Axial Prestretch in Aorta and Effect on Circumferential Distensibility

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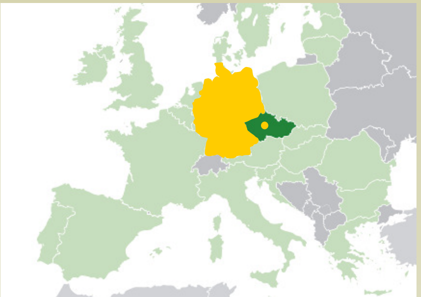
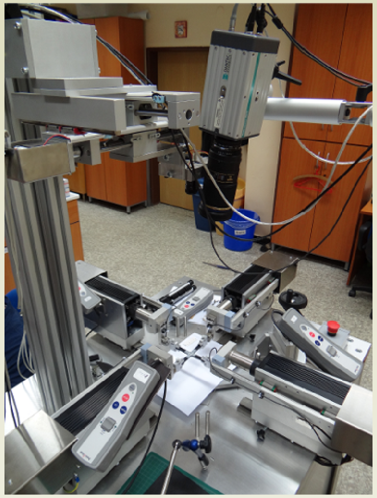
Introduction



Faculty of
Mechanical Engineering

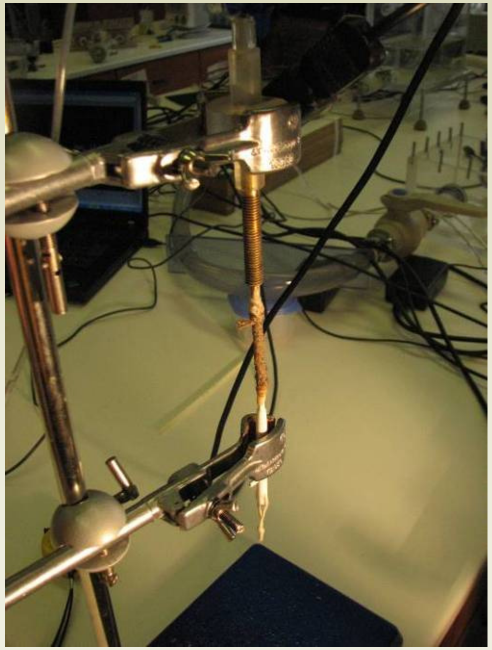
Lab of Cardiovasc Mech



Biaxial tensile testing

In vitro pulse wave velocitiy measuring

Lab of Cardiovasc Mech



Ex vivo inflation-extension test (VS-CABG)

INTRODUCTION

What I would like to show today

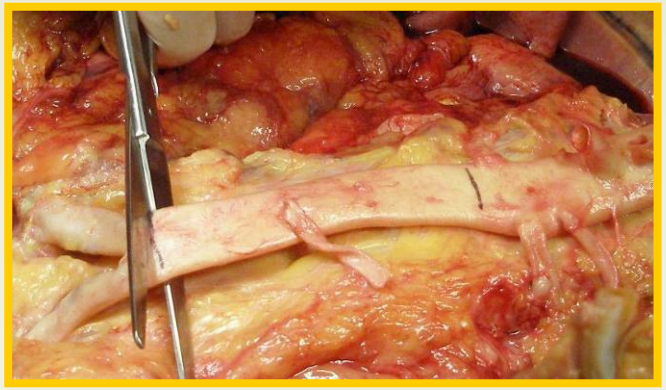
- Axial prestretch – basic facts
- Axial prestretch in ageing
- Effect of axial prestretch on mechanical response of arteries

INTRODUCTION

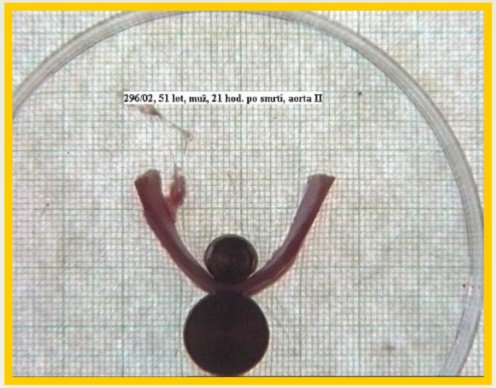
Stress-free state of arteries is not attained when only $P \rightarrow 0$

Additionally one has to

to excise

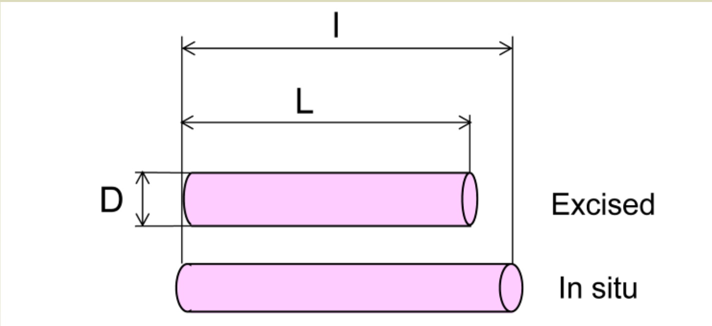


and to cut

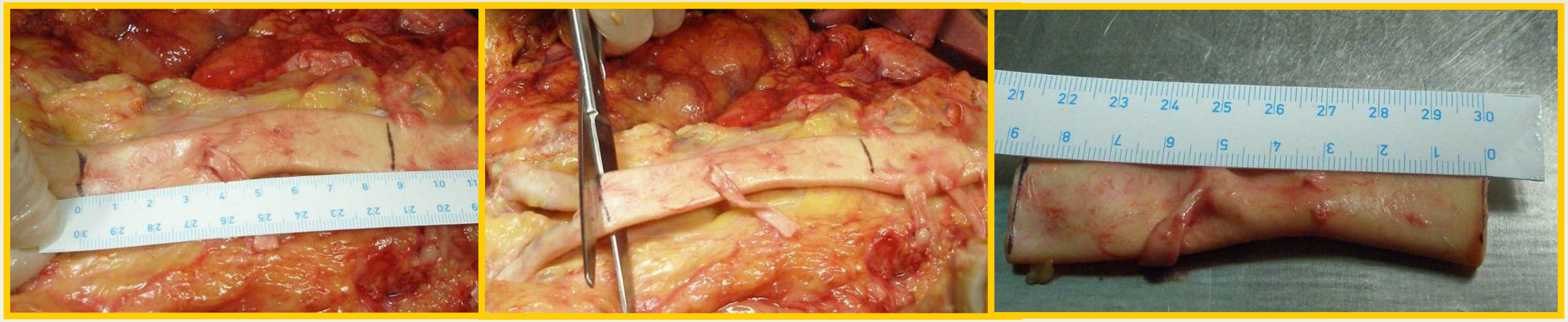


INTRODUCTION

Axial prestretch



$$\lambda = \frac{l}{L}$$

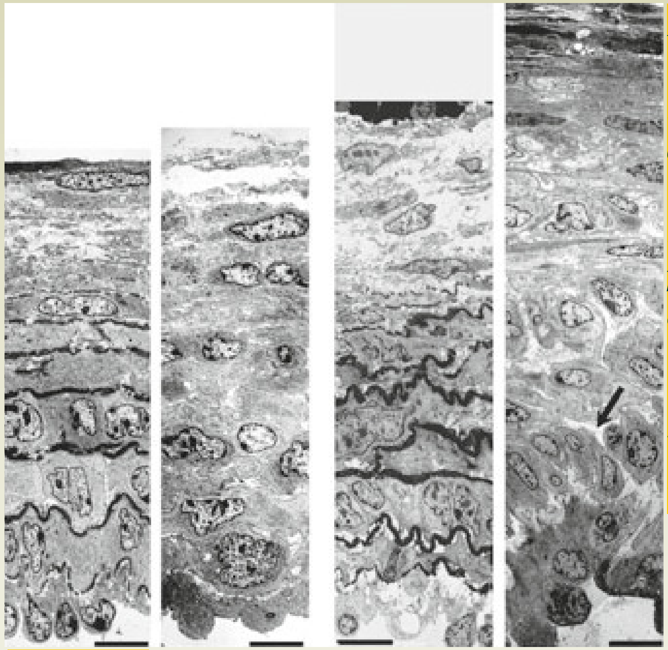


Human abdominal aorta

INTRODUCTION

Axial prestretch

Mouse abdominal aorta. A torsion occurs instead of a retraction in the excision from a body of Eln +/-



Histology

Electron microphotograph of mouse aorta

Embrionic (E) postantal (P) days

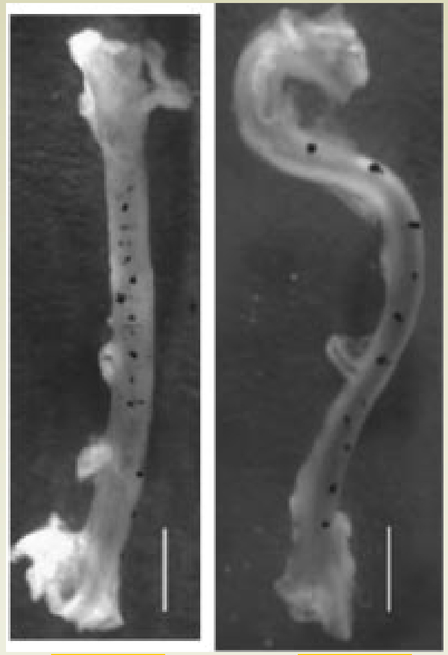
Wilde type vs. Elastin insufficient

E18 WT *E18 Eln -/-* *P1 WT* *P1 Eln -/-*

Cheng JK, Wagenseil J (2012) Extracellular matrix and mechanics of large artery development. *Biomech Model Mechanobiol* 11:1169-1186.

