Biomechanics of Abdominal Aortic Aneurysm

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The University of Limerick is located approximately 25km from Shannon Airport on the west coast of Ireland in the most westerly country in Europe.
Clinical Problem

- AAAs are a “silent killer”
- 10 - 13\textsuperscript{th} cause of death in men > 65yrs old
- 500,000 new cases Worldwide per year
- 8,000 – 10,000 deaths per year in the UK
- AAAs repaired if max diameter > 5.5 cm
- Max diameter ≠ rupture risk
- Or if growth rate > 1cm/yr
- Ultrasound
  - NHS AAA Screening Programme
Abdominal Aortic Aneurysm (AAA)

26yr old male
Healthy

76yr old male
Diseased

1.5 x Healthy Diameter

Doyle et al. (2010)
AAA Biomechanics

- AAA rupture occurs when wall stress exceeds wall strength
- Numerical tools used to predict *in vivo* wall stress
  - Finite Element Analysis (FEA)
  - Fluid-Structure Interaction (FSI)
- Peak wall stress shown to be better predictor of rupture than max diameter (Fillinger et al., J Vasc Surg 2003;37:724-732)
- AAA geometry linked to peak wall stress (Doyle et al., J Vasc Surg 2009;49:443-454)

↑ Diameter ≠ ↑ Stress
Rupture Risk Assessment:

Finite Element Analysis

- FEA essentially breaks an object into a number of discrete elements
- The behaviour of the resulting model can then be mapped under various stresses and strains
The use of Computer-Aided Diagnosis (CAD) for AAAs

- Wall stress
- Asymmetry
- Finite Element Analysis Rupture Index (FEARI)

In vivo validation of rupture locations
Computer-Aided Diagnosis (CAD)

- Common in other areas of medicine
  - Breast cancer
  - Colon cancer
  - Lung cancer

- CAD does not (and will never) replace the clinician
  - Plays a supporting role (2\textsuperscript{nd} opinion?)
  - Clinician is always responsible

\[ \text{CAD} = \text{Computer-Aided Detection (CADe)} + \text{Computer-Aided Quantification (CADq)} \]
CAD of AAAs

- Has essentially been around for years
  - Computer models of idealised AAAs in the late 1980’s
  - Advanced to patient-specific 3D reconstructions in 2000
    - Raghavan et al., J Vasc Surg 2000;31:760-769
  - Numerically predicted wall stress may be better predictor than diameter

- Very difficult to comprehensively validate
- Lack of confidence from clinicians......
CAD of AAAs

- However, we and other groups are working to change this........

TM McGloughlin and BJ Doyle.

*New approaches to abdominal aortic aneurysm rupture risk assessment: Engineering insights with clinical gain.*

Arteriosclerosis, Thrombosis and Vascular Biology 2010;30:1687-1694
CAD of AAAs - Methodology

- Study group (n = 52)
  - Electively-repaired cases (n = 42)
  - Ruptured cases (n = 10)

- CAD
  - 3D reconstructions in Mimics (Materialise, Belgium)
  - FEA in ABAQUS v6.9 (SIMULIA, Dassault Systèmes, USA)
    - 3D stress elements
    - Mesh independence = ± 2% in peak wall stress
    - 120 mmHg (16 kPa) internal pressure
    - Rigidly constrained proximally/distally
  - Custom MATLAB (MathWorks, USA) code to measure 3D asymmetry
  - Analysed results in SPSS v16
    - (P<0.05)
Computer-Aided Detection (CADe)

Mimics

Threshold/segment based on Hounsfield units

Smoothing becomes important

Marching squares/cubes algorithm

ILT

Lumen

Doyle et al., Biomed Eng Online 2007;6:38
CADe – 2D

Max Diameter

Proximal Neck Diameter

Distal Diameter

Ratios of diameters (ROD)

AAA Length

2D Asymmetry

Doyle et al., Nova Science Press, 2010
CADe – 3D

Anchors

Volumes

Surface Areas

Angles

% ILT

Volumes

Surface Areas

Doyle et al., Nova Science Press, 2010
## CADe - Results

<table>
<thead>
<tr>
<th></th>
<th>REPAIRED (n = 42)</th>
<th>RUPTURED (n = 10)</th>
<th>Δ(%)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/Female</td>
<td>34/8</td>
<td>7/3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Age</td>
<td>71.9 ± 6.4</td>
<td>69.1 ± 6.0</td>
<td>3.9</td>
<td>0.205</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>64.3 ± 12.7</td>
<td>81.7 ± 12.5</td>
<td>27.1</td>
<td>0.0003</td>
</tr>
<tr>
<td>AAA Volume (cm³)</td>
<td>228.2 ± 119.6</td>
<td>428.8 ± 120.8</td>
<td>87.9</td>
<td>0.015</td>
</tr>
<tr>
<td>Surface Area (cm²)</td>
<td>209.3 ± 73.7</td>
<td>317.1 ± 101.8</td>
<td>51.5</td>
<td>0.009</td>
</tr>
<tr>
<td>% ILT</td>
<td>50.9 ± 20.1</td>
<td>39.5 ± 14.8</td>
<td>-28.9</td>
<td>0.057</td>
</tr>
<tr>
<td>Length</td>
<td>111 ± 16</td>
<td>131 ± 25</td>
<td>18.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Diameter/Length</td>
<td>0.58 ± 0.09</td>
<td>0.63 ± 0.09</td>
<td>8.6</td>
<td>0.138</td>
</tr>
<tr>
<td>ROD</td>
<td>2.05 ± 0.45</td>
<td>2.26 ± 0.53</td>
<td>10.2</td>
<td>0.268</td>
</tr>
</tbody>
</table>
Computer-Aided Quantification (CADq)

