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CASE REPORT

Regions of High Wall Stress Can Predict the Future Location of Rupture of Abdominal Aortic Aneurysm

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Abstract Predicting the wall stress in abdominal aortic aneurysm (AAA) using computational modeling may be a useful adjunct to traditional clinical parameters that indicate the risk of rupture. Maximum diameter has been shown to have many limitations, and using current technology it is possible to provide a patient-specific computational risk assessment using routinely acquired medical images. We present a case of AAA rupture where the exact rupture point was clearly visible on the computed tomography (CT) images. A blind computational study based on CT scans acquired 4 months earlier predicted elevated wall stresses in the same region that later experienced rupture.

Keywords Abdominal aortic aneurysm · Computational model · Wall stress · Rupture · Risk

Introduction

The maximum diameter of an abdominal aortic aneurysm (AAA) is currently the most evidence-based measure used to indicate the risk of rupture. However, it is well known that this criterion may not truly represent rupture-risk in every case. Although alternative clinical factors, such as growth rate, are considered, the use of maximum anterior-posterior diameter is still the primary clinical parameter.

It is typical to acquire high-resolution computed tomography (CT) during the management of AAA that reach a clinically relevant size, usually to plan surgical repair. Utilising these CT datasets, one can easily reconstruct the AAA into three-dimensional (3D) volume renderings, which provide important geometrical information to the clinician and allow biomechanical insight [1, 2]. In particular, the in vivo AAA wall stress can be estimated using finite element analysis (FEA). We have previously

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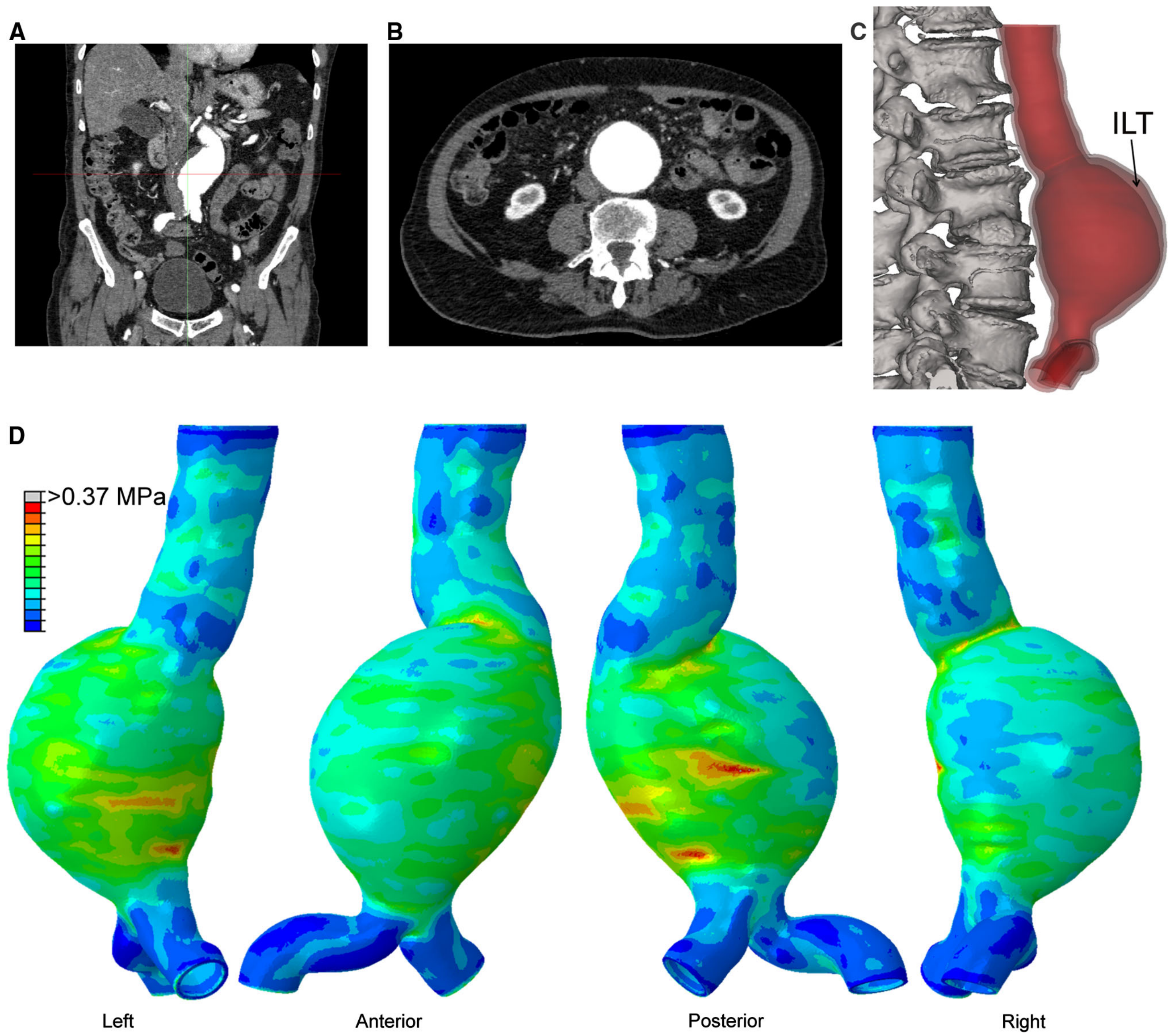

