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Pressure pulse wave velocity and axial prestretch in arteries

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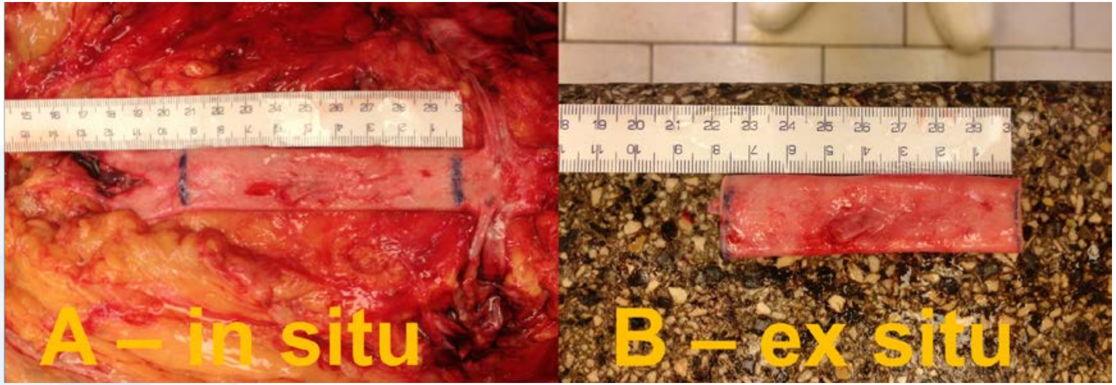
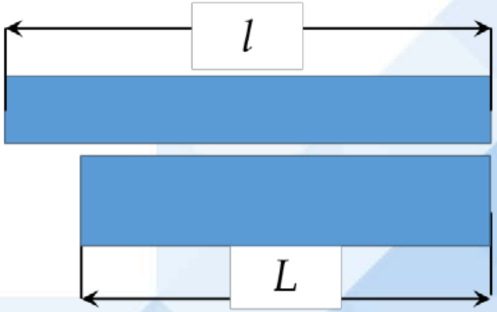
Aims & objectives: What is axial prestretch?

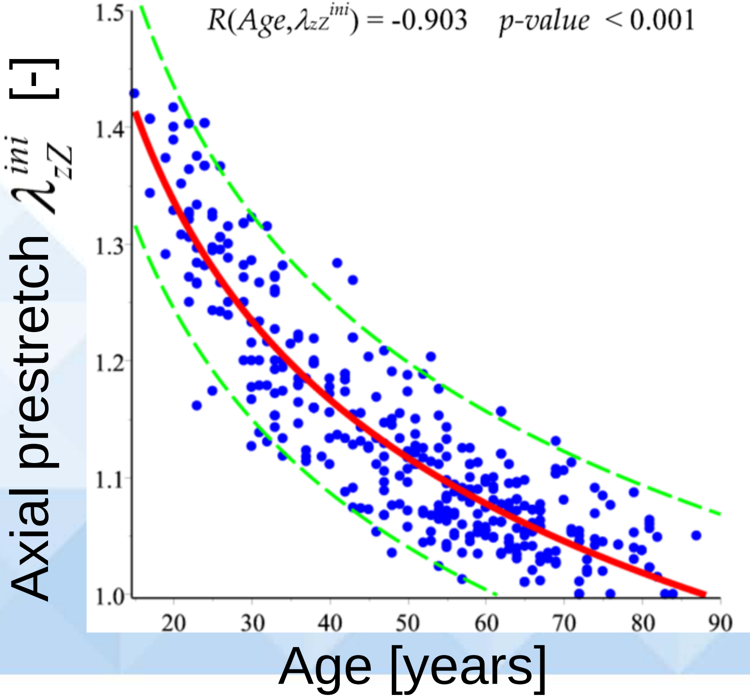




- Human abdominal aorta in autopsy with marks
- Arteries grow axially prestretched
- This is expressed by means of λ_{zZ}^{ini}

