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Patient-specific modelling of abdominal aortic aneurysms: The influence of wall thickness on predicted clinical outcomes

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ABSTRACT

Rupture of abdominal aortic aneurysms (AAAs) is linked to aneurysm morphology. This study investigates the influence of patient-specific (PS) AAA wall thickness on predicted clinical outcomes. Eight patients under surveillance for AAAs were selected from the MA^3RS clinical trial based on the complete absence of intraluminal thrombus. Two finite element (FE) models per patient were constructed; the first incorporated variable wall thickness from CT (PS_wall), and the second employed a 1.9 mm uniform wall (Uni_wall). Mean PS wall thickness across all patients was 1.77 ± 0.42 mm. Peak wall stress (PWS) for PS_wall and Uni_wall models was $0.6761 \pm 0.3406\ N/mm^2$ and $0.4905 \pm 0.0850\ N/mm^2$, respectively. In 4 out of 8 patients the Uni_wall underestimated stress by as much as 55%; in the remaining cases it overestimated stress by up to 40%. Rupture risk more than doubled in 3 out of 8 patients when PS_wall was considered. Wall thickness influenced the location and magnitude of PWS as well as its correlation with curvature. Furthermore, the volume of the AAA under elevated stress increased significantly in AAAs with higher rupture risk indices. This highlights the sensitivity of standard rupture risk markers to the specific wall thickness strategy employed.

1. Introduction

Abdominal aortic aneurysms (AAAs) are typically characterised by a large dilation of the aorta below the renal arteries. Each year over 10,000 deaths in the UK are attributed to rupture of AAAs [1]. Rupture occurs when the stress at any point in the wall exceeds its strength. Surgical repair is typically considered for asymptomatic aneurysms, when the maximum diameter passes 55 mm, or the growth rate exceeds 10 mm/year [2]. However, intervention also carries a risk (approximately 2.5%) of mortality [1]. Furthermore, ruptured aneurysms with maximum diameters below the 55 mm threshold account for 10–24% of all cases [3–5], conversely 60% of AAAs above 55 mm never rupture [6]. This indicates that maximum diameter criterion alone is not able to discern all cases which require intervention.

Several techniques have been suggested to complement the maximum diameter criterion; AAA wall stress predicted using computational models [7–13], AAA growth rate [14,15], rupture risk indices [16–18], integrity of thrombus [19], geometrical factors (e.g. growth, asymmetry) [20–23].

A number of computational studies [24], have suggested that peak wall stress (PWS) derived from finite element (FE) models has the ability to assess rupture risk more accurately than existing clinical indices. However, the accuracy of such predictions relies on realistic physical representation of the system they are modelling [25]. Ideally a number of physical factors must be known for the individual patient including a clear definition of the aneurysm geometry, its material properties, the manner in which it interacts with other bodily structures, and the internal/external forces acting on the aneurysm. Early computational models often employed straight tubes with symmetrical central dilations or asymmetric bulges to act as aneurysm analogues [21,22]. Due to the proliferation of high powered desktop computing and advances in three-dimensional imaging techniques, it is now possible to generate highly accurate virtual reconstructions of patient-specific (PS) aneurysms from medical imaging data [26] acquired using modalities such as computed tomography (CT) and magnetic resonance imaging (MRI). However, one particularly challenging aspect of the reconstruction process for AAAs is accurate determination of the vessel wall.

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At present, it is currently not possible to determine the wall-thrombus interface explicitly from CT with existing scanners, though recent developments in multimodal imaging may overcome this issue in the future [27], as a consequence virtually all early computational studies of AAAs have assumed a uniform wall thickness of 1.9 mm e.g. [28]. However, from previous studies [29–31] it is known that aortic wall thickness varies considerably from region to region within the same patient, and across different patients. Therefore, the assumption of a uniform wall may not be adequate when attempting to characterise the response of the aneurysm. As such, this is regarded as a serious limitation of current patient-specific modelling studies [32], yet only a handful of studies have attempted to address its effects [7,9–11,13,21,28,33–38].

This study aims to assess the importance of patient-specific wall thickness, derived directly from high resolution CT scans, in a small population of aneurysms which lacked thrombus, while also testing the validity of the widely applied uniform wall assumption and its impact on predicted clinical outcomes.

2. Methods

2.1. Patient selection and imaging

Computed tomography (CT) scans of 350 individual patients undergoing AAA surveillance, were selected from the MA^{3}RS clinical trial database [39] for reconstruction. Patients underwent both magnetic resonance imaging (MRI) and CT scanning as part of the trial. In each instance CT scanning of the aorta was performed from just below the thoracic arch to below the iliac bifurcation (Aquilion One, Toshiba Medical Systems Ltd, UK). The slice thickness was 0.5 mm, with a pixel size of 0.625 mm.

