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Development of a bellow-based test lung for spontaneous breathing

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Abstract: Spontaneous breathing in mechanical ventilation can lead to patient ventilator asynchrony. In the research concerning asynchrony, test lungs can help to reduce the number of animal experiments. However, the number of test lungs which can simulate spontaneous breathing are rare and expensive. This paper presents a test lung with two bellows and springs with an additional pressure source for spontaneous breathing. The test lung flow curves were similar to measurements of a human subject, but were not identical. A more flexible pressure source can improve the test lung to evaluate mechanical ventilators and their automation.

I. Introduction

Spontaneous breathing in mechanical ventilation has the risk of patient-ventilator asynchrony [1], which may lead to longer durations of mechanical ventilation and higher hospital mortality [2]. Therefore, both problems can be improved by further research of patient-ventilator interaction. While animal testing brought advancements in medicine, the use of animals is ethically debatable [3].

Considering the three R principle (replacement, reduction and refinement) [4], test lungs can reduce the number of animal experiments for mechanical ventilation. Among other test lungs that can simulate spontaneous breathing, the *QuickLung Breather* (Ingmar Medical, Pittsburgh, USA) has a bellow with springs, where one side is motorized. The *Human Patient Simulator* [5] is a test lung with a fixed volume with two valves. One valve is connected to a controllable pressure source; the other valve can be used to release air into the atmosphere. However, the *QuickLung Breather* is expensive with a fixed set of five fixed spontaneous breathing patterns and the *Human Patient Simulator* has a large deviation between the desired and the measured tidal volume. The presented test lung is a passive bellow-spring system combined with a pressure source to simulate spontaneous breathing.

II. Materials and methods

The test lung and its concept are shown in fig. 1. Two bellows (F-1181NBR, Thodacon Werkzeugmaschinen-schutz GmbH, Kolbermoor, Germany) are connected via a disc in between. On top, the mechanical ventilator (EVE IN, Fritz Stephan, Gackenbach, Germany) is connected to the test lung via a copper pipe (Lung compartment). At the bottom, a pressure source is connected to simulate the respiratory muscles (Muscle compartment). As a pressure source, we used another mechanical ventilator (Servo-i, Getinge, Sweden). Three springs (Z-081E-06I, Gütekunst, Metzingen, Germany) are attached to model the lung compliance of approx. 100 mL / mbar. The springs could be changed to model another compliance. Additionally, casing, guide rails and 3D-printed parts were used for construction.

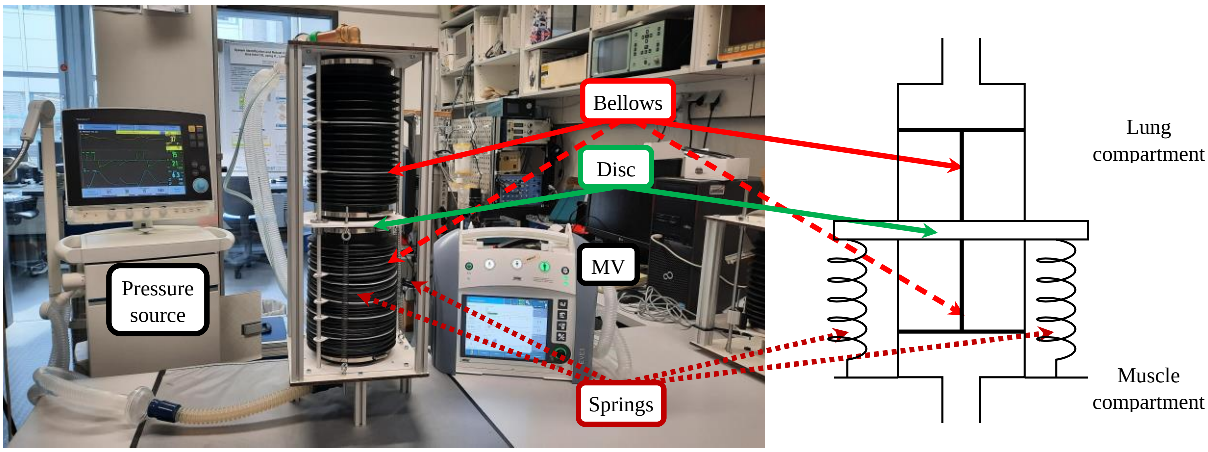

Figure 1: Left: Picture of a test lung. MV denotes the mechanical ventilator. The third spring is on the back of the test lung. Right: Schematic of the test lung.

