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Can Asthma in Children be Detected by the Estimated Parameter Values of the Augmented RIC Model ?

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Abstract—**This paper describes the estimation of the parameter values for the recently introduced augmented RIC respiratory system model from Impulse Oscillometry data obtained from both asthmatic and normal children. An analysis of these values has indicated that one of the capacitance parameters of the model provides good discrimination between these two groups of children; moreover, this finding corresponds well with current medical understanding of the pathology of asthma.**

Keywords—**Respiratory impedance, respiratory system model, parameter estimation, asthma**

I. INTRODUCTION

Asthma is a chronic disease that affects more than one child in 20 in the U.S. A critical step in fighting childhood asthma is its early detection since, if left untreated, it can lead to permanent damage of the airways and make it difficult to bring the condition under control. However, this is not an easy task especially when dealing with preschool children. One of the difficulties is that lung function is most commonly assessed at present by spirometry, which requires maximal coordinated inspiratory and expiratory efforts. The considerable degree of cooperation required from the subject under test makes spirometry inappropriate for younger children, and also for older adults. On the other hand, respiratory function assessment by the method of forced oscillation [1] requires minimal passive patient cooperation. Hence even young children can have valid measurements of their respiratory function and these measurements can be analyzed to determine if they have asthma.

In general, the forced oscillation technique measures the air pressure and rate of air flow at the entrance to the respiratory system, thereby obtaining its mechanical input impedance. In particular, the Impulse Oscillometry System (IOS) is a commercially available product for measuring this impedance by employing brief 60-70 ms pulses of pressure. IOS measurements yield frequency-dependent impedance curves that have been shown to offer the most reliable, reproducible, and best-suited method for demonstrating reversible airflow obstruction in preschool (children aged 2 to 5 years) asthmatics [2]. These impedance curves may also be correlated with models consisting of electrical components that are analogous to the mechanical resistances, compliances and inertances inherent in the respiratory system. Consequently, parameter estimates for such respiratory system models [3-8] can then possibly serve as a complementary quantitative measure for the detection and diagnosis of various respiratory diseases, including asthma.

In this paper, we describe follow-on work to [7, 8], which examined the performance of five respiratory models, including a newly introduced augmented RIC model, by estimating their parameters and then comparing the corresponding estimation errors (on average for each model), using IOS data obtained from adults and children, respectively. We present an analysis of the estimated parameter values for the augmented RIC model, derived from the IOS data for both asthmatic and normal children, that is aimed at determining if the model's parameters can discriminate between the two groups and the degree of discrimination that they may provide.

II. RESPIRATORY IMPEDANCE MODELS AND DATA

Various electric circuit models with lumped parameter components representing the respiratory system's various resistances (R – typically in units of $cmH_2O/l/s$ or kPa/l/s), inertances (I – $cmH_2O/l/s^2$ or $kPa/l/s^2$) and compliances (C – l/cmH_2O or l/kPa), have been studied over the years. The simplest are the RC and RIC models [3]. Some work has also been done on the DuBois model [1, 4], while Schmidt *et al.* [3] studied the Mead model and the other three above-mentioned models with respect to infant respiratory impedance. The extended RIC model was introduced in [5] and then analyzed in detail [6] to reveal its advantages as well as shortcomings. The latter then prompted the proposal of the augmented RIC model in [7]. Since the augmented RIC model is a relatively new model and also the focus of this paper, it will be the only one described in detail here.

The augmented RIC model was proposed as – and shown in [7] to be – an improvement of the extended RIC model. The additional element C_e (see Fig. 1), as compared to the extended RIC model, represents extrathoracic compliance due to upper airways shunt effects, which is thought to cause the increase in the resistive impedance at higher frequencies that is observed in a significant proportion of the IOS data. Such an upturn cannot be achieved by the extended RIC model and thus accounts for its poorer modeling performance in such cases [6]. Alternatively, the augmented RIC model can be regarded as a simplification of the Mead model (with its lung compliance C_l and chest wall compliance C_w parts ignored).

