HYPERELASTIC BEHAVIOR OF PORCINE AORTA UNDER SUB-FAILURE INFLATION LOADING

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INTRODUCTION

Traumatic Aortic Rupture (TAR) is a major cause of fatality in motor vehicle accidents. The loading conditions that lead to TAR are complex and involve multi-axial stresses and large deformations and therefore require using finite element analysis (FEA). The material model for aorta that is needed for FEA is the focus of this study. Since obtaining healthy samples of fresh human aorta is difficult, porcine aorta were used as the surrogate material. The available constitutive models for porcine aorta are primarily derived around the physiological state and it is not known if these models are capable of predicting the material mechanical behavior up to sub-failure loadings. In this study, the sub-failure mechanical behavior of porcine aorta was studied in quasi-static and impulse pressurization tests.

BACKGROUND

From pressure experiments on human cadaver and porcine aorta samples, it has been shown that 100 kPa internal pressure corresponds to 50% risk of failure [1]. To study the mechanisms leading to pressure-induced failure, it was therefore necessary to evaluate the behavior of aorta in pressures below this limit. It should be noted that studies using small ring-shaped membrane bulging experiments [2] have resulted in burst pressures of up to 700 kPa, which indicates heterogeneity of the failure properties of aorta. In this study, large cylindrical samples of descending aorta (200 mm long) are pressurized with one end fixed and one end free to displace in the longitudinal direction to prevent buckling. The goal was to characterize the global pressure-inflation properties and model it using an anisotropic hyperelastic material model.

METHODS

Inflation test setup

- Thoracic descending aorta samples were obtained from 4 month-old pigs, transported in ice-cold PBS solution to the lab where they were cleaned from surrounding tissues.
- After insertion of pressure sensors, intercostal arteries were ligated and photo targets were attached on the external surface of the samples.
- Samples were installed in an inflation setup filled with PBS at room temperature (Fig. 1).