Wagenseil JE, Ciliberto CH, Knutsen RH, Levy MA, Kovacs A, Mecham RP (2009) Reduced vessel elasticity alters cardiovascular structure and function in newborn mice. *Circ Res* 104(10):1217–1224.

http://dx.doi.org/10.1007/s10237-012-0405-8 http://dx.doi.org/10.1161/CIRCRESAHA.108.192054



WT *Eln+/-*

Wagenseil J, et al. (2005) Effect of elastin haploinsufficiency on the mechanical behavior of mouse arteries. *Am J Physiol Heart Circ Physiol* 289:1209-1217.

http://dx.doi.org/10.1152/ajpheart.00046.2005

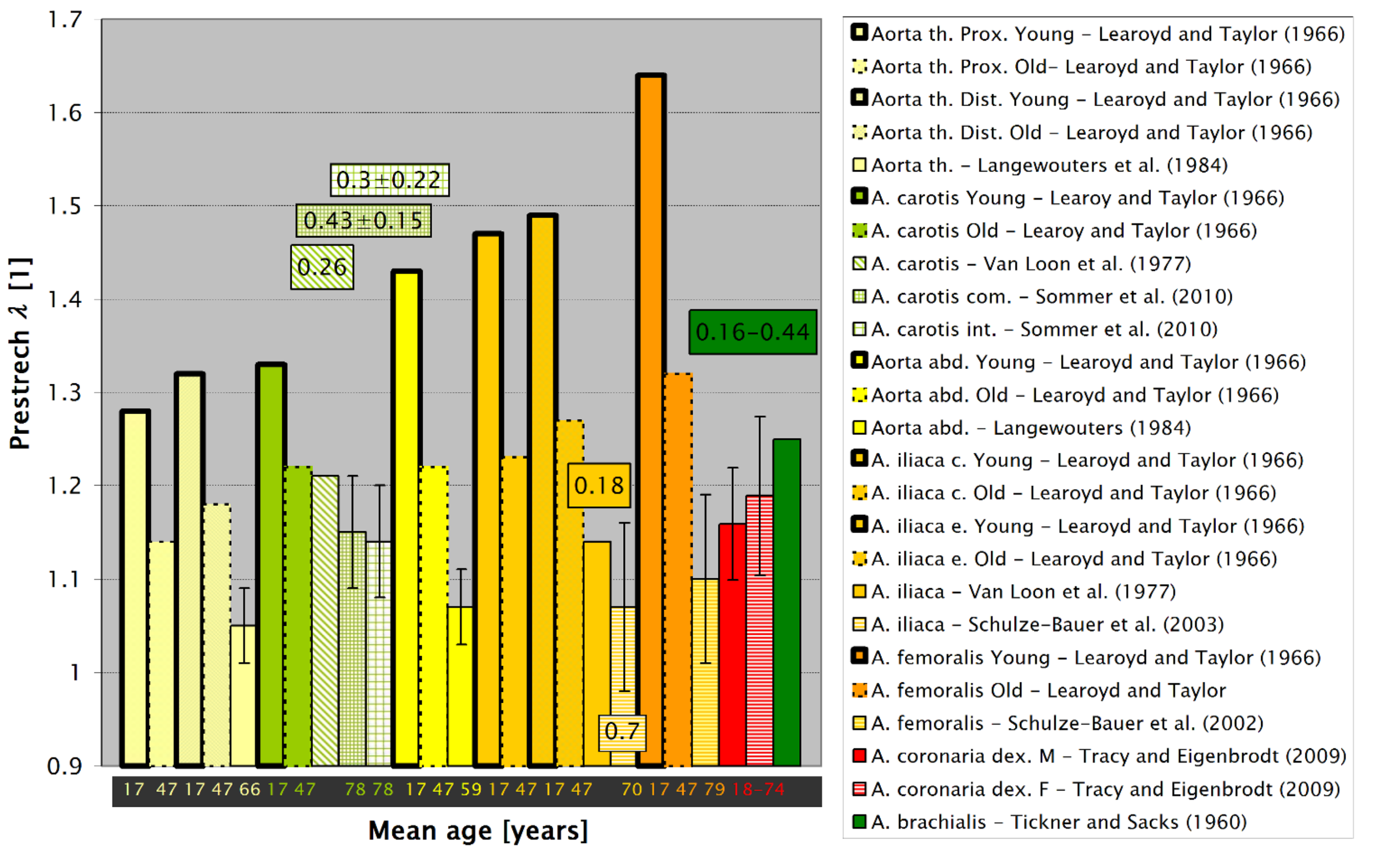
INTRODUCTION

It implies the hypothesis that elastin is a component of arteial wall responsible for the prestretch

INTRODUCTION

Axial prestretch topographical differences support elastin hypothesis

As a number of elastin membranes decreases with the distance from the heart, the prestretch increases.



Learoyd BM, Taylor MG (1966) Alterations with age in the viscoelastic properties of human arterial walls. *Circ Res* 18:278-292. Langewouters GJ, Wesseling KH, Goedhard WJA (1984) The static elastic properties of 45 human thoracic and 20 abdominal aortas in vitro and the parameters of a new model. *J Biomech* 17:425-435. Sommer G, Regitnig P, Költringer L, Holzapfel GA (2010) Biaxial mechanical properties of intact and layer-disected human carotid arteries at physiological and supraphysiological loadings. *Am J Physiol - Heart Circ Physiol* 298:898-912. Schulze-Bauer CAJ, Morth C, Holzapfel GA (2003) Passive biaxial mechanical response of aged human iliac arteries. *J Biomech Eng* 125:395-406. Van Loon P, Klip W, Bradley EL (1977) Length-force and volume-pressure relationships of arteries. *Biorheology* 14:181-201. Tracy RE, Eigenbrodt ML. (2009) Coronary artery circumferential stress: departure from Laplace expectations with aging. *ScientificWorldJournal.* 2009 Sep 15;9:946-60.

INTRODUCTION

Axial prestretch topographical differences support elastin hypothesis

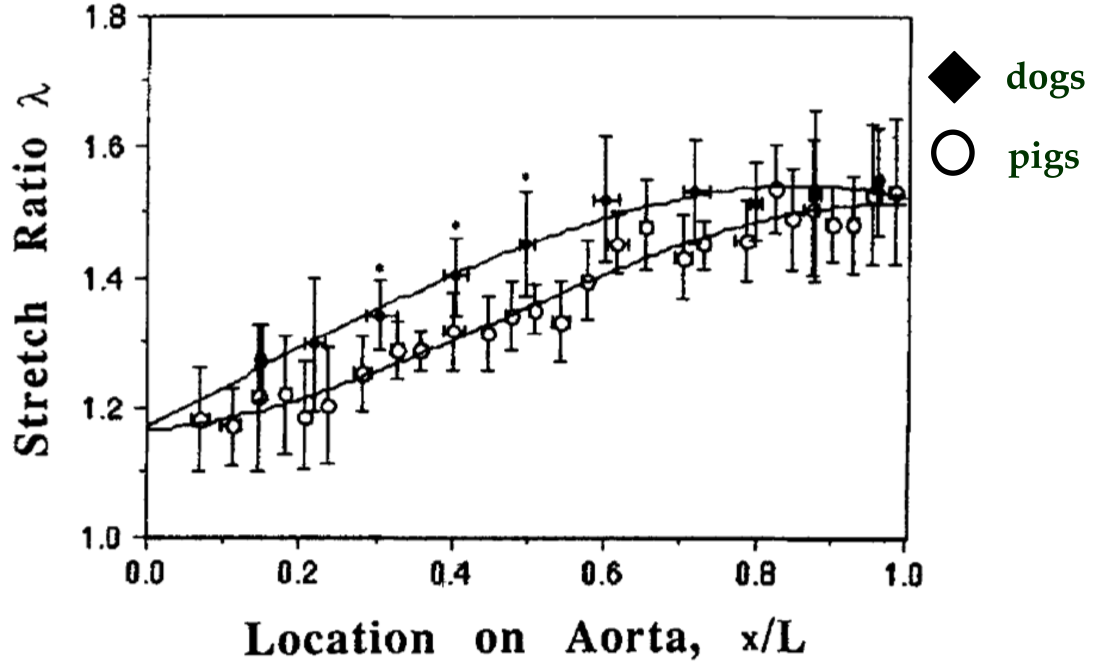
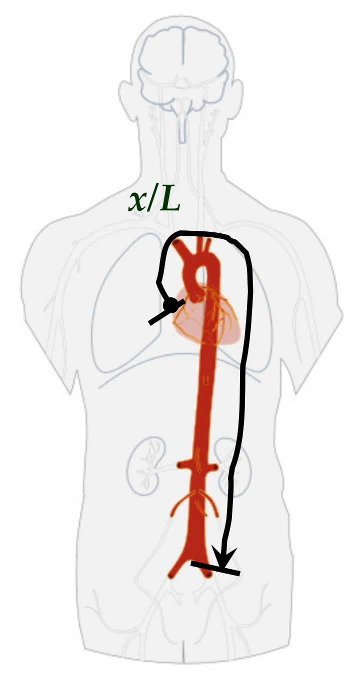


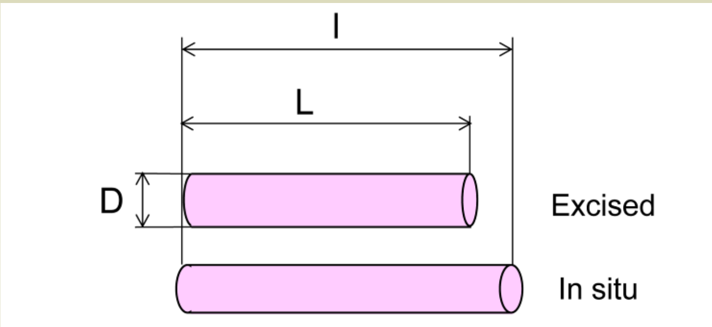
Fig. 1. The longitudinal stretch ratios *in situ* (mean ± S.D.) of the aortas of dog (◆, $n = 5$) and pig (○, $n = 9$) plotted as functions of longitudinal location on aorta, x/L. The error bars are standard deviations. Solid lines are polynomial regression curves. Regional variation and species differences are seen. *$p < 0.05$ compare to the value on the corresponding (nearest) points of porcine aorta.



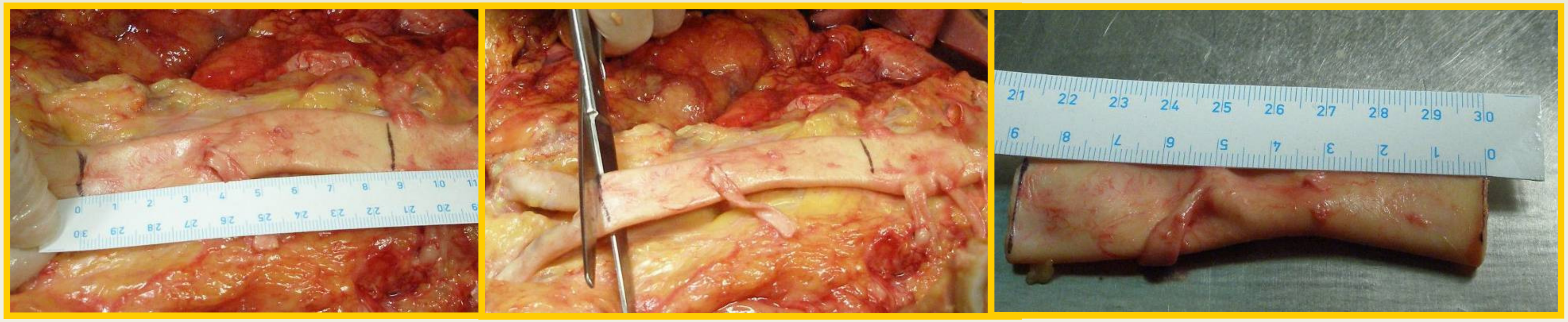
.Han H-, Fung Y-. Longitudinal strain of canine and porcine aortas. *J Biomech* 1995;28(5):637-41. http://dx.doi.org/10.1016/0021-9290(94)00091-H

