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Research Article

Respiratory System Model Take into Account Pathology

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Abstract: In this study, nonlinear phenomenon of respiratory system is analyzed. Airway is partitioned into four parts by different morphology which causes different fluid dynamic character. Reasons that cause nonlinear phenomenon for different parts are given. To simplify the representation, corresponding parameters are selected to compromise the complicity and precision. Then, the suggested representation of respiratory system is summarized so that the model can be used easily in lung simulator.

Keywords: Airway resistance analysis, fluid dynamic character, lung representation, nonlinear phenomenon

INTRODUCTION

Knowledge of the main viscoelastic parameters of the respiratory system in lung simulator is important for determining airflow in normal and patient condition. The simplest model used is first-order model which includes the total respiratory resistance and elastance. Recent studies have shown that this first-order model is, however, an oversimplified representation of nonlinear, multi-compartment respiratory mechanics (Adam and Janusz, 2006). Bernhard (2003) creates a mathematical nonlinear pressure-flow model with the following characteristic: avoid oversimplification model, airway partition by dynamic relationship, some mechanic parameters variation caused by pathology and tries to model very precisely the tracheobronchial tree. However, more comprehensive pathology should be taken into account in his modelling. A detailed computational model trying to include these nonlinearities can be found in the literature (Adam, 1998), which is a rather complex model that contains 132 parameters. In this case, the structural complexity is achieved at the expense of model linearization.

The aim of this study is to derive a computer model for lung simulation based on the influence of pathological changes localized in specific places in the respiratory system. The model take following factors into consideration: lung parameters change caused by different disease, the morphology of the airways, dynamic behavior of the lung and the chest wall, nonlinearities relating to gas turbulences and airway collapsing, as well as time-variability of mechanical properties following the ventilatory cycle. We will represent the dynamical nature of the bronchial tree with the model structure in a nonlinear way.

AIRWAY DIVISION BY NONLINEAR DYNAMIC CHARACTER

Morphometric model of the lung and the corresponding fluid dynamic: The morphometric model used to describe the behavior of the respiratory system is based on the symmetrical model proposed by Weibel (1963). In this model, the tracheobronchial tree is divided into 24 generations, where generation 0 is the trachea, generation 1 is extrapulmonary bronchus, generations 2 to 6 are larger intrapulmonary bronchi with cartilage, generations 7 to 16 are bronchioles with smooth muscle, generations 17 to 22 are all respiratory bronchioles and generation 23 corresponds to alveolar sacs. The airways multiply by regular dichotomy. Starting from the trachea, each branch of a given generation divides into two identical daughters, therefore generation n has 2^n branches.

The fluid can be divided into two types: turbulent flow and steady flow. Transform from steady flow to turbulent flow is decided by Reynolds number. The steady flow is parabolic flow with radius and obtain Poiseuille theorem. The turbulent flow shape is equal in center pipe and flow equation described by Rohrer's equation.

Airway segment based on different fluid dynamic performance: Based on anatomical structure, the entire respiratory system (including airway and lung) can be divided into two zones: conductive zone (generation 0 to 16) and respiratory zone (generation 17 to 23). In conductive zone, the airway resistance is the main effective factor. At the same time, in respiratory zone the compliance is the dominant parameter. The last 7 generations (respiratory zone) are modeled as a single

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viscoelastic element with constant values and the chest wall is combined in lung compliance value.

Summarized from fluid dynamic analysis, the conductive zone can also be segmented into two parts, i.e., the larger airway and the small airway, which have different flow behaviors. For lung simulator aim, we segment the airway by fluid dynamic performance of different generations. Existed analysis (Adam and Janusz, 2006) reveals three sections of the bronchial tree with distinct resistive properties. Generations 0-6 are characterized mainly by turbulent dissipation of the head pressure, laminar flow and airways collapsing dominate in generations from 7 to 16 (Mauroy *et al*., 2004) and lastly, flow in generations from 17 to 23 is approximately laminar, where compliance, not resistance, is the main parameter.

Dynamic properties of airflow in the bronchial tree follow gas and tissue inertia and airway wall compliance. The description of the physics can be simplified to a lumped parameter model aggregating the main phenomena (seen as resistance, inertance and compliance) within every airway generation. Therefore, the first airway section can be depicted as aggregated inertance and resistance in series; of course the resistance is dominant factor. The second part is represented by serial inertance and resistance with pleural pressure. And the third part is mainly compliance with additional resistance.