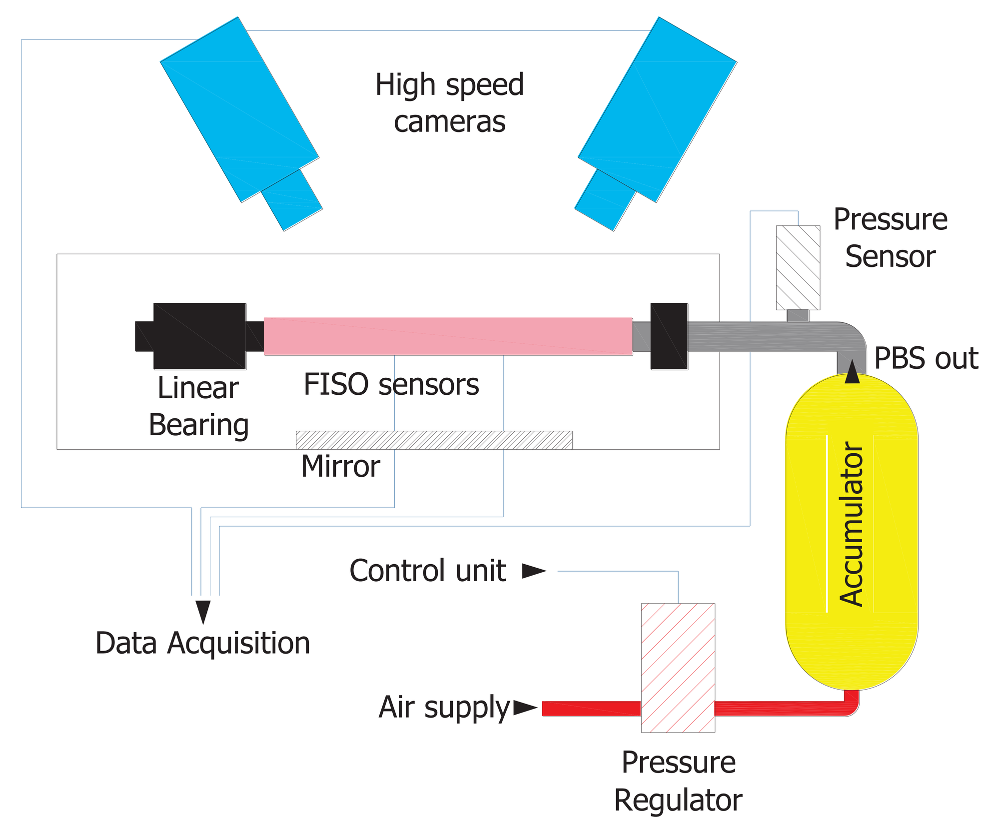

Figure 1— Inflation test setup

- Samples were pressurized with PBS through an accumulator. The pressure of the accumulator was controlled by an air pressure regulator with quasi-static and impulse profiles from 0 to 70 kPa (Fig. 2).

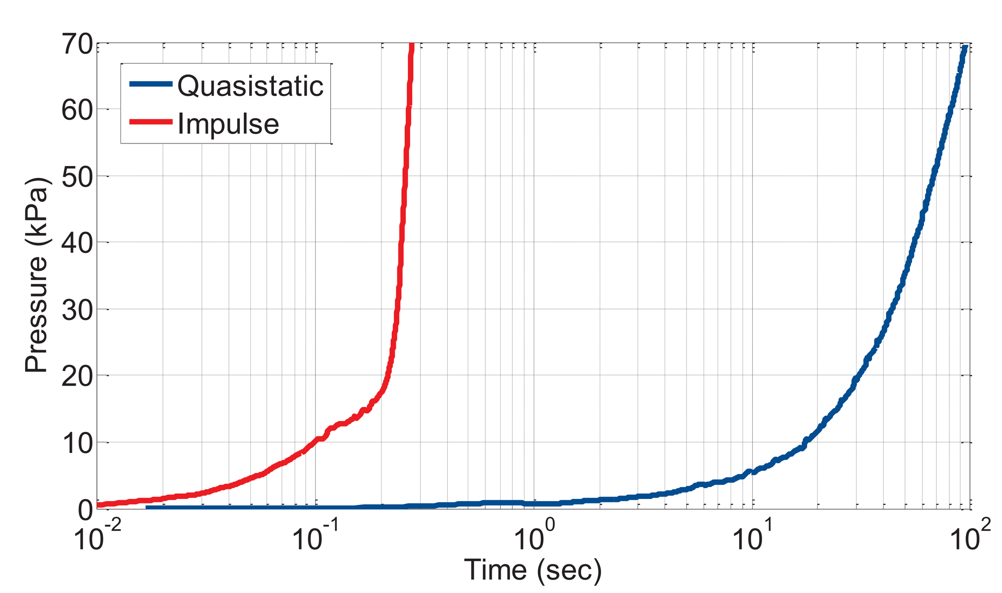

Figure 2— Typical pressure profiles recorded in the samples

- Internal pressure was recorded with two fiber optic pressure sensors. Another pressure sensor was used to measure the inlet pressure.
- 3D deformation of the sample was recorded with two high speed cameras in combination with a front face mirror.
- Coordinates of photo targets were calculated using a MATLAB code.