AGE-RELATED CHANGES IN PRESTRETCH

Axial prestretch in human abdominal aorta



$$\lambda = \frac{l}{L}$$



Age-Related Changes in Prestretch

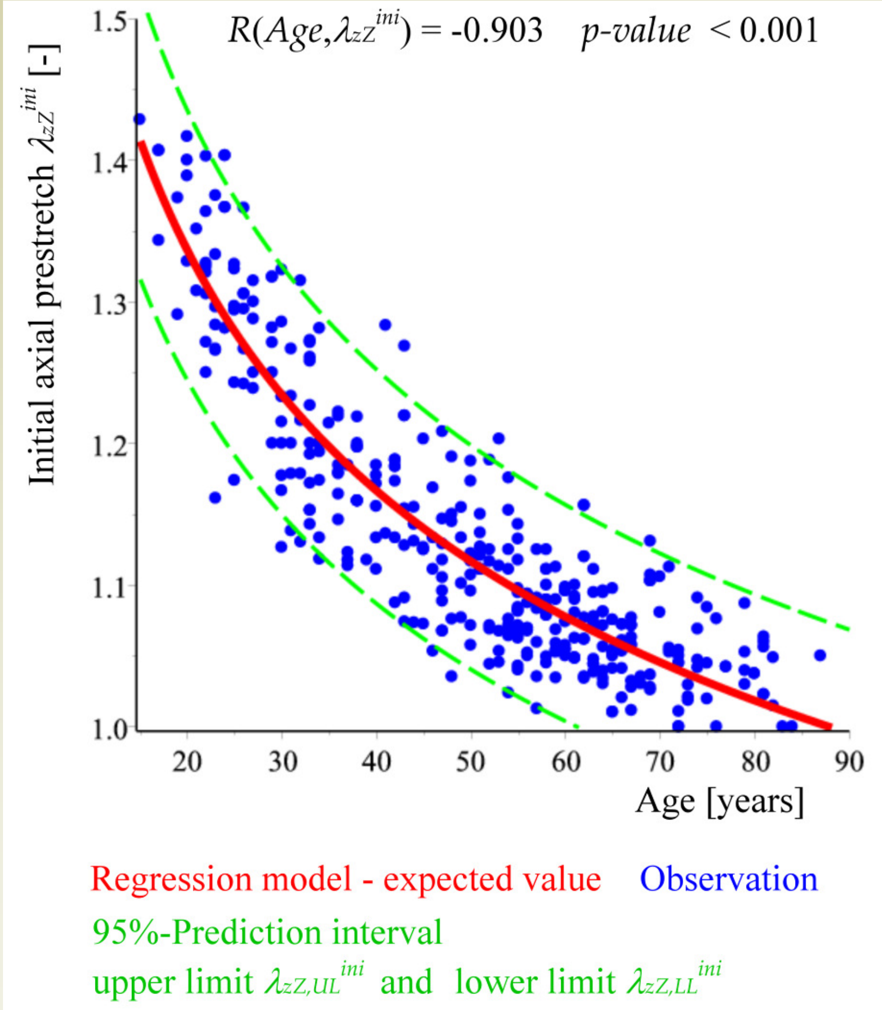
365 individuals

50/17 years

$\lambda = 1.14/0.1$

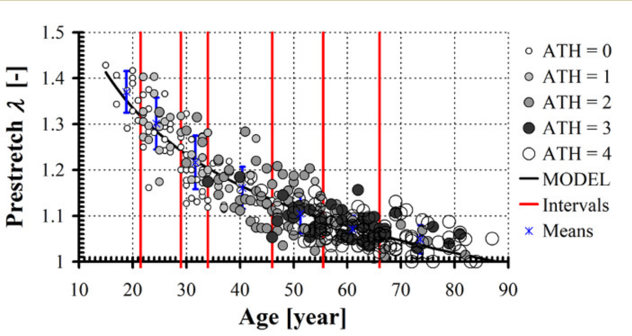
47/30 hours of PMI

mean/SSD

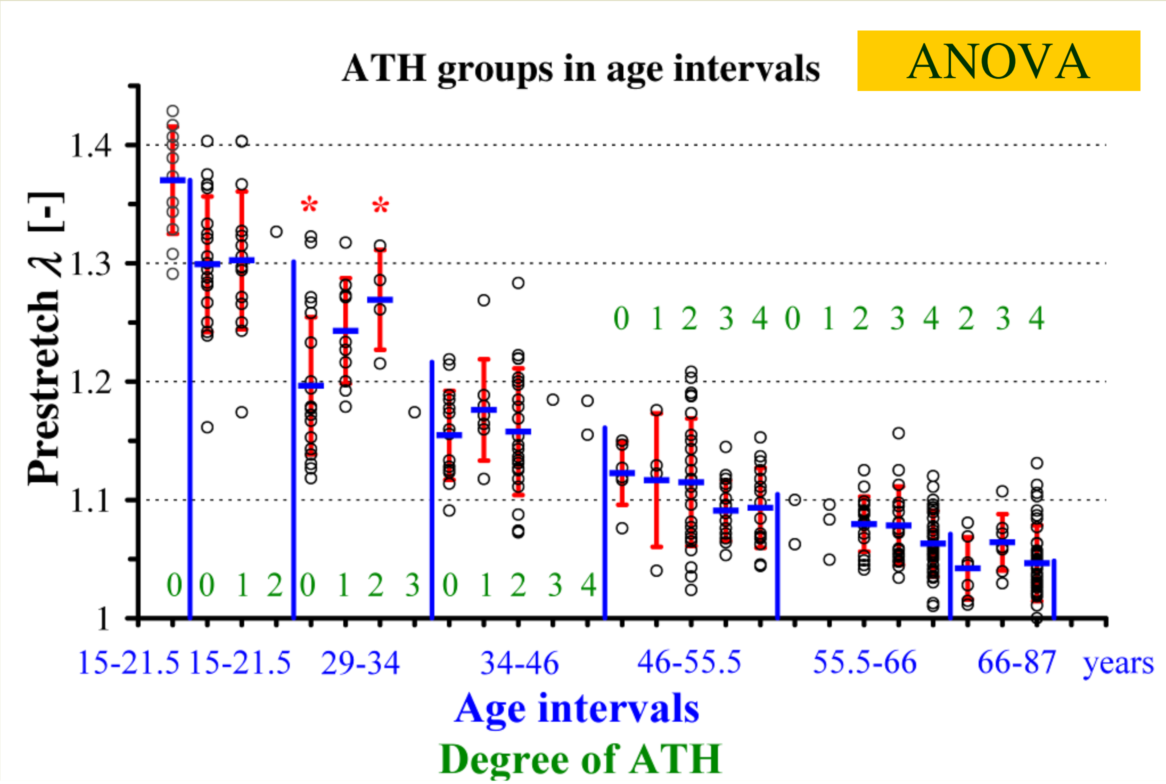


.Horny L, Netusil M, Vonavkova T (2013) Axial prestretch and circumferential distensibility in biomechanics of abdominal aorta. *Biomech Model Mechanobiol*, submitted to the journal.

Age-Related Changes in Prestretch



Does decrease in the prestretch correlate with ATH?



NO

Distinguish between ATHEROSCLEROSIS and ATRERIOSCLEROSIS!

Horny L, Adamek T, Kulvajtova M. (2013) Analysis of axial prestretch in the abdominal aorta with reference to post mortem interval and degree of atherosclerosis. *J Mechan Behav Biomed Mater*, in press. doi: 10.1016/j.jmbbm.2013.01.033

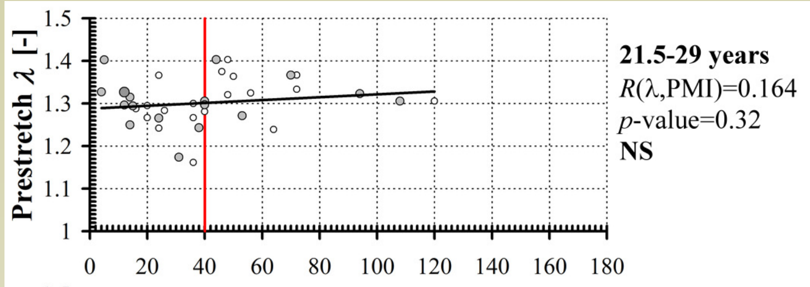
http://dx.doi.org/10.1016/j.jmbbm.2013.01.033

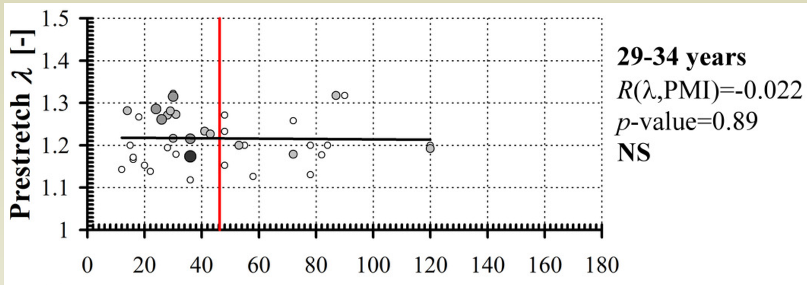
Age-Related Changes in Prestretch

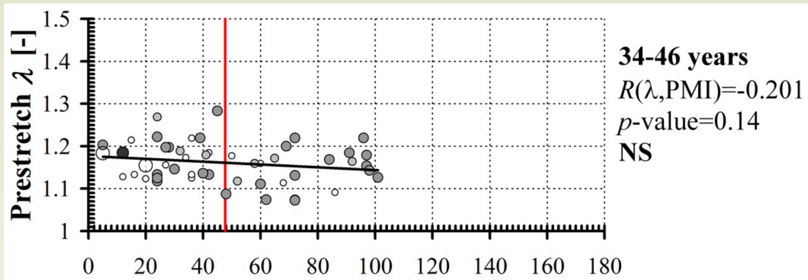
Is λ biased by Post Mortem Interval?