Fig. 1 Baseline contrast-enhanced CT scan; coronal (**A**) and axial view (**B**) showing 6.0 cm AAA. **C** 3D reconstruction with the wall transparent to reveal the modest amount of ILT present. **D** The computed von Mises wall stress distributions at peak systolic pressure. The majority of the sac experienced elevated wall stress, with the highest relevant wall stresses observed in the posterior and left posterolateral region. The patient's blood pressure was ~114/61 mmHg at this time

reported on the use of asymmetry as a potential diagnostic tool and showed the relationship with wall stress [1]. We have since advanced our methods to include the intraluminal thrombus (ILT), which is present in the majority of AAA, and also improved our FEA. Additionally, we significantly increased the cohort size to include ruptured cases as well as those electively repaired and demonstrated the influence of asymmetry in repaired AAA compared with ruptured cases [3]. However, effectively predicting rupture location is a challenging task. In our previous work, we were able to show that our computational methods predicted the location of AAA rupture; however, this was achieved by using an intraoperative sketch combined with preoperative CT data [3]. We have since sought more convincing imaging to demonstrate the clinical potential of FEA.

In this short report, we describe a patient with an infrarenal AAA who underwent initial preoperative CT, followed later by emergency CT for AAA rupture. The CT images happened to reveal exactly where the AAA ruptured, to the same precision that is capable with computational models. This was considered an excellent case to test the ability of FEA to predict the location of rupture.

