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Simulation of the respiratory CO_2 concentration with a blower-based lung simulator

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Abstract: Mechanical ventilation has become one of the most widely used life-supporting techniques in the world, providing a proper gas exchange even if the patients breathing is impaired. To verify the functions of these ventilators during development, bench tests, such as lung simulators, offer a wide range of test functionalities. Therefore, a simulator has to provide realistic features of the lung, including the ability to reproduce the varying gas concentration (physiological capnogram) at its interfaces. This paper presents the implementation of a gas mixing unit into an open blower-driven lung simulator to reproduce the respiratory CO_2 concentration of a patient.

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I. Introduction

In modern ventilation, highly automated functions (HAF), which may lead to improved patient care and a greater focus on patient-specific therapy, are becoming increasingly important [1]. However, HAF may also lead to significant increase in risk harming the ventilated patient [2]. To reduce this risk, HAF must be tested in terms of their functionalities before use. For this, bench tests using lung simulators could enable a wide range of automated test functions.

An important function of ventilators in intensive care units is the monitoring of the respiratory CO_2 concentration, also known as capnography. It provides information regarding the patient's conditions and therefore indicates as to when to adjust the specific ventilation settings [3]. Various authors have proposed to use end-tidal CO_2 as a controlled variable for the automation of ventilator settings e. g. Maennel et al. [4]. In order to test such functionalities, a test bench is required to reproduce the capnogram of a virtual patient.

This paper presents the implementation of a gas mixing unit (GMU) into a blower-driven lung simulator, lastly enhanced and adapted by D. Pysik et. al [5] in contrast to lung simulators based on bellows (e. g. TestChest®, ASL5000). The aim is to simulate the physiological CO_2 concentration during spontaneous breathing of a healthy adult patient at the interface of the lung simulator.

II. Material and methods

The setup of the lung simulator, as displayed in Figure 1, is based on the setup of D. Pysik et. al [5]. Overall, the setup can be divided into a sensing unit (SU), a ventilation unit (VU) and a GMU. The SU is located at the interface of the lung simulator, providing the required values of the measured flow, pressure and CO_2 concentration. The VU consists of two different paths: an inspiratory path and an expiratory path. Both paths contain a blower and a valve

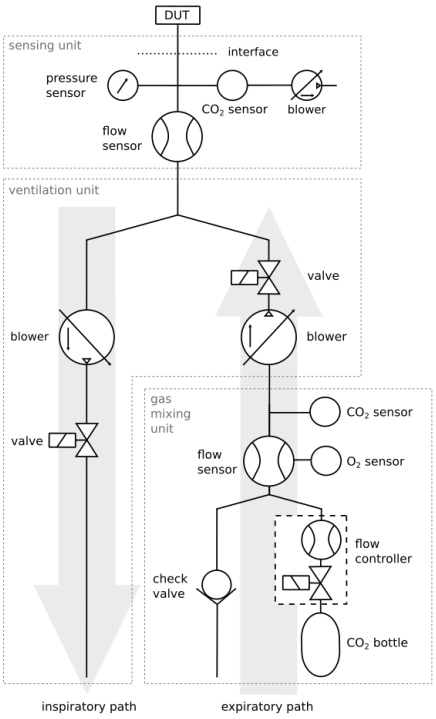

Figure 1: Flow chart of the lung simulator [6].

to reproduce a virtual patient's airway flow and pressure during ventilation. In the expiratory path, the GMU is installed. It enriches the expiratory air in the lung simulator with a defined amount of CO_2. To achieve this, the GMU also consists of two paths: a path that provides ambient air and a path that provides pure CO_2. To control the gas flow of CO_2, a flow controller is used. An additional check valve prevents the controlled gas mixture from escaping into the environment. Furthermore, a CO_2, as well as a Flow- and O_2 sensor are installed in the GMU to measure the concentration present there.

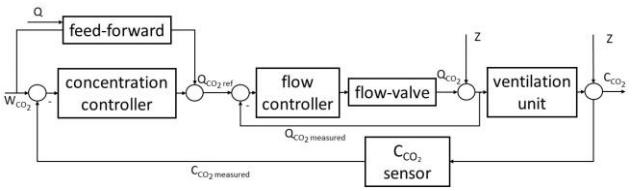

Figure 2: Block diagram of the invented control concept [6].