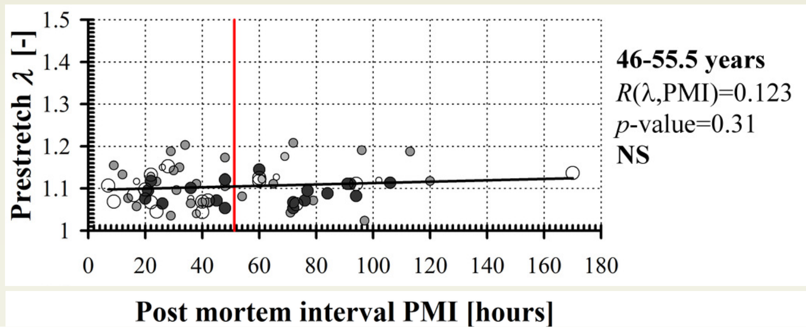
NO

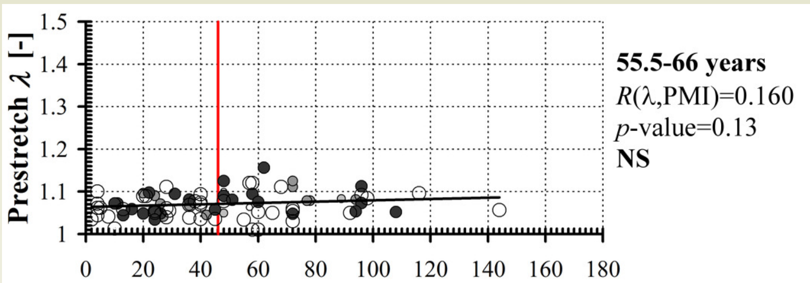
http://dx.doi.org/10.1016/j.jmbbm.2013.01.033

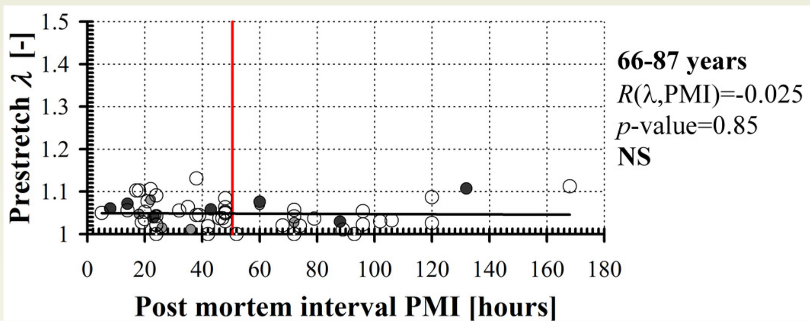












Age-Related Changes in Prestretch

Does λ depend on sex?

NO

Table 1 Measured data (mean±sample standard deviation) sorted with respect to decades of age

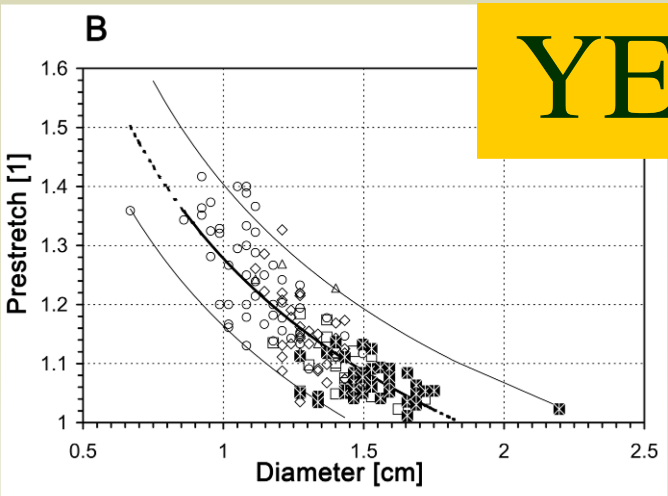
Age (years)	< 20	20–29	30–39	40–49	50–59	60–69	> 69
n_F	2	6	7	11	11	12	12
n_M	2	30	32	32	47	39	12
CAI_F (mm)	5.6±1.2	7.4*±0.7	9.1±1.1	10.1*±1.2	11.6*±1.2	12.6*±1.1	14.4*±2.1
CAI_M (mm)	6.7±0.4	8.1*±0.8	10.1±1.0	11.3*±1.1	13.2*±1.1	14.2*±1.2	15.9*±1.4
L_F (mm)	61.0±2.8	61.7*±4.1	69.3±12.2	77.2±8.8	78.2±9.4	79.3±8.6	84.8±16.4
L_M (mm)	71.0±5.7	68.7*±8.6	75.5±9.1	80.6±10.0	81.7±10.8	83.4±13.0	83.3±12.9
l_F (mm)	86.5±4.9	80.3*±4.9	80.7±11.3	86.6±8.3	86.1±9.4	86.0±7.6	87.8±16.7
l_M (mm)	96.5±9.2	88.9*±12.5	90.4±9.8	92.8±9.8	89.5±12.5	88.9±13.2	87.9±13.5
ΔL_F (mm)	25.5±2.1	18.7±2.2	11.4*±2.8	9.5*±3.4	7.9±2.1	6.7±2.5	3.1±2.4
ΔL_M (mm)	25.5±3.5	20.2±5.7	14.8*±3.8	12.2*±4.2	7.8±3.6	5.5±2.6	4.6±2.6
λ_F	1.42±0.02	1.30±0.04	1.17±0.07	1.13±0.06	1.10±0.03	1.09±0.04	1.04±0.03
λ_M	1.36±0.02	1.29±0.07	1.19±0.06	1.16±0.06	1.10±0.04	1.07±0.04	1.06±0.03
D_F (mm)	7.9±1.8	9.6±1.0	10.6*±1.1	11.3*±1.0	12.8*±1.2	13.6*±1.0	14.9*±2.0
D_M (mm)	9.1±0.7	10.5±0.8	12.0*±1.0	13*±1.0	14.4*±1.0	15.1*±1.1	16.8*±1.4
ATH_F	0[a]	0[a]	0[a]	2[a]	2[a]	3[a]	4[a]
ATH_M	0[a]	0[a]	0[a]	2[a]	3[a]	4[a]	4[a]
PMI_F (h)	29±10	47±27	32±18	42±21	55±24	57±35	52±33
PMI_M (h)	32±18	34±16	44±27	56±34	48±31	43±33	59±47

Horny L, Adamek T, Chlup H, Zitny R. (2012) Age estimation based on a combined arteriosclerotic index. *Int J Legal Med* 126(2):321-6. doi: 10.1007/s00414-011-0653-7

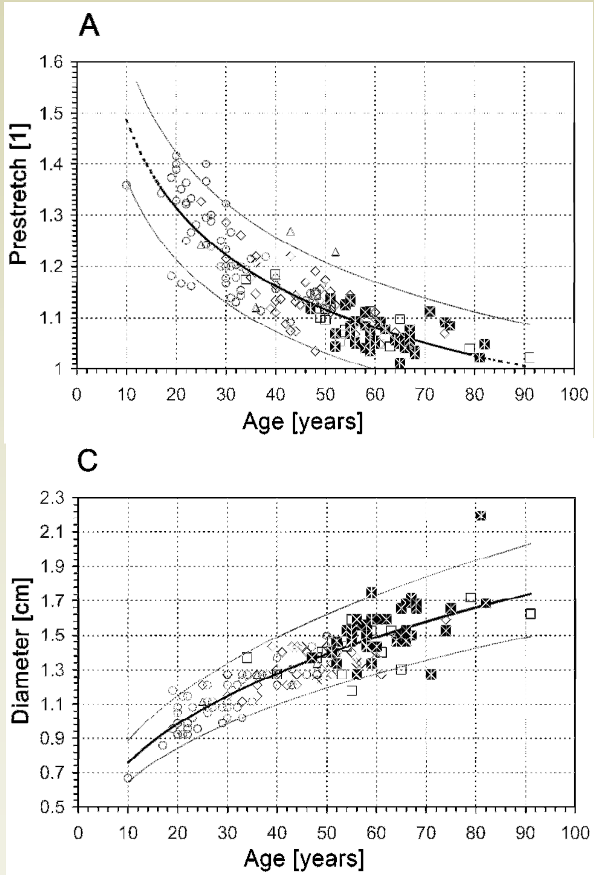
http://dx.doi.org/10.1007/s00414-011-0653-7

Age-Related Changes in Prestretch

Does λ depend on aortic diameter?



YES?



In fact, in age-adjusted data NO.

The statement is related to the prestretch and diameter treated in the same location (e.g. abdominal aorta).

Horny L, Adamek T, Gultova E, Zitny R, Vesely J, Chlup H, Konvickova S. (2011) Correlations between age, prestrain, diameter and atherosclerosis in the male abdominal aorta. *J Mechan Behav Biomed Mater* 4(8):2128-32. doi: 10.1016/j.jmbbm.2011.07.011 http://dx.doi.org/10.1016/j.jmbbm.2011.07.011

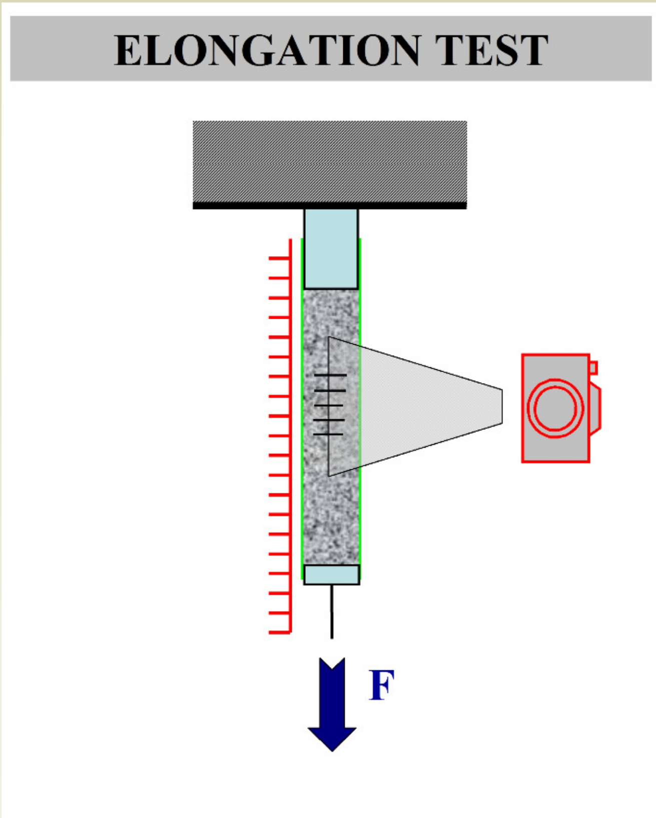
Changes in Prestress

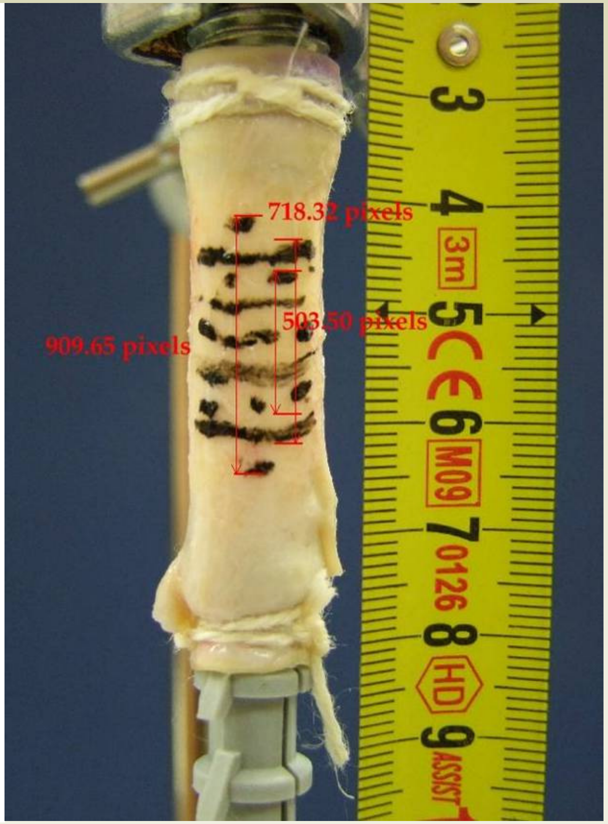
Axial prestretch decreases in age.

