The suitability of CFD in diagnosis and treatment of laryngeal diseases

Przydatność metody CFD w diagnostyce i leczeniu chorób krtani

ABSTRACT:
Computational Fluid Dynamics (CFD) is a fluids mechanics department that uses numerical methods to solve fluid flow issues. A review of the literature was done as well to summarize the usage of the CFD method in the assessment of airflow through the upper respiratory tract (GDO), especially in the larynx. CFD is now becoming a very useful tool not only for analyzing airflow patterns and mechanism of particle deposition in the larynx, but also for obtaining information on temperature, pressure, and shear stress changes in GDO. It is a tool with which one can safely plan surgical treatment as well as predict its potential effects.

KEYWORDS:
CFD, larynx, larynx diagnosis, treatment

STRESZCZENIE:
Metoda komputerowej dynamiki płynów (Computational Fluid Dynamics; CFD) to dział mechaniki płynów wykorzystujący metody numeryczne do rozwiązywania zagadnień przepływu płynów. W niniejszej pracy dokonano przeglądu piśmiennictwa dotyczącego zastosowania metody CFD w ocenie przepływu powietrza przez górne drogi oddechowe (GDO), ze szczególnym uwzględnieniem krtani. Metoda ta staje się obecnie bardzo przydatnym narzędziem nie tylko do analizy schematów przepływu powietrza i mechanizmu osadzania się cząstek w krtaniu, ale także do uzyskania informacji dotyczących zmian temperatury, ciśnienia, naprężeń ścinających w GDO. Jest ona narzędziem, z użyciem którego można bezpiecznie zaplanować leczenie operacyjne, jak również przewidzieć jego potencjalne skutki.

SŁOWA KLUCZOWE: CFD, diagnostyka krtani, krtani, leczenie

ABBREVIATIONS
BVFP – bilateral vocal fold paralysis
CFD – Computational Fluid Dynamics
CT – computed tomography
MRI – magnetic resonance imaging
SGS – subglottic stenosis
VCD – vocal cord dysfunction

INTRODUCTION
The development of computed imaging modalities has enabled to broaden knowledge about anatomy, physiology and pathophysiology of the human body in a scope of which researches were not aware a few decades ago. Scientists are eager to adapt new research methods, used successfully in the constantly developing fields of technology. Over the last three decades omnidirectional application in medicine has been seen in Computational Fluid Dynamics (CFD) which has thus far been used in aerodynamics, hydraulics, automotive, aerospace, space industries and in number of other fields.

CFD is a fluid mechanics department that uses numerical methods to solve problems in fluid flow. The principle of CFD is based on Navier–Stokes equations, describing the rule of conservation of linear momentum, mass and energy for a fluid flow. The method allows approximate determination of the distribution of speed, pressure, temperature and other fluid flow parameters [1]. CFD was first used in medicine in cardiology for the purpose of imaging blood flow dynamics. Another field in which CFD found application – since gas is a compressible and non-viscous liquid – is pulmonology. In both areas, as a non-invasive method CFD permits to visualize the mechanism of pathology, as well as learning about the effect of potential therapeutic intervention. This characteristic makes CFD unique compared to other commonly used diagnostic methods.

In line with the above, it appears appropriate to address the dynamics of airflow through the larynx, which is a physiological
place of the highest increase in air resistance in the respiratory tract. This resistance can increase drastically in pathologies of this organ and pose a threat to the patient’s life.

A review of the literature on the CFD usage in the assessment of airflow through the upper respiratory tract was performed with particular emphasis on the larynx. Performing CFD airflow simulation requires appropriate software, which consists of a mathematical and graphic module. Using CT or MRI images researchers create 3D models of the upper airways for simulating the airflow. There are many publications that demonstrate the remarkable usefulness of the method for quantitative measurement and visual estimation of air flow (laminar or turbulent), speed, pressure, shear stress, deposition of particles and temperature changes at different flow rates, in different parts of the nasal cavity. This is an opportunity for assessing the impact of existing anatomical factors and postoperative changes [2].

