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ScienceDirect
Medical Engineering & Physics 31 (2009) 328–336
Medical Engineering & Physics
www.elsevier.com/locate/medengphy

Study of tracheal collapsibility, compliance and stress by considering its asymmetric geometry

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Received 27 September 2007; received in revised form 29 May 2008; accepted 5 June 2008

Abstract

The shape of tracheal cartilage has been widely treated as symmetric in analytical and numerical models. However, according to both histological images and in vivo medical image, tracheal cartilage is of highly asymmetric shape. Taking the cartilage as symmetric structure will induce bias in calculation of the collapse behavior, as well as compliance and muscular stress. However, this has been rarely discussed. In this paper, tracheal collapse is represented by considering its asymmetric shape. For comparison, the symmetric shape, which is reconstructed by half of the cartilage, is also presented. A comparison of cross-sectional area, compliance of airway and stress in the muscular membrane, determined by asymmetric shape and symmetric shape is made. The result indicates that the symmetric assumption brings a small error, around 5% in predicting the cross-sectional area under loading conditions. The relative error of compliance is more than 10%. Particularly when the pressure is close to zero, the error could be more than 50%. The model considering the symmetric shape results in a significant difference in predicting stress in muscular membrane by either under- or over-estimating it. In conclusion, tracheal cartilage should not be treated as a symmetric structure. The results obtained in this study are helpful in evaluating the error induced by the assumption in geometry.
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Keywords: Trachea; Cartilage; Collapse; Compliance; Stress; Asymmetric

1. Introduction

The airway is composed of a series of tracheal rings with horseshoe-like cartilages connecting with muscular parts. As the only passage for the air to flow in and out, tracheal collapse behavior is very important for estimating the bio-function of the whole respiratory system, on which many clinical parameters are dependent, such as compliance and stress. Compliance reflects the expansibility of the airway and has a direct relationship with resistance during breathing and limitation flow when collapse happens [1–3]. It is also relevant to many clinical treatments, such as total liquid ventilation [4] requiring in-depth knowledge of the compliance. Stress in the muscular part depends on the collapse behavior and it has been widely accepted as one of the most important mechanical triggers inducing tissue remodeling [5,6] and damage [7,8].

When collapse happens, the flexible tracheal cartilage changes its curvature and the muscular membrane drops into the cavity causing clinical distress. Apart from its mechanical property, it has been mentioned that the shape of cartilage has a significant impact on the deformation of cartilage [9,10]. According to the histological image [11] and anatomical figure, tracheal cartilage is an asymmetric structure. Teng et al. [10] suggested using concentric ellipses to fit the inner wall and outer wall of cartilage, respectively, and choosing the middle points of the two ellipses to approximate the shape of cartilage, whilst determining both cartilage tips manually according to the real image. It was found that the tips were not in a horizontal line implying the asymmetric shape of the cartilage. However the cartilage was

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1350-4533/$ – see front matter. Published by Elsevier Ltd on behalf of IPEM
doi:10.1016/j.medengphy.2008.06.006

usually considered to be symmetric, treating the cartilage as a semicircle in analytic models [9,12,13] and generating a symmetric geometry according to the histological image [11] in numerical simulations. Although it has been thought taking asymmetry into account would not yield a sufficient improvement [12], we need a quantitative discussion on this aspect.

In this study, the cartilage shape is approximated by a skew ellipse [10]. Based on that, the collapse behavior of complete ring is discussed as well as the further parameters: compliance of the airway and stress in the muscular membrane. In order to discuss the deviation induced by the symmetric hypothesis, the Symmetric Model is reconstructed by half of the cartilage and the comparisons are made on collapse, compliance and stress. Moreover, in this study, instead of assuming that tracheal cartilage is a linear elastic material [14,9,15,12,11,13], Fung-type strain energy density function is used to describe its mechanical property [10]. Ogden [16] form strain energy density function is used to capture the mechanical property of the muscular membrane. Material constants in both functions are determined by fitting the experimental data.