And what about prestretching force and prestress?

CHANGES IN PRESTRESS

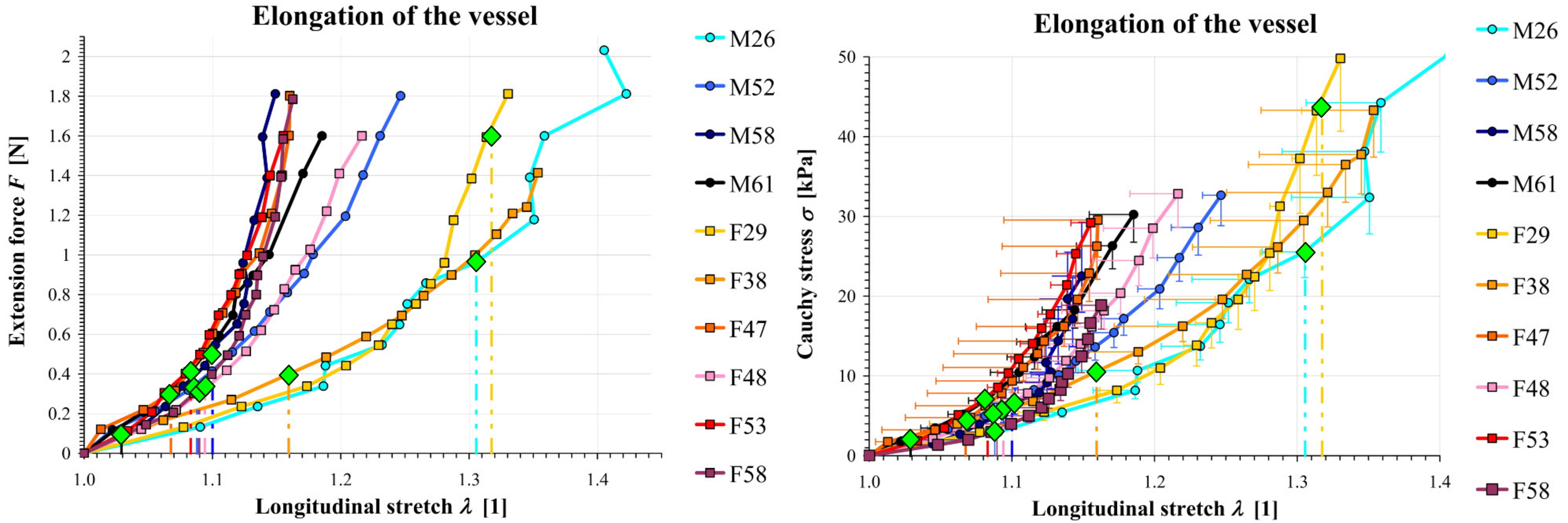
Prestretching force experiment





CHANGES IN PRESTRESS

Prestretching force and prestress correlate with age



Horny L, Adamek T, Zitny R. (2013) Age-related changes in longitudinal prestress in human abdominal aorta. *Arch Appl Mech* 83(6):875-88. doi: 10.1007/s00419-012-0723-4

http://dx.doi.org/10.1007/s00419-012-0723-4

◆ $\lambda\left(Autopsy\right)$

$$\sigma^{EXP} = \lambda_{zZ} \frac{Force}{Area_0}$$

Changes in Prestress

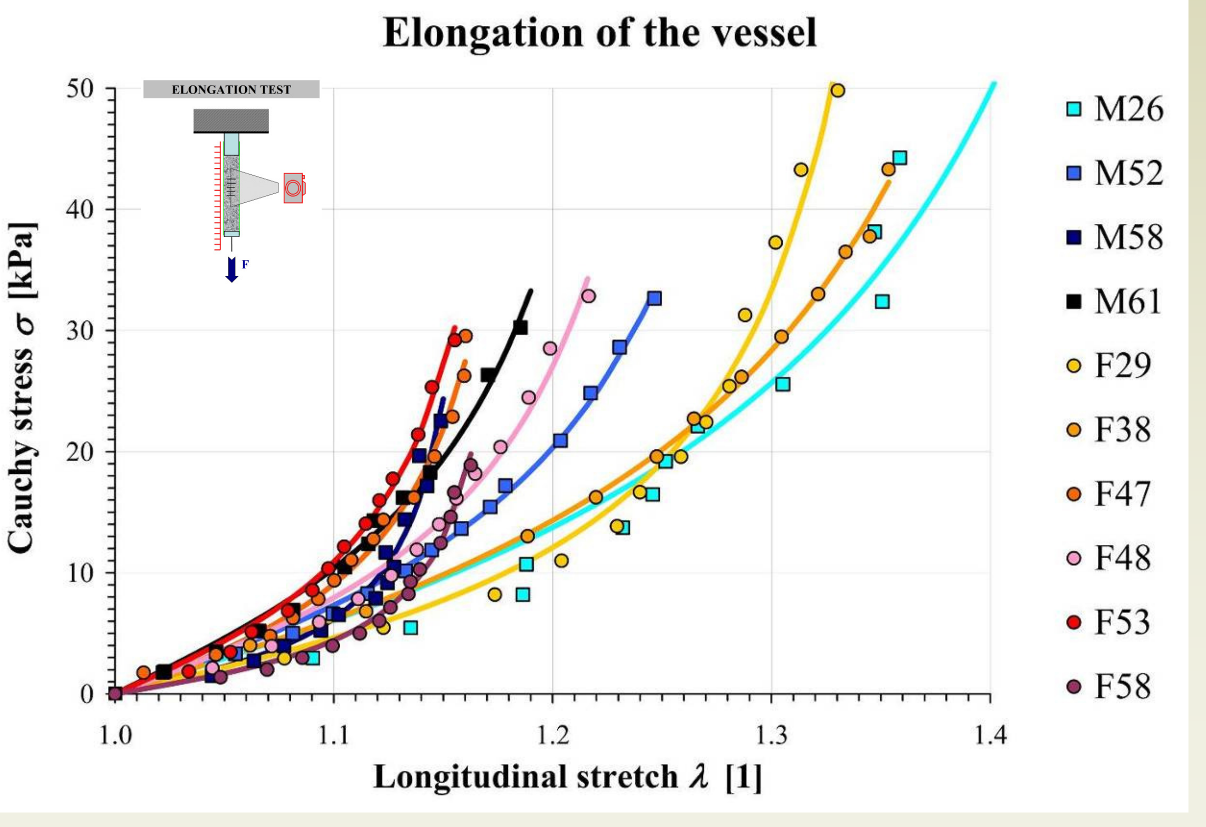
Stress-strain model

$$DefGrad = \begin{pmatrix} \lambda_{rR} & 0 & 0 \\ 0 & \lambda_{\theta\Theta} & 0 \\ 0 & 0 & \lambda_{zZ} \end{pmatrix} = \begin{pmatrix} \lambda^{-\frac{1}{2}} & 0 & 0 \\ 0 & \lambda^{-\frac{1}{2}} & 0 \\ 0 & 0 & \lambda \end{pmatrix}$$

$$\sigma^{EXP} = \lambda_{zZ} \frac{Force}{Area_0}$$

$$\sigma^{MOD} = \lambda \frac{\partial W(\lambda)}{\partial \lambda} - p$$

$$W = -\frac{\mu J_m}{2} \mathbf{ln}\left(1 - \frac{I_1 - 3}{J_m}\right)$$

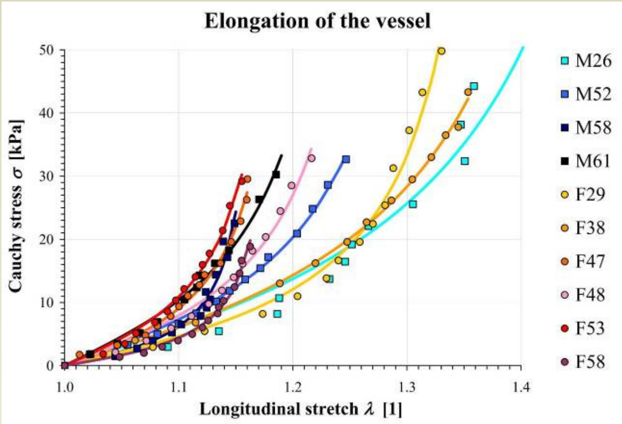


Horny L, Adamek T, Zitny R. (2013) Age-related changes in longitudinal prestress in human abdominal aorta. *Arch Appl Mech* 83(6):875-88. doi: 10.1007/s00419-012-0723-4

http://dx.doi.org/10.1007/s00419-012-0723-4

CHANGES IN PRESTRESS

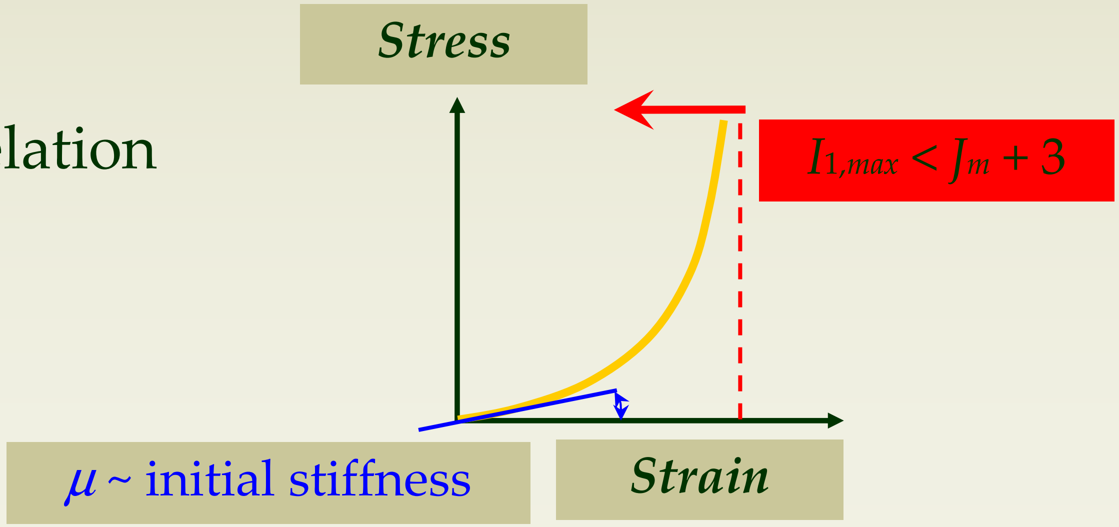
J_m (limiting extensibility parameter) correlates with age



$$W = -\frac{\mu J_m}{2} \mathbf{ln}\left(1 - \frac{I_1 - 3}{J_m}\right)$$

μ–*Age* non significant correlation

J_m–*Age* R=-0.818 (p<0.02)