Table 1: Components of the experimental setup [6].

Component	**Model designation**
CO_2 sensor in SU	Gas Sensing Solutions SprintIR-W
Blower	ebm-papst – RV45
CO_2 sensor in GMU	Sensirion – STC31
Flow- and O_2 sensor	Cubic Gasboard 8500FS-L240
Flow controller	Sensirion – SFC5500
Check valve	Custom 3D-print
Real-time machine	Speedgoat

Due to the implementation of the GMU in the expiratory path, the gas has to flow through the whole lung simulator and is mixed by the expiratory blower. Thus, a proper gas mixture can be ensured. An additional CO_2 sensor is located in the SU, which is used to measure the simulated capnogram at the interface. Since a side stream measurement is chosen, a blower is installed behind the CO_2 sensor, which provides a constant sample volume of 2.5 l/min through the sensor. The used components for the setup are displayed in Table 1.

In order to compensate flow-dependent delays, a cascaded control scheme was used (see Figure 2). The inner control loop consists of the flow controller, controlling the CO_2 gas flow Q_{CO_2}. The outer control loop controls the CO_2 concentration C_{CO_2} in the expiratory path to match the end expiratory reference concentration W_{CO_2}, instead of the concentration at the interface. A feedforward controller calculates a CO_2 flow based on the total expiratory flow that would result in the desired concentration. An additional PID controller is tuned to achieve reference tracking and better performance. The sensor communication and the control concept are implemented in a Simulink™ model and executed on the real-time target machine.

III. Results and discussion

In order to test the developed gas mixing concept, simulations of healthy spontaneous breathing patient [5] were carried out. For this scenario an end tidal concentration of 4.5 Vol.-% was chosen, which corresponds to a healthy person. Figure 3 displays the resulting capnogram at the interface. The simulation time is displayed at the x-axis, the y-axis presents the measured CO_2 concentration and the secondary y-axis displays the measured flow. Positive flow indicates the expiration and the negative flow indicates the inspiration of the patient. During the expiration, a short delay of about 0.4 s occurs before the CO_2 concentration starts to increase. This is based on the dead space of the simulator, located between the valve in the expiratory path and the interface.

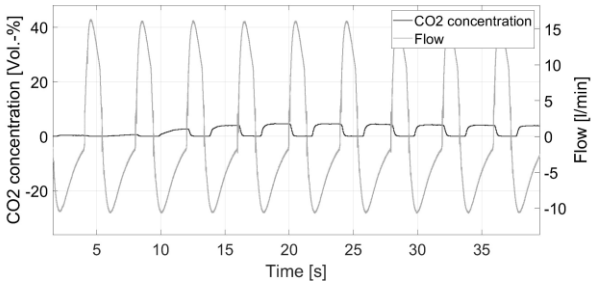

Figure 3: Reproduced capnogram of a healthy patient [6].

After the delay, the measured concentration reaches its characteristic plateau at the controlled value of 4.5 Vol.-%. With the beginning of the inspiration, the controlled gas concentration is flushed from the SU, resulting in a decreased CO_2 concentration. The system needs approximately 15 s to achieve the desired behavior. Whilst the reproduced capnogram is realistic for healthy subjects, it is highly dependent on the physical setup of the lung simulator. This, as well as the control of the concentration in the expiratory path, limits the simulation performance in the current approach.

IV. Conclusions

This paper proposes the implementation of a GMU into a blower-driven lung simulator, to reproduce the respiratory CO_2 concentration of a patient at the simulators interface. The proposed approach shows the principle applicability of a CO2 controlled, bellow-less lung simulator. The ongoing development of a multivariate control concept involving both expiratory as well as inspiratory branch of the system together with the change towards a CO2 mainstream sensor and a further reduction in deadspace will further enhance simulation performance. An extended control concept based on the CO_2 measurement in the SU is currently under development for the simulation of pathological changes.

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