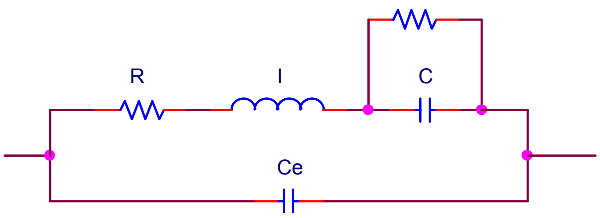

Fig. 1. Augmented RIC model

The augmented RIC model's impedance is given by

$$Z = \frac{A\left(RA + R_p\right)}{\left[A\left(1 - \omega^2 IC_e\right) + \left(\omega^2 R_p^2 CC_e\right)\right]^2 + \left[\omega C_e\left(RA + R_p\right)\right]^2} + j\frac{\omega\left(IA - R_p^2 C\right)\left[A - \omega^2 C_e\left(IA - R_p^2 C\right)\right] - \omega C_e\left(RA + R_p\right)^2}{\left[A\left(1 - \omega^2 IC_e\right) + \left(\omega^2 R_p^2 CC_e\right)\right]^2 + \left[\omega C_e\left(RA + R_p\right)\right]^2} \tag{1}$$

where $A = 1 + (\omega R_p C)^2$.

III. MODEL PARAMETER ESTIMATION

Estimating a model's parameters is similar in concept to curve-fitting. Therefore, it is necessary to first select a suitable error criterion E that is to be minimized, where

$$E = g\{f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_m(\mathbf{x})\} \tag{2}$$

in which $f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_m(\mathbf{x})$ are functions involving the n-vector $\mathbf{x}$ of parameters x_1, x_2, … , x_n, and the independent variables, *e.g.*, frequency, of the m data samples [9]. Error criteria that are commonly used in parameter estimation problems include least absolute value (LAV), least squares (LS), minimax, and maximum likelihood. The LAV criterion is nearly as accurate as LS for data with normally distributed errors, while the minimax function minimizes the maximum element [9]. But the LS criterion is by far the most commonly used one for curve fitting and parameter estimation, and was the criterion adopted for this present work. In its generalized form, the LS criterion

$$\min\left[E = \sum_{i=1}^{m}\{w_i f_i(\mathbf{x})\}^2\right] \tag{3}$$

minimizes the weighted (by w_i) sum of the squared errors (differences from the m data samples).

IV. PRIOR PARAMETER ESTIMATION RESULTS

The IOS data analyzed in this paper were collected recently from two groups of children. The first group of data was comprised of results from 156 tests of children with asthma (102 female and 54 male, 2 – 5 years old, 12.0 – 25.9 kg, 0.88 – 1.40 m), while the second group was comprised of results from 173 tests of normal children (107 female and 66 male, 2 – 5 years old, 12.0 – 25.9 kg, 0.88 – 1.40 m). The IOS data from each test were separated into two categories: resistive impedance (Z_R), and reactive impedance (Z_X). The data samples were at 5, 10, 15, 20, 25 and 35 Hz for both Z_R and Z_X. These twelve values were used for estimating the parameters of the RIC, extended RIC, augmented RIC, DuBois, and Mead models, as described in [8]. A linear LS algorithm was used for estimating the RIC model's parameters while a nonlinear LS algorithm was used to estimate the parameters of the other four respiratory models and the total estimation error (defined as the square root of the sum of the equally weighted least square real and imaginary impedance errors) was calculated for each test data processed.

For the test data from the asthmatic children, the mean total estimation errors for the five models were compared to each other. The DuBois model yielded the best fit while the augmented RIC model performed in between the Mead model and extended RIC model (see Fig. 2a). However, the Mead model typically demanded unrealistic values of C_l and C_w, and the DuBois model typically demanded unrealistic values of tissue compliance C_t – the majority being several orders of magnitude larger than the expected range of values (based on the existing literature). In contrast, the parameter estimates obtained for the augmented RIC model were in the expected range for such patients. Then for the test data from the normal children, the DuBois model again yielded the lowest mean total error followed by the Mead and augmented RIC models while the RIC model again provided the worst fit (see Fig. 2b) but again the estimates for C_l and C_w (Mead), and for C_t (DuBois) were typically unrealistic.

V. PRESENT ANALYTICAL RESULTS AND DISCUSSION

Having established that the augmented RIC model is a reasonable alternative to the DuBois and Mead models, and an improvement upon the extended RIC model, the parameter estimates of the augmented RIC model were analyzed further to determine if they could be used to discriminate between the asthmatic and normal children.