Different pathology and segments they influenced: The respiratory ventilation functional obstruction can be divided into two main types: restrictive hypoventilation and obstructive hypoventilation. The restrictive hypoventilation is mainly caused by two factors: respiratory muscle activation decrease and compliance decrease of lung. The disease, such as fibrosis, pneumothorax, pulmonary overventilation, lung edema, can cause compliance decrease and thus have influence on lung compliance. The obstructive hypoventilation is mainly caused by airway structure or obstacle. The disease typically emphysematous, asthmatic lung and larger airway occluded are obstructive.

The obstructive hypoventilation can also be divided into two types: Central airway obstacle and Peripheral airway obstacle. The central airway obstacle can further be divided into extrapleural and intrapleural obstacle. The extrapleural obstacle locates in trachea and main bronchi which extrapleural, correspond to generations 0 and 1. The extrapleural obstacle shows inspiration difficult. The intrapleural central airway obstacle locates at bronchi intrapleural and is expiration difficult. To show this different localization obstacle, we must subdivide the upper airway into two segments: the extrapleural segment and intrapleural segment, which have different symptom in respiratory disorders.

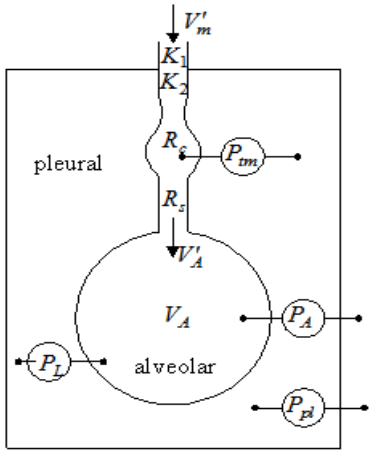

Fig. 1: The serial lung model has different parts and so have different fluid dynamic character correspond to pathology

Simplified model can be used with main character reserved: For the purpose of modeling, the pulmonary system has to be simplified to elements which represent specific physical features of the lung. The lung model is restricted to serial inhomogeneity with respect to both resistance and elastic properties of the airways. The currently prepared mathematical model is based on serial model which consists of one alveolar compartment connected to ambient air by a tube representing the airways. All alveoli are lumped to one compartment V_A, which is connected to ambient air by a tube representing the lumped airways. This tube consisted of four parts in series: one for the small airways, a compressible segment in between, one for the large airways intrapueural and the last one for large airways extrapleural. The alveolar compartment and the intrapulmonary airways are influenced by the intrathoracic pressure, which is equal to pleural pressure P_{pl}. In premilinary result, the serial model of lung can be schemed in Fig. 1.

WHICH PARAMETERS SHOULD BE SELECTED FOR DIFFERENT PARTS

Common rules for whole respiratory system: Flow through compliant tube is usually treated as incompressible, even though the fluid may be a compressible gas. Air compressibility may be important in coughs or forced expiration manoeuvres, when air is rapidly expired from the lung. In our model, we only consider airflow with normal speed, so the air compressibility can be neglected.

Fluid dynamic laws for different segments: The resistance of the upper airways R_u is modeled as a rigid part. R_u includes a flow dependent term and is expressed by the Rohrer's equation:

$$\Delta p = K_1 \times Q + K_2 \times Q^2 \quad (1)$$

where,
Δp = A pressure drop in the upper airways
K_1 = A factor related to the pressure drop due to laminar flow in the upper airways
K_2 = A factor related to the pressure drop due to turbulent flow in the upper airways
Q = The flow

The peripheral airways connect tightly with alveolar. The luminar diameter changes with the intrathoratic pressure when breathing, the resistance of the peripheral (small) airways R_s is variated as a result. In the inspiratory stage, bronchiles is pulled by elastic tissue, caliber become large, resistance R_s become small. Based on the dimensions of these airways, a Poiseuille flow is assumed in either stage of breath. So, the linear pressure drop in these airways is given by:

$$\Delta p = R_s \cdot Q \quad (2)$$

where R_s is the resistance of the small airways.

The resistance of the compressible segment represents the resistance in those airway generations, which are susceptible to the changes in transmural pressure P_{tm} being the difference between intrabronchial and pleural pressure. Transmural pressure can be expressed in the following equation (Verbraak *et al*., 1991):

$$P_{tm}(x) = \frac{1}{C}V + R_c(x)Q \quad (3)$$

We can conclude that P_m is determined by volume and flow both. The stiffness of airways increases from the alveoli towards the mouth.