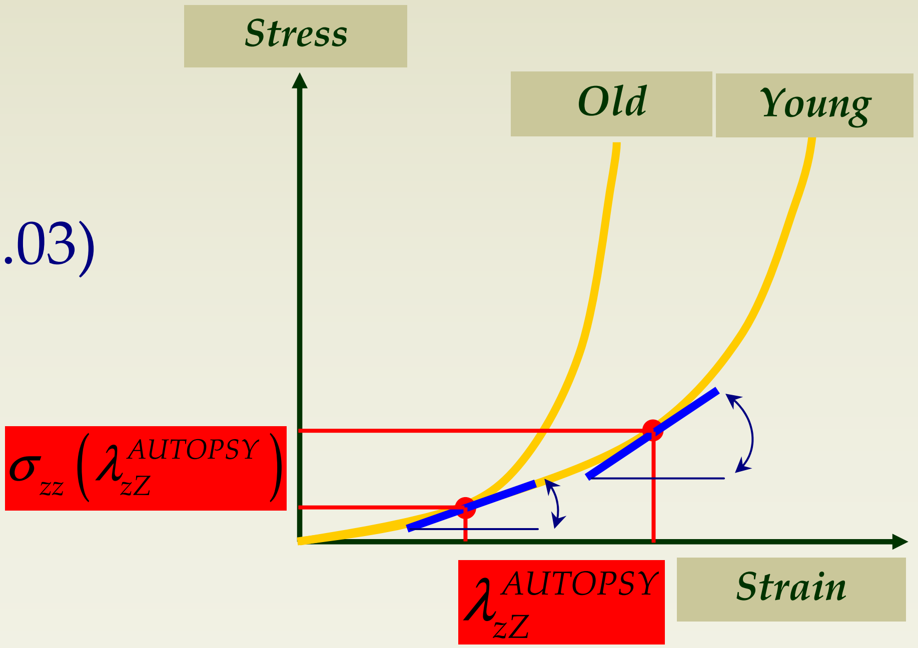
CHANGES IN PRESTRESS

Stiffness at prestrain in autopsy correlates with age

Spatial elasticity tensor *vs.* *Age*

$$\mathbb{C} = 2\mathbf{b}\frac{\partial \boldsymbol{\sigma}(\mathbf{b})}{\partial \mathbf{b}}$$

$ln(\mathbb{C}_{zzzz})$–$ln(Age)$ R=-0.632 (p<0.03)

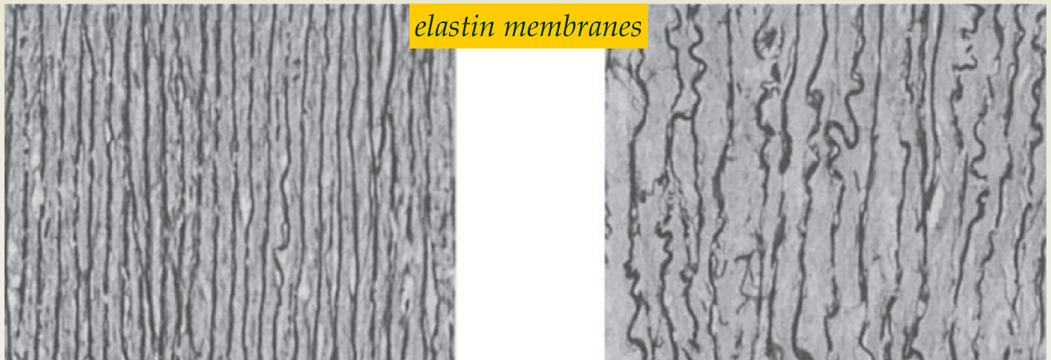


Horny L, Adamek T, Zitny R. (2013) Age-related changes in longitudinal prestress in human abdominal aorta. *Arch Appl Mech* 83(6):875-88. doi: 10.1007/s00419-012-0723-4

http://dx.doi.org/10.1007/s00419-012-0723-4

ARTERIOSCLEROSIS

Negative correlation between age and stiffness suggests a degradation of the material to be responsible for the decrease of prestretch/prestress



tiger, 15 yrs., $5 \cdot 10^8$ cycles (64bpm) jaguarindi, 15 yrs., $1 \cdot 10^9$ cycles (130bpm)

Elastin hypothesis

Avolio A et al. (1998) Quantification of alternations in structure and function of elastin in the arterial media. *Hypertension* 32:170-175.

http://hyper.ahajournals.org/content/32/1/170.full.pdf

EXPECTED CONSEQUENCES

How age-related changes in the prestretch can change mechanical response?

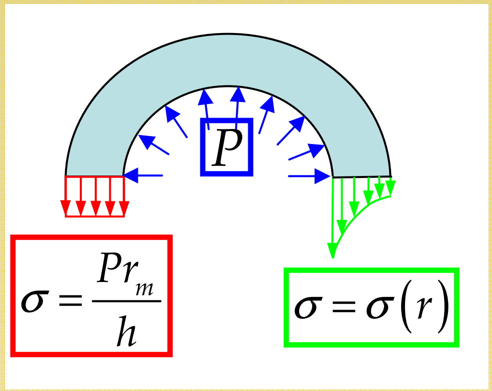
EXPECTED CONSEQUENCES

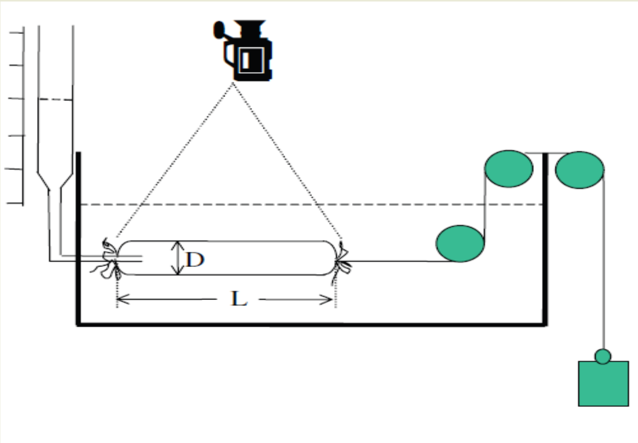
Inflation-extension response simulation

Analytic computational model

(A) thin-walled tube

(B) thick-walled tube





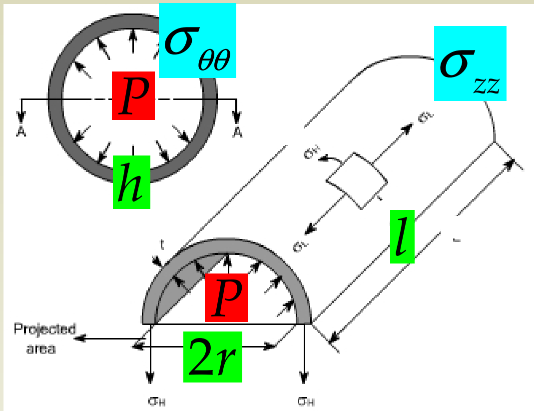
EXPECTED CONSEQUENCES

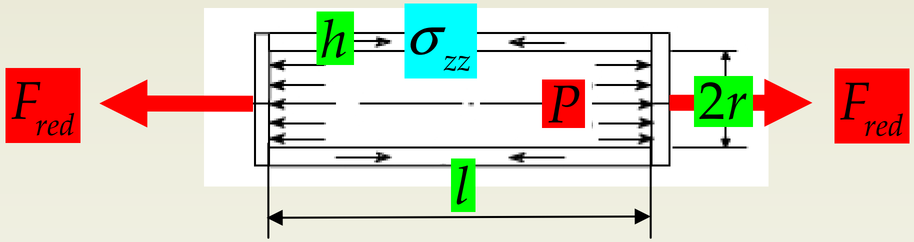
Thin-walled model

$$\sigma_{rr} = -\frac{P}{2}$$

$$\sigma_{\theta\theta} = \frac{rP}{h}$$

$$\sigma_{zz} = \frac{F_{red}}{2\pi rh} + \frac{rP}{2h}$$





Expected consequences

Inflation-extension response simulation

Constitutive equations

$$\sigma_{rr} = \lambda_{rR} \frac{\partial W}{\partial \lambda_{rR}} - p$$

$$\sigma_{\theta\theta} = \lambda_{\theta\Theta} \frac{\partial W}{\partial \lambda_{\theta\Theta}} - p$$

$$\sigma_{zz} = \lambda_{zZ} \frac{\partial W}{\partial \lambda_{zZ}} - p$$

$$W = \frac{c_1}{2}\left(e^{c_2 E_{\Theta\Theta}^2 + c_3\left(E_{ZZ}^2 + E_{RR}^2\right)} - 1 \right)$$

Material parameters and geometry dimensions adopted from

Labrosse MR, Gerson ER, Veinot JP, Beller CJ. (2031) Mechanical characterization of human aortas from pressurization testing and a paradigm shift for circumferential residual stress. *J Mechan Behav Biomed Mater* 17:44-55.

http://www.sciencedirect.com/science/article/pii/S175161611200210X

EXPECTED CONSEQUENCES

Computational model - thin-walled tube

$$\sum F_r: \quad \lambda_{rR}\frac{\partial W}{\partial \lambda_{rR}} - p = -\frac{P}{2}$$

$$\sum F_\theta: \quad \lambda_{\theta\Theta}\frac{\partial W}{\partial \lambda_{\theta\Theta}} - p = \frac{rP}{h}$$

$$\sum F_z: \quad \lambda_{zZ}\frac{\partial W}{\partial \lambda_{zZ}} - p = \frac{F_{red}}{2\pi rh} + \frac{rP}{2h}$$

