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Finite Element Analysis in Asymptomatic, Symptomatic, and Ruptured Abdominal Aortic Aneurysms: In Search of New Rupture Risk Predictors

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WHAT THIS PAPER ADDS

To evaluate finite element analysis (FEA) as a predictive risk model for abdominal aortic aneurysm (AAA) rupture, a single center retrospective analysis was performed to compare biomechanical properties in asymptomatic, symptomatic, and ruptured AAAs. Peak Wall Rupture Risk Index (PWRI) differentiates subgroups better than Peak Wall Stress (PWS). These preliminary results suggest that AAA patients with PWRI values greater than 1.0 may be at imminent risk of becoming symptomatic or even rupturing.

Objectives: To compare biomechanical rupture risk parameters of asymptomatic, symptomatic and ruptured abdominal aortic aneurysms (AAA) using finite element analysis (FEA).
Study design: Retrospective biomechanical single center analysis of asymptomatic, symptomatic, and ruptured AAAs. Comparison of biomechanical parameters from FEA.
Materials and methods: From 2011 to 2013 computed tomography angiography (CTA) data from 30 asymptomatic, 15 symptomatic, and 15 ruptured AAAs were collected consecutively. FEA was performed according to the successive steps of AAA vessel reconstruction, segmentation and finite element computation. Biomechanical parameters Peak Wall Rupture Risk Index (PWRI), Peak Wall Stress (PWS), and Rupture Risk Equivalent Diameter (RRED) were compared among the three subgroups.
Results: PWRI differentiated between asymptomatic and symptomatic AAAs ($p < .0004$) better than PWS ($p < .1453$). PWRI-dependent RRED was higher in the symptomatic subgroup compared with the asymptomatic subgroup ($p < .0004$). Maximum AAA external diameters were comparable between the two groups ($p < .1355$). Ruptured AAAs showed the highest values for external diameter, total intraluminal thrombus volume, PWS, RRED, and PWRI compared with asymptomatic and symptomatic AAAs. In contrast with symptomatic and ruptured AAAs, none of the asymptomatic patients had a PWRI value >1.0. This threshold value might identify patients at imminent risk of rupture.
Conclusions: From different FEA derived parameters, PWRI distinguishes most precisely between asymptomatic and symptomatic AAAs. If elevated, this value may represent a negative prognostic factor for asymptomatic AAAs.

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INTRODUCTION

Precise prediction of rupture in patients with abdominal aortic aneurysms (AAA) continues to be a problem. In routine clinical practice the maximum aortic diameter is the criterion most often used for AAA repair. The ESVS guideline (European Society of Vascular Surgery) reports an exponentially increasing annual rupture risk for patients exceeding diameters of 5.0—5.5 cm.[1] However, this sole parameter does not necessarily reflect the true risk of rupture in each patient.

The potential for several additional parameters, including the geometrical AAA shape,[2] female gender,[3,4] arterial hypertension,[5] smoking history,[6] familial AAA predisposition,[7] and large amount of intraluminal thrombus formation,[8] to elevate the individual rupture risk has been discussed, but these are rarely included in clinical decision making regarding AAA repair. The finite element analysis (FEA) software used in this study incorporates patient specific risk factors to calculate biomechanical rupture risk indices with

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a high investigator reproducibility,[9,10] thus having the potential to predict patient specific AAA rupture risk more precisely than maximum aortic diameter alone.[11] Clinical and experimental studies are still required to examine accuracy of the described FEA model.

The aim of this study was to compare biomechanical parameters from FEA in patients with asymptomatic, symptomatic, and ruptured AAAs to evaluate the predictive value of FEA in AAA rupture risk assessment.

METHODS

Study population

Computed tomography angiography (CTA) data from 60 patients with asymptomatic (*n* = 30 [all men], age 71 [50—86]), symptomatic (*n* = 15 [11 men], age 75 [49—85]), and ruptured AAAs (*n* = 15 [14 men], age 73 [60—88]) treated at a single center between 2011 and 2013 were selected consecutively according to the date of CTA investigation, and analyzed retrospectively. Vessel wall angulation is a limiting factor that disturbs FEA generation in asymptomatic and symptomatic AAAs. In addition, contrast extravasation complicates FEA generation in ruptured AAAs. If FEA generation was impossible in a certain case, this patient was excluded from the study and CTA data for the next patient was analyzed, until the predefined study population size was reached.

