A Finite Element Analysis Rupture Index (FEARI) Assessment of Electively Repaired and Symptomatic/Ruptured Abdominal Aortic Aneurysms

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Abstract— **Clinicians routinely use the maximum transverse diameter of an abdominal aortic aneurysm (AAA) to help gauge the severity of the condition, with AAAs that reach or exceed 5.5 cm deemed a rupture-risk. The effectiveness of the maximum diameter criterion has been questioned and novel techniques to predict the rupture threat of AAAs have recently emerged, including the methodology reported in this study. Preliminary work in a previous publication by the authors highlighted that the FEARI may be a useful additional tool to help assess the rupture threat of AAAs. In this study, 42 electively repaired AAAs and 10 symptomatic/ruptured AAAs were analysed using the FEARI approach. Results (mean ± standard deviation) show that diameter, peak wall stress and FEARI were all higher in the symptomatic group compared to the electively repaired group (diameter = 75.5 ± 13.3 mm v 64.8 ± 12.4 mm, peak wall stress = 0.86 ± 0.36 v 0.55 ± 0.23 MPa, FEARI = 1.01 ± 0.43 v 0.66 ± 0.3). Various geometrical comparisons were also compared between the two groups and results showed that the ILT volume, total AAA volume, total surface area, AAA length, ratio of diameter to length and the ratio of maximum diameter to infrarenal diameter (ROD) were all higher in the symptomatic group. The percentage volume of ILT was lower in the symptomatic group (40% ± 15 v 51% ± 20). The results of this study suggest that numerical modeling may help contribute to the clinical decision-making process in AAA repair and that useful information can be obtained using this approach.**

Keywords— **Aneurysm, rupture-risk, prediction, modeling.**

I. INTRODUCTION

Cardiovascular disease is the leading cause of death in the Western world, with abdominal aortic aneurysm (AAA) representing a significant portion of these deaths. AAAs are defined are a dilation of the lower region of the aorta, predominantly forming below the renal arteries and above the iliac bifurcation. AAAs are typically asymptomatic and are often referred to as a "silent killer." Detection is usually through ultrasound screening programmes or as part of medical imaging for unrelated conditions. AAAs are also often detected when a patient presents with abdominal or back pain. Upon detection, the maximum diameter of the AAA is the preferred rupture-risk parameter of clinicians and AAAs > 5.5 cm are usually referred for surgery. Smaller AAAs (< 5.5 cm) are often monitored using ultrasound approximately every 6 months to examine the growth rate. Growth rates exceeding 1 cm/year are also deemed high-risk and referred for repair.

There is a growing argument that diameter may not accurately describe the rupture-risk of all AAAs [1-8], as small AAAs can rupture and large AAAs may often remain stable for the duration of the patients life. Therefore, alternative rupture-risk parameters have emerged in recent years. Kleinstreuer and Li [4] recently proposed the Severity Parameter (SP) which uses eight weighted parameters together with computer software to determine the rupture-threat. The same authors have also reported an equation [5] that can predict the maximum wall stress of an AAA to within 9.5% of that computed using FEA. However, the accuracy of these two approaches [4,5] reduces greatly with geometric complexities and these tools also fail to pinpoint the location of peak stress which is vital to comprehensively determine the likelihood of rupture. A Rupture Potential Index (RPI) has also recently emerged from the Vorp group [2]. This method couples FEA-predicted wall stress with a statistical model to determine patient-specific wall strength [9]. Preliminary RPI results [2] have indicated that it may be better than diameter at identifying high-risk AAAs.

FEARI [3] is similar to RPI in that it relies on a simple ratio of wall stress to wall strength. However, FEARI uses wall strength data determined from actual bench-top mechanical tests of AAA tissue. FEARI values close to 1 indicate high risk of rupture and values near 0 represent a low risk. This paper examines the use of FEARI in both electively repaired AAAs and symptomatic/ruptured AAAs and discusses the potential of FEARI to identify AAAs that may be higher-risk than other similarly-sized aneurysms.

II. METHODOLOGY

This study comprised of electively repaired AAAs (n = 42: male = 34, female = 8, mean age = 71.9 ± 6.4 yrs) and symptomatic/ruptured cases (n = 10: male = 7, female = 3, mean age = 72.5 ± 7.4 yrs). A diameter-matched group of men (n =7) and women (n = 7) was also assembled from the cohort of electively repaired cases and examined.

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Each AAA is reconstructed into 3D from computed tomography (CT) datasets using the commercially available software Mimics (Materialise NV, Belgium). All reconstructions begin immediately below the lowest renal artery and end at the iliac bifurcation. As the wall thickness of the AAA wall is difficult to obtain from CT images, a uniform wall of 1.5 mm was assumed and applied to each of the geometries. The intraluminal thrombus was included in all reconstructions as its presence is believed to significantly alter the wall stress distribution and magnitude. This method of reconstruction is reported in detail elsewhere [10,11].