Less attention was paid to the airflow through the larynx, which is a critical organ for the breathing process. Breathing is a dynamic process in which the airflow increase from several hundred milliliters to several liters per second during deep breathing [3]. Correct function of the glottis plays a key role in the respiratory process, therefore it is relevant to know the boundary conditions that will enable proper functioning of the patient with laryngeal dysfunction. This knowledge is invaluable for relevant treatment of functional and morphological disorders of the larynx with dyspnea.

LITERATURE REVIEW

In 2009, Wang et al. constructed a model of the upper and lower respiratory tract based on CT images of a healthy man. Then, using CFD, they simulated airflow in a healthy patient and in 3 bronchostenosis variants. All cases presented a substantial increase in flow velocity at the level of the glottis and nasal valve. Furthermore, these levels also displayed the most significant pressure changes both on inspiration and expiration. Targeting glottic airflow on inspiration has a direct impact on the distribution of tracheal airflow. During exhalation, local bronchostenosis was seen to affect the tracheal flow rate profile, but this effect was significantly reduced due to the configuration of the trachea and glottis. After reaching the laryngeal cavity, the flow velocity profiles of all abnormal cases were almost the same as in the healthy model. It was therefore concluded that one of the functions of the tracheal and glottic structures is to eliminate the impact of bronchial structural abnormalities on the distribution of airflow in the upper respiratory tract (correction of pathological flow) [4].

In the same year, Kim and Chung observed in the CFD simulation that the mainstream air passes through the back of the larynx and trachea upon inhalation, and through the anterior portion during exhalation [5].

In the field of aeroacoustics in the human vocal tract, computational methods have considerable importance since direct flow and acoustic measurements in the vocal system are invasive and therefore almost unfeasible. In 2015, Šidlof et al. created two models of the vocal tract based on MRI during the phonation of vowels “i” and “u”. Spectra of the radiated sound evaluated on the basis of acoustic simulations showed good agreement with the frequencies of formants in humans. CFD simulations have suggested that vestibular folds induce amplification of higher harmonics in the radiated sound field. A comparison of convergent-divergent vibrations of the vocal fold to oscillations with a constant angle of convergence of medial surfaces revealed a decrease in non-harmonic frequency contents [6].

The following years brought publications on studies of laryngeal airflow with certain acquired or congenital disorders.

In 2015, Frank-Ito et al. observed changes in the occurrence of VCD (vocal cord dysfunction). Based on CT imaging of a healthy patient with correct separation of the vocal folds authors imitated the VCD episode. To estimate and compare changes in inspiratory flow during normal inspiration and a VCD attack, steady state laminar simulations were performed for three different breathing rates. There was an increase of local air velocity in the posterior laryngeal region, and a higher shear stress levels were observed in the same region, indicating the relationship between local shear stress and flow rate. The authors demonstrated that a VCD attack could reduce the air flow rate by more than 50%, disrupt it by generating high speed in the glottis, increase elevated levels of shear stress on the posterior wall of the larynx, and negatively affect laryngeal aerodynamics [7].

In 2016, Gokcan et al. researched airflow in patients with a congenital glottic web. They demonstrated that the role of vestibular folds during inspiration consists in proper targeting of air into the narrower portion of the glottis for a more uniform flow. Typically, when liquids are forced to pass through a narrower lumen, we can expect an increase in flow velocity and suction pressure, which can result in flow separation after exceeding a certain level. Furthermore, the authors suggest that the subglottic structures (including the elastic cone) play a major role in the phonatory function of larynx, although they also play a very substantial part in breathing, since the same area of the larynx may adapt to increase both breathing efficiency and voice production [3].

In 2017, Lin et al. studied airflow in subglottic stenoses and suggested that the constriction diameter has a much greater influence on airway resistance than its length. There is an inverse relationship between airway resistance and the subglottic cross-section, hence the double reduction of the cross-sectional area is associated with a two-fold decrease in airflow velocity. The pressure drop was largely limited to the region of stenosis [8].

