Initial findings and potential applicability of computational simulation of the aorta in acute type B dissection

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Objective: Type B aortic dissection can be acutely complicated by rapid expansion, rupture, and malperfusion syndromes. Short-term adverse outcomes are associated with failure of the false lumen to thrombose. The reasons behind false lumen patency are poorly understood, and the objective of this pilot study was to use computational fluid dynamics reconstructions of aortic dissection cases to analyze the effect of aortic and primary tear morphology on flow characteristics and clinical outcomes in patients with acute type B dissections.

Methods: Three-dimensional patient-specific aortic dissection geometry was reconstructed from computed tomography scans of four patients presenting with acute type B aortic dissection and a further patient with sequential follow-up scans. The cases were selected based on their clinical presentation. Two were complicated by acute malperfusion that required emergency intervention. Three patients were uncomplicated and were managed conservatively. The patient-specific aortic models were used in computational simulations to assess the effect of aortic tear morphology on various parameters including flow, velocity, shear stress, and turbulence.

Results: Pulsatile flow simulation results showed that flow rate into the false lumen was dependent on both the size and position of the primary tear. Linear regression analysis demonstrated a significant relationship between percentage flow entering the false lumen and the size of the primary entry tear and an inverse relationship between false lumen flow and the site of the entry tear. Subjects complicated by malperfusion had larger-dimension entry tears than the uncomplicated cases (93% and 82% compared with 32% and 55%, respectively). Blood flow, wall shear stress, and turbulence levels varied significantly between subjects depending on aortic geometry. Highest wall shear stress (>7 Pa) was located at the tear edge, and progression of false lumen thrombosis was associated with prolonged particle residence times.

Conclusions: Results obtained from this preliminary work suggest that aortic morphology and primary entry tear size and position exert significant effects on flow and other hemodynamic parameters in the dissected aorta in this preliminary work.

The current in-hospital outcomes of type B aortic dissection are generally regarded as acceptable, with 90% of patients surviving the initial episode. Two distinct subgroups have a worse prognosis. They are those who develop immediate complications in the short term and those who develop aortic aneurysmal degeneration in the longer term. Immediate complications including acute expansion and rupture, malperfusion syndromes, and retrograde dissection are frequently lethal. Emergent intervention is associated with a significant morbidity and mortality. Long-term survival in type B dissection survivors is also a cause for concern. The International Registry of Acute Aortic Dissection demonstrated that nearly one in four patients will die within 3 years of discharge from presentation of an acute type B dissection, and that up to 66% of these deaths were attributable to aorta-related complications. False lumen patency is recognized to be a key predictor of both acute in-hospital complications and development of subsequent aneurysmal dilatation. Thoracic endovascular aortic repair (TEVAR) offers a logical solution to both problems by coverage of the entry tear of the dissection with the aim of depressurizing and thrombosing the false lumen. However, endovascular treatment of type B dissections is not without risk. A randomized trial of stent graft placement vs medical treatment failed to demonstrate improved outcomes in those undergoing TEVAR. Patients with thrombosis of the false lumen have improved outcomes, whereas those with a patent or partially thrombosed false lumen have an increased risk of early complications as well as late aortic expansion and death. If it were possible to accurately predict which patients with type B dissections would go
on to develop complications in the acute setting and which go on to develop thoracic aortic aneurysms, these subgroups would greatly benefit from early aortic stabilization by stenting and subsequent aortic remodeling. Currently, a patent false lumen and large maximal false lumen area are the principal predictors of adverse outcome, but there is no method to predict which patients will achieve spontaneous false lumen thrombosis.

The influence of dissection tear configurations on flow patterns in the aorta has been examined using ex vivo mechanical models and computational fluid dynamics (CFD). We have previously reported on the use of CFD in a patient-specific aortic dissection model, and the aim of this initial study was to use CFD methodology to analyze morphologic characteristics of the dissected aorta to determine the influence of morphology on flow, wall shear stress patterns, and turbulence in patients presenting with acute type B aortic dissection.

