Tracheal stenosis and Computational Fluid Dynamics (CFD)

S. Batzella [1] G. De Nunzio [2 3] R. Buccolieri [2] M. Donativi [2 3] S. Di Sabatino [2] P. Ialongo [4] G. Culla [5] G. Galluccio [1]

[1]Endoscopia Toracica Osp. Forlanini, Roma, Italy

[2]Dipartimento di Matematica e Fisica, Univ. del Salento, Italy

[3]Istituto Nazionale di Fisica Nucleare sez. di Lecce, Italy

[4]Radiologia osp. Forlanini, Roma, Italy

[5]Riabilitazione respiratoria Osp. S. Filippo Neri, Roma, Italy

Tracheal stenosis is a narrowing of the trachea due to neoplastic or benign pathologies. The stricture of the trachea induces an increase in the air flow with variations in pre- and post-stenotic pressure. The increase in respiratory muscles effort induces dyspnoea and stridor and eventually respiratory failure. The tracheo-bronchial flow is usually studied by routinary spirometry (FEV1 and flow-volume curve). Both the FEV1 and the flow-volume curve furnish global quantitative information of flow (volume of air per second) but are not able to discriminate the anatomical site of flow alterations.

The geometry of upper airways is very complex both in normal and pathological conditions and the evaluation of the air flow at different anatomical sites is very difficult. CFD (Computational Fluid Dynamics) represents the most valid tool to predict the dynamics of the air flow in the airways.

Benign tracheal stenoses depend on various diseases such as infection and systemic inflammation, but iatrogenic stenoses (post intubation or tracheostomy) are the most frequent. Irrespective of etiology, the final result ends in scar tissue formation with fibrosis and narrowing of the lumen. The fibrosis can involve the tracheal wall less or more deep and for a shorter or a longer tract.

The anatomical characteristics of the stenosis can be studied with HRCT (High Resolution Computed Tomography) and virtual bronchoscopy. If compared with endoscopy, CT has shown to be more effective in identifying the presence and the degree of the stenosis. The realization of a three-dimensional reconstruction with the CT and the application of CFD techniques allow to study the geometry of the airways and provide information on morphology, area and length of the stenosis as well as the forecast of the dynamics of the air flow at different levels of ventilation, the type of flow (laminar, turbulent, transitory) and the decrease of pressure throughout the stenosis.

The turbulence can be described by the Reynolds number that expresses the relative importance between the inertial force and viscosity during the flow motion.

In this paper a three-dimensional reconstruction of the trachea was analyzed by CFD. The trachea reconstruction was obtained from a CT scan in two patients with benign tracheal stenosis (Figure 1). The air flow was simulated at different levels of ventilation corresponding to rest, light and moderate physical activity. Then the limitations of flow were compared with the ventilatory level achieved by the same subjects during cardio-pulmonary exercise test.

The first model of tracheal stenosis (Patient 1) was built from data collected by CT scan performed on a patient 75 years old, male, with post intubation tracheal stenosis who underwent endoscopic tracheal dilation. The patient affected with COPD was intubated for an episode of acute respiratory insufficiency due to pneumonia. The second model of tracheal stenosis (Patient 2) was derived from a CT scan of a 36 year-old patient, female, in good health, non-smoker, without previous diseases. The patient, with idiopathic cicatricial stenosis, had been previously submitted to intervention of endoscopic tracheal dilation.

The models were used to simulate the characteristics of aerial flow in stenotic and non stenotic airways.

The DICOM images were first processed by a semi-automatic segmentation tool written in MATLAB, with the purpose of identifying and extracting the extraparenchymal airways (essentially trachea and main bronchi). In order to reduce simulation complexity, and to make result interpretation easier, the extracted volume measures were automatically taken (lengths, angles, lumens) and a simplified model of the trachea/carena/bronchi structure was built.

After construction, the geometric model was divided into elementary cells in order to obtain a mesh and to resolve the Navier-Stokes equations, both in laminar and turbulent conditions . The software used was GAMBIT, which allows a simple and fast reconstruction of geometric models. The file mesh was read by the FLUENT CFD code.

To assess the subjects' cardiorespiratory function a spirometry with flow volume curve and a cardio pulmonary incremental (25 W per step of 2 min.) exercise test (with measurement of maximum heart rate, ventilation min. and VO2 peak) were carried out (Ergocard instrumentation, Remco Italy Cardioline utilizing the program EXP'AIR version 1:28 16 Medi soft).

The results of simulation for both models (with and without stenosis) for the two patients, in terms of pressure and speed profile, were compared in order to assess the effect of tracheal stenosis. In this analysis a number of assumptions were made. A uniform input speed was assumed in correspondence of the flat surface at the input of the model. The larynx, which is located above the trachea , and the lower bronchi, which extend below the main bronchi, were not considered in order to simplify the study of flow at the level of the stenosis, even if it is well known that the flow of the larynx causes a jet that influences the air flow into the trachea. Finally , the geometry of the actual paths was simplified: in particular the presence of the cartilaginous rings was neglected, thus assuming a model with smooth walls, and we considered a perfectly circular section of the trachea , bronchi and stenosis. Nevertheless the analysis was able to demonstrate that the presence of stenosis modifies the flow characteristics in human airways . The results showed that the tracheal stenosis influences the flow pattern which becomes less and less uniform with increasing input flow rate. These conditions induce an important pressure drop between pre and post stenotic trachea .

The pathophysiological evaluation in vivo confirmed the results of the simulation with CFD. In essence, the CFD simulation was able to predict the ventilatory levels at which the tracheal stenosis causes a marked increase in the post stenotic pressure drop as well as indirectly predicting the maximal sustainable effort

In our opinion this paper, which for the first time compares CFD analysis of flow variations in a model of stenotic trachea and pathophysiological data of ventilatory limitation in real patients, may represent the starting point for future studies to confirm the reliability of functional prediction by computer simulation of effort capacity in patients with impaired patency of the trachea. Furthermore it may be relevant to characterize tracheal stenosis not only from an anatomical point of view, but also dynamically. This might show the functional outcome of endoscopic dilation or surgical resection . The information that may be obtained, in terms of modification of pressure drop and of turbulence, and in terms of prediction of effort capacity, will probably allow a more precise pre-and postoperative study of the tracheal stenosis as well as provide an objective indication in the follow up for more stringent criteria for reintervention .

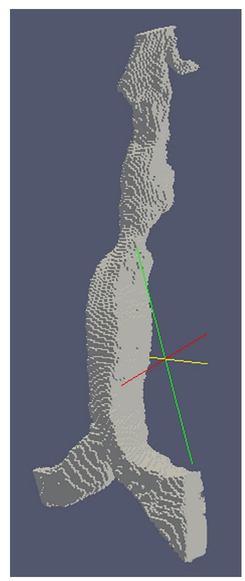

Figure 1. External airways reconstruction from CT scan. The stenosis is clearly visible.