AAA have considered the tissue as isotropic. However, recent biaxial tensile tests conducted on AAA tissue samples demonstrate the anisotropic nature of this tissue (VandeGeest et al., 2006). The purpose of this work is to study the influence of geometry and material anisotropy on the magnitude and distribution of the peak wall stress in AAAs. Three dimensional computer models of symmetric and asymmetric AAAs were generated with maximum relative diameter, length of the aneurysm, and degree of asymmetry as individually controlled variables. A five parameter exponential type structural strain energy density function has been used to model the anisotropic behaviour of the AAA tissue (Holzapfel et al. 2000). The anisotropy is defined by the orientation of the collagen fibres (a parameter of the model) which has been introduced within the finite element model of different aneurisms. The results show a remarkable influence of material anisotropy on the magnitude and distribution of the peak stress (up to a 60%) for the same geometry. The results also show a larger sensitivity of anisotropic AAAs to geometric parameters. The study suggest that anisotropy must be considered in stress calculations for the identification of patients with risk of AAA rupture.

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6022 Mo, 09:00-09:15 (P6)

A computational parametric study on the permeability of intra-luminal thrombus and aortic wall within abdominal aortic aneurysms

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The formation of an abdominal aortic aneurysm (AAA) occurs over the time course of months to years and may eventually result in rupture, an event associated with a 50% mortality rate. Knowledge of the mechanical environment within the AAA may help to better diagnose those AAAs who require immediate operative treatment [1].

Noninvasive assessments of AAA wall stress via finite element (FE) techniques have previously been reported in the literature [1]. Previous FE simulations of AAA have shown that the intra-luminal thrombus (ILT) acts to decrease the stress acting on the adjacent AAA wall [2]. However, reports from other research groups have suggested a less protective role for the ILT in AAA [3]. All of the AAA FE analyses to date have assumed that the AAA wall and ILT (if present) act as a solid continuum.

The purpose of the current work was to analyze the effect of modeling the aneurysm wall and ILT as porohyperelastic (PHE) materials in the FE analysis of AAA. Towards this aim, a computational parametric study was performed on an axisymmetric cylindrical model of a AAA utilizing various values of ILT and AAA wall permeability. The stresses, fluid velocities, and local pore pressure values within the ILT and AAA have been quantified. Typical results from PHE simulations were compared to corresponding results from AAA simulations assuming AAA materials act as a purely solid continuum.

Ongoing research within our laboratory will include more realistic AAA geometries, the coupling of mass transport with PHE, and the experimental determination of PHE material properties for AAA and ILT.

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7193 Mo, 09:15-09:30 (P6)

Transient blood flow – wall interaction in abdominal aortic aneurysms

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The fundamental mechanical factor linked with abdominal aortic aneurysm (AAA) rupture is wall stress, frequently quantified as either the principal or Von Mises stress exerted along the diseased arterial wall. Intraluminal pressure as an impinging normal force on the wall has been determined to be the dominant influence on this stress under static conditions, and thus the majority of numerical modeling studies of AAA mechanics have focused on quasi-static computational solid stress (CSS_S) predictions. Often viewed as numerically insignificant are the flow-induced effects within AAAs. In the present investigation, partially and fully coupled fluid–structure interaction (FSI) computations of virtual AAAs are presented and compared with static and transient CSS analyses to identify the effects of fluid flow on the wall stress and assess the significance of each computational technique on the resulting biomechanics of the abdominal aorta. Ten virtual AAAs were modeled to isolate the hemodynamics and geometry (wall thickness and asymmetry) effects on the AAA wall mechanics. The fluid dynamics in a compliant asymmetric aneurysm model is characterized by the development of ring-shaped vortices during systole that are ejected from the sac shortly after peak pressure is achieved. The distortion energy stored in the vessel as it expands during the cardiac cycle contributes to the early formation of recirculation regions in the aneurysm that yield high velocity gradients at the distal end of the aneurysm. These flow patterns, in combination with the geometrical features of the model and the elastic characterization of the wall material, determine the distribution of flow-induced wall stresses. Arterial compliance affects the energy stored within the AAA wall over time and causes the maximum FSI-predicted wall stress to occur prior to peak systole, while the CSS-predicted wall stress occurs at the distal peak systolic pressure condition. The CSS predictions underestimate the peak wall stress by as much as 18% for AAA models with a uniform wall thickness, regardless of the asymmetry of the aneurysm sac.