CFD can also be used to plan and predict the effects of surgical treatment using computer models of the larynx. Gokcan et al. (2010) assessed the effects of bilateral posterior transverse laser cordotomy in the treatment of bilateral vocal fold paralysis (BVFP). They studied flow parameters such as velocity, pressure values at the glottic level, flow turbulence, wall shear stress. During the peak flow, they observed a rapid decrease in pressure in the supraglottic region and an increase in flow velocity. This resulted in the appearance of turbulence and vortex structures that further reduced respiratory efficiency. They
In 2013, Hundertmark-Zauskova et al. performed a series of two-dimensional CFD models, searching for the optimal geometry of the larynx in terms of freedom of breathing after surgery for vocal and vestibular folds [10]. Their research showed that the distance between vestibular folds affects airflow resistance and volumetric flow rate.

In 2016, Zdanski et al. demonstrated that non-invasive imaging and derived CFD indices can be useful tools for diagnosis and planning of operative treatment in subglottic stenosis (SGS) in children. Preliminary limit values were determined and parameters defining which patients required surgical intervention were established. The authors showed that computational modeling enables obtaining objective measurements helpful in making therapeutic decisions. Geometric and CFD variables were sensitive in determining which SGS patients required surgical intervention [11].

In 2017, Marków et al. evaluated the respiratory efficiency of patients after unilateral arytenoidectomy with posterior cordectomy in BVFP. It has been observed that in patients with a glottic field <40 mm² even a small widening can result in a significant respiratory improvement. Widening the glottal field, which is >40 mm² before surgery, begins to lose its therapeutic value [12].

In 2019, Rios et al. also investigated the possible effects of surgery on laryngeal models in 3 patients with BVFP. They performed virtual posterior cordotomy, laterofixation and posterior cricoid expansion. They showed an improvement in airflow, reduction of speed and resistance in all cases of glottic expansion [13].

Numerical simulations using methods of computational fluid dynamics have also proven to be an effective and reproducible way to track particle deposition in the larynx. In 2017, Perkins et al. used CFD to investigate the deposition patterns of inhaled corticosteroid particles targeting laryngeal and vocal fold granulomas. In the normal model, larger particles (16–20 μm) were deposited in the oropharynx, while smaller particles (1–15 μm) were more diffused in the airways or penetrated into the trachea and lungs. The particle size range that most effectively deposited in a healthy glottis was 8–10 μm (2.8–3.5%). The presence of granuloma affected the particle deposition at the level of vocal folds. The authors demonstrated that with the increase in the virtual size of the granuloma and the change of its location towards the posterior commissure, the size and the density of particle deposition in the glottis increases. With a large posterior granuloma, the particle size range was 7–14 μm, for the normal model – 8–10 μm, and for small anterior granuloma – 6–10 μm. The maximum deposition was 10.8% for particles with a size of 9 μm with a large granuloma of the posterior commissure (50% of the length of vocal fold), while in the model of the normal larynx it was 3 times less – 3.5% [14].

To assess the effects of surgical treatment of patients with BVFP, CFD simulations research is currently in progress in the Clinical Ward of Otorhinolaryngology and Laryngological Oncology in Zabrze, the Silesian Medical University in cooperation with the Institute of Environmental Engineering and Biotechnology, University of Opole (Fig. 1.).

CONCLUSIONS

CFD is now becoming a very useful tool not only for analyzing airflow patterns and the mechanism of particle deposition in the larynx, but also for obtaining information on temperature, pressure and shear stress changes in upper airway respiratory tract. It is a tool with can be used safely to plan surgical treatment as well as predict its potential effects. Due to limited availability, the use of CFD currently remains an academic experience that will perhaps open the way for determining the parameters and surgical techniques ensuring the best treatment result.
References