Previous studies have determined that the reference values for respiratory impedance are strongly correlated to subject height and weight [10]. Hence, Fig. 3a shows a scatter plot of the estimated values of the R parameter, representing central resistance, for both the normal and asthmatic children versus their height, while Fig. 3b shows a scatter plot of the same estimated values versus their weight. Trend lines for those values belonging to the normal group and for the asthmatic group, based on linear regression using a least squares error criterion, are also plotted. In Fig. 4, 5, 6 and 7, the same types of plots and trend lines are shown for the estimated values of the I, C, R_p and C_e parameters, respectively.

As can be seen from these plots, there is little difference in the scatter pattern and trend line for each parameter's values plotted versus either height or weight. Comparing between the parameters, it is clear that the C parameter, representing airway capacitance, provides significantly better discrimination between the asthmatic and normal children, with the trend line values for the asthmatic group (given by the equations C = 0.0839*height – 0.0520 and C = 0.00167*weight + 0.00596) being about 50% of the trend line values for the normal group (given by the equations C = 0.0966*height – 0.0382 and C = 0.00258*weight + 0.01668). More specifically, 90.8% of the normal children and 91.3% of the normal children had C values *above* the corresponding asthmatic trend line values for their height and weight, respectively; 92.9% of the asthmatic children and 92.3% of the asthmatic children had C values *below* the corresponding normal trend line values for their height and weight, respectively. Finally, 91.9% of the normal children had C values above the corresponding asthmatic trend line values for *both* their height and weight, while 92.9% of the asthmatic children had C values below the corresponding normal trend line values for both their height and weight.

This association of asthma with reduced respiratory capacitance is hardly surprising. In [11], it was noted that the capacitive properties of the small peripheral airways are responsible for low frequency reactance (and for AX, which is the magnitude of the integral of the reactance Z_X from 5 Hz to resonant frequency f_{res} where $Z_X = 0$) and this correlates with the frequency dependence of both low frequency resistance and low frequency reactance. While asthma used to be commonly thought of as 'bronchomotor tone', *i.e.*, constriction of larger airways that causes wheezing, this understanding has been augmented over the past decade by an increasing awareness of the significance of inflamed small peripheral airways in the pathology of asthma. When small airways are inflamed, their lumen is decreased and their wall thicknesses increased. Both of these factors contribute to decreased capacitance of the small airways (and to some degree an increase in resistance).

It has been known for a few years now that low frequency reactance is the more sensitive indicator of the severity of asthma. Therefore, it is also worth noting here that a reduced value of C in the augmented RIC model increases the frequency-dependence of both Z_X and Z_R at low frequencies (and thus AX, which is correlated), as seen in Fig. 8.

VI. CONCLUSIONS

This paper has described the estimation of the parameter values for the recently introduced augmented RIC model from the IOS data of asthmatic and normal children. An analysis of these values has indicated that the C parameter of the model, representing airway capacitance, provides significant discrimination between these two groups of children; this finding corresponds well with current medical understanding of the pathology of asthma.

ACKNOWLEDGMENTS

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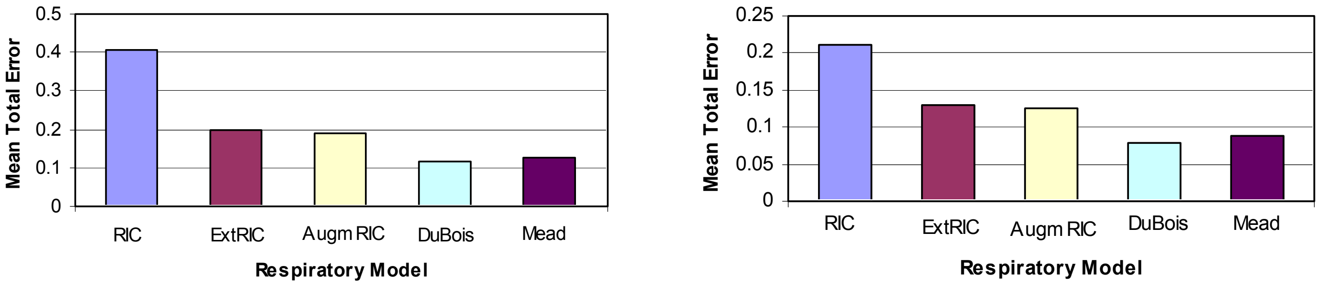

Fig. 2. Mean total errors for (a) asthmatic child patients and (b) normal child subjects