Strategy

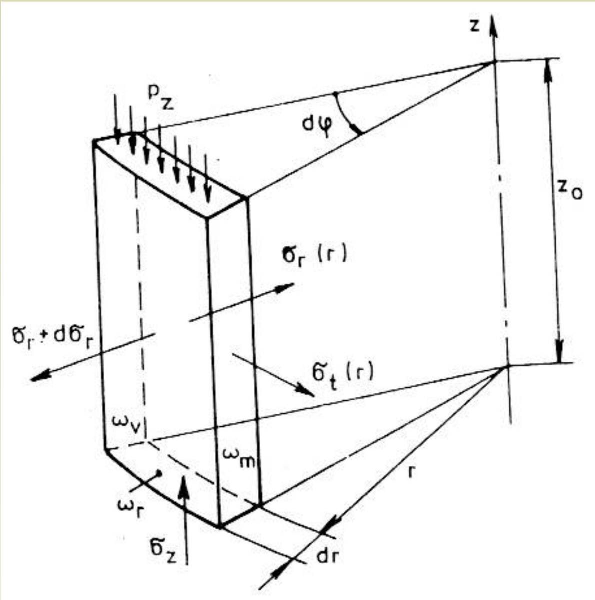
(1) eliminate p from eq. 1

(2) determine F_{red} at $P = 0$ and $\lambda_{zZ}(autopsy)$

(3) solve eq. 2 and 3 for $\lambda_{\theta\Theta}$ and λ_{zZ} at $P = 1,2,..,20$ kPa

EXPECTED CONSEQUENCES

Computational model - thick-walled tube

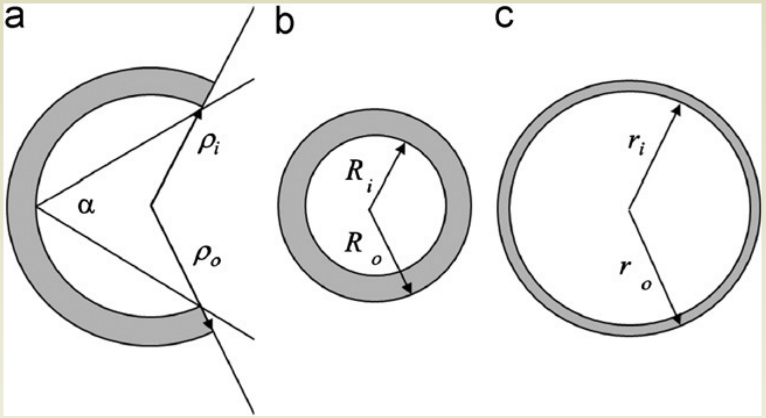


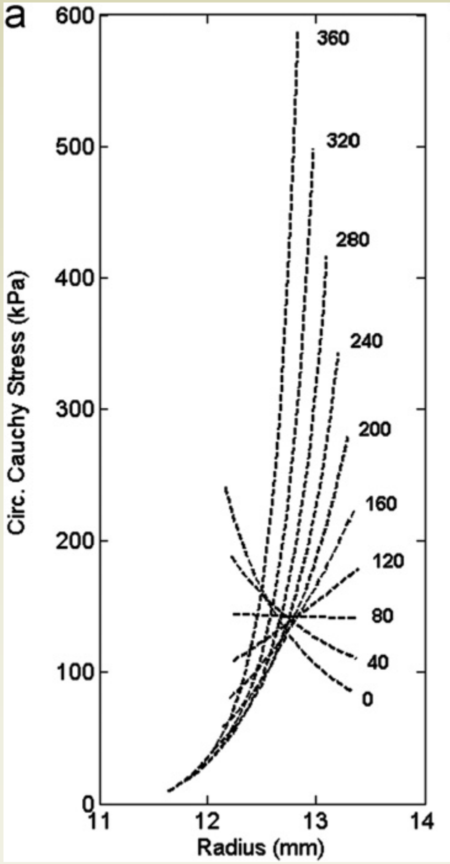
$$P = \int_{r_i}^{r_o} \lambda_{\theta\Theta} \frac{\partial \hat{W}}{\partial \lambda_{\theta\Theta}} \frac{dr}{r}$$

$$F_{red} = \pi \int_{r_i}^{r_o} \left(2\lambda_{zZ} \frac{\partial \hat{W}}{\partial \lambda_{zZ}} - \lambda_{\theta\Theta} \frac{\partial \hat{W}}{\partial \lambda_{\theta\Theta}} \right) r dr$$

EXPECTED CONSEQUENCES

Computational model - thick-walled tube





$$\sigma_{rr} = -\int_{r}^{r_o} \lambda_{\theta\Theta} \frac{\partial \hat{W}}{\partial \lambda_{\theta\Theta}} \frac{dx}{x}$$

$$\sigma_{\theta\theta} = \lambda_{\theta\Theta} \frac{\partial \hat{W}}{\partial \lambda_{\theta\Theta}} + \sigma_{rr}$$

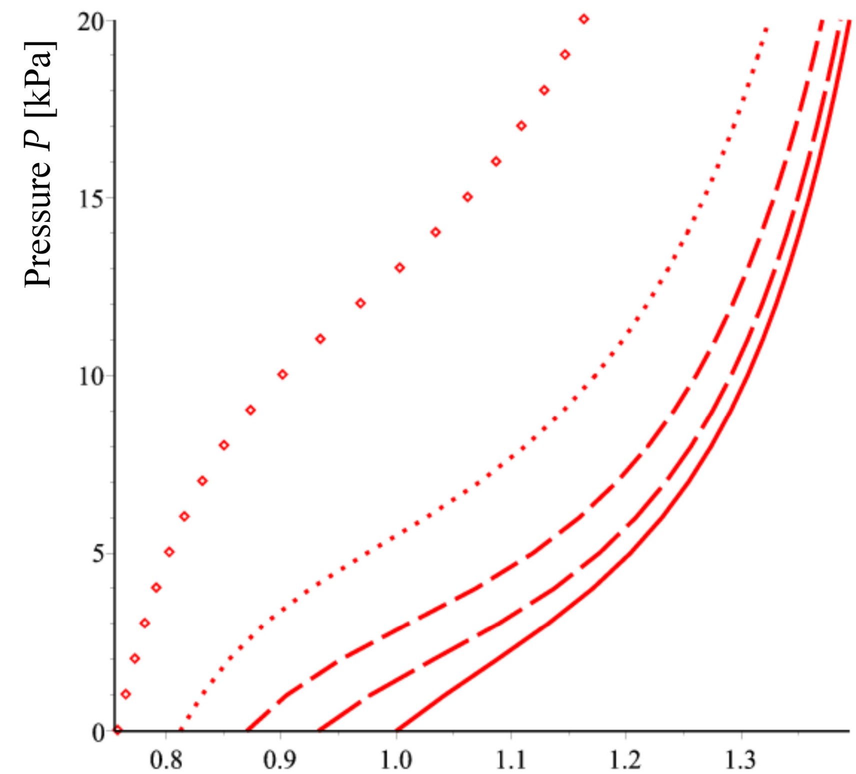
$$\sigma_{zz} = \lambda_{zZ} \frac{\partial \hat{W}}{\partial \lambda_{zZ}} + \sigma_{rr}$$

http://www.sciencedirect.com/science/article/pii/S175161611200210X

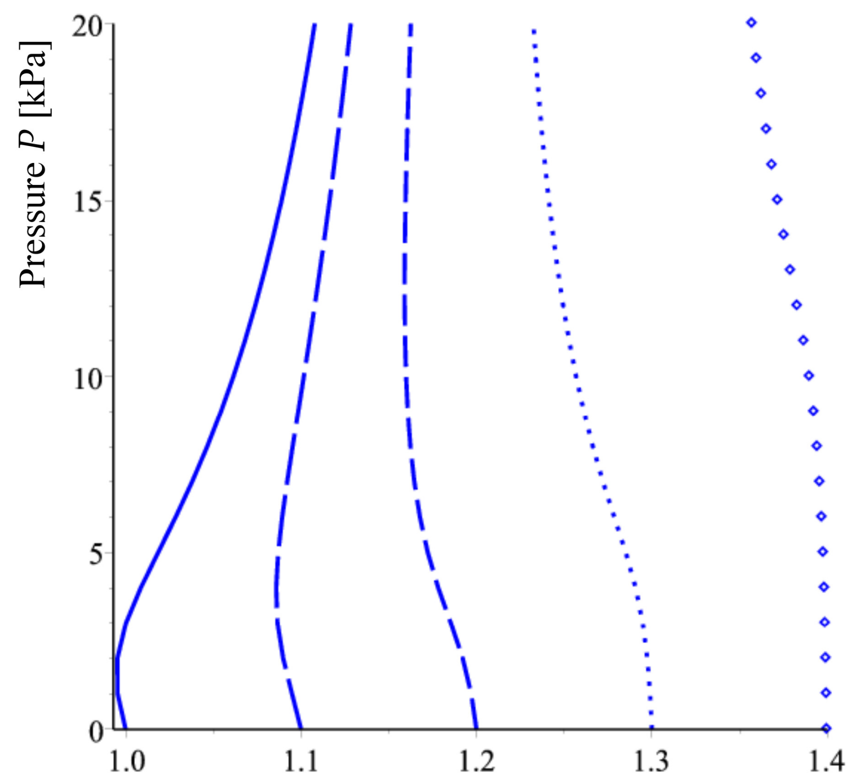
EXPECTED CONSEQUENCES

Thin-walled tube for 38 years old male

in Laborosse et al. 2013 http://www.sciencedirect.com/science/article/pii/S175161611200210X



Circumferential stretch $\lambda_{\theta\Theta} = \dfrac{Deformed\ r}{Reference\ R}$



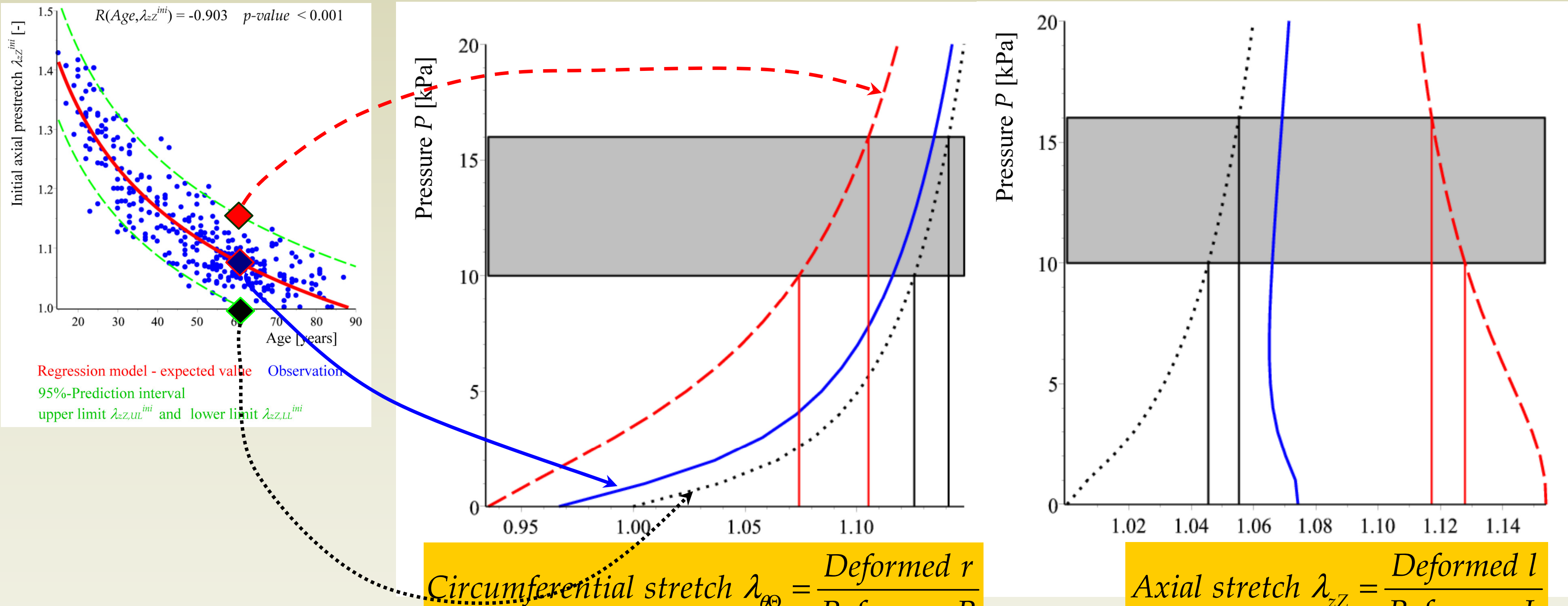
Axial stretch $\lambda_{zZ} = \dfrac{Deformed\ l}{Reference\ L}$

Horny L, Netusil M, Vonavkova T (2013) Axial prestretch and circumferential distensibility in biomechanics of abdominal aorta. *Biomech Model Mechanobiol*, submitted to the journal.

