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Determination of the critical closing pressure for a 3D printed collapsible model of an idealized upper airway geometry

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Abstract: Obstructive sleep apnea is a common sleep disorder caused by a partial or complete collapse of the upper airway due to a shift of soft tissues. A parameter to measure the airway collapsibility is the critical closing pressure, which defines the pharyngeal pressure at which the airway collapses. A 3D printed collapsible model of an idealized upper airway geometry was used to perform deformation and pressure measurements and thus to determine the critical closing pressure. The influence of increasing airway resistance on the deformation behavior was examined by changing the size of the inflow area.

I. Introduction

Obstructive sleep apnea (OSA) is a common sleep disorder characterized by repeated partial or complete obstruction of the upper airway. One parameter to measure the upper airway collapsibility and thus to determine the severity of OSA is the critical closing pressure (P_{crit}). P_{crit} defines the pharyngeal pressure at which the airway collapses [1]. The critical closing pressure depends on a range of parameters, e.g. the airway geometry and the neuromuscular activation of the surrounding soft tissue [2]. A review of several studies has demonstrated that nearly all patients diagnosed with OSA are associated with a P_{crit} greater than -5 mbar [1]. Clinical observations have shown an increased severity of airway obstruction with rising P_{crit} [1].

The aim of this study is to develop a collapsible 3D printable model of an idealized pharyngeal geometry. The model should consist of two rigid segments, representing the nose and trachea, which are connected with a constricted flexible segment, representing the pharynx. The model should be used to study deformation behavior and to determine the critical closing pressure P_{crit}. The setup should include the application of a constriction disc at the inflow. By inserting the disc, circular inflow openings are created which, due to varying diameters, have an area of 75 % (corresponding to the constriction geometry of the model), 90 % and 95 % of the original inflow area, in order to simulate increasing airway resistance due to pharyngeal or nasal constriction.

II. Material and methods

A flexible model of an idealized airway geometry, a constricted tube with an inlet and outlet diameter of 20 mm and a diameter of 10 mm at the center of constriction [3], was 3D printed with a Form 2 SLA printer (Formlabs, Somerville, Massachusetts, USA) using Elastic Resin (Formlabs, Somerville, Massachusetts, USA) with a Shore A hardness of 50 [4]. The wall thickness of the model was set to 1 mm. The flow set up shown in Fig. 1, consists of a customized suction engine to generate air flow, a mass flow meter (SFM 3000, Senisiron, Stäfa, Switzerland), the model with connected rigid inlet and outlet pipes with installed pressure tabs and a differential pressure sensor (AMS 5915, Analog Microelectronics GmbH, Mainz, Germany). The effect of the reduction of the inflow area to 75 %, 90 % and 95 %, representing an increase of airway resistance, was examined by applying varying constriction discs to the inflow. The smallest reduction value of 75 % was chosen as this corresponds to the constriction geometry of the model. For each examined reduction of inflow area,

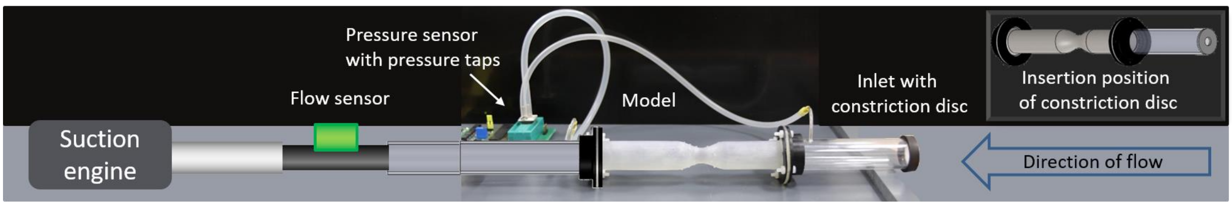

Figure 1: Flow setup for pressure and deformation measurements. Two pressure tabs are installed upstream and downstream of the model. At the inflow, constriction discs can be applied to reduce the inflow area. A customized suction engine generates flow.

