Kopelent, V., Roubík, K.: Effectivity of Tracheal Gas Insufflation on Artificial Lung Ventilation. In *Biomedical Engineering* [CD-ROM]. Zürich: Acta Press, 2004, p. 417–127. ISBN 0-88986-379-2.

# EFFECTIVITY OF TRACHEAL GAS INSUFFLATION ON ARTIFICIAL LUNG VENTILATION

Vit Kopelent,
Department of Radioelectronics,
Faculty of Electrical Engineering,
Czech Technical University in Prague,
Technicka 2, 166 27, Prague 6, Czech Republic,
email: kopelev@fel.cvut.cz,
phone: +420224352109,fax: +420224355829

Karel Roubik,
Department of Radioelectronics,
Faculty of Electrical Engineering,
Czech Technical University in Prague,
Technicka 2, 166 27, Prague 6, Czech Republic
email: roubik@feld.cvut.cz
phone: +420224352248,fax: +420224355829

## ABSTRACT

The aim of this work was to find out the effect of tracheal gas insufflation during conventional and high frequency artificial lung ventilation upon arterial blood gases. The complicated lung structure does not allow an exact modelling according to the anatomical lung structure. Therefore, the respiration system is modelled as an axial symmetrical straight pipe with a growing radius. A base of the model is convention-diffusion equation, which is solved by numerical simulation. After that, the TGI catheter was added into the model for description of tracheal gas insufflation effect. The TGI catheter was modelled as an additional source of ventilation gas mixture. The outputs of the final model were compared not only with an animal experiment but also with another model derived from the electro-acoustic analogy. A good agreement of both the models was achieved. The acquired results are useful and directly applicable in TGI effect investigation and will, hopefully, contribute to the fast TGI introduction into the clinical practice.

## KEY WORDS

Artificial lung ventilation,Tracheal gas insufflation, Biomedical Computing.

## 1. Introduction

There are many 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. Some of them, e.g. high frequency ventilation (HFV), have been introduced into the clinical use recently. Some ventilatory techniques are still examined by researchers and they are not yet used for ventilation of patients. Tracheal gas insufflation (TGI) is one of these ventilatory techniques providing additional ventilatory support to conventional or high frequency ventilation leading to improved oxygenation and $CO_2$ removal without increase in tidal volume or pressure amplitude in the respiratory system.

Understanding and exact evaluation of TGI effect are very important tasks for future clinical introduction of the method and they cannot be carried out without modelling of gas flow in the respiratory system. This is not easy task because of complex behaviour of gas during its movement and because of complexity of the respiratory system. The aim of the study is to model gas flow and its effects during both conventional and high frequency ventilation in the respiratory system. Furthermore, introduction of tracheal gas insufflation into the model is carried out so that final mathematical model could predict clinical outcomes of the conjugate applications of CV + TGI and HFV + TGI.

## 2.0 Tracheal Gas Insufflation

Tracheal gas insufflation is a method within the 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].

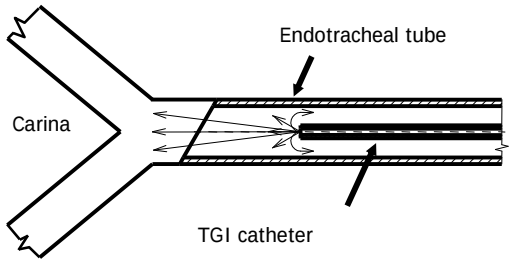


**Fig. 1: Principle of tracheal gas insufflation.**

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

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TGI may offer a surprising result. Description of TGI effects during CV and HFV is the main aim of 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.

