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Metabolic model of the human respiratory system

Petr Kudrna[1], Jakub Johánek[1], Martin Rožánek[1], Karel Roubík [1]
Affiliation 1: Department of Biomedical Technology, Czech Technical University in Prague,
Kladno, Czech Republic, petr.kudrna@fbmi.cvut.cz

***Abstract*—The aim of the work was to design a metabolic simulator of the human respiratory system consuming oxygen and producing carbon dioxide. The respiratory quotient, tidal volume, mechanical parameters of the system and other parameters should be similar to the physiological values in (healthy) men so that the simulator could be used for simulation of artificial ventilation of real patients. The model consists of a high-volume plastic box assuring the desired lung compliance, a propane-butane burner equipped with a water-based cooling system, oxygen and CO_2 analyzers of the "intrapulmonary" gases and a control system. The simulator is an educational device suitable for testing of the influence of the ventilatory parameters upon the intrapulmonary conditions similarly as during artificial lung ventilation of a human patients.**

***Keywords*—simulator; ventilator; respiratory system.**

I. Introduction

Mechanical ventilation is a lifesaving technique that is used in cases of failure of spontaneous breathing; an actual or imminent serious failure of ventilation and oxygenation function of the respiratory system. Mechanical ventilation is used as a standard for all patients, regardless of weight and age [1], [2].

The first devices for artificial lung ventilation began to be used increasingly in anaesthesia and intensive care during the 1950s. The 1955 release of Forrest Bird's "Bird Universal Medical Respirator" in the United States changed the way mechanical ventilation was performed with the small green box becoming a familiar piece of medical equipment [2]. The unit was sold under the name Bird Mark 7 Respirator and informally called the "Bird". It was a pneumatic device and therefore required no electrical power source to operate.

Nowadays, the progress in development of artificial ventilation technology is most evident in patient safety, ventilation modes and monitoring of ventilation functions, which are better understood.

Despite this, the mortality is about 40 %, with combined complications having significantly higher mortality. To understand the principle of the individual functions and modes, equipment for providing artificial ventilation models – lung models, or artificial lungs – is necessary. Models of the lung are mainly used in the verification of the functioning of the ventilator, during calibration, and also for training of respiratory therapists [1], [4].

The most widely used lung models are designed to simulate the mechanical properties – lung compliance and flow resistance. However, simulation of gas exchange is not the standard feature of these models.

The aim of this work is the design and implementation of a simulator of human respiratory system, which would allow for the exchange of respiratory gases and the possibility to study the effect of ventilation parameters on the composition of the gas in the simulated alveolar space of the model.

II. Methods

The design of the metabolic simulator should be credible. The basic requirement for the simulator is to be similar to the real object – an adult man. Another requirement is the safe operation of the model, and a clear monitoring of the ventilation parameters. Last but not least, it's important to be able to connect a variety of ventilators for artificial lung ventilation. The proposed model consists of three major parts:

1. Simulation of the mechanical parameters of the respiratory system of an adult man.
2. Simulation of the metabolism of oxygen and production of CO_2.
3. Measurement and control of the simulator, including the provision of monitoring intrapulmonal parameters.

Components of model are further described below:

A. Respiratory system model – mechanical parametres

The model of the respiratory system is designed to represent mechanical parameters of an adult man. It is very important to maintain consensus in the parameters of pulmonary compliance. Compliance is generated by the volume (137 L) of the box with rigid walls made of plexiglas.

The adiabatic compliance value of the model is 0,966 L/kPa vs. approx 1 L/kPa [1]. The flow resistance of the respiratory tract can be adjusted using a set of interchangeable pneumatic resistances. The resistances are involved before the entering into the metabolic simulator; their replacement during a simulation is not possible.

B. Simulation of the metabolism of O_2 and production of CO_2

The equipment for the simulation of metabolism consists of the propane-butane micro burner Bunsen (Carl Friedrich Usbeck, Radevormwald, Germany) and the water cooling

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system. This system, called metabolic unit, has several important properties.