The majority of AAAs (75%) tend to have thrombus [10], this can cause great difficulty during the reconstruction phase due to the poor contrast between thrombus and adjacent wall structures, as can be seen in the last panel of Fig. 1a. Therefore, to allow reconstruction of wall thickness direct from the CT scan the selection criteria for the current study was based on the total absence of intraluminal thrombus, in such instances only the lumen and wall are visible directly on the CT scan (Fig. 1b), meaning patient-specific wall geometry can be easily extracted using basic segmentation tools.

In this study, the absence of thrombus was verified by a qualified cardiovascular surgeon on MRI scans of each patient. After exclusion only 10 patients remained, of these 10 only 8 patients had a corresponding CT available for reconstruction (7 male and 1 female). All AAAs were infrarenal, with the main sac approximately located between the L4 and L2 vertebrae. The mean patient age was 76 years (64–83 years) and the mean maximum diameter from ultrasound was 46 mm (36–59 mm), individual patient details for all 8 patients investigated are presented in Table 1.

Table 1
Patient details for each of the reconstructed aneurysms. Strength estimation relies on knowledge of patient family history of AAAs, where this information was unavailable a worst case scenario of yes was assumed as indicated by the accompanying*.

Patient	Age	Gender	Family history	Diameter from US (mm)	AAA type
1	83	Male	No	44	Fusiform
2	80	Male	Yes	40	Fusiform
3	81	Male	No	59	Fusiform
4	82	Female	No	44	Fusiform
5	70	Male	No	41	Saccular
6	64	Male	Yes*	36	Saccular
7	65	Male	No	59	Fusiform
8	81	Male	No	47	Fusiform

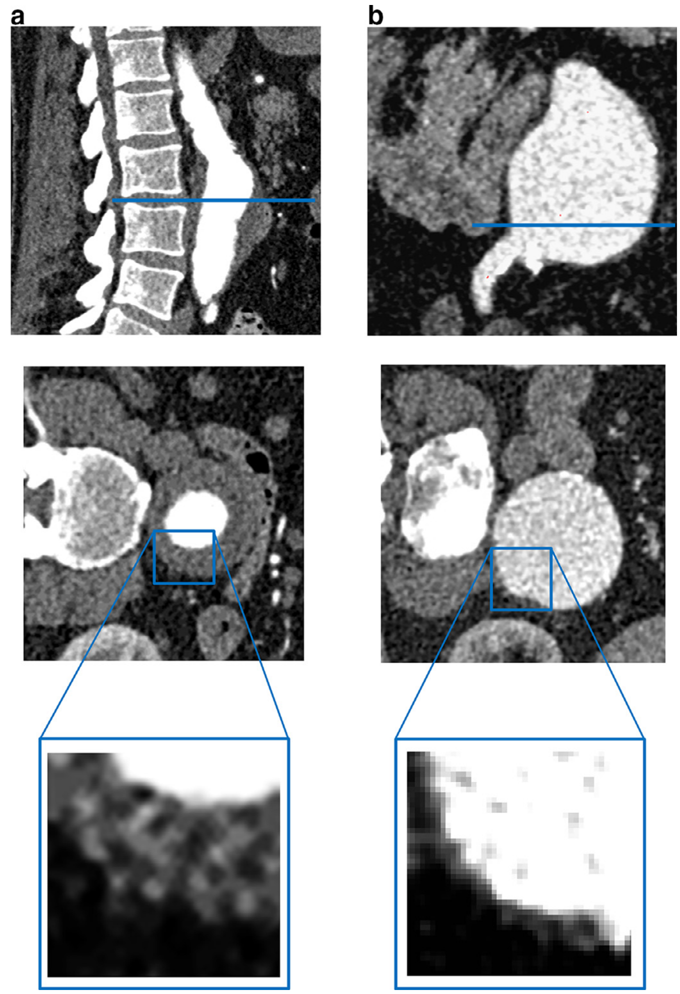

Fig. 1. Comparison of two AAAs one with intraluminal thrombus (a) and one without (b). The blue line in the top panel indicates the location of the cross-sectional slices presented for each AAA (middle panel). The bottom panel then presents a zoomed in view of each cross-sectional slice. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Three-dimensional reconstruction and meshing

Segmentation and reconstruction of each patient-specific AAA was carried out with commercial software (Mimics innovation suite, Materialise, Belgium) and followed the general workflow presented in Fig. 2. The luminal region was segmented automatically using a thresholding approach, and the outer wall was segmented in a semi-automatic manner using a 3D live wires approach with manual correction of the wall contours on certain slices where the outer boundary was ambiguous (e.g. close to the duodenum). Given that there was physically no thrombus in these selected patient, a true patient-specific wall thickness (PS_wall) was then obtained as the difference between the contrast enhanced lumen and the outer wall, without any need for incorporation of complex "black box" wall thickness estimation algorithms. For comparison a uniform wall thickness version (Uni_wall) of each AAA was also reconstructed, this approach involved merely offsetting the luminal surface outward in the radial direction by a fixed distance, 1.9 mm [28], thereby creating an aneurysm with a constant uniform wall thickness.

In all cases, for both wall types (PS_wall and Uni_wall), volume preserving smoothing was performed to remove scanning artefacts and tetrahedral volume meshing operations were performed in