METHODS

Four patients presenting with acute type B dissections for whom computed tomography (CT) scans were performed at initial presentation were selected for a multiple case study of acute phase flow analysis. All patients had initial CT scans as part of their routine evaluation and interval follow-up scans during long-term surveillance. All patients had patent false lumens at the time of presentation. All patients were male, ages ranged from 53 to 68 years, and initial management was based on clinical presentation (Table I). Two patients (1 and 2) presented with acute complicated type B dissection and underwent urgent TEVAR immediately. Two other patients (3 and 4) presented with acute uncomplicated dissections and were medically managed. An additional 44-year-old male patient with an acute uncomplicated type B dissection with sequential CT surveillance scans was analyzed in a separate longitudinal single case study to examine factors putatively associated with aortic remodeling.

Three-dimensional (3D) aortic dissection geometry (the size, shape, and position of the entry tear and the aortic anatomy) was reconstructed from each patient’s CT images. All patients underwent CT imaging of the whole trunk (Philips CT scanner MX8000 IDT 16; Philips Medical Systems, Amsterdam, The Netherlands). The CT scans were not cardiac gated. These were clinical scans of the entire aorta-iliac segment, and the radiation dose would have been unacceptably high had they been ECG gated.

Table I. Clinical details of patients in multiple case studies

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Sex</th>
<th>Age</th>
<th>Operative status</th>
<th>Presentation</th>
<th>Complication</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>55</td>
<td>Emergent</td>
<td>Acute malperfusion</td>
<td>Limb ischemia</td>
<td>Femoro-femoral crossover graft</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>53</td>
<td>Emergent</td>
<td>Acute malperfusion</td>
<td>Renal failure</td>
<td>TEVAR</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>60</td>
<td>Medical</td>
<td>Uncomplicated type B</td>
<td>—</td>
<td>Medical</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>68</td>
<td>Medical</td>
<td>Uncomplicated type B</td>
<td>—</td>
<td>Medical</td>
</tr>
</tbody>
</table>

TEVAR, Thoracic endovascular aortic repair.

To reconstruct the complete geometry of the aorta, two-dimensional (2D) cross-sectional images of the aorta were obtained from the ascending aorta to the iliac bifurcation. Spiral CT with overlapping 2-mm-thick slices was used with an interslice distance of 1 mm and an in-plane resolution of less than 1 mm. The segmentation of all images and 3D geometry reconstruction of the inner wall surface for each patient was achieved using an image processing package Mimics (Materialise HQ, Leuven, Belgium). A 3D reconstruction was achieved by assembling the stack of 2D slice images in their correct axial location, followed by volume rendering, combined with smoothing, to outline the contours of the anatomic structures from the masks of 2D images to form the 3D surface with triangular grids.

As the primary focus of this study was the flow behavior in the dissected thoracic aortic segment, aortic branches other than the iliac arteries were ignored during the geometry reconstruction process. Blood was treated as a Newtonian and incompressible fluid with a dynamic viscosity of 4.0 mPa and a density of 1060 kg/m³, and the vessel walls were assumed to be rigid with no slip. The 3D geometry represented by surface triangles was exported into ICEM CFX (ANSYS) for mesh generation. The computational mesh consisted of 3D tetrahedral cells in the core region and prismatic cells in the fluid boundary layer at the wall.
The Navier-Stokes equations were solved numerically with a commercial finite-volume-based computational fluid dynamics (CFD) solver (ANSYS CFX 11) with the laminar-turbulent transitional version of the hybrid shear stress transport turbulence model. The model incorporates empirical correlations to cover a range of transition mechanisms that lead to turbulent (chaotic) flow, which differs from generally disturbed flow.

To minimize the influence of initial flow conditions, all simulations were carried out for three cardiac cycles to achieve a periodic solution, and the results presented here were obtained in the third cycle. Time-integrated parameters such as time-averaged wall shear stress (TAWSS) and relative residence time (RRT) were calculated via ANSYS CFX-Post and CEI ENSIGHT 8 (CEI Inc, USA). TAWSS is calculated by averaging the time-varying wall shear stress (WSS) over the cardiac cycle. RRT is related to the duration that a particle spends in particular subregions and is highest in separated, recirculating flow. It can be related to the inverse of the distance, δ, traveled in these subregions during the cardiac cycle. RRT is calculated as

\[
RRT = \frac{1}{\delta} = \frac{1}{(1 - 2 OSI) TAWSS}
\]

where OSI is related to the azimuthal variation of flow direction during the cardiac cycle and is highest in recirculating flows, where it can approach its maximum value (0 ≤ OSI < 0.5).