The micro-burner consumes oxygen from the modelled respiratory system (from the inner space of the plastic box) during burning of propane-butane and it produces CO_2, heat and water vapour.

$$C_3H_8 + 5O_2 \rightarrow 3CO2 + 4H_2O + heat \qquad \text{(Propane)}$$

$$2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_20 + heat \qquad \text{(Butane)}$$

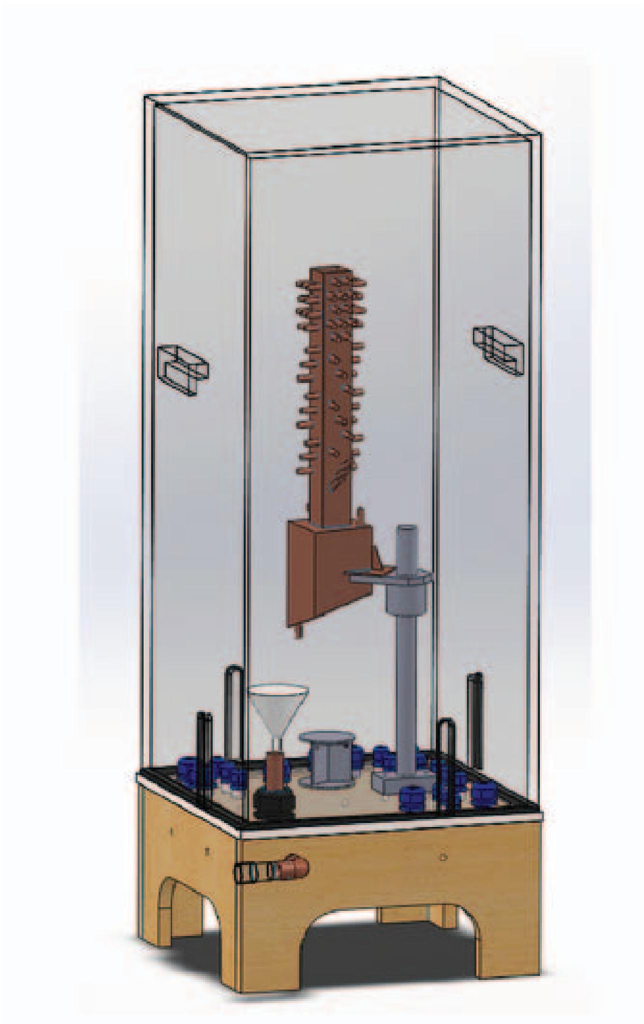

Fig. 1. Design of the metabolic simulator

The corresponding respiratory quotients for propane and butane are 3/5 = 0.6 and 8/13 = 0.615 respectively. As there is a very small difference between them, the total respiratory quotient is approximately 0.6 regardless of the actual propane/butane ratio in the cylinder. This ratio is suitable for the simulator, as the respiratory quotient varies between 0.3 and 0.7 when lipids are metabolised, it is 0.8 for proteins and 1 for carbohydrates [3].

The amount of produced CO_2 and consumed O_2 can be adjusted by modification of gas flow in the propane-butane micro burner. Ignition is performed electronically by command of the operator.

The water cooler has two functions: firstly, it cools the flue-gas to a temperature similar to the temperature of the cooling water, and secondly, the cooler assures the water vapour condensation. Considering the very low partial pressure of water vapour at the temperature of the cold water, nearly all water vapour from the flue-gas condensates in the cooler and therefore it does not affect the volume and/or compositions of the alveolar gas.

C. Measurement and control of the simulator, including the provision of monitoring intrapulmonal parameters, safe operation

In order to assure the detailed monitoring of the ventilation and monitoring of the concentration of gases inside the simulator (intrapulmonary conditions), two monitoring units and one unit for controlling have been connected.

The first monitor is the monitor of ventilation Florian (Acutronic, Switzerland), which consists of pressure and airflow sensors connected between the ventilator and the model (see Fig. 3). The monitor provides values of the basic ventilatory parameters, it computes airway resistance and lung compliance in real time.

The second monitoring unit Carescape B650 (GE Medical, Helsinki, Finland) consists of an oxygen analyser, carbon dioxide analyser and a pump that forces the alveolar gas to flow through the analysers and then back to the alveolar space. Two sampling pipes leading into the alveolar space allow these connections.

To ensure safe operation of the simulator, sensors of temperature; pressure; condensate level; coolant flow; flammable gas detector have been installed. These sensors are connected to the A/D converter 6009 NI USB (National Instruments, Austin, USA). Output data are transferred to a PC where they are recorded and evaluated using the software LabVIEW (National Instruments, Austin, USA).

In case of an emergency situation, the system disconnects the supply of gas to the burner; open the safety valve for entering of fresh air into the simulator, and open second safety valve for the gas to escape outside the model.