5887 Mo, 09:30-09:45 (P6)

Proper analysis of finite element results for predicting abdominal aortic aneurysm rupture

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The investigation of finite element stress analysis as a tool for predicting patient-specific abdominal aortic aneurysm (AAA) rupture risk has grown considerably in recent years. The results of these models occasionally show the maximum arterial wall stresses to be highly localized in regions of the aneurysm that have been shown clinically to rarely experience rupture (e.g. at the aortic bifurcation). Mesh generation from a limited set of medical imaging data and lack of knowledge as to the actual local wall thickness are probable reasons for these non-physiological computational results. Mesh refinement of the localized high-stress regions typically leads to even greater localizations of larger stress values. Predicting aneurysm rupture risk based solely on the single maximum finite element stress value is therefore reckless. Instead, a new method has been developed to properly analyze the finite element results of patient-specific AAA models. Rather than consider wall stress only at a single element or node, this new method also takes into account the differences in stress between neighboring elements over regions of prescribed area. A test bed of 25 patient-specific AAA models with known outcomes was used to determine the optimal parameters (maximum stress difference between neighboring elements and prescribed area). A separate test bed of 100 patient-specific models has confirmed that this new method predicts AAA rupture better than current diameter-based methods and better than using only the maximum stress at a single element or node.

14.1.2. Abdominal Aortic Aneurysms and Stent-Grafts

4063 Mo, 11:00-11:15 (P8)

The influence of 3D geometry on abdominal aortic aneurysm wall stress

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In an effort to establish a more reliable abdominal aortic aneurysm (AAA) rupture risk index, the influence of geometric parameters beyond peak transverse diameter on wall stress has been previously investigated both experimentally and computationally in simplified AAA models. This paper is primarily concerned with the influence of curvature and torsion of the AAA centreline on the wall stress distribution that has been so far neglected.

A decoupled fluid structure approach [1] is employed to compare the computed time varying flow field and wall stress in a simplified symmetric AAA model and a parametrically modified AAA model. Population mean values were prescribed for the curvature and torsion of the inlet, sac and iliac sections in the modified model. These values were extracted [2] from 25 patient specific 3D reconstructed AAA models. To generate the modified computational model a new modelling approach is introduced whereby a generic parameterized finite element model is adapted to the specifications of the required model. In this case the parameterization refers to the centreline curvature and torsion of the AAA model which are handled independently for the inlet, sac and iliac sections.

Our results showed that significant inlet curvature and torsion modulates the intra-aneurysmal hemodynamics, breaks flow symmetry, and alters the distribution of flow induced aneurysmal wall loading. The latter, in conjunction with the development of curvature induced stress concentration regions, significantly alters the aneurysmal wall stress distribution in the modified AAA model. This suggests that AAA rupture risk classification based on centreline curvature and torsion could be used in conjunction with parameters such as peak aneurysm diameter, sac volume and asymmetry to improve patient management.

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5552 Mo, 11:15-11:30 (P8)

Experimental and numerical studies on physiological flow behaviour in an asymmetric model of abdominal aortic aneurysm

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An abdominal aortic aneurysm (AAA) is a localized dilatation of the abdominal aorta downstream from the renal arteries including sometimes the iliac bifurcation. Rupture is the main complication of AAAs, in 80% of cases, it leads to death. The knowledge of the local haemodynamic, including velocity, vorticity, shear and pressure distributions, may be used to improve medical diagnosis on AAA rupture.
Numerical and experimental studies are therefore carried out in a three dimensional asymmetric model of AAA with or without iliac bifurcation, to analyse the behaviour of physiological flows in AAA. Velocity measurements are performed using particle image velocimetry (PIV). In addition, a finite volume method [1] is used to perform three-dimensional unsteady numerical simulations. Different Womersley parameter values and Reynolds number values are used to assess the parameters affecting the flow behaviour. These parameters model a normal physiological flow rate, a moderate exercise flow rate and an intensive exercise flow rate.
For the first time, rigid walls versus compliant ones and iliac bifurcation model downstream from AAA versus straight artery model have been experimentally investigated to analyse both the compliance and the bifurcation influences on AAA flow behaviour. Compliant wall mechanical behaviour is characterized using a classical traction bench [2].
The secondary flow patterns and more particularly the vortices trajectories and their impact on the distal AAA wall are found to be highly dependent on the flow waveforms, the wall behaviour and on the iliac bifurcation presence. These results can help to improve medical diagnosis on AAA rupture. In a future work, we would like to numerically model the thrombus formation to better represent the pathological condition.

