PRETERM LAMBS TRACHEAL DUCT COLLAPSIBILITY: A FINITE ELEMENT STUDY

Monica Soncini (1), Gianfranco B. Fiore (1), Chiara Corno (1), Paola Bagnoli (1), Gabriele Dini (1), Fabio Acocella (2), Roberto Colombi (3), Maria L. Costantino (1)

(1) Department of Bioengineering
Politecnico di Milano
Milano
Italy

(2) Institute of Surgical Clinics and Radiology
Medical Veterinary Faculty, Università degli Studi
Milano
Italy

(3) Surgical Pathology Service
Macedonio Melloni Hospital
Milano
Italy

INTRODUCTION

Knowledge of the mechanical behavior of immature tracheae is crucial in order to understand the effects exerted on central airways by ventilatory treatments, particularly of tidal liquid ventilation (TLV) [1]. Although the adult respiratory system has been deeply studied with both experimental and computational approaches, the infant and fetal lungs have never been examined so accurately, in spite of their peculiar characteristics and pathologies.

The aim of this study is the investigation of the mechanical behavior of preterm lamb tracheae, in terms of compliance, and particularly collapsibility, at pressure conditions which may occur during TLV. Both computational methods and experimental tests were used to this purpose.

MATERIALS AND METHODS

Histological analyses of five tracheal samples were conducted on both longitudinal and cross sections, in order to acquire morphometric information. A 3-D, parametric, finite-element, structural model of one tracheal ring, based on histology measurements, was developed, aimed at simulating the collapsibility of different tracheal regions. Numerical analyses were then performed to evaluate the ring's collapsibility at pressures ranging between –30 and 0 cmH_2O. Results were compared with data collected during experimental collapsibility tests performed on the five tracheal samples, to verify the model's reliability.

Computational finite-element model

The 3-D finite-element model developed was parameterized in order to represent rings belonging to three different tracheal regions (cranial, median, caudal) (Fig.1, left). Each ring model consists of three structures; a cartilaginous arc, a smooth muscle, completing the ring posteriorly, and a connective tissue accounting for all the tissues covering the whole ring at the inner and outer surface (Fig.1, right). The geometrical models were discretized with four-nodes tetrahedral elements using GAMBIT (Fluent Inc. Lebanon, NH).

Both the cartilage and soft tissues were assumed to be homogeneous and isotropic materials. The cartilage was modeled as a linear elastic material with a Poisson ratio ν=0.3 and elastic modulus E=2.02 Mpa [1]. Concerning the soft tissues, both the smooth muscle and the connective tissue were assumed as non-linear, elastic and nearly incompressible (ν=0.475) materials, described by a strain energy function in the Ogden form.

Loads were assigned to simulate the tracheal duct collapsibility. Pretensioning (10% in longitudinal direction) and intraluminal uniform pressure loads (–5, –10, –20, –30 cmH_2O) were applied through five successive steps. Numerical analyses were performed, on the rings halved along the symmetry plane xy, in order to reduce the computational time, by ABAQUS code (ABAQUS /Explicit version 6.2.1, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA).

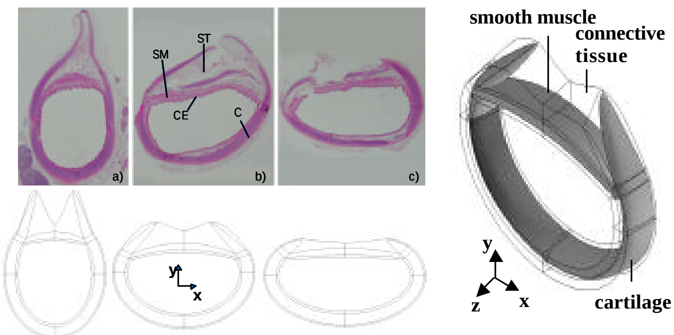

Figure 1. Left: Cross sections of cranial (a), median (b) and caudal (c) tracheal regions; histological images (upper panel) and geometrical model sections in the xy plane (lower panel). Right: 3-D geometrical model of a halved tracheal median ring

In vitro collapsibility tests

Tests were performed on preterm lamb tracheal samples (birth anticipated by caesarean section at 120-130 days of gestational age), to evaluate the pressure/volume curves in static conditions.

Tracheal samples (n=5) were tested in order to obtain the volume-specific compliance at transmural pressure $\Delta P = -10$ cmH_2O and $\Delta V/V_0$ vs. ΔP curves. An experimental setup was designed and built up to perform these tests (Fig.2; H/C heater/cooler unit, T thermocouple thermometer, WM water manometer, P pipettes, S syringe, TR tracheal sample tied to holders, C camera.) maintaining the sample immersed in thermostatted saline solution (37°C). The sample length was pretensioned by 10% to reproduce the in vivo tracheal conditions and transmural pressures of –5, –10, –20, –30 cmH_2O were applied.