III. Results

The designed and constructed metabolic simulator (Fig. 3), when connected to an artificial lung ventilator Avea (Care Fusion, San Diego, California, USA), behaves as an adult men. Its mechanical parameters are similar to those of the respiratory system of an adult patient. In this case: $C_{RSmodel} = 0.966$ L/kPa in model vs. $C_{RS} = 1$ L/kPa approximately in an adult.

The propane-butane gas flow, the metabolic unit, consumes approximately the same quantity of oxygen as an adult patient. It results in composition of the alveolar gas ($pO_2 = 15\text{-}16$ kPa) that is similar to alveolar gas inside the real lungs (pO_2 model = 14 kPa) when a standard ventilatory parameters are adjusted on the ventilator: tidal volume

$V_T = 500$ mL, ventilatory frequency $f = 20$ bpm and oxygen fraction $FiO_2 = 0.21$ in the inspiratory gas.

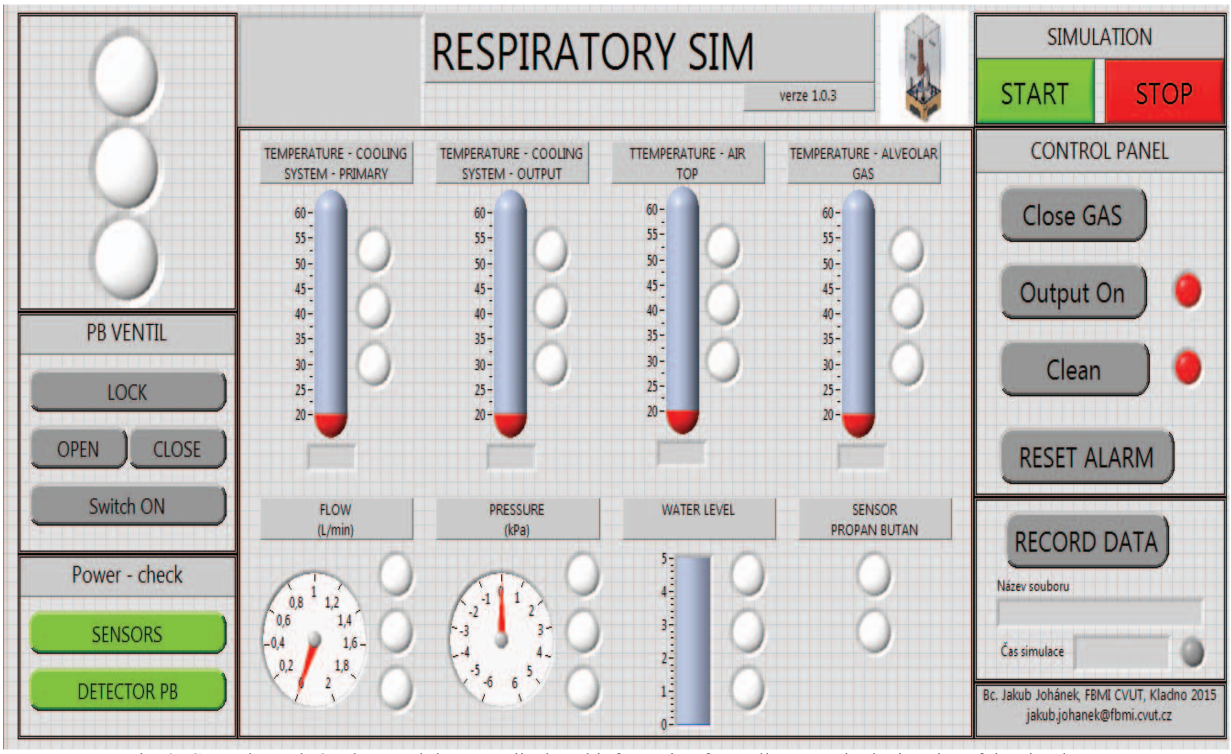

Fig. 2. Control panel. On the panel there are displayed information from all sensors in the interior of the simulator.

Fig. 3. Real metabolic simulator in lab

IV. Conclusion

The designed metabolic simulator of respiratory system is usable for training in respiratory care, as it reacts to changes of the ventilator regimen and ventilatory parameters correspondingly to an adult patient. The simulator is also an educational device suitable for testing of the influence of the ventilatory parameters on the intrapulmonary conditions similarly as during artificial lung ventilation of a human patient. Moreover, the model is applicable for testing of ventilators as it has well defined mechanical parameters and suitable monitoring capabilities.

V. Acknowledgement

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