The total serial lung model can be represented by equation:

$$P = K_1Q + K_2Q^2 + K_3Q + K_4Q + \frac{1}{C}V \quad (4)$$

where K_3 is R_s and $K_4$is R_c, as illustrated in Fig. 1.

Although the equation is simple, the decision of each coefficient is a rather complicate work. Based on the previous description, some confine should be added on the coefficients selection.

Pathophysiology and corresponding mechanic parameters: The parameter values for model are divided into five classes (Guido *et al*., 2001): the Normal lung (N), the Emphysematous lung (E), the Fibrotic lung (F), the Asthmatic lung (A) and the lung with a large increase in Upper airway resistance (U). The characteristic for the various parameters are generalized from reviews of pulmonary pathophysiology and those for upper airway resistance for class U are derived from patients with bilateral vocal cord paralysis. The physiological condition is analyzed individually in following context:

- Normal lung has only two parameters, i.e., lung compliance C and airway resistance R, needed in model. Because airway resistance in normal physiology has few change, resistance of inflow and outflow remain constant.
- Chronic Obstructive Pulmonary Disease (COPD) phenotype refers to chronic bronchitis and emphysema in which the airways become narrowed. Emphysema is modelled by a lower value of the elastic recoil P_L and thus increase the lung Compliance (C). Because of a lower P_L the traction on the walls of the respiratory bronchioles is smaller and consequently pleural pressure will be less negative with respect to alveolar pressure, causing a narrowing of the small airways and therefore an increase in R_S.
- Asthma is a common chronic inflammatory disease of the airways characterized by variable and recurring symptoms, airflow obstruction. It is generally believed that airway inflammation mainly reside in small airway, but recent studies show that inflammation can exist in whole airway up to trachea. In asthma both upper and peripheral airway resistances are increased, which is reflected in increased coefficients of all airway segment.
- Fibrosis is the formation or development of excess fibrous connective tissue in an organ or tissue as a

Table 1: Lung disease and its mechanical parameters variation

Type	Emphysema	Asthma	Fibrosis	Upper airway obstruction
Alveoli	Yes		Yes	
Pheripheral airway	Yes			
Middle airway		Yes		
Upper airway		Yes		Yes

Table 2: Parameters should be adjusted in different pathology

	K_1	K_2	K_3	K_4	C
Emphysema				Yes	Yes
Asthma	Yes	Yes	Yes		
Fibrosis					Yes
Upper airway obstruction	Yes	Yes			

reparative or reactive process, as opposed to a formation of fibrous tissue as a normal constituent of an organ or tissue. Scarring is confluent fibrosis that obliterates the architecture of the underlying organ or tissue. In fibrosis the characteristic physiological disorder is the increased stiffness of the lung tissue, which is modelled by an increase of P_L and a decrease of C.

- To simulate patients with an upper airway obstruction, only turbulent flow resistance are greatly increased.

For the upper respiratory condition, we can give the following variance summation, shown in Table 1, which indicates which segment mechanic parameters should be adjusted in lung simulator.

The parameters of every part can be adjusted solely, at the same time parameters of different part should be adjusted according to pathology. Combine the hydrodynamics of airway with pathology, the parameters that should be tuned can be summarized as Table 2.

Although coefficients can be adjusted arbitrarily, some correlation must be considered in simulation procedure, in other words, coefficients should be adjusted by some rules, as the following constraints be added on the model:

- Airway resistance of breath in and out are different.
- Coefficients K_1 and K_2 should be tuned simultaneously.
- K_4 and C should be changed at the same time.
- K_3 is influenced by P_{tm} which is affected by volume and flow.
- Airway resistance partition for different airway segment is related to physiology; in healthy condition resistance is mainly caused by large and middle generation airways. However, in pathology resistance increase is caused by peripheral airways.

CONCLUSION

Respiratory system simulation is a rather complex problem because there are too many factors and parameters that should be considered; in Adam (1998) model even 132 are used. The simplified model should be identifiable and ought to be considered as still valid. Which parameters should be selected in modeling construction is a dilemma condition. This study aims to build a model for a lung simulator which oriented from the pathophysiology. Some dynamic parameters that will subtle change the normal breath are neglected, such as air compressibility and air inertance. Then the factors that less important in identifying different respiratory pathology are omitted. To grasp the two key points, i.e., simplicity and validation, a rather simple model while valid for pathology identification is built, which is the main task for medical patient simulator. In conclusion, the lung model this study established is a good compromise for lung simulator.

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