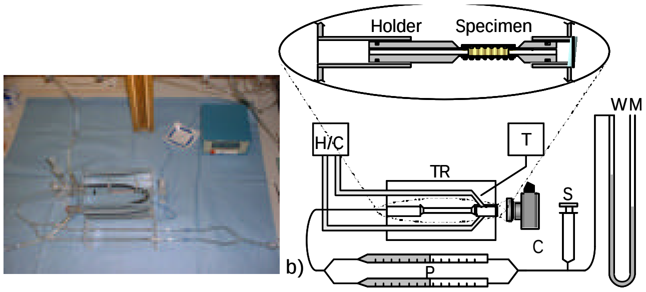

Figure 2. Experimental setup for the compliance tests: a) photograph; b) circuit layout: the holders system and trachea sample are detailed in the upper inset

RESULTS

Figure 3 shows the deformed configurations of the three simulated rings. The lumen occlusion is strongly dependent on the cartilaginous ring shape and on the smooth muscle length. The median and caudal regions display similar collapse behavior, however, the caudal model shows a greater lumen occlusion and a wider internal contact surface, due to the greater open region of the cartilaginous ring. In the cranial portion, the two extremities of the cartilage lean against one another during collapse, still leaving the lumen open, when the maximum pressure load is applied. The cranial region appears to be the least compliant, while the caudal ring is the most compliant.

The volume-specific compliance (C_{s-10}) at –10 cmH_2O, calculated for the cranial, median and caudal ring is equal to 0.024, 0.052 and 0.075 cmH_2O^{-1}, respectively.

The results of computational simulations were compared to experimental data (Fig.4; dotted line) to verify the model's reliability. In order to allow for a direct comparison, two different duct tracheal models were assumed; an "equivalent" duct model (constituted by three equal segments of cranial, median and caudal rings), and a "median" duct model (constituted by median rings only). The best model predictions occurred at pressure ranging from –30 to –10 cmH_2O; maximum errors of 2.7% was found for the "median" model and 12.6% for the "equivalent" model. (Fig.4).

CONCLUSIONS

Model predictions are quite good ΔP of –10 cmH_2O and lower. The faulty prediction at $\Delta P = -5$ cmH_2O may be due to inaccuracy in the description of the tissues' mechanical characteristics at low stress.

The 3-D model here presented can be extended, in the future, to represent tracheae with different shapes and dimensions, or belonging to different subjects; it can also be modified to represent airways belonging to generations distal to the trachea, for which the experimental characterization is more difficult, due to their small dimensions.

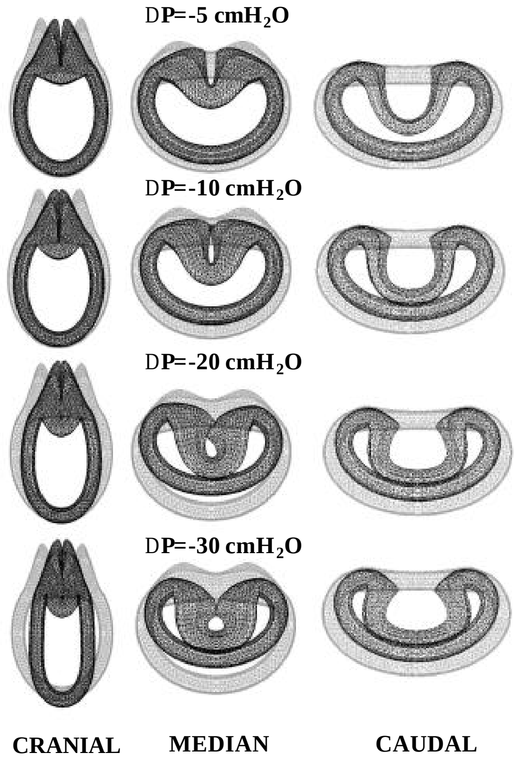

Figure 3. Deformed (in black) and undeformed (in light grey) shapes obtained for the cranial, median and caudal tracheal regions

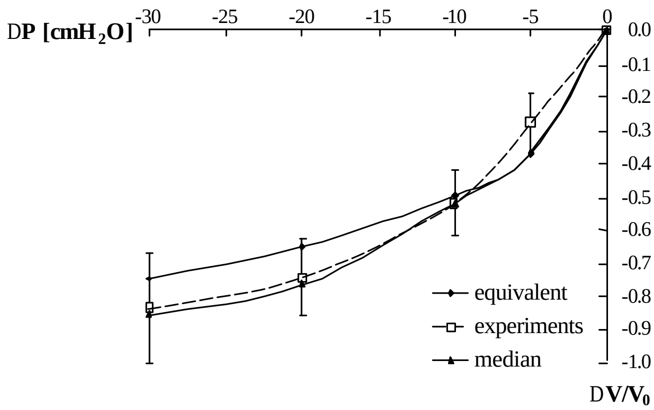

Figure 4. Comparison of the $\Delta V/V_0$ vs. ΔP curves of the "equivalent" and "median" duct models with the experimental data.

REFERENCES

1. Bhutani, V. K., Shaffer, T. H., 1983, "Effect of liquid ventilation on preterm lamb tracheal mechanics", Biology of the Neonate, Vol. 44, pp. 257-263.
2. Begis, D., Delpuech, C., Le Tallec, P., Loth, L., Thiriet, M., Vidrascu, M., 1988, "A finite-element model of tracheal collapse", Journal of Applied Physiology, Vol. 64, pp. 1359-1368.