SUMMARY
The compliance of soft tissues in human upper airway is quite important as it could disturb respiratory activity and induce sleep apnea. The mechanisms of upper airway collapse, however, have not yet been fully understood. In this study, we reconstructed 3-Dimensional models of human upper airway and human soft palate to carry out fluid/structure interaction simulations between the nasal airflow and the soft palate. The airflow was considered as laminar and incompressible, while the soft palate was assumed to be isotropic and homogeneous. Adina (Version 8.6.5, ADINA R&D, Inc.) was used to solve the transient equations of airflow, soft palate and fluid/structural interaction for two respiratory cycles at a ventilation rate of 7.5 L/min. Results of the second cycle were used for analysis. Our simulation showed that the compliance of soft palate did not influence airflow patterns in nasal cavity much. During expiration, soft palate tended to move upwards and towards the posterior pharyngeal wall. During inspiration, it tended to move downwards, while coronal displacement varied between -0.32 mm and 0.16 mm. The inspirational pressure in pharynx was more sensitive to movement of soft palate comparing to expiration.

INTRODUCTION
The compliance of soft tissues in human upper airway (such as tongue and soft palate) happens during regular respiration due to the interaction between intraluminal pressure of the airflow and the tissues. At awaken state, the activation of muscles surrounding the airway could adjust the shape and posture of the soft tissues, maintaining the patency of the pharyngeal airway. However, both the upper airway dilator muscles and respiratory pump muscles are less activated during sleep, which makes the pharynx more collapsible [1]. Particularly, cessation of respiration happens during sleep in patients with obstructive sleep apnea (OSA) mostly due to the collapse of the pharyngeal airway around the uvula.

In the past, computerized tomography (CT) and magnetic resonance imaging (MRI) were used to study morphologies and dynamic properties of upper airways and soft tissues [2]. As the dynamic upper airway patency is mainly determined by the compliance of soft tissues either due to muscle activation or pressure and drag effect of the airflow, fluid dynamic analysis and structural analysis are two approaches to further evaluate the compliant mechanisms of the pharyngeal soft tissues. The compliance of the soft palate has been studied using physical pharyngeal models and 2D numerical simulations. However, as the pharynx is naturally a 3D asymmetric region, 2D models might be too simple to capture some important dynamic characteristics of the compliance of pharyngeal soft tissues, such as lateral movement of tissues, volumetric change of tissues and airways and turbulence of the airflow.

In this study, we intended to reconstruct a realistic 3D human upper airway model to study the dynamic properties of the pharyngeal airflow and soft palate during calm respiration using fluid/structural interaction (FSI) simulations. The fluid domain consists of the nasal cavity and part of the pharynx upon the epiglottis. The whole soft palate was segmented. Simulations of two calm respiration cycles were carried out, and the results of the second cycle were analyzed. The airflow properties of the fluid domain with/without movement of the soft palate were evaluated and compared. The dynamic properties of the soft palate were also evaluated during both inspiration and expiration.

METHODS
MRI images of a 35 years old healthy Chinese male were obtained for model reconstruction. The same process as reported in our previous study was processed to build the model and discretize the fluid and structure domains using Mimics (Version 12.1, Materialise n.v.) and Hypermesh (Version 10.0, Altair Engineering Inc.) [3]. As shown in fig. 1, the pharynx was enclosed by the posterior surface of the tongue and the pharyngeal wall. The anterior side of the soft palate connected with the hard palate (fixation area), with the rest immersed in the fluid domain.

In the fluid domain, the air was assumed as incompressible with viscosity of $1.7894 \times 10^{-5}$ kg/(m·s) and density of 1.225 kg/m³. A sinusoidal velocity load was applied at the outlet corresponding to ventilation rate of 7.5 L/min. Zero ambient gauge pressure was applied at the hemisphere. Laminar model was used to simulate calm respiration, as the maximum volume flow rate was around 20 L/min. The wall of the nasal cavity, the posterior surface of the tongue and the pharyngeal wall were assumed as solid wall. The interface between the
pharyngeal airway and the soft palate was the only moveable fluid/structural interface. The soft palate was considered as isotropic and homogenous, with an average Young’s modulus of 1000 Pa, Poisson’s ratio of 0.45 and density of 1060 kg/m³. To constrain the soft palate within the fluid domain, a contact condition was specified between the fluid/structural interface and the wall of the pharyngeal airway. Commercial software Adina (Version 8.6.5, ADINA R&D, Inc.) was used to solve the transient equations for airflow, soft palate movement and airflow/soft palate interaction.

RESULTS AND DISCUSSION
Fig. 2 showed the mean pressure at nasopharynx and laryngopharynx using both computational fluid dynamics (CFD) and FSI simulations. Both the pressures at the nasopharynx and the laryngopharynx showed cosine pattern with/without interaction between the soft palate and the airflow. The pressure at the nasopharynx in model with fluid/structural interaction was found to be almost the same as model without interaction, which implied that the airflow in laryngopharynx did not affect the pressure distribution in nasal cavity much. The absolute pressure difference between nostrils and laryngopharynx was apparently larger in model with FSI interaction than model without movement of soft palate. It was notable that the pressure difference between CFD model and FSI model was larger during inspiration than expiration. Interestingly, during expiration the mean pressure at the laryngopharynx was lower than nasopharynx. This might be because that laryngopharynx is the narrowest region in the upper airway, where the velocity magnitude is much larger than the nasopharynx resulting in a lower pressure distribution.

CONCLUSIONS
The current model was useful in analyzing mechanisms of compliant property of human soft palate. The inspirational pressure in pharynx was found to be more sensitive to movement of soft palate comparing to expiration. The compliance of soft palate did not influence airflow patterns in nasal cavity much.

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