As mentioned above, the TGI catheter is a source of ventilation mixture with a constant flow. It can be described by relation:

$$Q_{insp} = Q_{vent} - Q_{TGI} ,$$

where $Q_{insp}$ is inspiratory flow at the airway opening, $Q_{vent}$ is ventilatory flow from ventilator and $Q_{TGI}$ is a constant flow from TGI catheter. The equation says that the behaviour of the respiratory system behind the distal end of the catheter is the same as ventilation with $Q_{vent}$, i.e. $Q_{vent} = Q_{insp} + Q_{TGI}$ . Expiratory flow is:

$$Q_{exp} = Q_{vent} + 2 \cdot Q_{TGI} .$$

At this expression $Q_{TGI}$ appears two times, because TGI is a continuous source, one $Q_{TGI}$ represents flow during inspiration and the second one represents $Q_{TGI}$ during expiration.

## 2.1 Mathematical Modelling of Gas Flow

Bases of the gas flow modelling during artificial ventilation have been described by Jongh [4] where a 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 the 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 to 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 the paragraph: "Tracheal gas insufflation".

The convection-diffusion equation is solved by numerical simulation. The respiratory system is divided into many nodes in $x$ (axial) direction with a variable length of $\Delta x$. Each node is characterised by: length of $\Delta x$, 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. The 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.

For inspiratory phase, the air flows to the lung, therefore its velocity is positive ($v \geq 0$). The new velocity, proximally to the distal end of the catheter, is computed as inspiratory flow $Q_{insp}$ divided by cross-sectional area at this point. The velocity behind the catheter is computed as a sum of the velocity before the catheter and the velocity from the TGI catheter. The flow velocity from the distal end of the catheter to the end of the respiratory system can be computed as a ratio of the flow to cross-sectional area for each calculation node.

For expiratory phase, the air flows from the lung and its velocity is negative. The new velocity proximally to the distal end of the catheter is computed as a ratio of expiratory flow $Q_{exp}$ to cross-sectional area at this node. The new velocity behind the distal end of the catheter is computed as $Q_{vent}$ divided by cross-sectional area at a particular node.

Both situations for inspiration and expiration were simplified. Exact modelling of outflow from the TGI catheter is also complicated, eg. by presence of whirls. The real situation was modelled, as a tube with a bigger diameter, causing that the velocity in the centre of the tube is smaller.

The calculation of concentrations is divided into two phases as well. At the airway opening (node zero), the oxygen concentration equals to the oxygen concentration of the ventilatory mixture. During inspiratory phase, the ventilatory mixture is transported to the end of the respiratory system. The oxygen concentration must be recalculated according to $Q_{insp}/Q_{TGI}$ ratio at the distal end of the TGI catheter. For expiratory phase, the concentration is recalculated as $Q_{exp}/Q_{TGI}$.

As mentioned above, Jongh's model had to be modified, because the regional gas consumption was not involved. A function was find, which simulates the oxygen consumption, in order to introduce the oxygen consumption into the model with a minimal change of Jongh's algorithm. The function represents the oxygen consumption at generations where alveoli are present

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only. Whole tidal volume is delivered to the first generation where alveoli are present. To the next generation, only a fraction of the whole tidal volume is derived, that is equal to the tidal volume minus volume of the first generation including the alveolar space. It can be described by terms: $V_{17} = V_{tot}$,

$$V_{18} = V_{17} - O_{17},$$
$$V_{19} = V_{18} - O_{18},$$
$$\dots$$
$$V_N = V_{N-1} - O_{N-1},$$

where $V_{17}$ stands for volume delivered to the first generation with alveoli, $V_{tot}$ stands for a total volume supplied by ventilator to the airways, $V_{18}$ ... $V_N$ stand for volumes delivered to the generations 18 … N and $O_{18}$ ...$O_N$ stand for volumes consumed at generations 17 … N-1. For 19th generation it can be derived:

$$V_{19} = V_{tot} - O_{17} - O_{18}.$$

Finally, a universal term can be written:

$$V_N = V_{tot} - \sum_{n=G}^{N-1} O_n ,$$

where $G$ stands for a number of the first generation with alveoli appearance.