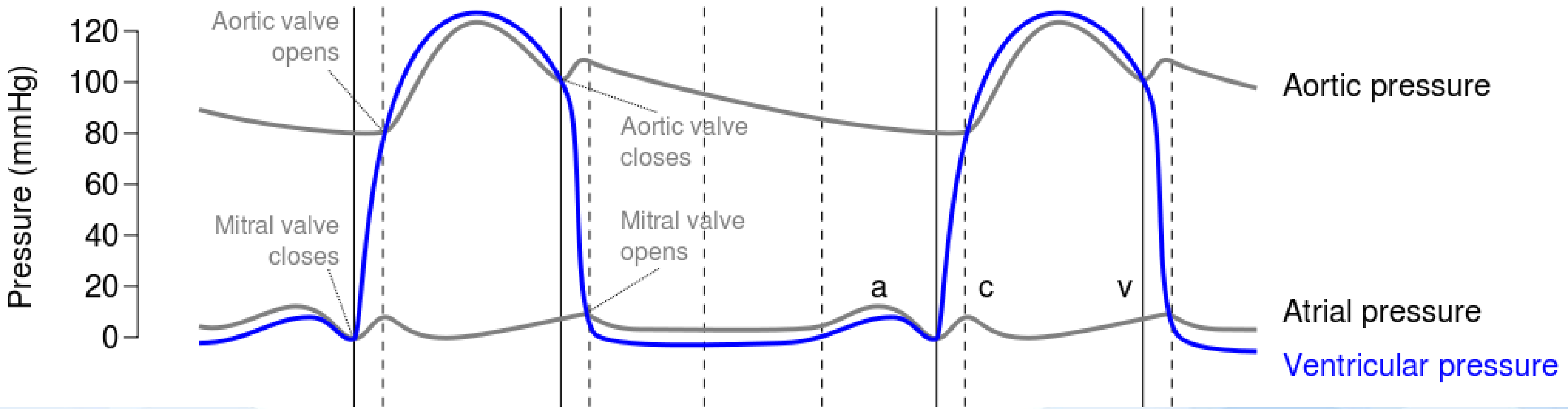
$$\lambda_{zZ}^{ini} = \frac{l}{L}$$

Aims & objectives: Prestretch declines in aging



- Arteriosclerosis (calcification and fragmentation of elastic membranes in medium layer in an arterial wall) is accompanied by the decline in the prestretch

Aims & objectives: Heart pumps blood in pulses



- Pressure pulse is transmitted by arteries as a mechanical wave

Aims & objectives: How does axial prestretch of aorta change pressure pulse wave velocity?

- Human aorta is nonlinearly elastic tube
- Human aorta is axially prestretched
- This prestretch depends on age
- Which means it changes during our lives
- How do such changes affect pressure pulse velocity?

Methods: Simulation based on computational model with assumptions simplifying the problem

- Transmission of the pressure pulse wave is very complicated fluid-structure interaction where a complexity arises especially from
  - nonlinear and viscoelastic behavior of the aortic wall
  - nonlinearly viscose behavior of the blood
  - pulsatile character of the blood flow
  - complex geometry
  - existence of residual stresses in the wall

Methods: Simulation was based on assumptions as follow

- Inertial effects in aortic wall motion are negligible
- Aorta is thin-walled tube which bears axial load due to the prestretch F_{red}, as well as the load arising from closed ends of the tube
- In such a case, equilibrium equations of aortic segment are given by (1)
- σ_{rr}, $\sigma_{\theta\theta}$, σ_{zz} – radial, circumferential and axial stress, P – pressure, r and h are deformed radius and thickness

$$\sigma_{rr} = 0 \qquad \sigma_{\theta\theta} = \frac{rP}{h} \qquad \sigma_{zz} = \frac{rP}{2h} + \frac{F_{red}}{2\pi rh} \qquad (1)$$

Methods: Simulation was based on assumptions as follow

- Mechanical behavior of the aortic wall is incompressible, anisotropic, and hyperelastic and follows elastic potential W expressed in (2)
- μ, k_1, k_2 denote material parameters, and I_1, I_4, and I_6 are deformation invariants

$$W = \frac{\mu}{2}\left(I_1 - 3\right) + \sum_{j=4,6} \frac{k_1}{2k_2}\left(e^{k_2\left(K_j - 1\right)^2} - 1\right) \qquad (2a)$$

$$K_j = \kappa I_1 + \left(1 - 3\kappa\right) I_j \quad j = 4,6 \qquad (2b)$$

Methods: Simulation was based on assumptions as follow

- Kinematics of the inflation and extension of the cylindrical segment of the aorta is given by (3)

$$\begin{array}{l} R \to r \\ \Theta = \theta \\ Z \to z \end{array} \quad \Rightarrow \quad \begin{array}{r} \lambda_{rR} = \left(\lambda_{\theta\Theta}\lambda_{zZ}\right)^{-1} \\ \lambda_{\theta\Theta} = r/R \\ \lambda_{zZ} = l/L \end{array} \qquad (3)$$

- Constitutive equation for aortic wall is given by (4)

$$\sigma_{rr} = \lambda_{rR}\frac{\partial W}{\partial \lambda_{rR}} - p \qquad \sigma_{\theta\theta} = \lambda_{\theta\Theta}\frac{\partial W}{\partial \lambda_{\theta\Theta}} - p \qquad \sigma_{zz} = \lambda_{zZ}\frac{\partial W}{\partial \lambda_{zZ}} - p \qquad (4)$$

