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COMPUTATIONAL FLUID DYNAMICS SIMULATION OF AIRFLOW ALTERATION IN THE TRACHEA BEFORE AND AFTER VASCULAR RING SURGERY

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INTRODUCTION

Vascular rings, congenital intracardic anomalies of the aortic arch and the vessels emerging from the heart, completely encircle the trachea and esophagus [1]. The vascular ring results in narrowing and obstruction of the trachea and the esophagus. Due to the existence of a complete or partial vascular ring compressing either the trachea or esophagus, symptoms of a vascular ring in children include cough, stridor, chronic cough, dysphagia, persistent wheeze, and noisy breathing [2]. Some studies reported that the vascular ring surgery provides an excellent chance to improve the patient respiration conditions, especially for relief of symptoms[1-3]. Al-Bassam et al. reported that the thoracoscopic division of vascular rings in infants and children is a safe and effective surgery rather than an open thoracotomy[4]. Even after the treatment of a surgical division of the vascular ring, however, the fixed obstruction is relieved but the patient continues to have dynamic collapse because the compressed trachea segment is always malacic. Airway resistance to flow in the airway, thus, is a key factor for not only clinical diagnosis severity assessment but also therapeutic decision in tracheal stenosis. Furthermore, Malvè et al. (2011) utilized the finite element-based commercial software code (ADINA R&D Inc.) to model the fluid structure interaction of a human trachea under different ventilation conditions [5]. They also found that the positive pressure in the trachea does not result in the airway collapse during the time period of mechanical breathing. Therefore, the purpose of this study is to use the computational fluid dynamics (CFD) technique to calculate the local pressure drops in the tracheal segment for different inspiratory and expiratory flow rates due to preoperative and preoperative vascular ring surgery.

METHODS

Figure 1 shows the entire flowchart for computational fluid dynamics simulations. In this study, the modeling of air flow transport within the airways was used by the forth steps.

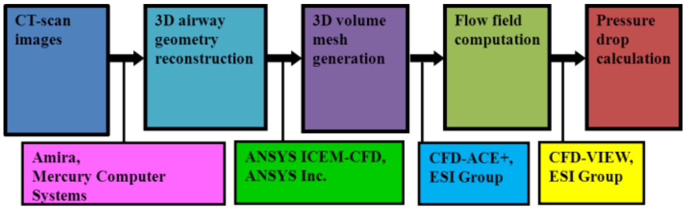

Fig.1 Steps for simulations. The overall flowchart includes the patient-specific CT-scan images, 3D airway geometry reconstruction, 3D volume mesh generation of the airway, air flow field computation, pressure drop in the airway, and corresponding software tools for each stage in the computer simulation.

Firstly, the three-dimensional (3D) airway geometry was reconstructed by the Amira software (Amira, Mercury Computer Systems, Chelmsford, MA). CT-scan images were acquired by the CT-Scanner (Philips Brilliance 40) and then saved in the Digital Imaging and Communications in Medicine (DICOM) file format. All 3D airway geometry reconstructions of the subject's anatomy were obtained from the routine CT scan images, as shown in Fig. 2. Secondly, the 3D volume mesh generation of the airway was created by the ANSYS software (ANSYS, ANSYS Inc., Southpointe, Canonsburg, PA). Thirdly, the air flow field in the airway (i.e., viscous pressure drop and velocity within the airways) was solved by the CFD-ACE+ software (ESI Group, Huntsville). The Navier-Stokes equations were used for solving the airflow field. Finally, the pressure drop of air flow passing through the airway was calculated by the CFD-VIEW software (ESI Group, Huntsville). In this study, we calculated the pressure changes in the fixed length trachea at inlet/outlet velocities of 0.01, 0.1, and 1 m/s for inspiration and expiratory phases. Note that in this numerical simulation the density of air is 1.161 kg/m^3 and the viscosity of airflow is 1.846×10^{-5} kg/m/s. The no-slip boundary conditions were applied on the airway walls and a uniform velocity profile was used at the inlet.