The pressure source needs to imitate the applied negative pressure in the lung during spontaneous breathing. To achieve this, the pressure source applies a higher pressure p_{mus} to preload the springs and the bellow of the muscle compartment. During spontaneous inspiration, the pressure source decreases p_{mus}, such that the bellow of the muscle compartment will condense, while the bellow of the lung compartment expands.

Fig. 2 shows the mathematical model of the test lung. In the lung compartment, the mechanical ventilator and the left bellow apply the forces F_{mv} and F_{bel}, respectively, on the disc with mass m. In the muscle compartment, the muscle pressure source, the three springs and the right bellow apply the forces F_{mus}, F_{spr} and F_{bel}, respectively. Each bellow has a spring constant k_{bel} and damping coefficient d_{bel}, which were assumed to be the same for both bellows. The effect of the three springs was summarized by the spring constant k_{spr}. The force balance equation is given by

$$F_{mv}(t) - F_{mus}(t) = \left(k_{spr} + 2\,k_{bel}\right) x(t) + 2\,d_{bel}\,\dot{x}(t) + m\,\ddot{x}(t). \quad (1)$$

The forces F_{mus} and F_{mv} can be calculated via $F_{mus} = p_{mus} \cdot A$ and $F_{mv} = p_{mv} \cdot A$, respectively, where p_{mv} denotes the applied pressure of the mechanical ventilator and A the disc area between the bellows. The model was used to parametrize all components, such that the test lung can generate spontaneous tidal volumes of approx. 500 mL.

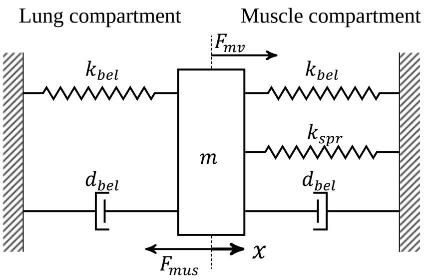

Figure 2: Mechanical diagram of the test lung.

The test lung was used to imitate the volume flow measurements in continuous positive airway pressure mode from an open-access database (Subject 24, male, 22 years, 75kg, CPAP at 7 cmH2O, medium-short breaths) [6,7]. Fresnel et al. [8] discovered an inversely linear dependence between the inspiratory time T_{insp} and the spontaneous respiratory rate f_s:

$$T_{insp}\, f_s = 0.0125s\, f_s + 0.125 \quad (2)$$

The spontaneous respiratory rate was assumed to be 30 per minute, which leads to an inspiration-to-expiration ratio of 1:1. The settings of the pressure source were adjusted empirically to match the test lung airway flow to the subject flow. The pressure source applies 30 mbar during spontaneous inspiration. The pressure increases to 35 mbar during spontaneous expiration, with a rise time of 20 percent. The mechanical ventilator was set to CPAP mode at 7 mbar.

III. Results

The comparison between the test lung flow and the subject flow is shown in fig. 3. The flows were aligned after the measurement. At the start of inspiration, the test lung flow increases faster than the patient flow, but after its peak, the test lung flow is less steep than the subject flow. During expiration, the minimum test lung flow is lower than the subject flow. Differences can be explained by the different used mechanical ventilators and the lack of subject information regarding the respiratory resistance and compliance. The test lung can be improved if a controllable pressure source is used.

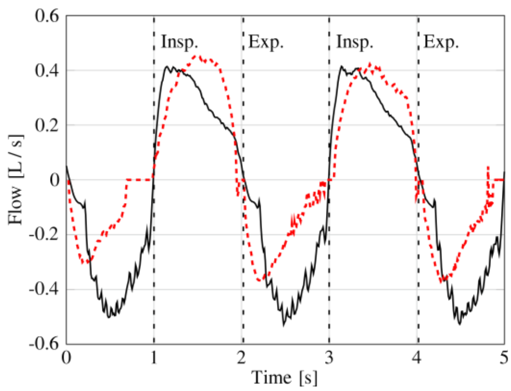

Figure 3: Airway flow measured by the test lung (black) in comparison to the database measurements (red) [6,7].

IV. Conclusion

The proposed test lung demonstrates that spontaneous breathing can be simulated with an additional pressure source. The generated spontaneous breaths are similar to that of a human subject, but are not identical. In the future, a flexibly controllable pressure source can enable patient-ventilator interactions, such as reflexes, to test mechanical ventilators and their automation.

AUTHOR'S STATEMENT

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