Respiratory Physiology & Neurobiology 234 (2016) 69–78

Contents lists available at ScienceDirect

Respiratory Physiology & Neurobiology

journal homepage: www.elsevier.com/locate/resphysiol

The effects of curvature and constriction on airflow and energy loss in pathological tracheas

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ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form 1 August 2016
Accepted 1 September 2016
Available online 13 September 2016

Keywords:
Trachea
Airflow
CFD
Goiters
Energy loss

ABSTRACT

This paper considers factors that play a significant role in determining inspiratory pressure and energy losses in the human trachea. Previous characterisations of pathological geometry changes have focussed on relating airway constriction and subsequent pressure loss, however many pathologies that affect the trachea cause deviation, increased curvature, constriction or a combination of these. This study investigates the effects of these measures on tracheal flow mechanics, using the compressive goitre (a thyroid gland enlargement) as an example.

Computational fluid dynamics simulations were performed in airways affected by goitres (with differing geometric consequences) and a normal geometry for comparison. Realistic airways, derived from medical images, were used because idealised geometries often oversimplify the complex anatomy of the larynx and its effects on the flow. Two mechanisms, distinct from stenosis, were found to strongly affect airflow energy dissipation in the pathological tracheas. The jet emanating from the glottis displayed different impingement and breakdown patterns in pathological geometries and increased loss was associated with curvature.

1. Introduction

Many pathologies affect the flow of both air and blood in the human body by changing the shape of the relevant conduit. This change of shape has often been characterised by a constriction to the conduit (e.g. degree of stenosis) and related to the pressure drop. Several studies have hypothesised that the degree of constriction can be used as a predictor for the physiological impact of the pathology. For example, in the airways, Brouns et al. (2007) considered the degree of tracheal stenosis in a straight tracheal geometry, whilst in haemodynamics Schrauwen et al. (2015) investigated pressure losses in straightened atherosclerotic coronary arteries. However, the constriction of the conduit may be only one of several geometric changes caused by the pathology. Typically, conduits in the human body exhibit some degree of curvature and certain pathologies increase curvature. These additional geometric factors have previously been overlooked in the airway literature. Brouns et al. (2007) presented a means to predict increased tracheal pressure loss from the degree of constriction. Their study introduced an index to calculate pressure loss from stenosis degree, however the analysis did not include the influence of curvature (or other geometric changes) thus the index falls short of a complete geometric characterisation. The importance of different geometrical effects was highlighted by Mylavarapu et al. (2013) who investigated the resistance in a trachea with a subglottal stenosis. They focused on changes to this resistance in four possible surgical procedures. All four virtual surgery cases increased the cross sectional area of the airway, yet two cases demonstrated a rise rather than the expected fall in airway resistance, demonstrating that constriction is not the only factor in determining tracheal resistance. This study highlights the need for a more in depth understanding of the relationship between airway anatomy and the impact this has for the subject in terms of resistance to airflow and breathing effort, particularly in terms of how surgical procedures may modify this anatomy.

Analysis of tracheal flow mechanics using CFD has seen significant attention in healthy geometries (Lin et al., 2007; Choi et al., 2009; Ma and Lutchen, 2006; Comerford et al., 2013). These studies have observed a number of fluid mechanics phenomena as the flow enters the trachea through the constriction of the glottis, these include: breakdown and impingement of the jet; turbulence; and secondary flow vortices due to the curvature of the vessel. However,

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http://dx.doi.org/10.1016/j.resp.2016.09.002
1569-9048/

the trachea can be affected by a number of pathologies that further influence the geometry causing constriction, deviation or a combination of both, thus altering the flow mechanics and breathing effort.

A number of studies have investigated the influence of different pathologies on tracheal flow mechanics (Brouns et al., 2007; Mihăescu et al., 2008; Malvè et al., 2011; Mimouni-Benabu et al., 2012; Hamilton et al., 2015). As already mentioned, Brouns et al. (2007) simulated the influence of tracheal stenosis in an idealised tracheal geometry. The stenosis they considered was axis-symmetric and positioned in the sub-glottal region. Their results indicated that for an idealised stenosis, the relationship between pressure and flow (a power law) increases from normal only when severely constricted (60% and 85% luminal area reduction).

Further studies on flow in stenosed airways have been performed by Mihăescu et al. (2009), Mimouni-Benabu et al. (2012) and Vial et al. (2005). These studies further highlight the need for increased understanding of how airway anatomy affects the work of breathing and how this can affect clinical and surgical planning.

The degree of involvement of the upper airways in defining flow needs to be considered. Lin et al. (2007), Xi et al. (2008), Choi et al. (2009) and Pollard et al. (2012) have demonstrated that including some of the upper airway geometry is necessary for an accurate description of the fluid mechanics in the trachea. This is primarily because the glottal jet – which forms due to the glottal constriction – influences turbulent flow structures in the trachea. As to how much of the upper airways must be considered, Saksono et al. (2011) reported that the whole nasal cavity must be included, however Choi et al. (2009) reported that simulations truncated at the mid-laryngopharynx level provide a good description of tracheal flow mechanics (when compared to simulations of the whole upper airways), with similar results found with truncation immediately above the glottis. Therefore, inclusion of the most constricted section upstream of the trachea is deemed sufficient – in this study, this is assumed to be the glottis.