The *in vivo* wall stress is predicted using the common approach of finite element analysis (FEA) [6]. All computations were performed using ABAQUS v6.9 (Dassault Systemes, RI, USA). Each 3D geometry is meshed using quadratic tetrahedral 3D elements with the ILT assumed by be completely tied to the aortic wall. A static uniform blood pressure was applied to the luminal surface of each model to represent the force of the cardiac pulse acting on the wall. All models were rigidly constrained at the proximal and distal regions to represent tethering to the remainder of the aorta. Peak von Mises wall stress was determined for all geometries along with the exact location of peak stress.

Wall strength varies from patient to patient and also can vary significantly within the same patient. Previous reports by both Raghavan et al. [12,13] and Thubrikar et al. [14] have presented the results of uniaxial tensile tests on AAA wall specimens. By combining this previously published work, it was possible to generate population-mean regional wall strength values. Based on this previous work, results from 148 AAA wall specimens from 69 patients could be further analysed and divided into regional-specific wall strength values resulting in ultimate tensile strength (UTS) values for each region, as shown in Table 1.

Table 1 Regional UTS values [3] obtained by combining and averaging previous experimental data [12-14]

AAA Region	UTS (MPa)
Anterior	0.7744
Posterior	0.8658
Left	0.9221
Right	0.9187
Anterior/Left	0.8482
Anterior/Right	0.8465
Posterior/Left	0.8939
Posterior/Right	0.8922

The finite element analysis rupture index (FEARI) is defined by Eqn.1. The equation returns values ranging from 0 to 1, with 1 indicating AAA rupture.

$$\text{FEARI}=\frac{\text{Wall Stress}}{\text{Wall Strength}} \tag{1}$$

The FEARI approach is shown in Figure 1. The location of peak wall stress predicted using FEA and the cross-section through which the peak wall stress acts is noted and segmented into the primary regions. Each region corresponds to the UTS shown in Table 1. Wall stress is then divided by wall strength to obtain the FEARI.

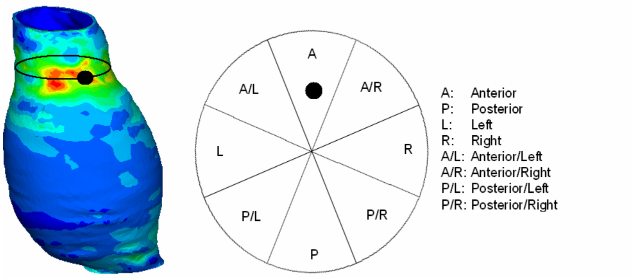

Fig. 1 FEARI methodology. Peak wall stress cross-section is segmented into the various regions and prescribed an UTS value. Eqn.1 then returns a rupture-risk indication

III. RESULTS

Various geometrical comparisons were determined between the two groups and results show that the diameter, total AAA volume, ILT volume, total surface area, AAA length, ratio of diameter to length and the ratio of maximum diameter to infrarenal diameter (ROD) were all higher in the symptomatic/ruptured group (Diameter: 75.5 ± 13.3 v 64.8 ± 12.4 mm, total AAA volume: 352.6 ± 177.5 v 231.9 ± 138.9 mm^3, ILT volume: 151.4 ± 124.4 v 130.3 ± 120.1 mm^3, surface area: 279.9 ± 101.8 v 211.9 ± 72.6 mm^2, length: 123 ± 23 v 111 ± 15 mm, diameter/length: 0.62 ± 0.1 v 0.59 ± 0.09, ROD: 2.27 ± 0.51 v 2.03 ± 0.46). The percentage volume of ILT was lower in the symptomatic/ruptured group (40 ± 15 v 51 ± 20).

As with previous publications, the wall stress in the AAAs examined is not evenly distributed and peak stress regions primarily occur at regions of inflection, observations which have been also noted in numerical and experimental work [1,3,6,7,10,15]. Peak wall stress was on average higher for the symptomatic/ruptured group than the electively repaired group (0.86 ± 0.36 v 0.55 ± 0.23 MPa). In the diameter-matched group, peak wall stress was higher in women than men (0.65 ± 0.33 v 0.46 ± 0.11 MPa). Locations of peak wall stress varied throughout the cases of both groups.

FEARI was higher in the symptomatic/ruptured group than the electively repaired group (1.01 ± 0.43 v 0.66 ± 0.3) as shown in Figure 2 with diameters varying throughout both groups (Figure 3). There was a poor relationship (R^2 = 0.1602) between FEARI and diameter indicating that FEARI does not necessarily increase with diameter (Figure 4). In the diameter-matched group FEARI was higher in women compared to men (0.79 ± 0.45 v 0.49 0.09).

