MODELING OF THE GAS EXCHANGE IN THE LUNG STRUCTURE

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Abstract. The article deals with mathematical simulation of gas flow during artificial lung ventilation. Results of the mathematical modelling are compared with results of the animal ventilatory experiment and with another modelling approach. The model and algorithm are able to predict tracheal gas insufflation effect on conventional or high frequency ventilation.

Introduction

Artificial lung ventilation is inseparable part of critical care medicine today. Therefore it is necessary to design a new ventilatory technique, which will be safe to a patient. Safety means, that the pressure amplitude used will be small and CO_2 removal will be sufficient. There are many ventilatory techniques of conventional artificial lung ventilation (CV) of patients with acute respiratory failure that are widely used in the clinical practice, but there are still some limiting factors of their usage, many of adverse effects and there are also frequent cases when the artificial lung ventilation fails. Therefore new unconventional ventilatory techniques have been developed, for example high frequency ventilation (HFV). These techniques lead to decreasing of tidal volume (TV) and to increasing of breathing frequency. Some techniques are still being developed and not used in clinical practice yet. One of them is tracheal gas insufflation (TGI).

TGI is an additional technique to artificial lung ventilation (CV or HFV) leading to improved oxygenation and CO_2 removal without increasing of TV or pressure amplitude. For introduction of this method into the clinical practice, it is necessary to evaluate its influence on patients. This is impossible without animal experiments and mathematical modelling, because some data are not measurable directly on patient.

The aim of this work is to find a lung model and to describe the influence of tracheal gas insufflation (TGI) on artificial lung ventilation. Because of the complicated lung structure, some simplifications must be introduced. Therefore the lung structure is modeled as a diverging tube with exponentially growing diameter. The outputs of the model were compared with an animal experiment. A good agreement with reality was achieved.

Tracheal gas insufflation

Tracheal gas insufflation is a method within array of supporting unconventional ventilation techniques. TGI is based on fresh air delivery to the endotracheal tube or to the airways using a thin TGI catheter with a constant TGI flow of fresh air. The distal end of the TGI catheter ends several centimetres above carina (Fig. 1). TGI is used as a conjugate technique to conventional artificial lung ventilation [1]. Expired gas in the trachea, endotracheal tube and in some main bronchi is washed out and replaced by fresh air delivered from the TGI catheter. This principle partly protects lung from the re-inspiration of already expired gas. The effect is equivalent to the anatomic dead space reduction [2].

A new method of ventilation based on combination of TGI with HFV has been documented in one experimental study [3]. Considering the effect of V_D in HFV and effect of V_D reduction during TGI, the combination of HFV and TGI may offer a surprising result. Description of TGI effects during CV and HFV is the main aim this study. The mathematical model of gas flow during CV and HFV must be completed by TGI flow source and calculation algorithms must be accordingly adapted.

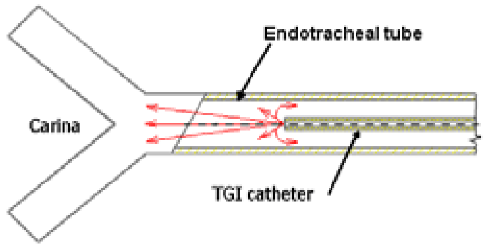

Fig. 1: Principle of tracheal gas insufflation.

Mathematical modelling of lung structure

Bases of the gas flow modelling during artificial ventilation are described by Jongh [4] where convection-diffusion equation is presented. Unfortunately many simplifications have been applied and several incorrect principles not respecting physiological processes have been introduced into the computation. Therefore it was necessary to make changes in the model and employ simulation of regional oxygen consumption, regional velocity calculation, etc. The convection-diffusion equation is:

$$\frac{\partial c}{\partial t}+v\frac{\partial c}{\partial x}-D\frac{a}{A}\frac{\partial^2 c}{\partial x^2}-\frac{D}{A}\frac{\partial a}{\partial x}\frac{\partial c}{\partial x}=Q$$

where: a is cross-sectional area of the bronchial tube(s) [cm^2], A is cross-sectional area of the bronchial tube(s) including alveoli [cm^2], Q is consumption of oxygen [cm^3/s], D is diffusion coefficient [cm^2/s], v is axial velocity [cm/s] and c is fractional oxygen concentration [-].

The first term on the left-hand side represents oxygen concentration $c(x,t)$ variation in time. The second term describes the convection, the third one represents the molecular diffusion and the last one involves the varying cross-sectional area into diffusion processes. The term on the right-hand side represents oxygen consumption in the alveolar space. The consumption of oxygen per generation can be calculated proportionally to the alveolar volume of the generation. The summed consumption of oxygen over all generations equals the total oxygen consumption. Geometry of the model follows morphometric lung data [5].

TGI catheter must be added into the model for description of tracheal gas insufflation effect. The TGI ventilation is modelled as an additional source of ventilation gas mixture. Clinical arrangement is described in paragraph 3.

The convection-diffusion equation is solved by numerical simulation. The respiratory system is divided into many nodes in x (axial) direction with variable length of Δx. Each node is characterised by: length of Δx, cross-sectional area of the bronchial tubes per generation, cross-sectional area of the bronchial tubes including alveoli per generation, radius of equivalent circular area to the total cross-sectional area of bronchial tubes with alveoli per generation, alveolar oxygen consumption per generation and cumulative volume of alveoli of all previous generations from the airway opening. TGI flow source is situated to a node corresponding with the distal end of the TGI catheter. Corrections of axial velocity and oxygen concentrations must be conducted at this point. The correction depends on the ventilatory phase.

Very important part of the modelling is a validity of the TGI gas flow model. Two results are available for comparison: 1. results of the mathematical simulation by the created model, 2. results of an animal experiment [6]. Unfortunately the results are obtained for different objects: simulation is carried out using the model of an adult (78 kg), but the experimental results come from the animal experiment on a group of rabbits (2.5 kg). However different the examined objects are, the results still can be compared [7]. Some appropriate anatomical and ventilatory parameters are proportional to the body weight. The fact that they are measured in human being or in different animal species does not play a very significant role. Some essential ventilatory parameters are equal in both cases.

The last difference between the theoretical and experimental approaches is that mathematical modelling produces values of alveolar partial oxygen pressure P_AO_2 whereas the animal experiment provides values of arterial partial oxygen pressure P_aO_2. There is a small physiological difference between these two values in healthy objects. But when studying only changes of these values, there are always proportional and they have to be very similar.

Results

Results of the animal experiment confirmed that TGI is more efficient during HFV then during CV. The difference in increased oxygenation is $\Delta P_aO_2\,_{\mathrm{HFV+TGI}} - \Delta P_aO_2\,_{\mathrm{CV+TGI}} = 11.2 \pm 3.6$ % and for mathematical simulation $\Delta P_AO_2\,_{\mathrm{HFV+TGI}} - \Delta P_AO_2\,_{\mathrm{CV+TGI}} = 14.4$ %. Alveolar P_AO_2 is calculated as steady-state alveolar oxygen fraction multiplied by atmospheric pressure. The presented results show a good agreement of the theoretical simulation with the animal experiment.

Conclusion

The presented results show a good agreement of the theoretical simulation with the animal experiment not only in trends, but very good agreement of measured and simulated differences in oxygenation confirms validity of the model. There are however some limitations of the model emerging from many simplifications. On the other hand behaviour of human or animal objects is not possible to describe exactly due to complexity of physiological processes varying in time. Therefore the chosen approach to the modelling and the final algorithm can be assessed as well corresponding one with reality.

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