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5187 Mo, 11:30-11:45 (P8)

Rupture mechanisms in circulatory system vascular tissue

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Rupture of circulatory vascular tissue under non-impact loading has been attributed to disparate mechanisms. The cause of aneurysm rupture has been postulated to be stress exceeding a uniaxial limit in saccular or abdominal aortic aneurysms, a limit-point instability such as is observed in expanding rubber balloons, dynamic resonance, and large radius or curvature. Excessive strain has been postulated as the cause of rupture of small veins during shock wave lithotripsy. The presence of thrombus or plaque is thought to respectively lower wall stress or induce stress concentrations. Nonlinear dynamics, not resonance, can explain the bruit, a detectable sound due to the aneurysm wall vibration at a frequency above that of blood pressure (Haslach 2002), so dynamics may influence rupture.
Uniaxial tensile tests of flat strips of bovine artery tissue have shown that rupture begins in the intimal layer, as expected. The fracture surface shows protruding fibers of different length due to fiber pull-out from the matrix or fiber fracture. Uniaxial fatigue tests examine whether dynamic loading may raise the local temperature above body temperature and threaten the reducible collagen fibril cross-links.
The hypothesis presented is that rupture causing functional failure primarily depends on the behavior of the mesoscale structures of collagen fibers. Dynamic loading influences this behavior once damage has occurred. Previous degeneration may be partially due to the cyclic stress and strain effect on the cells; stress may do more than pull apart bonds as implicitly assumed in earlier models. Once a crack initiates, the crack may grow due to fatigue. A model for vascular tissue rupture is biaxial non-linear viscoelastic and accounts for the dynamic behavior of the composite structure, in particular the collagen fibers.

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5454 Mo, 11:45-12:00 (P8)

Relationship between growth rate and maximum wall stress in abdominal aortic aneurysms

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This study explores the relationship between wall mechanical stress and the expansion rate of abdominal aortic aneurysms (AAA). Weakening of the wall by enzymatic protease enhances aortic dilatation. It is known that cells along the aortic wall can respond biochemically to mechanical stress [1]. Four AAA patients with initial aneurysm diameters ranging from 3.3 mm to 6 mm had 1 to 4 follow-up scans over a period of up to 45 months. Patient-specific models were reconstructed based on CT images acquired from each scan and wall stress was calculated using a finite element package ADINA. Predicted maximum wall stresses were set in relation to their corresponding growth rates (mm/year). As suggested in previous studies [2,3], there is no simple correlation between the peak wall stress in AAA and its maximum diameter. Our new findings are that AAAs with low peak wall stress (under 350 kPa) have lower growth rates (0 to 0.33 mm/year) and AAAs with high peak stress level (above 350 kPa) have relatively high growth rates (0.73–1.1 mm/year). The results also show that for a given patient with a growing aneurysm the maximum wall stress increases with the increase in its expansion rate and reduces when the growth rate slows down. This suggests that mechanical stress may affect the pathology of the degrading aneurysm wall.

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5791 Mo, 12:00-12:15 (P8)

Reduction of post-operative abdominal aortic graft pressures

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Introduction: Abdominal aortic aneurysm (AAA) is an irreversible dilation of the abdominal aorta. It affects up to 5% of males over the age of 55. If the aneurysm goes unnoticed or is untreated it may rupture.
Traditional treatment involves removal of the diseased segment of the aorta and replacement with a graft fabricated from synthetic material such as polyester or ePTFE.Such an operation involves problems such as large blood loss, prolonged cross clamping of the aorta (increasing blood pressure), large risk of complications and long recovery periods.
Recent research has suggested that the introduction of a graft may give rise to an increase in blood pressure and cause an associated rise in cardiac load. The objective of this study was to examine the influence of new geometrical features on aortic pressure measurements in a range of *in vitro* models.
Materials and Methods: Wave reflections, aorto/iliac area ratio and graft stiffness are all believed to play a role in increasing aortic blood pressure. In order to assess the influence of these parameters on aortic pressure an experimental investigation was conducted.
A computer controlled piston pump was used to generate a physiologically realistic aortic flow rate in a range of compliant silicone rubber models. These included models based on currently used AAA graft geometries and on a new tapered graft which is under development. Pressure measurements were obtained using a 0.5 mm pressure catheter at a location 5 cm proximal to the iliac bifurcation in the model.
Results: The maximum and minimum pressures were recorded for ten samples for each model. The novel geometry was found to reduce both the peak pressure and the minimum pressure by approximately 9 mm of Hg when compared with conventional grafts.