Detailed methodology for the flow models, boundary conditions, and numerical simulation has been previously reported.12

Table II. Geometric features of four AD subjects with percentage of flow rate into the false lumen in AD subjects at peak cardiac phase

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Primary tear dimensions, mm</th>
<th>Ratio (tear/true lumen diameter)</th>
<th>Distance of primary tear from arch top, mm</th>
<th>Flow into false lumen, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33</td>
<td>36</td>
<td>93%</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>28.8</td>
<td>19.6</td>
<td>93%</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>9</td>
<td>51%</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>10.8</td>
<td>32%</td>
<td>20</td>
</tr>
</tbody>
</table>

AD, Aortic dissection.

Fig 2. Geometric description of the aortic dissection models. Each subject has two pictures: right-anterior view of the reconstructed model (left) and transparent view (right). The primary tear can be seen clearly from the transparent views. AD, Aortic dissection.
Fig 3. Particle paths of blood flow in each aortic dissection model demonstrating accelerated flow through the tear and false lumen complex flow (right-anterior view [left] and left-posterior view [right]). Paths are color coded based on velocity; red is the highest velocity, blue is the lowest. AD, Aortic dissection.
Three important morphologic parameters were measured based on the anatomic models of the dissection subjects: the height and maximal width of the entry tear and the vertical distance between the peak of the aortic arch and the upper margin of the tear. In this cohort of patients, the entry tear was not ubiquitously found just distal to the left subclavian artery but occurred from the root of the left subclavian artery to the midthoracic aorta.

All of the parameters were measured as shown in Fig 1. The height of the tear is defined as the distance between the upper and the lower margin of the tear, whereas the width is the maximum dimension in the horizontal direction. We used the highest point of the aortic arch, the peak, as a landmark to avoid the variability of the left subclavian artery takeoff between different subjects. The vertical distance between arch peak and the upper edge of the tear was analyzed. If the aorta was dissected such that the false lumen ballooned up above the nondissected arch, we used the highest point of the true lumen.

Particle paths are defined as the trajectories that individual fluid particles follow and are effectively a “recording” of the path a fluid element in the flow takes over a time period. Particle paths were tracked in the dissected aortas of the four subjects, and the paths were color coded according to the local blood velocity. In each case, 80 evenly distributed particles were emitted from the inlet.

Linear regression analyses were used to calculate the trend line and the coefficient of determination value $R^2$ for the relationship between blood flow into the false lumen and tear size and position.

RESULTS

Multiple case study

Aortic geometry and entry tear characteristics. The geometry of aortic dissection models was found to be complex. The 3D reconstructions demonstrated that the false lumen always originated from a tear on the outer curve of the descending thoracic aorta and the false lumen always compressed the true lumen. From the transparent views of Fig 2, it can be seen that shapes and dimensions of primary tears are quite different among the four subjects. The shape of tear is noncircular because intimal tears propagate both longitudinally and circumferentially. The primary tear dimension of the four subjects was heterogenous and ranged from 9 to 36 mm. The distance of the primary tear from the peak of the arch varied from 1 to 20 mm. Details of all geometrical parameters are listed in Table II.