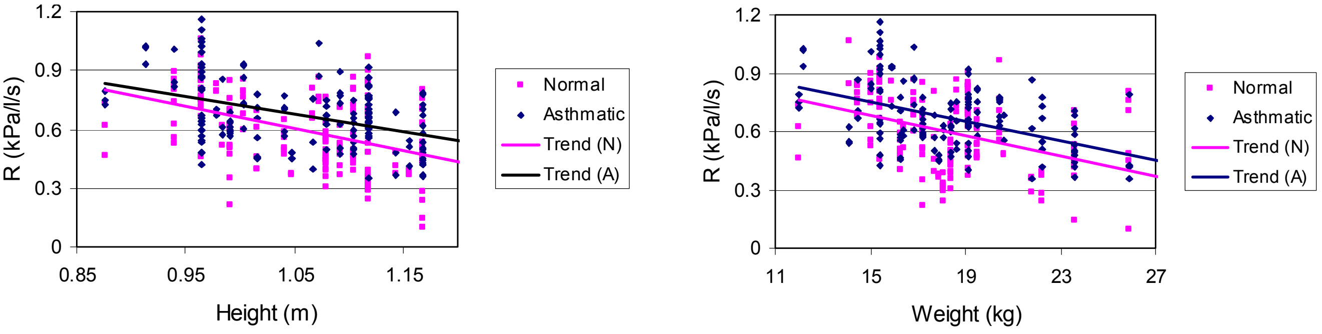

Fig. 3. Estimated value of R parameter versus (a) child’s height and (b) child’s weight

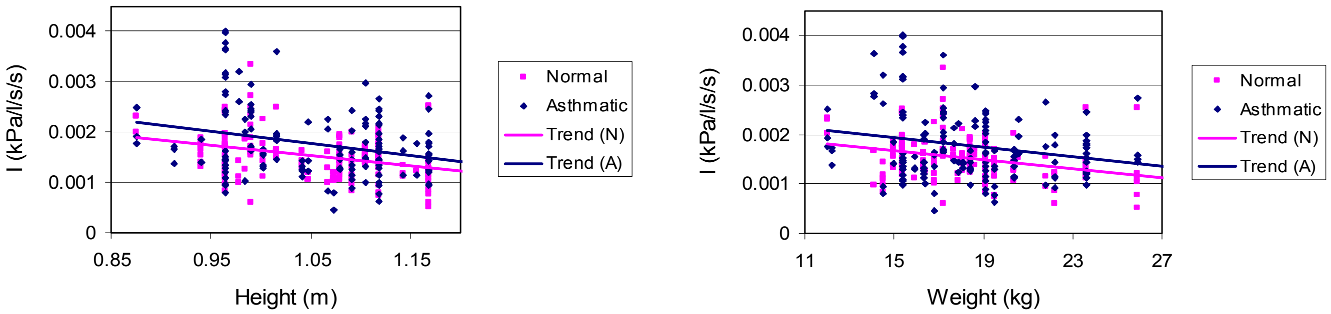

Fig. 4. Estimated value of *I* parameter versus (a) child's height and (b) child's weight

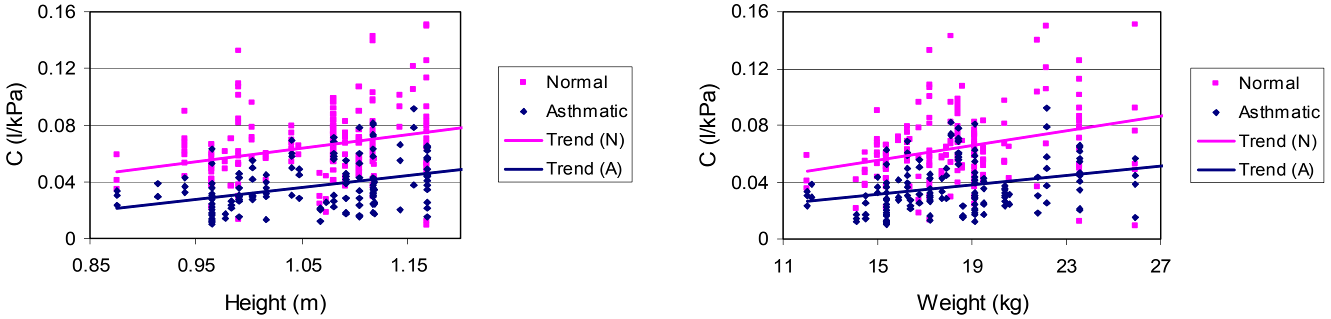

Fig. 5. Estimated value of *C* parameter versus (a) child's height and (b) child's weight