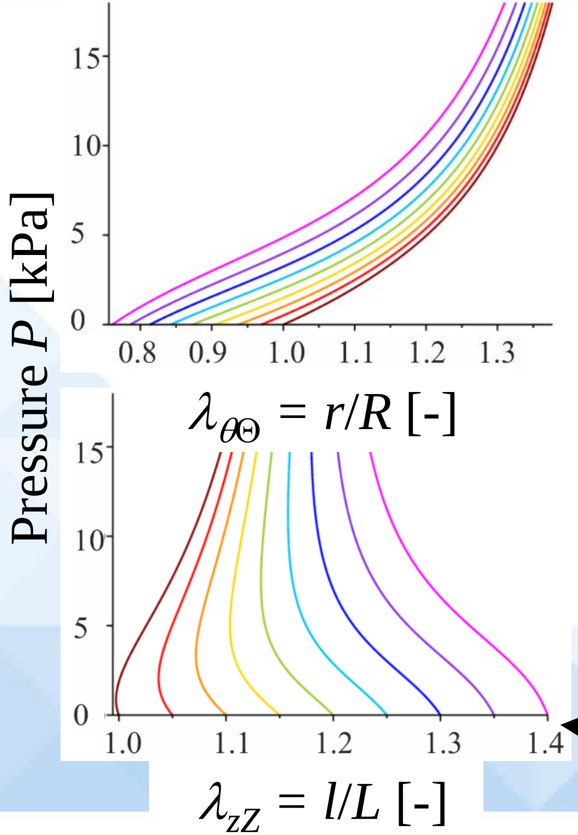
Methods: Simulation was based on assumptions as follow

- Adopting long wave assumption and neglecting viscous effects in pressure wave propagation, 1D model for conservation of mass and momentum give (5) that is Moens-Kortweg solution considering linearized blood flow but nonlinear elasticity of the wall

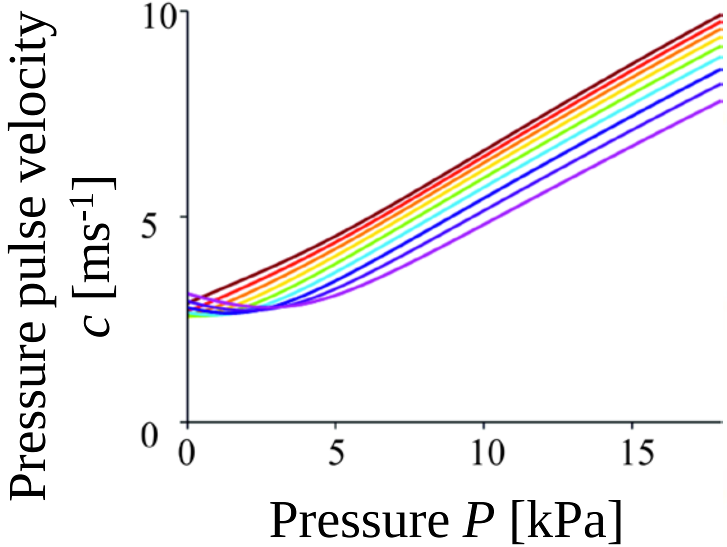
- Pressure pulse wave velocity c is computed from (5) considering pressure–deformation behavior determined from nonlinear elastostatics

$$c = \sqrt{\frac{\lambda_{\theta\Theta}}{2\rho} \frac{\partial P}{\partial \lambda_{\theta\Theta}}} \qquad (5)$$

Results

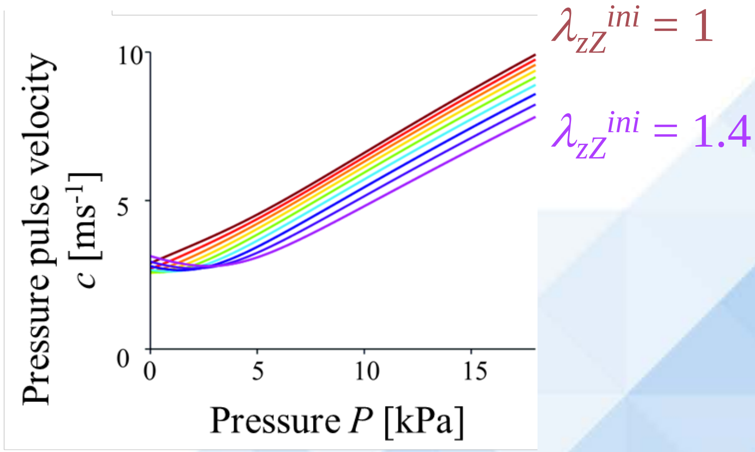


$$c = \sqrt{\frac{\lambda_{\theta\Theta}}{2\rho}\frac{\partial P}{\partial \lambda_{\theta\Theta}}}$$



Axial prestretch $\lambda_{zZ}^{ini} = 1, 1.1, \ldots, 1.4$

Conclusions:



Simplified computational model based on combination of nonlinear elastostatics for aortic wall and linearized inviscid 1D blood flow suggests that at physiological pressures:

- Pressure pulse velocity depends on the prestretch almost linearly
- Pressure pulse velocity decreases when axial prestretch increases
- We hypothesize that the prestretch helps to maintain optimal value of the pulse velocity

- **References**

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