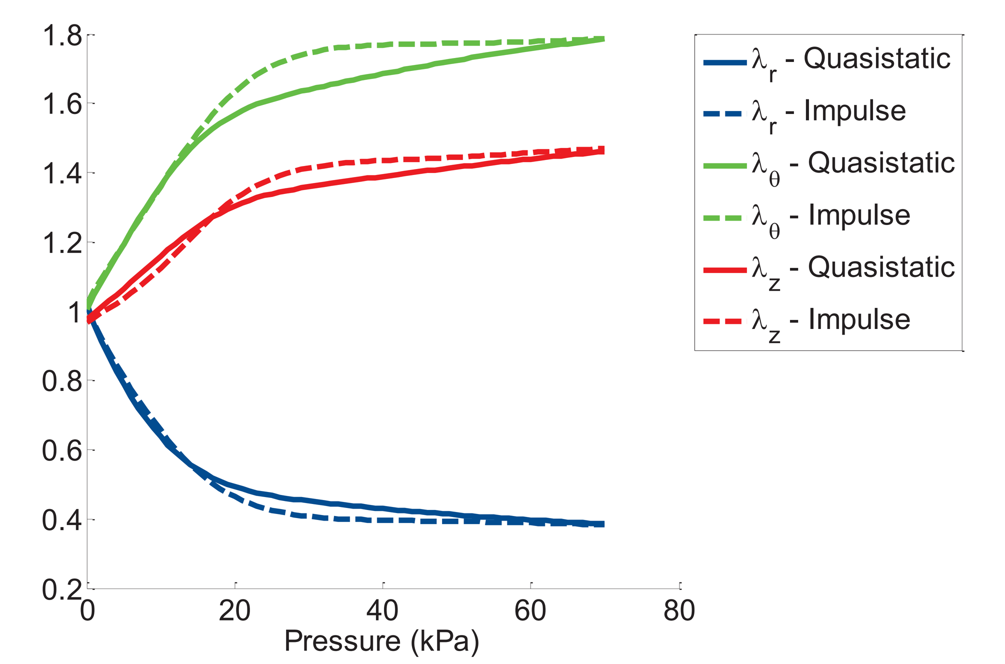

Figure 3— Stretch ratios in inner radius in quasi-static (solid line) and impulse (dash line) loading averaged over all samples

Hyperelastic model

- Aorta was assumed to be an anisotropic thick-walled cylinder with a Fung-type exponential hyperelastic strain energy density function.

$$W = \frac{c}{2}(e^Q - 1)$$

$$Q = c_1 E_r^2 + c_2 E_\theta^2 + c_3 E_z^2 + 2c_4 E_r E_\theta + 2c_5 E_r E_z + 2c_6 E_\theta E_z$$

with c and c_i representing the material parameters to be determined.

- MATLAB lsqcurvefit function was used to fit the model results to internal pressure and longitudinal force (pressure × lumen area) by optimizing for the material parameters, while the convexity requirement of W was taken into account.
- MATALB surface fitting toolbox was used to fit an overall strain energy density function to all the individual strain energy density functions.
- Minimum R^2 for sample curve fitting and for overall surface fitting were 0.95 and 0.85 ($p<<0.05$).

RESULTS

- Material behavior in quasistatic and impulse loading were not significantly different, so the hyperelastic model was fitted to the results of both test protocols and listed in Table 1.

Table 1— Material parameters

Material parameter	Mean	95% confidence interval
c (kPa)	37.03	34.24-39.83
c_1	3.48	3.304-3.656
c_2	2.381	2.343-2.419
c_3	1.377	1.323-1.431
c_4	1.389	1.224-1.554
c_5	1.379	1.307-1.451
c_6	0.897	0.853-0.941

