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Young's Modulus Measurement on Pig Trachea and Bronchial Airways

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Abstract—**Young's Modulus was measured on the trachea and first three generations of pig airways by compression. A simple and low-cost system for measuring the elastic properties of small bio-materials is presented. The force-displacement measurements have been undertaken on dissected cartilage and trachea mucosa from pig trachea and bronchial segments. Young's Modulus of trachea wall, 1.78±0.51 MPa, is found to be dominated by the trachea cartilage of value 1.74±0.85 MPa while the modulus for trachea mucosa was 0.15±0.03 MPa. The Young's Modulus of the airway wall from the first three generations of bronchi decreases from 1.35±0.17 to 0.35±0.10 MPa which is also found to be dominated by the airway cartilage. Airway mucosa is found to have similar Young's modulus of 0.036±0.005 MPa for the first three generations of bronchial airways.**

I. Introduction

AIRWAY diseases such as asthma are related to the airway wall elasticity. Elasticity measurements on airway walls can lead to a better understanding of respiratory ventilation mechanisms and also provide useful information and reference values for clinical tools, such as ultrasound and MRI elastography [1]-[8].

Stiffness measurements on human and animal trachea rings have been studied in the past two decades [9]-[13]. However, the elastic properties of airway walls from different generations of bronchi are little documented. In this study, a simple and low-cost system has been developed for measuring the elastic properties of small bio-materials. Force-indentation measurements of the trachea and the first three generations of bronchial wall segments from the same pig have been performed. The Young's modulus of the cartilages and mucosa are also compared.

II. Basic Principles

Hardness and Young's Modulus from a Force-Distance Curve

The compression method of loading and unloading is

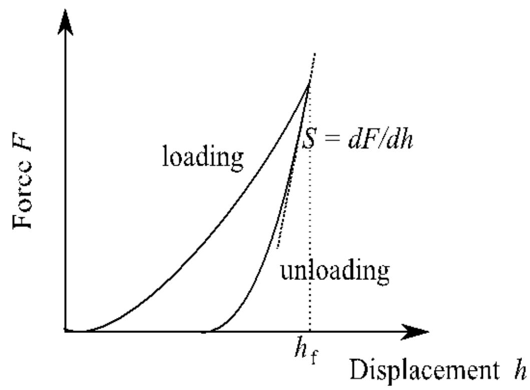

Fig. 1. Schematic illustration of a cycle of loading and unloading force-displacement curve [14]. The unloading stiffness is defined as the slope of the force and displacement at the initial unloading process. h_f is the final displacement of the material.

based on the fact that the displacements recovered during unloading are largely elastic, in which case the Young's modulus, E, can be simply analyzed from the unloading curve where the Hooke's law holds [14]. Young's modulus of an elastic material is a ratio of uniaxial stress (ε) over strain (σ) which can be related to an external force (F) over the uniaxial length changing (ΔL) by

$$E = \frac{\varepsilon}{\sigma} = \frac{F / A_0}{\Delta L / L_0} = \frac{F}{\Delta L} \cdot \frac{L_0}{A_0} \qquad (1)$$

where L_0 is the initial length and A_0 is the initial cross-sectional area of the material without any applied force.

In this study, the Young's modulus was calculated from the initial unloading process, i.e.,

$$E = \frac{dF}{dh} \cdot \frac{L_0 - \Delta L}{A_0 + \Delta A} = S \cdot \frac{L_0 - h_f}{(w + \frac{h_f}{2})^2} \qquad (2)$$

where (L_0 - h_f) is the material length at initial unloading process while (w + $h_f/2$) is the material width at initial unloading process with the assumed Poisson's ratio of 0.5 [15]-[17]. The elastic unloading stiffness, S = dF/dh, is defined as the slope of the unloading curve during the initial stages of unloading.