Peak Wall Stress

Lumen
ILT

Uniform thickness wall (1.5 mm)
Hyperelastic wall (Raghavan & Vorp, 2000)
Hyperelastic ILT (Wang et al, 2001)

Tetrahedral elements
Uniform loading (120 mmHg)
Rigidly constrained (proximally/distally)
Mesh independence (Doyle et al, 2007)
CADq - Results

Peak Wall Stress

- Ruptured (n = 10)
  - $0.89 \pm 0.35$ MPa
- Repaired (n = 42)
  - $0.57 \pm 0.23$ MPa
- 51% difference
- $P = 0.018$
CADq
3D Asymmetry

Lumen
ILT
Complete AAA
CADq
3D Asymmetry

### CADq - Results

**3D Asymmetry**

<table>
<thead>
<tr>
<th>Asymmetry Type</th>
<th>REPAIRED</th>
<th>RUPTURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumen Asymmetry</td>
<td>0.002</td>
<td>0.033</td>
</tr>
<tr>
<td>Total Asymmetry</td>
<td>0.661</td>
<td>0.008</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.032</td>
<td>0.174</td>
</tr>
</tbody>
</table>

*Lumen asymmetry better correlated to PEAK STRESS than diameter in repaired and ruptured cases*
CADq
Finite Element Analysis Rupture Index (FEARI)

FEARI = $\frac{\text{FEA Wall Stress}}{\text{Averaged Wall Strength}}$

Each region has a wall strength obtained by compiling previously published work

Doyle et al., Vasc Dis Prev 2009;6:114-121
Regional UTS obtained from previous reports on tensile strength

- Raghavan et al., J Biomech 2006;39:3010-3016
- Thubrikar et al., J Med Eng Tech 2001;25:133-142
- Raghavan et al., Ann Biomed Eng 1996;24:573-582

149 samples from 69 patients

UTS Range 0.77 – 0.92 MPa
CADq - Results

FEARI

n = 42

- A/L: 4
- A/R: 10
- L: 6
- P/L: 1
- P: 8
- R: 3

n = 10

- A/L: 3
- A/R: 4
- L: 1
- P/L: 2
- P: 2
- R: 4

- REPAIRED
- RUPTURED
Mean FEARI 60% higher in ruptured group ($P=0.019$)

- **Repaired:** $0.65 \pm 0.30$
- **Ruptured:** $1.04 \pm 0.42$
CAD of AAAs

- Diameter: 11 cm vs 11 cm
- Wall Stress: 0.44 MPa vs 1.13 MPa
- Lumen Asymmetry: 20 mm vs 45 mm
- FEARI: 0.51 vs 1.30

Would this AAA have ruptured???
In Vitro Validation of Rupture Sites

Doyle BJ, A Cloonan, MT Walsh, DA Vorp and TM McGloughlin.  
*Identification of rupture locations in patient-specific abdominal aortic aneurysms using numerical and experimental techniques.*  
Journal of Biomechanics, 2010;43:1408-1416

McGloughlin TM and BJ Doyle.  
*New approaches to abdominal aortic aneurysm rupture risk assessment: Engineering insights with clinical gain.*  
Arteriosclerosis, Thrombosis and Vascular Biology 2010;30:1687-1694

Doyle BJ, DS Molony, MT Walsh and TM McGloughlin.  
*Abdominal aortic aneurysms: New approaches to rupture risk assessment.*  
Rupture Risk Assessment: *In vitro validation*

- Rupture occurs when stress from intraluminal pressure exceeds the strength of the wall
- Demonstrated in lab
  
  Doyle et al. (2009) Medical Engineering & Physics

- 18/20 (90%) correlated with FEA and Ruptured at Inflection Point
Results

FEA peak wall stress correlated with experimental rupture site in 80% (16/20) of cases

Compare locations
In Vivo Validation of Rupture Sites

Intermittent claudication (trouble walking)

Patient collapsed 1wk later

Emergency open repair of ruptured AAA

Currently performing retrospective in vivo validation, where possible
Summary

- More parameters needed to accurately determine rupture risk
  - Diameter & growth rate are not enough

- CAD may be an effective tool
  - Quick (~3hrs)
  - FEA can predict rupture locations
  - Wall stress should be examined
  - Asymmetry may be a useful adjunct
  - FEARI converts wall stress into actual risk factor

- CAD can include a large number of parameters
  - Rupture Potential Index (Vorp group)
  - Severity Parameter (Kleinstreuer group)
Summary

- Ruptured cases have **HIGHER**:
  - Diameter (27%, $P=0.0003$)
  - Peak Wall Stress (60%, $P=0.018$)
  - Posterior Wall Stress (47%, $P=0.01$)
  - Total Volume (88%, $P=0.015$)
  - Surface Area (52%, $P=0.009$)
  - Length (19%, $P=0.03$)
- 29% **Less ILT** in ruptured cases ($P=0.057$)
Summary

- Peak stress is **51% higher** in ruptured AAAs
  - Repaired = 0.59 MPa
  - Ruptured = 0.89 MPa
    \[ P = 0.018 \]
- Asymmetry is **33% higher** in ruptured AAAs
  - Repaired = 18.9 mm
  - Ruptured = 25.2 mm
    \[ P = 0.1 \]
- FEARI is **59% higher** in ruptured AAAs
  - Repaired = 0.65
  - Ruptured = 1.04
    \[ P = 0.02 \]

However, size *(diameter)* remains an influencing factor.........
Summary

- Several limitations
  - Wall thickness
  - Further wall strength data
  - Further work on risk factors
  - Further validation
  - Translation to clinics

- 92% of clinicians use max diameter and growth rate*
  - 19% were not aware of biomechanics-based risk factors
  - 69% were aware but did not know how to implement

Acknowledgements

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- Dr Fintan Wallis (Radiology)
Questions???