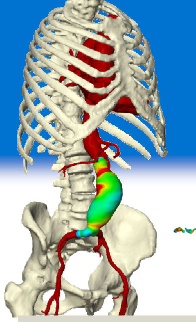

Impact of Model Complexity on Patient-Specific Wall Stress Analyses of Abdominal Aortic Aneurysms

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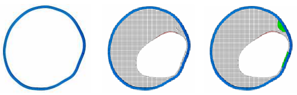
Introduction

An abdominal aortic aneurysm (AAA) is an abnormal widening of the subphrenic aorta, which in case of rupture is fatal in 90%. As prophylactic surgery is not without potential risk, it is necessary to assess the individual rupture risk. Thereby, a new approach is based on wall stress distribution and determination of peak wall stresses using the finite element method. However, simulation techniques performed by research groups differ significantly in quality and complexity. To clarify the influence of model complexity on results, commonly used FE models are compared with recently worked out advanced models applied on four AAAs exemplarily [1].

Complexity Options

Geometrical modeling (*NoILT*, *ILT*, *ILTwCa*)



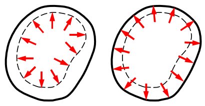
NoILT: Intraluminal thrombus is not considered
ILT: Intraluminal thrombus is included in simulation
ILTwCa: ILT and calcifications (existent in 80% of all AAAs [2]) are considered

Material model (*LinMat*, *NonLinMat*)

ILT and calcifications are modeled with NeoHookean material with $E=1.05 \cdot 10^5$ Pa, $\nu=0.45$ and $E=5.0 \cdot 10^7$ Pa, $\nu=0.40$ [2]. Different material laws are applied on AAA wall:
LinMat: NeoHooke, $E=1.044 \cdot 10^6$ Pa, $\nu=0.49$
NlnMat: Raghavan&Vorp [3], $\alpha=0.174 \cdot 10^6$Pa, $\beta=1.88 \cdot 10^6$Pa, $\nu=0.49$

Mechanical model (*NoOrthPress*, *OrthPress*)

NoOrthPress: Pressure acts on initial lumen surface
OrthPress: Pressure acts on deformed lumen surface



Prestressing (*NoPreStress*, *PreStress*)

CT images used for segmentation show a configuration loaded by in vivo forces.
NoPreStress: Reconstructed geometry is considered stress free. Full systolic pressure is applied to the lumen in a standard FEM simulation.
PreStress: Prestressed state for a diastolic pressure of p=85mmHg is calculated first [4]. An adequate forward calculation method allowing deformation is then used for increasing pressure to systolic level.

Models

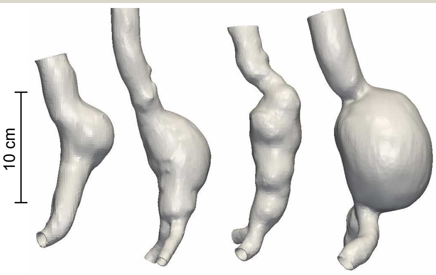


Figure 1 Overview of AAAs. Left to right: Male37, Female59, Male42, Male40.

3D reconstructions of four AAAs from our database are depicted in Figure 1. Some morphological characteristics are given in Table 1. Hex dominant finite element meshes are created using Harpoon (Sharc Ltd.). Displacements at the cutting surfaces are constrained to zero. Load is modeled as systolic blood pressure p=121mmHg.

The aforementioned options would allow for 24 distinct models with different degrees of complexity for each AAA. In this work we highlight changes in the simulation results using 6 selected models, presented in Table 2. Model 6 is applicable on the morphology Male42, exhibiting high grade of calcification, only. Finite element solutions are performed using our in-house finite element solver 'baci'.