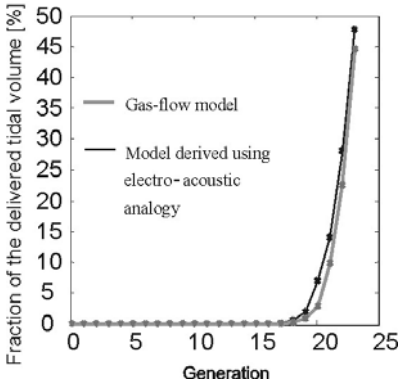


**Fig. 2: Fraction of the delivered tidal volume at ventilatory frequency 5 Hz in percents.**

After modification of the equation according to the requirements of the model, it was introduced into the entire algorithm. The final function is:

$$V(k+1) = (1 - cumalv(k) / factot) \cdot V_{tot} ,$$

where $V(k+1)$ stands for volume delivered into generation with index $k+1$, $cumalv(k)$ stands for the sum of alveolar volumes of a generation before generation $k+1$, $factot$ is the total volume of all alveoli present at the respiratory system and $V_{tot}$ stands for the total volume supplied by ventilator to the airways. The result can be seen in Fig 2.

## 2.2 Animal Experiment

Validity of the TGI gas flow model is tested by comparison of results predicted by the modelling with results of animal TGI experiment on a group of rabbits.

A special experimental set has been designed so that a proper and quantitative description of TGI effect on the blood gases could be carried out during both CV and HFV. An experimental volume controlled ventilator for HFV has been constructed in order to maintain constant tidal volumes during the entire experiment, independent on respiratory mechanics changes, continual distension pressure (*CDP*), TGI flow, relaxation level, etc. The ventilator is suitable for CV as well. The ventilator consists of two parts. During inspiration it works as a constant flow generator, where $V_T$ can be adjusted by airflow level and inspiratory time adjustment. A negative expiratory pressure generator assures the expiratory period. *CDP* is determined by the pressure generator characteristics, which can be easily changed.

TGI flow is generated using a source of humidified gas at adjustable pressure (15 – 100 kPa) and TGI catheter (18 cm long, inner diameter of 0.7 mm) placed into the endotracheal tube 3 cm above its distal end. A catheter for surfactant application, which is integrated into the endotracheal tube wall, is used for *CDP* monitoring.

Nine healthy rabbits (1.8 – 3.2 kg) under the ketamine–xylazine anaesthesia and vecuronium have been used for experiment (a. carotis has been cannulated for systhemic pressure measurement and arterial blood sampling, vv. marginales for continuous infusion of ketamine for anaesthesia maintainance). Endotracheal tube Vygon No. 4.0 has been introduced after tracheostomia.

The protocol consists of three stages: 1) HFV without TGI flow. HFV parameters: ventilatory frequency $f$ = 10 Hz, *CDP* = 0.8 kPa, inspiration ratio $Ti/T$ = 0.5. $V_T$ is experimentally set to reach normocapnia ($P_aCO_2$ = 42 ± 2 Torr). This $V_T$ ($V_T$ = 2.2 ± 0.4 ml/kg) is taken as the reference value during the next two experiment stages. 2) HFV with TGI flow. TGI flow is set to 0.5 l/min while the total tidal volume, comprising the tidal volume generated by ventilator $V_T$ and the volume generated by TGI flow during inspiratory period, is maintained constant and at the same level as the tidal volume of normocapnic ventilation determined in the first stage of the experiment. Arterial $P_aO_2$ and $P_aCO_2$ are analysed 5 minutes after the change of TGI flow. 3) HFV without TGI. This is a final control stage, after which the whole sequence of stages is repeated stepwise for TGI flows 1 l/min and 2 l/min respectively. Statistical analyses of $P_aO_2$ and $P_aCO_2$ changes in stage 2 for each TGI flow are carried out and the relative contribution of TGI to the total minute ventilation is calculated. Analogical three-step design is used for evaluation of TGI effect during CV.