Previously, LES approaches have been presented for modelling airflow in healthy subjects (Lin et al., 2007; Choi et al., 2009; Comerford et al., 2013). Mihăescu et al. (2009) compared flow calculated using steady Reynolds-averaged Navier–Stokes (RANS) calculations and unsteady LES in a paediatric trachea with subglottal stenosis, concluding that LES is the preferred tool to capture the flow features associated with the stenosis such as large radial velocity gradients. In the study reported here, the accuracy of LES is compared with that of very high resolution simulations devoid of turbulence modelling assumptions. CFD simulations have also been found to closely match experimental results in an idealised healthy extra-thoracic airway (Heenan et al., 2003; Ball et al., 2008). Some differences were observed, but can potentially be attributed to limits on mesh resolution. Whilst further previous studies have investigated air flow in stenotic tracheas, those not including the glottis are not considered here.

Calmet et al. (2016) and Bates et al. (2015a) both analysed the flow regime in highly resolved simulations, concluding that flow in the complex geometries of the airways at these flow rates is likely to be non-laminar with mild turbulence observed.

Highlighting the increase in respiratory effort through properties other than constriction has clinical significance. The American Thyroid Academy (Stang et al., 2012) propose basing the surgical decision making on the ratio of 1D measurements (the airway diameter in a CT slice) of the tracheal anatomy, a measure which again does not consider the influence of other geometric factors. In this study we investigate the relative importance of these previously overlooked geometric measures through one specific pathology, the compressive goitre.

Combining geometric measures with CFD as a clinical management tool for pathological changes has been demonstrated by Hamilton et al. (2015), who used area and pressure loss as measures for functional analysis of the development of a transplanted trachea.

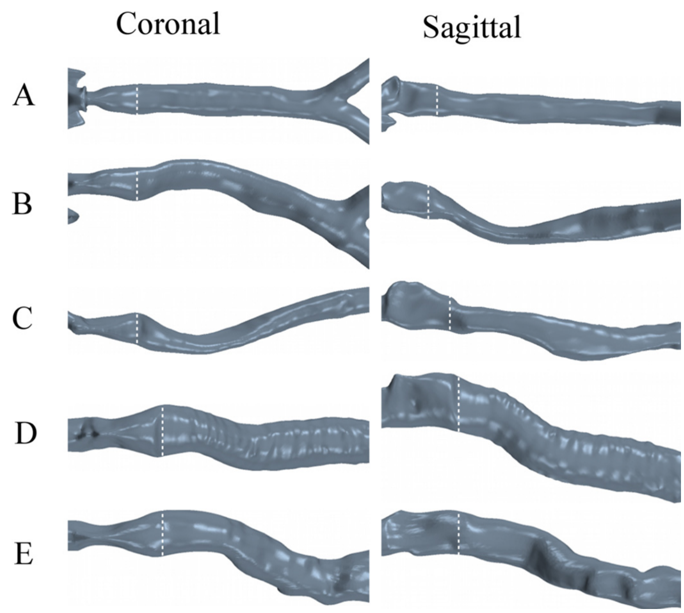

Fig. 1. Sagittal and coronal views of tracheal geometries. A was described as normal, B and C show both curvature and constriction, whilst D and E show increased curvature from the normal case, but without constriction. Each geometry extends above the glottal region shown here to ensure that natural inflow conditions have developed across the area of interest. The dashed white line represents the location of the first tracheal ring.

A goitre is an enlargement of the thyroid gland, which in certain cases can extrinsically compress the trachea, causing it to displace or deform. This can lead to symptoms such as difficulty in swallowing, coughing and shortness of breath or an inability to breathe at higher flow rates. The decision to operate to remove a goitre is based on a number of patient parameters, including analysis of CT images. Additional diagnostic complications arise when patients suffer also from lung pathology, masking the influence of the compressive goitre.

The primary purpose of the present paper is to demonstrate how CFD simulations of tracheal flow can enhance understanding of the relationship between pathological tracheal anatomy and losses of pressure and energy. This relationship can provide useful insights for surgical planning. Given the limited number of cases considered, necessitated by the cost of detailed LES simulations, the focus is not to examine the broad range of possible geometries, but to facilitate a better understanding of how geometry affects the airflow and the consequences in terms of factors that must be considered in any clinically relevant metric.

2. Materials, methods and their justification

2.1. Selection of geometry

To provide an in-depth analysis of geometric factors that are important for breathing mechanics five tracheal geometries were studied: one normal and four pathological cases (affected by compressive goitre). The normal case provides a reference, similar to the studies of a number of healthy tracheal geometries in the literature (Lin et al., 2007; Choi et al., 2009; Ma and Lutchen, 2006; Longest and Vinchurkar, 2007) to compare with the pathological cases.

The five geometries which were studied are shown in Fig. 1. All geometries are imaged at high lung volume, nominally total lung