A schematic illustration of force-displacement curve is

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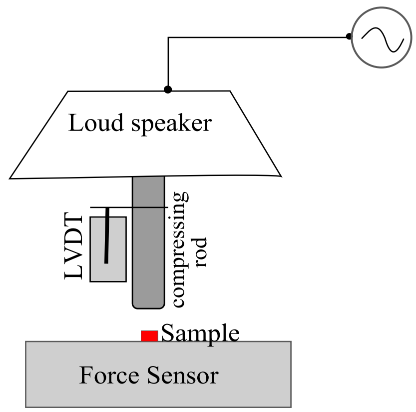

Fig. 2. The system diagram for measuring the elastic modulus. The compressing rod is driven by a dynamic loud speaker. The distance is measured by a LVDT (linear variable distance transducer). The sample is placed on top of the force sensor which monitors the force applied on the sample.

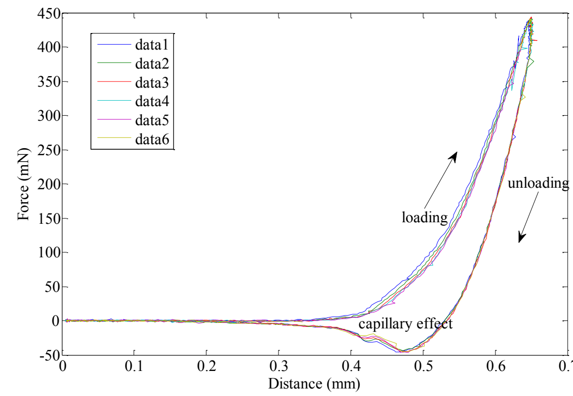

Fig. 3. The force-displacement curve from a tracheal segment repeated 6 times. A pulling force occurred at the end of the unloading curve caused by the capillary force between the sample, compressing rod, and the force sensor.

shown in figure 1 where one cycle of loading and unloading of an indenter on a material (which is relatively soft to the indenter) is presented [6].

III. System

The system developed for measuring the elastic properties of small biomaterials is shown in figure 2. A loud speaker (4", BG 10, 8 Ω, Visaton, Germany) is used as the actuator for driving the compressing rod. The compressing rod is made of stainless steel with a flat end of diameter 1.25 cm (which is 2-3 times larger than the samples), and fixed under the speaker. The loud speaker is powered by a modified stereo amplifier (K4003, Velleman-Kit, Beigium) and the input signal is controlled by a computer.

A liner variable distance transducer (LVDT, Position sensor M-0.5, Applied Measurements Ltd., UK) is used for measuring the displacement of the compressing rod. The digital noise from the LVDT is approximately 4.05 mV which corresponds to 5.95 µm.

A force sensor modified from a balance (50g, resolution 0.01g, APS-50, Farnell, UK) is placed under the compressing rod. The digital noise from the force sensor is approximately 4.02 mV which corresponds to 0.09 mN. The sample is placed on the force sensor and under the compressing rod.

IV. Experiment Setup

The measurement was performed on a pig trachea wall segment (with cross sectional area of about 4 mm x 4 mm) and airway wall segments from first three generations of bronchi (with cross sectional area of about 2.5 mm x 2.5 mm). The airway segments were taken from an adult Tamworth pig (about a year and half old) which was supplied by the local butcher and killed for other purpose. All the samples were preserved at 4^{o}C in PBS solution (Phosphate Buffer Saline, 100 mL, Invitrogen, USA) and the measurements were undertaken within 48 hours of death. The mucosa and cartilages were dissected from the segments.

The system was tested with two different types of silicone rubber (2-mm thick, 4mm x 4mm cross-sectional area) which have elastic moduli of 0.32 MPa (794N, DowCorning, USA) and 1.80 MPa (Bond Flex 100HMA, Bostik, UK). The system gives values within 3% of the published values from the silicone sample datasheets. The force-displacement measurements were taken under a constant speed of 0.1 Hz (loading and unloading) and repeated 6 times for each sample. The system displacement has also been considered and subtracted from all the force-distance curves. All the measurements were performed at the room temperature (about 21±1^{o}C).

