A Novel Strategy to Translate the Biomechanical Rupture Risk of Abdominal Aortic Aneurysms to their Equivalent Diameter Risk: Method and Retrospective Validation

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WHAT THIS PAPER ADDS

Reported biomechanical abdominal aortic aneurysm (AAA) rupture risk assessment studies suffer from severe limitations such as high operator variability, small sample sizes, and clinically difficult interpretation of the results. The present paper used a gender-specific computational method of low operator variability and tested the biomechanical rupture risk assessment on the largest patient cohort so far. The concept of equivalent diameters relates biomechanical results to basic conclusions drawn from large clinical AAA trials, and hence supports a sound clinical interpretation of biomechanical results. Finally, the retrospective and size-adjusted analysis verified that biomechanical risk indicators are higher in ruptured than non-ruptured cases.

Objective: To translate the individual abdominal aortic aneurysm (AAA) patient's biomechanical rupture risk profile to risk-equivalent diameters, and to retrospectively test their predictability in ruptured and non-ruptured aneurysms.
Methods: Biomechanical parameters of ruptured and non-ruptured AAAs were retrospectively evaluated in a multicenter study. General patient data and high resolution computer tomography angiography (CTA) images from 203 non-ruptured and 40 ruptured aneurysmal infrarenal aortas. Three-dimensional AAA geometries were semi-automatically derived from CTA images. Finite element (FE) models were used to predict peak wall stress (PWS) and peak wall rupture index (PWRI) according to the individual anatomy, gender, blood pressure, intraluminal thrombus (ILT) morphology, and relative aneurysm expansion. Average PWS diameter and PWRI diameter responses were evaluated, which allowed for the PWS equivalent and PWRI equivalent diameters for any individual aneurysm to be defined.
Results: PWS increased linearly and PWRI exponentially with respect to maximum AAA diameter. A size-adjusted analysis showed that PWS equivalent and PWRI equivalent diameters were increased by 7.5 mm ($p = .013$) and 14.0 mm ($p < .001$) in ruptured cases when compared to non-ruptured controls, respectively. In non-ruptured cases the PWRI equivalent diameters were increased by 13.2 mm ($p < .001$) in females when compared with males.
Conclusions: Biomechanical parameters like PWS and PWRI allow for a highly individualized analysis by integrating factors that influence the risk of AAA rupture like geometry (degree of asymmetry, ILT morphology, etc.) and patient characteristics (gender, family history, blood pressure, etc.). PWRI and the reported annual risk of rupture increase similarly with the diameter. PWRI equivalent diameter expresses the PWRI through the diameter of the average AAA that has the same PWRI, i.e. is at the same biomechanical risk of rupture. Consequently, PWRI equivalent diameter facilitates a straightforward interpretation of biomechanical analysis and connects to diameter-based guidelines for AAA repair indication. PWRI equivalent diameter reflects an additional diagnostic parameter that may provide more accurate clinical data for AAA repair indication.

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INTRODUCTION

The natural history of abdominal aortic aneurysms (AAAs) is determined by proteolytic degradation of elastin and collagen in the aortic wall resulting in dilatation and eventual rupture. AAA rupture has a total mortality between 75% and 90%, and death from ruptured AAAs ranks among the 10th leading cause of death in men above the age of 65.[1]

The indication for elective AAA repair is determined by the likelihood of rupture.[2] Consequently an accurate evaluation of rupture risk is of vital importance in reducing aneurysm related mortality, without substantially increasing the rate of elective AAA repair.

Data on AAA rupture risk has been provided from different sources.[3] According to the current clinical view, AAA rupture risk is based on the maximum diameter; a diameter of 55 mm or more is a generally accepted as indication for repair in males.[3,4] This kind of rupture risk assessment is, however, undergoing discussions,[5,6] since AAAs with a diameter less than 55 mm may rupture[7,8] whereas many aneurysms larger than 55 mm may never rupture.[8] Large AAA diameter is not the only risk factor, and rupture has also been associated with shape,[9] female gender,[10–13] family susceptibility,[14–16] high mean arterial pressure (MAP), smoking,[9,17] and fludeoxyglucose (FDG) uptake on positron emission tomography (PET).[18] Nearly all large AAAs have intraluminal thrombus (ILT),[19] which is associated with a weaker[20] and thinner[21] underlying aneurysm wall, and ILT growth has been associated with risk of rupture.[22] Consequently, the diameter criterion has clear limitations.

