of similar breaths included in the averaging of the TBFVC ranged from 6 to 57 (mean 28.1).

The expiratory loading produced strong changes in the TBFVCs (Fig. 3) along with significant ($p<0.05$) changes in peak expiratory mouth pressure (PEP_m), tidal peak expiratory flow (TPEF), expiratory time (t_E), ratio of inspiratory to expiratory time (t_I:t_E), and respiratory rate (RR) as measured by the PNT (Table I).

The difference between the IP and PNT TBFVCs as assessed by the d_{max} value was found to be (mean$\pm$SD) 7.4 %$\pm$3.6 % and 6.2 %$\pm$3.0 % during free and loaded breathing, respectively (Fig. 4). Most measurements (28 of 33) were found to have d_{max} below 10 %. The difference in d_{max} values between free and loaded breathing was not statistically significant ($p=0.46$).

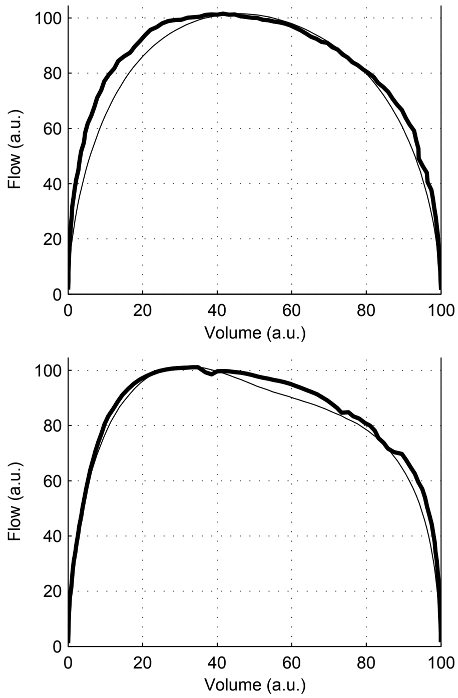

Fig. 3. Expiratory tidal breathing flow-volume curves obtained simultaneously with impedance pneumography (black) and pneumotachograph (gray) during free (upper) and loaded (lower) breathing having largest difference d_{max} between PNT and IP 5.6 % ja 5.0 %, respectively.

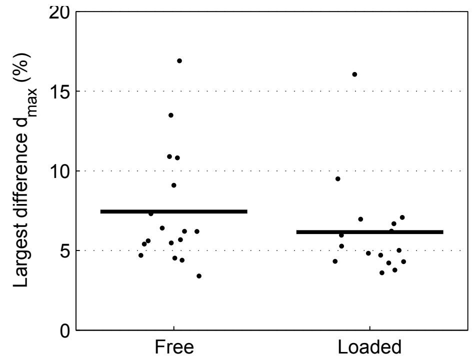

Fig. 4. Largest difference (d_{max}) between the normalized tidal breathing flow volume curves obtained with pneumotachograph and impedance pneumograph as illustrated in Figure 2. Each dot represents one measurement and the lines denote the mean value.

IV. DISCUSSION

The intense expiratory loading used in this study produced clear effects on the control and mechanics of the breathing (Table I). This poses multiple potential hazards for the accuracy of IP measurements for example through substantial changes in the cyclic pattern of the respiratory muscle activation and motion of the chest wall [21], and changes in cardiorespiratory coupling and cardiac mechanics [22]. Indeed, one of the major difficulties in accurate respiratory flow measurement with IP has been posed by the cardiogenic oscillations (CGO). Recently a filter algorithm based on CGO ensemble averages modulated by instantaneous lung volume was proposed to solve the problem [23]. This study brings further evidence of its efficacy under conditions that are rather complex from a cardiopulmonary standpoint. Namely, the pleural pressure changes modulate the heart rate and stroke volume [22], which contribute to the shape and frequency of the measured CGOs.

Furthermore, the electrode placement is most important in determining the dynamic ratio between the lung volume changes and the measured impedance. The electrode configuration used in this study had been previously presented only for prone subjects [19], but was now used in the supine position and found to work appropriately.

We conclude that the agreement between normalized TBFVCs produced with PNT and IP was found excellent. This was enabled by correct electrode positioning and appropriate filtering of the cardiac impedance signal. The agreement was not affected by change in respiratory flow pattern or the changes in the respiratory mechanics as induced by the respiratory loading.

TABLE I

PEAK EXPIRATORY MOUTH PRESSURE (PEPM), TIDAL PEAK EXPIRATORY FLOW (TPEF), EXPIRATORY TIME (T_E), RATIO OF INSPIRATORY TO EXPIRATORY TIME (T_I:T_E), RESPIRATORY RATE (RR), AND TIDAL VOLUME (VT) GIVEN AS MEAN±SD OBTAINED WITH A PNEUMOTACHOGRAPH ILLUSTRATE THE EFFECT OF THE EXPIRATORY LOADING ON RESPIRATION. *: P-VALUE < 0.05

Parameter	Free	Loaded
PEP_m ($cm_{H_2O} s/l$) *	0.61 ± 0.03	4.38 ± 0.28
TPEF (ml/s) *	327 ± 17	228 ± 14
t_E (s) *	2.65 ± 1.24	3.95 ± 1.88
t_I:t_E (1) *	0.80 ± 0.03	0.53 ± 0.02
RR (min^{-1}) *	14.8 ± 4.3	12.6 ± 4.8
VT (ml)	533 ± 195	576 ± 271

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