2. Methods

2.1. Material test

Five tracheal rings above the bifurcation from an adult pig provided by a local slaughterhouse were used to perform the test. Briefly, after the soft tissue was removed, the cartilage was mounted on an Instron MicroTester 5548 (Instron Ltd., USA) to perform the test, which provided the experimental data of force applied on the tips and displacement between them (Fig. 1a). After the test, the shape of the cartilage was recorded. By fitting the experimental data, the material constants included in the constitutive law were determined. Please refer Ref. [10] for details about the material test and parameters fitting. A section with 20 mm length of muscular membrane connecting the cartilage tips, as well as the part attached on the inner wall of cartilage, was cut to perform the uniaxial test. After five times' preconditioning, the test was performed with the stretch ratio ranging from 1 to 1.5 with an extension velocity of 3 mm/min. All the tests were performed at room temperature and the humidity was maintained by an atomizer.

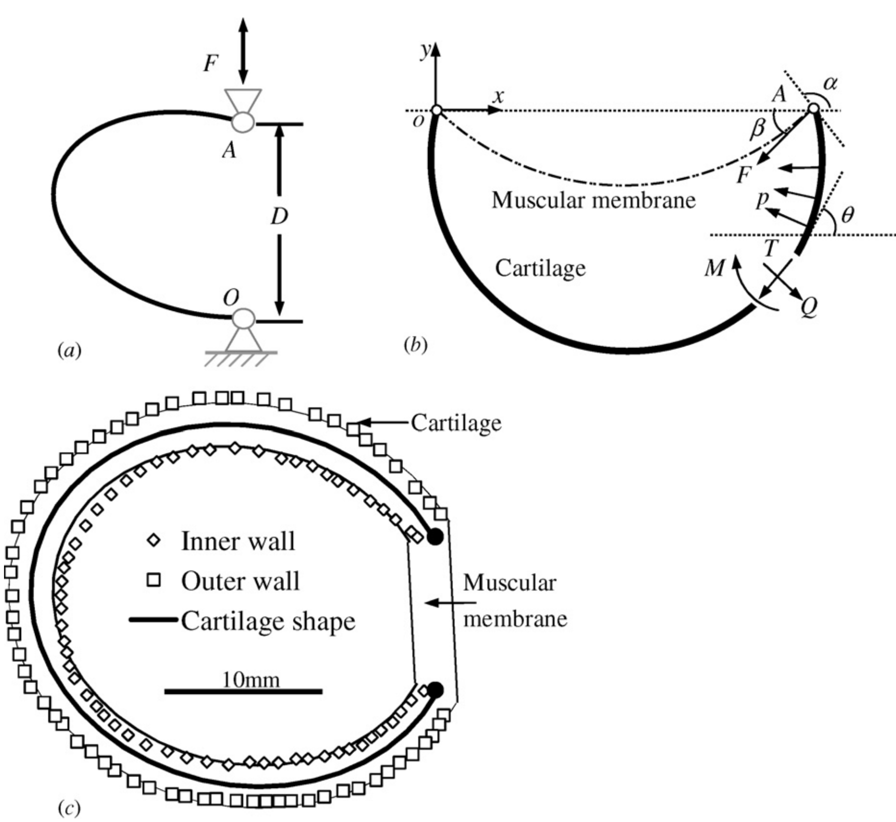

Fig. 1. (a) Schematic drawing of the material test used to get the mechanical property of cartilage (the tip O is fixed and tip A is mounted on a movable arm; the force, F, and distance (D) change, ΔD, are recorded simultaneously during the test); (b) the drawing for analysis of a deformed tracheal ring (the joints between the cartilage and muscular membrane are modeled as hinges); (c) the boundary of a tracheal ring. The points represent the inner and outer walls; the thin lines, part of ellipses, are the regression curves for the wall boundaries; the thick line is built by the middle points of these two lines to represent the cartilage shape; and the two black dots denote the tips of the cartilage.