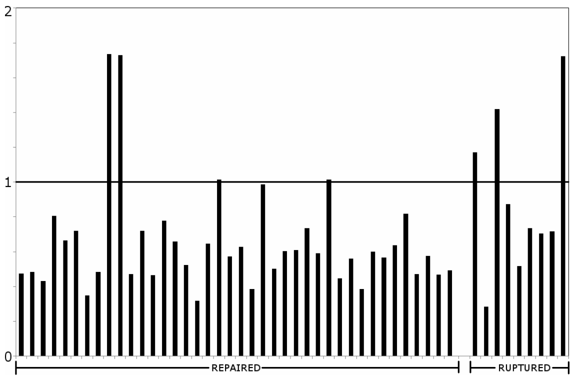

Fig. 2 FEARI results for the repaired and symptomatic/ruptured groups. Y-axis represents FEARI where 0= safe and 1 = rupture. Horizontal line indicates failure based on the FEARI model

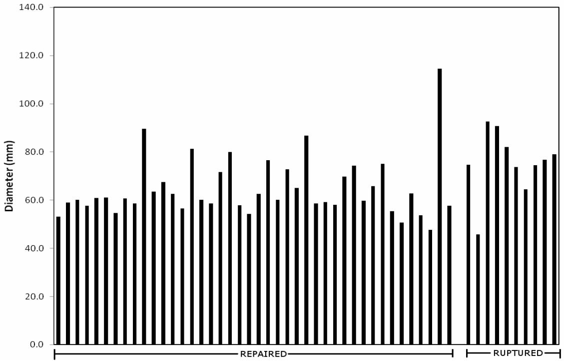

Fig. 3 Diameter measurements for all cases examined. Although the mean diameter was higher for the symptomatic/ruptured group, diameter does not accurately describe the risk of rupture within the repaired group

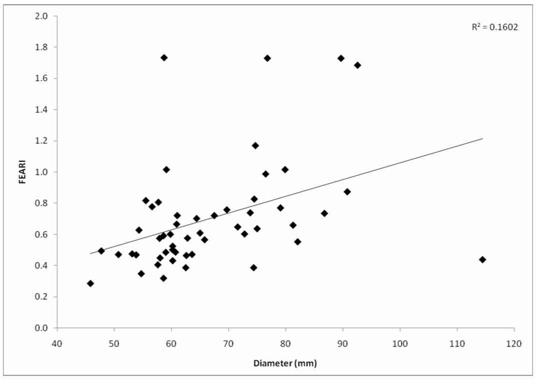

Fig. 4 Relationship between FEARI and diameter for all cases examined. A poor relationship was observed ($R^2 = 0.1602$)

IV. Discussion

The short-comings of diameter to accurately describe the risk of rupture in AAA is well reported. Regardless of the data indicating these pitfalls, clinicians still favor maximum diameter as the threshold to determine surgical repair. Although surgery is not usually based solely on maximum diameter as there are several variables that must be considered, i.e. is the patient fit for surgery, biomechanical parameters receive little attention. It is believed that this is primarily due to the ease of which diameter can be determined and the fact that statistics show that larger AAAs represent a greater risk. However, small AAAs can rupture and large AAAs can remain stable. Therefore, there is clear need to develop a reliable rupture-risk parameter that is quick, cheap and easy to perform.

FEARI can return risk indications in approximately 3 hours, including the time to reconstruct the aneurysm from medical images, the time to solve the problem with FEA, and the post-analysis of results. The results presented in this paper are still preliminary in nature, however they do indicate that FEARI may be clinically useful. FEARI was higher in cases that were acutely symptomatic or had ruptured when compared to electively repaired cases. Also, from the cohort examined in this study, diameter does not appear to represent rupture-risk.

Peak wall stress is independent of diameter. For example, in this study an AAA of diameter = 59 mm had a much higher wall stress than an AAA of diameter = 114 mm (1.73 v 0.44 MPa). This was due to the differences in geometry between the cases, a finding that is apparent throughout the study group. AAAs that are asymmetric and have low levels of ILT have higher wall stress than more fusiform AAAs with large percentages of ILT. Also, women are more likely to rupture than men [16], and in this study women had higher peak wall stress (0.65 ± 0.33 v 0.46 ± 0.11 MPa) and higher FEARI (0.79 ± 0.45 v 0.49 0.09) than men. Another interesting observation is that the mean FEARI for the symptomatic/ruptured group is 1.01, with 1.0 representing the theoretical value of rupture. This implies that all these cases had ruptured, which indeed they had.

The FEARI approach can be significantly improved through further work on the mechanical data of AAA tissue. Currently, the wall strength model employed is based on tissue samples harvested from 69 patients. Ideally this number would be significantly increased. A collaborative effort from several international institutions could harvest and test the tissue so that more accurate population-mean values are obtained for the primary regions of the AAA. The number of cases examined also needs to be significantly increased. This would help in achieving statistical significance in the results. There are also some aspects to the numerical modeling that could be improved. Boundary conditions such as constraints and loading can always be enhanced by employing patient-specific blood pressures and hopefully someday patient-specific wall thickness. Fluid-structure interaction (FSI) could also be applied to determine wall stress as it accounts for the flow and force of the blood though the cardiac cycle.

V. CONCLCUSIONS

FEARI may be a useful tool and serve as an additional parameter to diameter in the decision-making process of the clinician. AAA rupture occurs when the wall stress exceeds the wall strength, and therefore wall stress alone is not enough to govern rupture. Further work is needed on the FEARI approach, in particular, on the tissue strength data, but these preliminary results appear promising. This study has further highlighted the short-comings of the diameter criterion and has presented a simple to use parameter that may be a useful adjunct to both diameter and growth rate in rupture-risk assessment.

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