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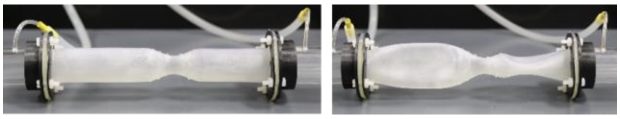

Figure 2: Model in its initial shape vs. deformed model. The critical closing pressure is defined as the downstream pressure that was measured when the model started to deform.

steady flow measurements were conducted for increasing Reynolds numbers, starting with a Reynolds number of 2000 (concerning the non-constricted pipe) and increasing the Reynolds number in steps of 1000 respectively, until a collapse of the model occurred. This range was chosen as it turned out to be the range of interest in which a collapse can be observed for all three constriction degrees. We recorded the downstream gauge pressure. The critical closing pressure P_{crit} was determined as the downstream gauge pressure, for which the model started to collapse, meaning that the model changed from its normal to a deformed shape. An example of the initial shape and the deformed shape of the model is shown in Fig. 2.

III. Results and discussion

We successfully recorded the critical closing pressure, which is defined as the downstream pressure at which the model collapses, for varying inflow area reductions (75 %, 90 % and 95 % reduction of inflow area) representing different airway resistances. In all three cases the collapse of the model took place when a downstream gauge pressure of approximately -6.5 mbar was reached, leading to a determined P_{crit} of -6.50 mbar ± 0.14 mbar. The results showed that the value of the critical pressure does not change due to different airway resistances.

Fig. 3 visualizes the relationship between downstream gauge pressure and flow rates for varying airflow resistances. The determined critical pressure value is depicted (dotted line) and represents the threshold at which a collapse of the model will take place. It can be seen that with a higher restriction of the inflow area, respectively, a higher airway resistance, already low flow rates are sufficient for the downstream pressure to fall below the critical pressure and the model thus collapses. Regarding OSA, a higher airway resistance for example due to a narrowed airway might indicate a more likely collapse of the upper airway. In addition, the measurements show that with increasing airway resistance, a more negative downstream pressure is needed to gain a certain flow rate. Regarding physiological respiration, this represents the effect that higher airway resistance (e.g. narrowed airway) leads to a higher inspirational effort, respectively a more negative inspirational pressure. In case that the inspirational pressure falls below the critical closing pressure an airway occlusion will occur, explaining why a narrowed airway is one potential factor that might lead to OSA [5, 6].

IV. Conclusions

In this study, we have successfully introduced a collapsible model of an idealized airway geometry which was produced with additive manufacturing. Pressure measurements were carried out to determine the critical

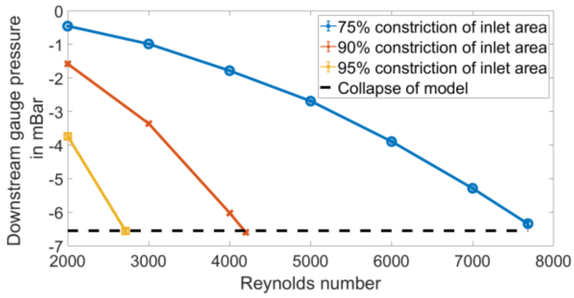

Figure 3: Downstream gauge pressure measurements for the determination of the critical closing pressure were carried out. The measurements were made with three varying constriction degrees of the inflow area. Flow was increased until the downstream pressure reached the critical closing pressure. A reduction of the inflow area leads to a decrease of downstream pressure. As soon as the downstream pressure falls below the critical closing pressure (dotted line) the model collapses.

closing pressure of the model with respect to varying airway resistances. We have shown that, independent of the airway resistance, the closing pressure is -6.5 mbar ± 0.14 mbar. For a higher applied airway resistance we have shown that the critical pressure and thus the collapse is already reached with lower flow rates. This demonstrates that a high airway resistance e.g. in form of a narrowed airway, might be one potential factor leading to OSA and implies that widening the airway geometry (e.g. with a mandibular advancement splint) can prevent the airway from collapsing. The critical closing pressure can be seen as a threshold value at which a collapse of the airway will occur. A higher closing pressure leads to a more probable collapse of the airway, which is why the closing pressure can be used as a measure of the airway collapsibility. This study demonstrates that it is possible to investigate complex physiological mechanisms with an idealized model of the upper airway and shows the relevance of the critical closing pressure in OSA. Future research could examine the critical closing pressure with a realistic airway geometry also taking into account realistic elastic tissue properties.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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