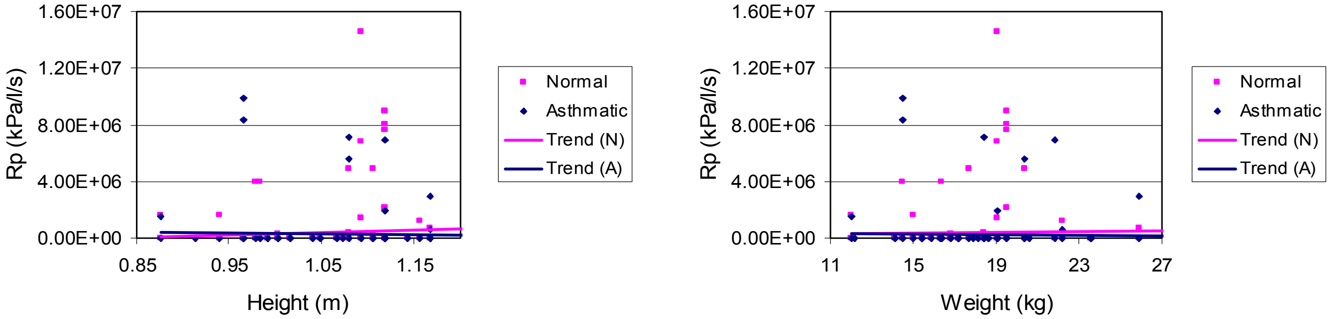

Fig. 6. Estimated value of R_p parameter versus (a) child's height and (b) child's weight

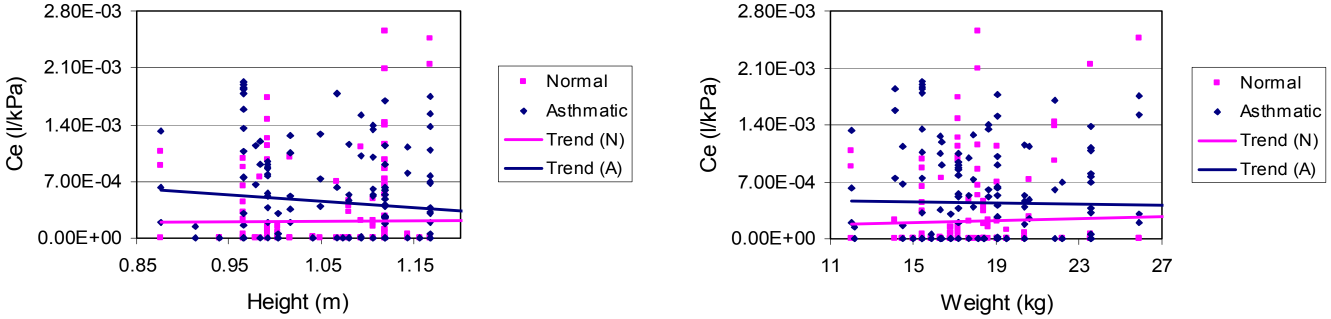

Fig. 7. Estimated value of C_e parameter versus (a) child's height and (b) child's weight

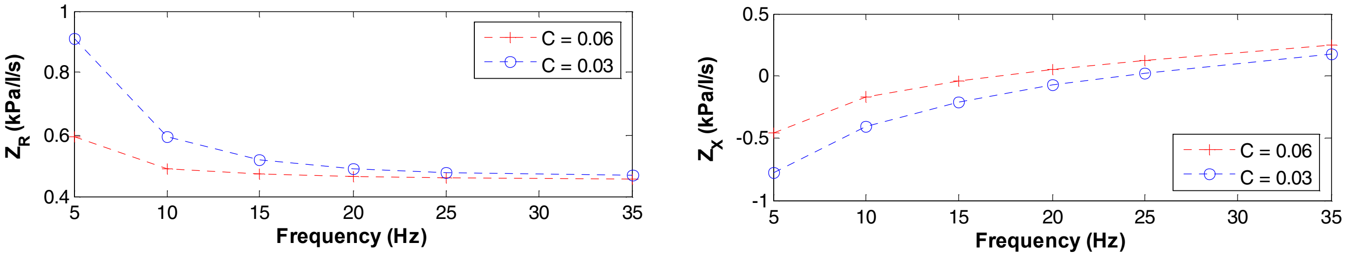

Fig. 8. Comparison of Z_R and Z_X curves for two values of *C*