Flow pattern. Geometry plays a key role in determining the nature of hemodynamic patterns. Irregular geometry, including narrowing and dilatation, can induce disturbed and turbulent flow. Fig 2 illustrates the geometric complexities of dissected aortas, especially in the upper descending aorta where the proximal tear occurs. Because of differing geometries, the flow patterns varied significantly among these subjects, but similar characteristics of flow pattern can be observed. The flow accelerated when passing through the narrowed true lumen sections. A certain volume of flow entered the false lumen through the proximal tear with high velocity, and impinged upon the inner surface of the false lumen opposite to the tear, as demonstrated by the particle paths in Fig 3. Blood then flowed distally in the false lumen. Flow in the false lumen was more complicated than in the true lumen, with the presence of separated, recirculating, disturbed, and turbulent flow. In subjects with relatively large false lumens, the dilated space tended to lead to longer particle residence time; in subject 3, fluid particles spent more than three cardiac cycles (2.4 seconds) in the false lumen near the proximal tear.

Table II illustrates the percentage of blood flow rate entering the false lumen. All the data recorded correspond to peak systole when the flow rate is the highest. Results
demonstrate significant variability of flow rate into the false lumen between the acute complicated and acute uncomplicated subjects. Patient 1 demonstrated 95.5% of flow into the false lumen, with consequent marked reduction of flow into the true lumen. Clinically, this patient presented with limb ischemia, while patient 2 had 77% of flow into the false lumen and clinically presented with visceral malperfusion. This contrasts with the two uncomplicated cases in whom the blood flow into the false lumen were 51% and 40%, respectively.

Relationships between the false lumen flow data and the geometric parameters of tear location and size were investigated. The ratio of tear width to aortic diameter at the tear was used to analyze the relationship with flow percentage in the false lumen in Fig 4, since large tears in smaller-diameter aortas may have more impact than the same size tear in a larger aorta. Linear regression analysis demonstrates a significant relationship between percentage flow entering the false lumen and the ratio of tear maximum width to aortic diameter. The amount of flow into the false lumen is also positively related to the height of the tear size demonstrated in Fig 5.

The vertical distance between the peak of the aortic arch and the upper margin of the tear were measured and analyzed with respect to the relationship between distance and percentage flow rate into the false lumen. Fig 6 demonstrates an inverse relationship between the distance from the tear to the arch and flow rate into the false lumen. The closer the tear to the arch peak, the greater the volume of flow into the false lumen.

Wall shear stress. WSS, the frictional force exerted by blood flow across the luminal surface of vessels, is an important hemodynamic parameter, which still cannot be measured directly by current in vivo techniques. Determination of WSS via patient-specific CFD analysis remains the best option to date. The distributions of time-averaged wall shear stress (TAWSS) contours on the inner surfaces of the four subjects are presented in Fig 7. The maximum TAWSS values for the four subjects were 8.2 Pa (1), 8.8 Pa (2), 14.1 Pa (3), and 11.3 Pa (4). The edge of the proximal tear experienced extremely high TAWSS where blood flow is accelerated and velocity is high. Particle tracking demonstrates that the velocity of blood flow entering the false lumen was always high when passing through the tear, which could explain the high TAWSS along the edge of the tear.

Single case study. The patient presented with an uncomplicated acute type B dissection and was followed up with regular CT surveillance scans over a 28-month
Fig 9. Geometrical description of the single-case model illustrating progressive false lumen thrombosis over time.

Current management of acute type B aortic dissection is hampered by our inability to predict the clinical sequela of the dissection process in individual patients. Treatment algorithms currently fall into three categories: those patients who spontaneously develop false lumen thrombosis who would benefit from best medical management alone, those patients who rapidly develop acute complications requiring urgent intervention, and those chronic cases, which have persistent false lumen patency and subsequently develop aortic dilatation. Confident prediction of which group individuals will fall into will facilitate optimal management. TEVAR is not without complications, and intervention should only be undertaken in those patients in whom a demonstrable benefit accrues.

Our results demonstrate that the aortic geometry of individual dissections varies significantly. As a consequence, blood flow patterns and wall shear stress also vary. The key questions are how these differences alter clinical progression of the dissecting process and whether they are of any predictive value for individuals.