## 2.3 Correctness and Suitability Evaluation of the Model

Two results are available for evaluation: 1. results of the mathematical simulation by the created model and algorithm, 2. results of the animal experiment. Unfortunately the results are obtained for different objects: simulation is carried out using the model of an

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adult (78 kg), but the experimental results come from animal experiment on a group of rabbits (2.5 kg). However different the examined objects are, the results still can be compared, because according to several large studies [6], 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 (ventilatory frequency, inspiratory time fraction), other parameters are proportionally recalculated (TGI flow during both cases are proportional, i.e. TGI flow contributions to the both inspiratory flows are equal).

The last difference between the theoretical and experimental approaches is that the 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. This statement is valid only in healthy objects where no alveolo-capillary oxygen transfer block is present, represented for example by interstitial lung edema, increased pulmonary arterio-venous shunt, etc.

## 2.4 Results

Results of the animal experiment are presented in graphic form in Fig. 3. TGI is more efficient during HFV then during CV. The difference in increased oxygenation is $\Delta P_aO_{2\,HFV+TGI} - \Delta P_aO_{2\,CV+TGI} = 11.2 \pm 3.6\,\%$ for the biggest TGI flow of 2 l/min.

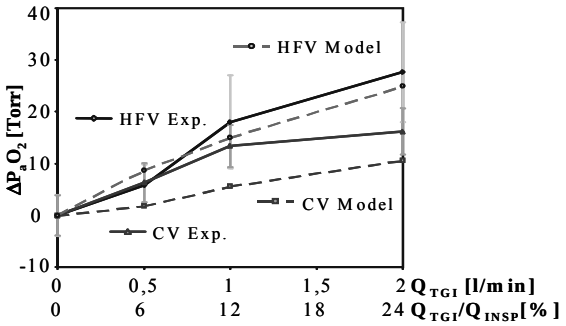


**Fig. 3: Results of the animal experiment and mathematical simulation.**

Results of the mathematical simulations are presented in Fig. 4. The TGI flow chosen for the simulations is equally proportional to the inspiratory flow 2 l/min during the animal experiment, i.e. the TGI flow represents 24 % of inspiratory flow in both animal and theoretical cases. TGI effect is also stronger during HFV than during CV. The difference in final alveolar partial pressures of oxygen is $\Delta P_AO_{2\,HFV+TGI} - \Delta P_AO_{2\,CV+TGI} = 14.4\,\%$. Alveolar $P_AO_2$ is calculated as a steady-state alveolar oxygen fraction multiplied by the atmospheric pressure.

Results from comparing models with different approaches were also good. The presented model solves convection-diffusion equation, another one is derived from the electro-acoustic analogy [7].

The electro-acoustic model can simulate impedance change and the respiratory system reactions on ventilatory parameters changes. The outputs of the models are different and they can not be compared, but one parameter can. This parameter is fraction of the delivered tidal volume. That outputs are presented on Fig. 2, maximal difference between the models is 4%.

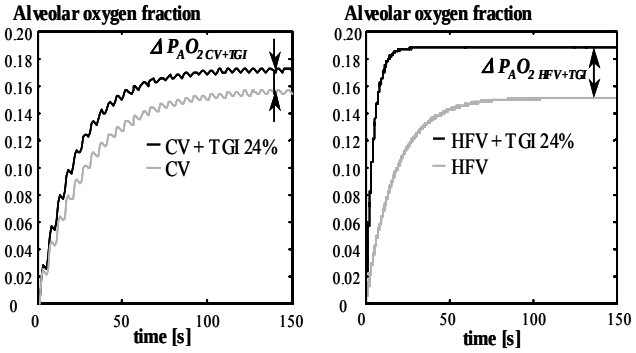


**Fig. 4: Improvement of alveolar oxygen fraction during CV and HFV with application of TGI.**

## 3. Conclusion

The presented results show a good agreement of the theoretical simulation with the animal experiment and another modelling approach 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.

## 4. Acknowledgement

This research work has been supported by the research program No. MSM 210000012 at CTU in Prague and GA ČR 102/03/H086.

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