According to the biomechanical rupture risk hypothesis, an aneurysm ruptures if wall stress overcomes wall strength at a certain location in the wall.[6] A biomechanical analysis is typically based on finite element (FE) predictions and such studies showed that peak wall stress (PWS)[23,24] and peak wall rupture index (PWRI)[25,26] discriminate better between ruptured and non-ruptured aneurysms than the maximum diameter. Specifically, the PWRI relates mechanical stress and strength of the aneurysm wall, and incorporates risk factors associated with aneurysm wall weakening including female gender, ILT thickness and large relative expansion with respect to the normal infrarenal diameter.[27] No clinical trial, however, has investigated threshold values of these parameters for AAA repair, consequently they have limited clinical relevance.

The present study used the concept of risk-equivalent diameters, i.e. where biomechanical rupture risk values are translated to equivalent diameters of the average aneurysm patient. Specifically, the average patient is defined as the mean response of our non-ruptured patient cohort weighted by the gender ratio of the UK small aneurysm trial.[3] Retrospectively collected ruptured and non-ruptured cases were used to test to what extent biomechanical indices can discriminate among the groups.

METHODS

Patient cohort and data acquisition

Data from 40 ruptured and 203 non-ruptured aneurysmal infrarenal aortas from 229 patients (179 male and 50 female) were retrospectively considered for this study (Table 1). Patients underwent contrast-enhanced computed tomography angiography (CTA) of the aorta at Karolinska University Hospital and Sankt Göran Hospital in Stockholm, University Hospital and St Joseph Hospital of Liege, and University Hospital in Heidelberg at typical image resolutions (in-plane, from 0.39 mm to 0.8 mm; slice thickness, from 1.0 mm to 5.0 mm). A considerable portion of our cohort is not in the diameter range of primary clinical importance, 50 mm to 60 mm say, but investigating a larger diameter spectrum might help to identify reasons why some small AAA rupture whereas many large cases do not. Prior to CTA, patient data were recorded for non-ruptured cases, and for the ruptured cases blood pressure at the last admission before rupture was used. If this information was not available, blood pressure of 140/80 mmHg was considered. No gender differences for age and systolic/diastolic pressure among the different groups were recorded (Table 1). The female–male ratio was lower in the ruptured (6/34) than in the non-ruptured (44/159) group. CTA scans recorded with strongly inhomogeneous lumen intensity were a priori rejected to minimize user interactions to build the computational models. The collection and use of anonymized data from human subjects was approved by the local ethics committees.

Image reconstruction and biomechanical analysis

Aneurysms were reconstructed and analyzed with the diagnostic system A4clinics (VASCOPS GmbH, Graz, Austria). The reconstruction process used deformable image segmentation models and required minimal user interactions dependent on the complexity of the aneurysm and the quality of the image data. Centerline-based maximum diameter, PWS, and PWRI were calculated automatically. FE models that specifically account for the ILT, and the thinning of the aneurysm wall covered by it, were used; all modeling details have been reported elsewhere.[21,25,28] The FE method is an established numerical concept that divides any geometry into a large number of small finite elements, which together define a (hypothetical) biomechanical model of the aneurysm. The hypothetical model (FE model) was pressurized by the mean arterial pressure (MAP; 1/3 systolic pressure + 2/3 diastolic pressure), which in turn predicted the mechanical stress (force per area) in the wall of the aneurysm. Apart from geometry and arterial pressure, a FE model requires constitutive descriptions for the wall and the ILT. A constitutive description is a mathematical model of biomechanical properties, which relates stress and strain (deformation) and/or describes the strength of the tissue. The FE models used in the present analysis considered isotropic constitutive descriptions for the ILT and the aneurysm wall. An isotropic constitutive model is a