Current literature shows that false lumen size and patency are the most important predictors of adverse early as well as later outcomes, but the reasons for false lumen patency remain to be elucidated. These data suggest that both tear size (both circumference and length) and tear position significantly alter the flow rate into the false lumen, which in turn is associated with false lumen patency. Fig 6 shows the relationship between the position of the tear and the flow rate into the false lumen, with a sharp decrease in the flow rate the further the tear is from the aortic arch. Figs 3 and 4 demonstrate that the greater the size of the tear, the greater the flow rate into the false lumen. Clinical correlation is revealing. In terms of acute presentation, subjects 1 and 2 were both complicated by acute malperfusion, while subjects 3 and 4 were acute uncomplicated presentations. The two subjects complicated by malperfusion had larger dimension tears than the uncomplicated cases with significantly larger tear-to-true lumen diameters (93% and 82% compared with 32% and 55%, respectively). Table II shows the resultant flow rate into the false lumen was much higher in the patients with malperfusion (95% and 76.7% vs 51% and 40.3% of total aortic flow, respectively).

The multiple case study provides an instantaneous snapshot of aortic geometry and hemodynamic factors at the time of acute dissection, while the single longitudinal case study illustrates the subsequent progression of an uncomplicated type B dissection to false lumen thrombosis. In common with the two uncomplicated cases, this subject had a small initial tear with a low flow rate into the false lumen. The initial tear initially increased in size, a process associated with increased TAWSS (50 Pa) at the site of the tear. The tear size then stabilized, and the TAWSS fell to 15 Pa (Fig 8). The time blood particles are in contact with the aortic wall appears to be an important driver for false lumen thrombosis. Fig 10 demonstrates that RRT and turbulence intensity contours correlate well with subsequent areas of thrombus formation in the false lumen. A larger prospective study may allow us to more accurately define which aortic and tear morphology is associated with spontaneous false lumen thrombosis, obviating the need for early intervention.
The flow pattern in the dissected aortas was found to be complex with recirculating and disturbed flow dominating in both the false and true lumen and the region surrounding the tear experienced the highest levels of turbulent flow. Disturbed and turbulent flow influence physiological parameters and processes, including flow resistance, wall remodeling, and inflammation. Previous studies have suggested that abnormal hemodynamic stresses and recirculating and turbulent flow within the diseased aorta are an important influence in the formation, degeneration, and ultimate rupture of aortic aneurysms.\textsuperscript{15,18} Shear stress can affect endothelial cell functions, such as proliferation, apoptosis, migration, permeability, and remodeling.\textsuperscript{19,20} Low shear stress may increase monocyte adhesion attributable to flow reattachment, and recirculating flow would enhance the delivery of monocytes to the vessel wall.\textsuperscript{21} Disturbed flow and turbulence in blood flow influence flow resistance, pressure, wall shear stress, wall remodeling, inflammation, and mass transport from the blood to the vessel wall.\textsuperscript{22} High WSS has been found around the edge of the proximal tear point, which may contribute to increase in the initial tear size, since it can stimulate the production of matrix-degrading proteases.\textsuperscript{17}

**CONCLUSIONS**

This article presents the analysis of aortic morphology in five acute type B aortic dissection subjects using patient-specific CT data and flow characteristics acquired using a correlation-based transitional flow model. This preliminary pilot study is small, and strong inferences from these data cannot be drawn, but if reproducible with larger numbers, computational aortic flow simulation may offer predictive value in differentiating complicated and uncomplicated acute type B dissections. These preliminary data suggest that the location and size of the proximal tear determine the amount of flow circulating in the false lumen. The linear regression analyses are suggestive but not powered to prove this relationship, and further work is needed. Current consensus suggests false lumen patency predicts both immediate and long-term adverse outcomes for acute type B dissections, and the ability to accurately predict false lumen patency at the time of the initial presentation would be a major advantage in clinical decision making.

**AUTHOR CONTRIBUTIONS**

Conception and design: XX, RG
Analysis and interpretation: ZC, NW, XX, RG
Data collection: ZC, CR, JC, MH
Writing the article: ZC, RG
Critical revision of the article: NW, NC, XX, RG
Final approval of the article: ZC, CR, JC, MH, NW, NC, XX, RG
Statistical analysis: ZC, XX
Obtained funding: XX, RG
Overall responsibility: RG

**REFERENCES**


Submitted Dec 19, 2011; accepted Jul 15, 2012.