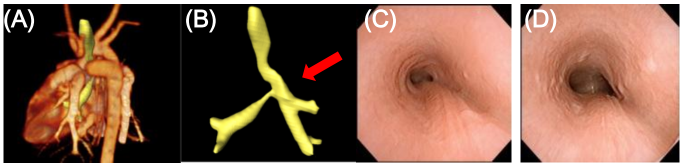

Fig. 2 3D geometry reconstruction and endoscopic images of the trachea. The red arrow indicates the tracheal stenosis due to the vascular ring. (A)3D surface geometry of the heart and the trachea (B)Compressed tracheal airway due to the vascular ring disease (C)Tracheal stenosis before the vascular ring surgery (D)Expanded tracheal airway after the vascular ring surgery.

RESULTS AND DISCUSSION

After the vascular ring surgery, the compressed narrowing trachea became larger. Figure 3 shows that the velocity distribution in the trachea before and after the vascular ring surgery. For the inspiratory velocity of 0.1 m/s, the maximum velocity in the trachea was about 1.952 m/s before the surgery. After the surgery, the maximum velocity decreased and 1.775 m/s. When the inspiratory velocity was at 0.1 m/s, the pressure drop changes were 0.178 and 0.096 Pa before and after the vascular ring surgery.

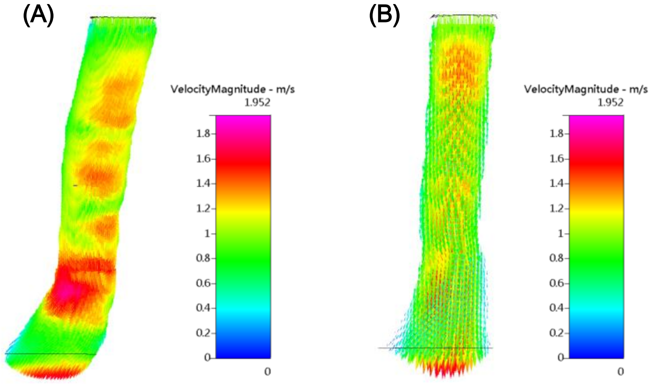

Fig. 3 Velocity distribution before and after the vascular (A)before surgery (B)after surgery.

Moreover, Table 1 shows the pressure change for different velocities. For the same inspiration air flow rate of 708.96×10^{-7} m^3/s and the inlet velocity of 1 m/s, the pressure drop in the trachea before the surgery was 4.988 Pa, which was higher than 2.827 Pa. On the other hand, the patient after the vascular ring surgery had less work of breath when keeping the same inlet airflow rate of 708.96×10^{-7} m^3/s (as shown in Table 1). In other words, the airway resistance was reduced to 54.04% after the vascular ring surgery. In contrast, For the same expiration air flow rate of 70.896×10^{-7} m^3/s and the velocity of 1 m/s, the pressure drop in the trachea before the surgery was 0.205 Pa, which was higher than 0.121 Pa. In numerical simulations, the airway resistance for expiratory phase was larger than that for inspiratory phase. As the compressed airway relieved, the viscous pressure drop in the tracheal airway decreases significantly after a surgical treatment for vascular ring. In addition, the improvement percent of vascular ring treatment is significant, especially for a low inlet velocity condition. In clinical practice, patients with airway stenosis are difficulty to do exams such as symptoms score or pulmonary function test because of their conditions. But we find the CFD method to solve the problems as we mention above. Therefore, our preliminary data give clinicians a new non-invasive approach to monitor airway obstruction severity in these children patients who were unable to do the pulmonary function tests.

Table 1. Pressure changes for different velocities before and after the vascular ring surgery

		Inspiration			**Expiration**	
Velocity (m/s)	0.01	0.1	1	0.01	0.1	1
Air flow rate ×10^{-7} (m^3/s)	7.089	70.896	708.964	7.089	70.896	708.964
Pressure change (Pa)						
Before surgery	0.011	0.178	4.988	0.013	0.205	6.018
After surgery	0.006	0.096	2.827	0.008	0.121	3.821

CONCLUSION

The CFD method can be evaluated the outcome of the vascular ring surgery. This information is important to assist to monitor airway obstruction severity in these patients who were unable to do the pulmonary function tests.

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