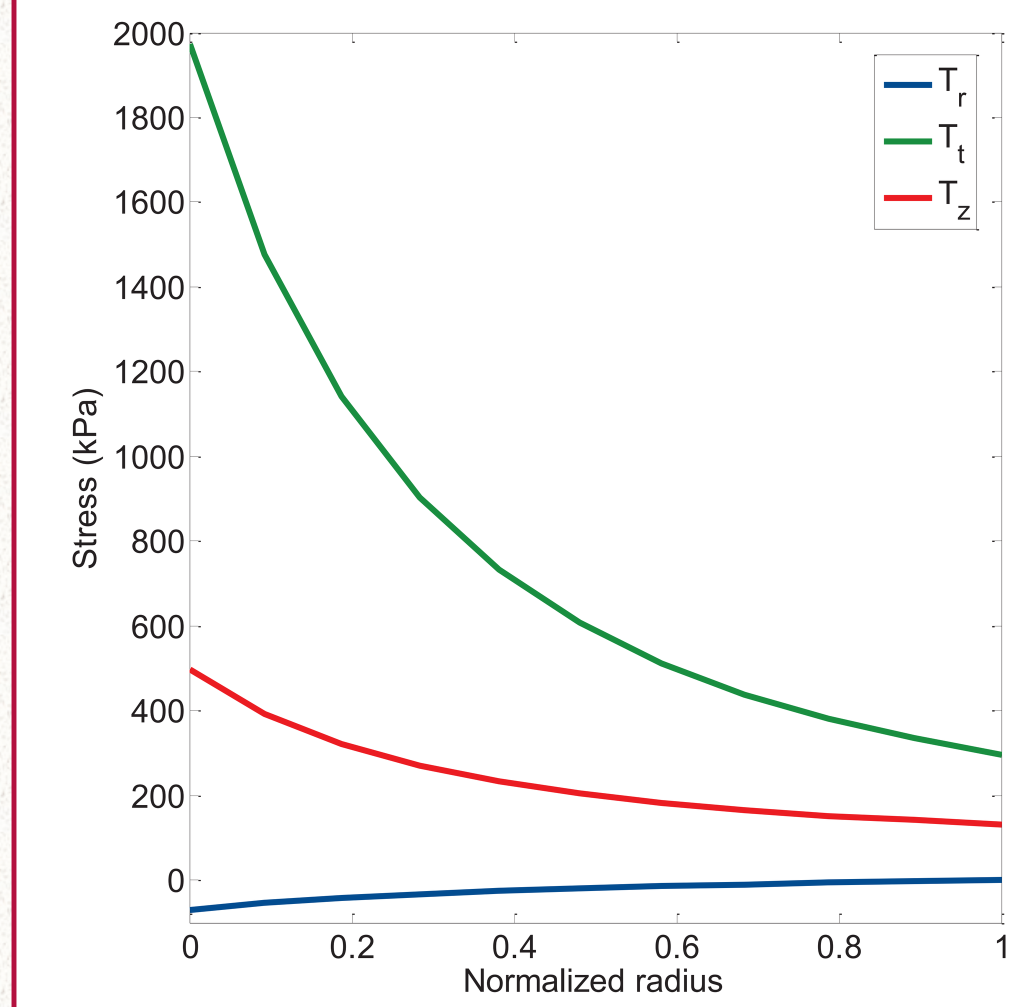

Figure 4 — Stress distribution in the cross section of aorta at 70kPa internal pressure and longitudinal stretch ratio of 1.4

DISCUSSION

As in the isotropic case, the maximum stress occurs in the circumferential direction (Fig 4). However in most cases of TAR, aortic tear occurs in the transverse direction [1]. It can be concluded that either the structure of artery (e.g. orientation of SMC's) creates a higher failure threshold for the circumferential direction or that other mechanisms of failure (such as stresses due to contact with internal or external objects) significantly increase the longitudinal stresses.

It should be noted that the model used in this study does not include the heterogeneity that has been reported in the mechanical properties of aorta [3] which can affect the magnitude of the predicted stresses. The strain energy at impulse loading was slightly lower than in quasi-static loading. Although this difference was not significant but requires more investigation.

CONCLUSION

Porcine descending aorta under loading up to 70 kPa internal pressure was modeled using a Fung-type hyperelastic strain energy function. The sensitivity of the model to the loading rate was not statistically significant.

References

1. CR Bass, et. al. (2001). Material properties for modeling traumatic aortic rupture. *Stapp Car Crash Journal*. vol. 45.

2. SP Marra, et. al. (2006). Elastic and rupture properties of porcine aortic tissue measured using inflation testing. *Cardiovascular Engineering*. vol. 6.

3. A. Hemmasizadeh et. al. (2012). Material properties of aorta determined from nanoindentation tests. *Journal of the mechanical behavior of biomedical materials*. (under review)