EXPECTED CONSEQUENCES

Thin-walled tube for 61(a) years old male

in Laborosse et al. 2013 http://www.sciencedirect.com/science/article/pii/S175161611200210X



$$\text{Circumferential stretch } \lambda_{\theta\Theta} = \frac{\text{Deformed } r}{\text{Reference } R}$$

$$\text{Axial stretch } \lambda_{zZ} = \frac{\text{Deformed } l}{\text{Reference } L}$$

$$\lambda_{zZ}(autopsy) = 1.153$$

$$\lambda_{zZ}(autopsy) = 1.074$$

$$\lambda_{zZ}(autopsy) = 1$$

Horny L, Netusil M, Vonavkova T (2013) Axial prestretch and circumferential distensibility in biomechanics of abdominal aorta. *Biomech Model Mechanobiol*, submitted to the journal.

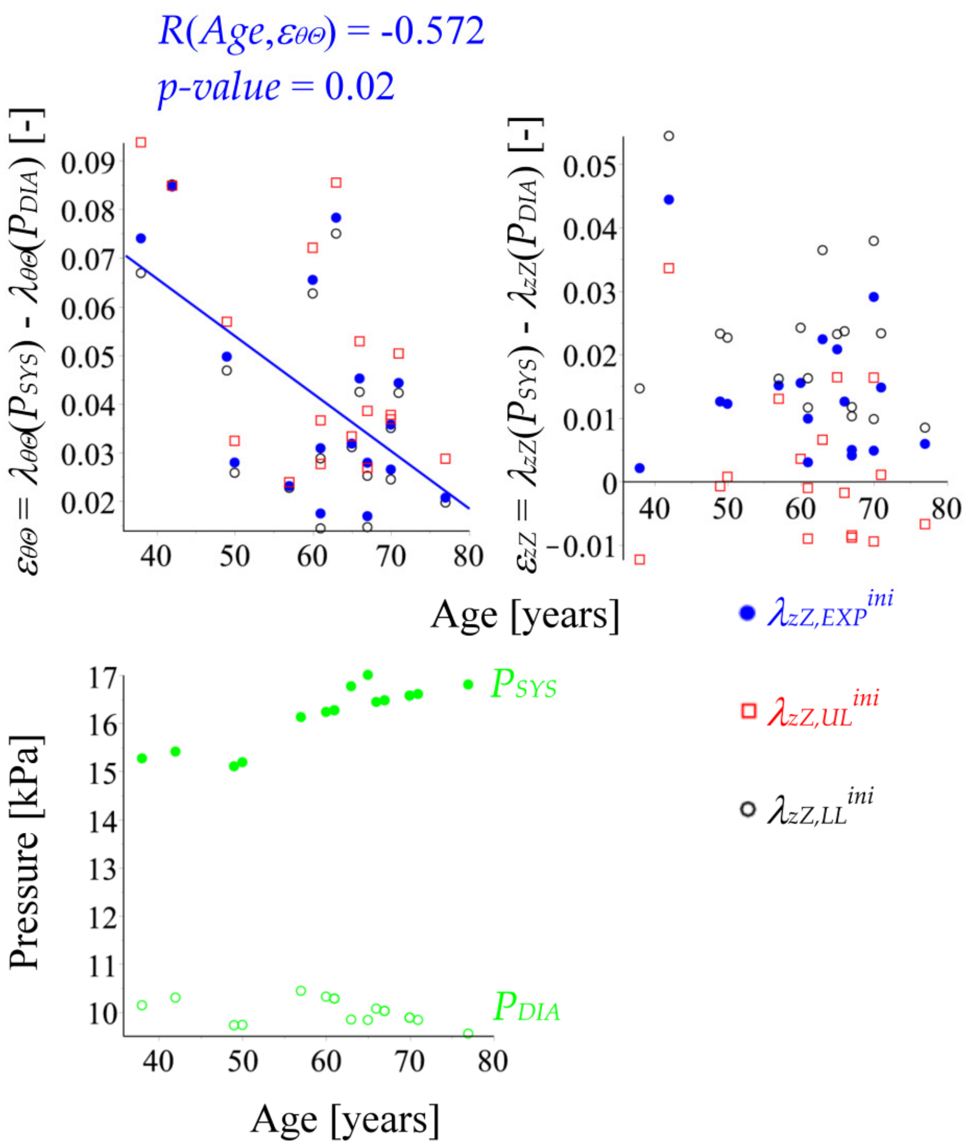
EXPECTED CONSEQUENCES

17 abdominal aortas

from Laborosse et al. 2013

http://www.sciencedirect.com/science/article/pii/S175161611200210X

Re-computation with thick-walled tube model confirmed conclusion from thin-walled one.



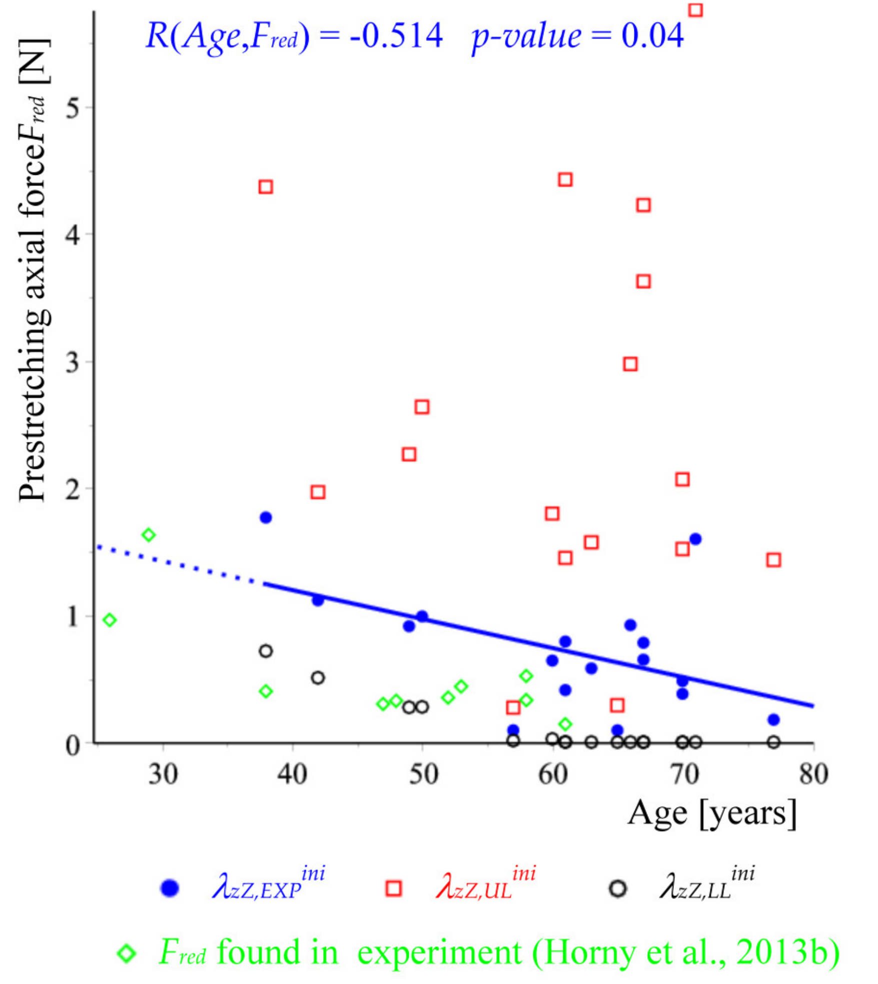
Higher axial prestretch endows artery with higher circumferential distensibility.

Horny L, Netusil M, Vonavkova T (2013) Axial prestretch and circumferential distensibility in biomechanics of abdominal aorta. *Biomech Model Mechanobiol*, submitted to the journal.

EXPECTED CONSEQUENCES

Computed prestretching force F_{red}

Prestretching force decreases with increasing age.



Simulation for 17 abdominal aortas from Laborosse et al. 2013

Horny L, Netusil M, Vonavkova T (2013) Axial prestretch and circumferential distensibility in biomechanics of abdominal aorta. *Biomech Model Mechanobiol*, submitted to the journal.

SUMMARY

- Axial prestretch, force and prestress decrease with age

- This decrease may contribute to the loss of circumferential distensibility and to the increase of axial stress variation during pressure cycle

SOME OPEN PROBLEMS

- Observation of axial strains in vivo (in clinics?)

Cinthio M, Ahlgren ÅR, Bergkvist J, Jansson T, Persson HW, Lindström K. (2006) Longitudinal movements and resulting shear strain of the arterial wall. Am J Physiol - Heart Circ Physiol 291(1):H394-402. doi: 10.1152/ajpheart.00988.2005 http://dx.doi.org/10.1152/ajpheart.00988.2005

- Does axial prestretch take place in aneurysms?

- And what about axial prestretch in curved parts of arteries?

SOME OPEN PROBLEMS

- The last and the most fundamental:

  Does prestretch comes from external bonds or is it residual strain induced by incompatible growth of artery wall components?

AXIAL PRESTRETCH IN AORTA

Thank you very much for the attention.

Interested in details, questions or suggestions? Contact me lukas.horny@fs.cvut.cz
Presentation
http://users.fs.cvut.cz/~hornyluk/files/Axial-prestretch-in-aorta-Frankfurt-2013-Horny-L.pdf