V. Results

The force-displacement curve from trachea wall segment is shown in figure 3. Each measurement was repeated for six times under the loading-unloading period of 10 seconds during which the sample was fully recovered. Note that at the end of the unloading, a pulling force between the sample, the rod, and the force sensor occurs because of the capillary effect.

The measured Young's modulus from the segments is shown in figure 4 (with the assumed Poisson's ratio of 0.5). Young's modulus of trachea wall was approximately 1.78±0.51 MPa, which is dominated by the cartilage with E=1.74±0.85 MPa. The tracheal mucosa has much larger Young's modulus of 0.14±0.02 MPa compared to bronchial mucosa with E=0.036±0.08 MPa. The Young's modulus of bronchial wall decreases greatly from the second generation (E=0.41±0.09 and 0.35±0.10 MPa) compared to the first generation (E=1.35±0.17 MPa).

The measured Young's modulus from trachea and the first three generations of bronchial airway walls, cartilages, and mucosa are shown in figure 4 and also listed in table 1 with the approximate outer diameters of each airways and the thickness of the segments.

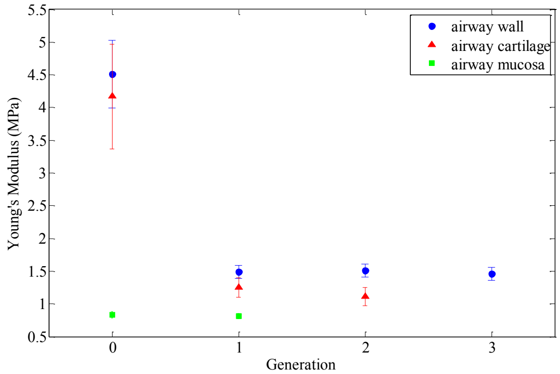

Fig. 4. The measured Young's modulus (E) of airway walls, cartilages, and mucosa from trachea (generation 0) and the first three generation of bronchial airways (generation 1-3).

VI. Discussion

A low-cost system for measuring the elastic modulus of small bio-material has been developed. The system can also be used for measuring dynamic modulus. Young's modulus of pig airway walls, cartilages, and mucosa from the trachea and first three generations of bronchi has been measured and found to decrease generation by generation. In each generation, the Young's modulus of airway wall has been found to be dominated by the modulus of airway cartilage. The measured Young's modulus from a pig tracheal cartilage has smaller value compared to the results from Sera *et al.* [18]-[20] with the value of E=5.8±2.9 MPa but a different measuring method, which can be due to different pig species and ages. As it has been well documented that there are many anatomy similarities between pig airways and human airways, to study the elastic properties of pig airways can be helpful for understanding the mechanical properties of human airway.

VII. Future Work

More adult pig specimens will be undertaken for this study to give a statistical result. The dynamic force modulus will also be measured with our developed system.

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TABLE I
Airway Dimensions and Young's Modulus

airways	outer diameter (mm)	segment thickness (mm)	Young's Modulus (MPa)
tracheal g0	22.51±15.00	2.23±0.07	1.78±0.51
bronchial g1	11.00±1.00	1.78±0.21	1.35±0.17
bronchial g2	7.00±1.00	1.51±0.22	0.41±0.09
bronchial g3	4.00±0.50	1.16±0.12	0.35±0.10
tracheal cartilage g0c		1.39±0.31	1.74±0.85
bronchial cartilage g1c		1.32±0.20	1.44±0.25
bronchial cartilage g2c		1.05±0.004	0.44±0.05
bronchial cartilage g3c		0.52±0.05	0.16±0.03
tracheal mucosa g0m		0.405±0.027	0.14±0.02
bronchial mucosa g1m		0.303±0.109	0.041±8e-3
bronchial mucosa g2m		0.551±0.220	0.031±1.7e-3
bronchial mucosa g3m		0.331±0.020	0.042±e-7

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