Table 1 Selected AAA features

AAA	max. dia.	age	shape	calcification
Male37	45 mm	71 y.	sacciforme	slight
Female59	54 mm	48 y.	fusiforme	slight
Male42	48 mm	66 y.	fusi-saccif.	severe
Male40	87 mm	68 y.	fusiforme	slight

Table 2 Combinations of complexity assumptions

model no.	ILT	material	pressure	prestress
model 1	NoILT	LinMat	NoOrthPress	NoPreStress
model 2	NoILT	LinMat	OrthPress	NoPreStress
model 3	NoILT	NlnMat	OrthPress	NoPreStress
model 4	ILT	NlnMat	OrthPress	NoPreStress
model 5	ILT	NlnMat	OrthPress	PreStress
model 6	ILTwCa	NlnMat	OrthPress	PreStress

Results

Table 3 Max. von Mises stress [kPa] for 4 AAAs under model variants 1 through 6

AAA	model no. 1	2	3	4	5	6
Male37	460	620	480	250	220	-
Female59	520	820	540	420	350	-
Male42	540	760	560	360	320	220 / 520 in Calc.
Male40	840	2300	700	560	480	-

Table 4 Max. displacement [mm] for 4 AAAs under model variants 1 through 6

AAA	model no. 1	2	3	4	5	6
Male37	5.8	9.8	5.8	4.9	1.05	-
Female59	6.6	11.9	6.4	6.2	1.35	-
Male42	7.9	12.2	7.3	6.0	1.24	0.80
Male40	15.7	28.6	13.5	12.9	2.10	-

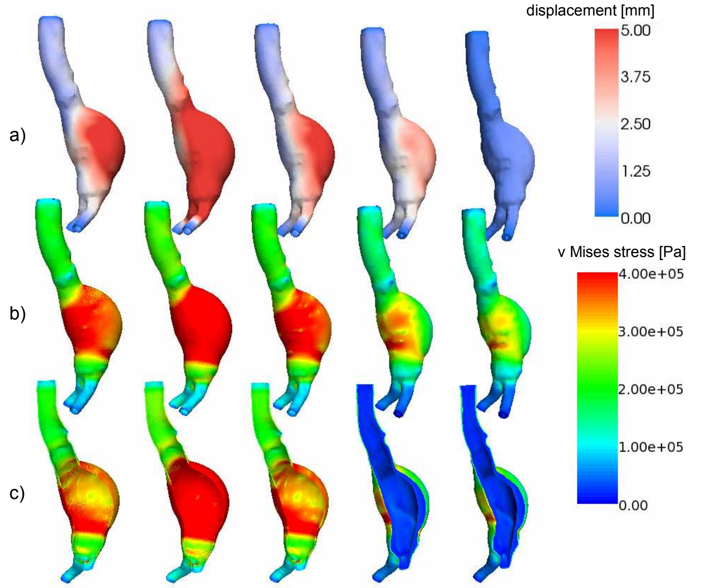


Figure 2 Female59 models. Columns show different complexity grades. a) displacements; b) von Mises stress distribution on outer wall surface; c) Cut through models, von Mises stress

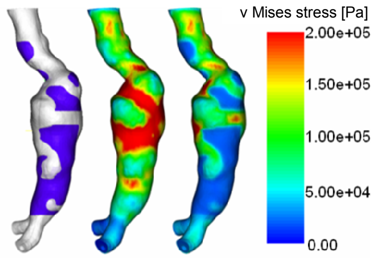


Figure 3 Male42 models: Left: ILT (grey) and calcifications (violet). Middle and right: Von Mises stress distribution.

Application of models 1 through 5 to the four AAAs yields von Mises Cauchy stresses and maximum displacements documented in Table 3 and 4. Deformation and von Mises stress distribution under influence of model 1 through 5 are exemplarily given for Female59 in Figure 2. The influence of explicit treatment of calcifications is depicted in Figure 3, where only model 5 and model 6 of Male42 are compared to each other.

Conclusion

In all simulations with model 1 through 4 displacements are unrealistically large. Application of a prestressing technique in model 5 and 6 leads to physically meaningful deformations. Peak wall stresses are increased especially in models 1 through 3, when ILT is omitted. Using model 5 regions of high wall stresses are located at concavely shaped areas of the wall, especially between the small bulges of the AAA. It is striking that calcium deposits are mainly found at these positions. Consequently, using model 6 explicitly considering calcifications the AAA wall at these regions is almost held stress free by the underlying stiff calcified plates which show a considerable load bearing effect.

In order to obtain results with realistic displacements and stress ranges it is necessary to model AAAs at least with complexity of model 5. This means that a nonlinear material law has to be used for thrombus and AAA wall modeling, existent thrombus must be included, the blood pressure acts on the deformed configuration and the predeformed state in the CT images has to be considered. For severely calcified AAAs application of model 6 is regarded as crucial for realistic simulation results. If calcifications are neglected, one should keep in mind that stress results are not valid at calcified areas of the AAA.

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