Patient characteristics are shown in Table 1. Inclusion criteria were elective repair of AAA with maximum diameter >5.0 cm without symptoms or signs of rupture on the preoperative CTA in the asymptomatic AAA group, and extravasation of contrast medium and/or retroperitoneal hematoma on CTA for the ruptured AAA group. Patients with AAA associated symptoms, for example abdominal and/or back pain who were undergoing prompt AAA repair after ruling out other differential diagnoses and who did not have CTA morphological signs of rupture, were assigned to the symptomatic AAA group. FEA was generated and compared from CTAs of non-ruptured (asymptomatic and symptomatic AAA group) and ruptured CTAs (ruptured AAA group). All patients underwent either open surgical or EVAR repair.

CTA scans of the abdominal aorta were acquired with a 64 slice CT scanner using standard radiologic parameters (in plane resolution 0.33 mm, slice thickness 0.7—1.0 mm). Both elective and emergency CTA for asymptomatic, symptomatic and ruptured AAAs were generated within this protocol. Brachial systolic blood pressure (Riva-Rocci) was recorded in all patients with ruptured AAAs during emergency CTA diagnostics. For asymptomatic and symptomatic AAAs, a systemic blood pressure of 130/80 mmHg was assumed. Patient specific risk factors like gender, smoking history, and arterial hypertension were collected in all groups for retrospective FEA. This study was permitted by the local ethics committee.

Finite element model

FEA was performed by a single experienced investigator using the DICOM data format of CTA. Commercially available CE certified semi-automatic analyzing software (A4clinics; VASCOPS GmbH, Graz, Austria) was used. Analysis was based on the three subsequent steps of AAA vessel wall reconstruction from CTA data, segmentation (i.e. mesh generation) and calculation of morphological (diameter/volume measurements) and biomechanical parameters (PWS, PWRI, RRED). Reconstruction of AAA morphology was semi-automatic, allowing capture of external and contrasted internal vessel surfaces. Both the external vessel wall and intraluminal thrombus (ILT) were divided into voxels for subsequent biomechanical calculation. In all patients FEA was performed between the renal arteries and the aortic bifurcation.[11] The effects of ILT and AAA wall properties were described by previously suggested isotropic models.[11] Specifically, all FEA model properties (wall thickness, mesh size, constitutive tissue properties, etc.) were homogenous in all AAA subgroups, and details regarding image segmentation have been reported before.[12] The following mechanical and geometrical parameters were calculated:

- Peak Wall Stress (PWS): Tensile stress exerted on the vessel wall based on aneurysm shape, diameter and blood pressure values. The maximal value (in kilo Pascal) within an AAA corresponds to the PWS.
- Peak Wall Rupture Index (PWRI): This index relates tensile stress (PWS) to vessel wall strength (PWRI = PWS/wall strength) and additionally incorporates patient specific risk factors like gender and intraluminal thrombus. The PWRI value ranges from 0.0

Table 1. Patient characteristics and co-morbidities of AAA subgroups.

	Asymptomatic AAAs (*n* = 30)	Symptomatic AAAs (*n* = 15)	Ruptured AAAs (*n* = 15)
Age	71 (50—86)	75 (49—85)	73 (60—88)
Male sex	30 (100%)	11 (73%)	14 (93%)
Arterial hypertension	29 (97%)	13 (87%)	12 (80%)
Smoking history	20 (67%)	5 (33%)	8 (53%)
Coronary heart disease	12 (40%)	8 (53%)	6 (40%)
Dyslipidemia	10 (33%)	4 (27%)	1 (7%)
Peripheral arterial occlusive disease	4 (13%)	1 (7%)	2 (13%)
BP systolic during CTA (in mmHg)	130 assumed	130 assumed	126 (80—170)
BP diastolic during CTA (in mmHg)	130 assumed	130 assumed	74 (50—80)

Absolute and median values ± standard deviation, (lowest—highest values) are shown.CTA = computer tomography angiography; BP = blood pressure.