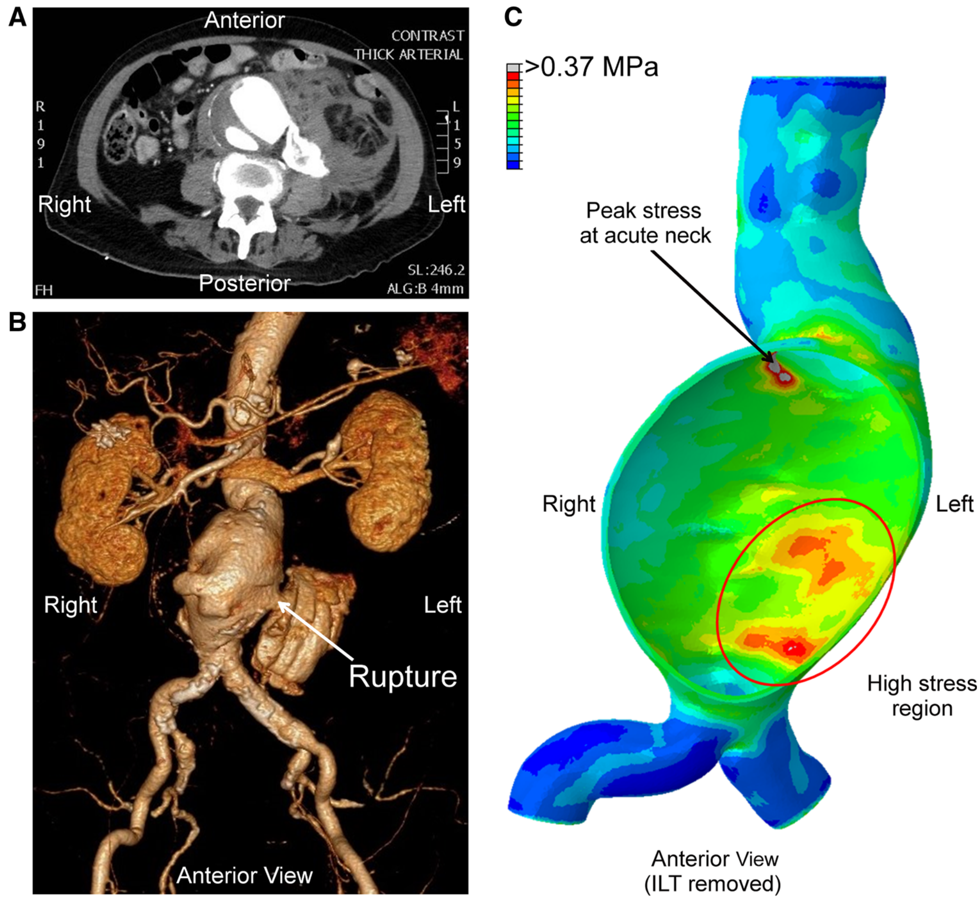

Fig. 2 **A** Contrast-enhanced axial CT scan 4 months later showing the isolated rupture in the left posterolateral wall immediately distal to the maximum diameter region. **B** The 3D volume rendering clearly illustrates the rupture location. **C** Anterior "cut-through" view of the wall stresses with the ILT removed from the image. The high stress region is *circled*. There is close agreement between the rupture location and our computational predictions. The peak wall stress was located at the acute proximal neck; however, this is typical of acute anatomical angles and was disregarded as clinically irrelevant during the blinded interpretation of FEA data. The patient's blood pressure was labile at the time of emergency CT, ranging from 83/47 to 94/60 mmHg. Orientations are indicated on each image

Case Presentation

An 88-year-old male was diagnosed with a 6.0-cm AAA via ultrasound and contrast-enhanced CT was subsequently performed (Fig. 1A, B). Although the patient was fit for surgery, he deferred for personal reasons. The patient had a long history of hypertension, which was controlled for many years, and there was no record of family history for AAA. Blood pressure was ~114/61 mmHg at the time of baseline CT. 4 months later, the patient was admitted with suspected AAA rupture and underwent emergency CT scanning. Blood pressure measurements were labile at this time; however, measurements of 83/47 and 94/60 mmHg were recorded. Imaging confirmed a localized rupture in the left posterolateral region, which was clearly visible on the contrast-enhanced images and 3D volume rendering (Fig. 2A, B). The AAA also had expanded and the maximum diameter was now 6.5 cm. Open surgical repair was performed with a tube graft, and the patient made a slow but full recovery.

The baseline CT dataset was used to perform a biomechanical analysis. The location of rupture was withheld from the analyst (B .J. D.), and FEA was conducted in line with our previous work using the patient's peak systolic blood pressure of 114 mmHg [3]. There was a modest amount of ILT present in the sac (<25 % of total sac volume; Fig. 1C). We determined that the region of highest von Mises wall stress was the left posterolateral distal wall of the sac (Fig. 1D). There was almost no thrombus lining the wall in this region. After the biomechanical analysis, wall stress data were independently inspected (P. E. N.) and compared to the location of rupture using the CT data (Fig. 2A, B). We observed close agreement between the actual rupture point and the computational predictions (Fig. 2).

Discussion

Biomechanical analysis at baseline revealed elevated wall stresses in the left posterolateral region of the AAA, which was precisely where the rupture occurred 4 months later. The patient had moderately rapid growth (5 mm over 4 months) and high wall stresses in the time leading to rupture. Rapid expansion has been previously linked to elevated wall stresses [4]. Efforts during recent years have enabled patient-specific modeling of AAA to become a potentially useful clinical tool. It is possible for biomechanical analyses to be performed at the time of AAA detection in order to complement the maximum diameter criterion and other clinically relevant factors. A typical analysis can be completed in a matter of hours using our methods, and we are continuously striving to further reduce this time and ensure robustness of results. This case illustrates the potential utility of the method to identify patients who may be prone to rapid growth and/or rupture. However, large-scale testing of the capabilities of FEA in AAA management is still needed before clinical translation.

We have attempted to validate our methods retrospectively using currently available data; however, a search through our databases at several institutions has failed to locate CT images with such accurate visualization of AAA rupture. In addition, many patient records that note rupture location only indicate the approximate region of rupture, for example, posterolateral wall. In order to demonstrate the accuracy of computational modeling effectively, much more precise information is needed, such as that presented here. We hope that more CT images with precise rupture location can be obtained in order to help increase the sample size of much-needed future validation studies.

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Conflict of interest Barry Doyle, Timothy McGloughlin, Karol Miller, Janet Powell, and Paul Norman have no conflict of interest to declare.

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