Despite the recent technical developments, surgery on the thoracic aorta remains challenging and is associated with significant mortality and morbidity. Decisions about when and if to operate are based on a balance between surgical risk and the hazard of aortic rupture. These decisions are sometimes difficult in elective cases of thoracic aortic diseases, including aneurysms and dissections. Abnormal wall stress derived from flow alterations influences disease progression. Therefore, a better understanding of the complex hemodynamic environment inside the aortic lumen will facilitate patient-specific risk assessments of complications, which enable clinicians to provide timely prophylactic interventions. Time-resolved 3D phase-contrast (4D flow) MRI has many advantages for the in vivo assessment of flow dynamics. Recent developments in 4D flow imaging techniques have led to significant advances in our understanding of physiological flow dynamics in healthy subjects and patients with thoracic aortic diseases. In this clinically focused review of thoracic aortic diseases, we demonstrate the clinical advances acquired with 4D flow MRI from published studies. We provide a systematic overview of key evidences and considerations regarding normal thoracic aortas, thoracic aortic aneurysms, aortic dissections, and thoracic aortas with prosthetic graft replacement.

**Keywords:** 4D flow MRI, thoracic aortic disease, aortic aneurysm, aortic dissection, bicuspid aortic valve

**Introduction**

When an aortic aneurysm or dissection is recognized, communicating to the appropriate physician is of paramount importance. The main objective in safely managing thoracic aortic diseases is to prevent catastrophic complications during the follow-up period. The central management feature for these diseases is the rigorous control of blood pressure; meanwhile, any patient at risk of subsequent life-threatening complications should be referred for surgery. Surgery on the thoracic aorta remains challenging and incurs significant mortality and morbidity, including cerebral infarction and irreversible spinal cord ischemia. On the other hand, mortality for thoracic aortic rupture is exceedingly high; only 41% of patients with thoracic aneurysm ruptures reach a hospital alive. Thus, the decision of when and whether to operate is based on the balance between surgical risk and the hazard of aortic rupture. In general, the appropriate timing of prophylactic intervention for thoracic aortic diseases is determined by aortic size criteria derived from studies on the natural history of thoracic aortic disease. However, under certain circumstances, prophylactic intervention might be beneficial before the aorta reaches a size threshold. In some examples, most dissections occur in aortas with diameters below the threshold, referred to as the aortic size paradox. Patients with acute aortic dissection with a nondilated aortic diameter sometimes exhibit rapid expansion within a few weeks. Accordingly, ongoing debate has focused on the feasibility of predicting patient-specific risk of complications and improving outcomes by providing timely endovascular or surgical interventions.

Time-resolved 3D phase-contrast (4D flow) MRI has great potential for evaluating flow dynamics in vivo. This technique is an exceptionally powerful noninvasive tool, enabling visualization of complex flow patterns and the calculation of variables related to flow dynamics in the entire thoracic aorta. The use of 4D flow MRI has increased our
understanding of thoracic aortic aneurysm formation, late complications of chronic aortic dissection, and aortic prosthesis performance. This evolving imaging modality shows promise as a tool for the preventative management of aortic diseases.9

In this clinically focused review of thoracic aortic diseases, we demonstrate the clinical advances acquired with 4D flow MRI from published studies. We provide a systematic overview of key evidence and considerations, regarding normal thoracic aortas, thoracic aortic aneurysms, aortic dissections, and thoracic aortas with prosthetic graft replacement.

Normal Aorta
In the thoracic aorta, flow is comprised of two components, primary and secondary flow. The primary flow is parallel to the main direction of fluid motion and the secondary flow is perpendicular to or opposite of the primary flow. Even in the normal thoracic aorta, secondary flow can be observed due to its morphological characteristics, including flow vortices in the aortic root (Fig. 1) and counter-rotating helices in the ascending aorta and aortic arch (Fig. 2).

Flow vortices in the aortic root were initially described by Leonardo da Vinci in the 1500s. His annotated representation of blood flow through the aortic valve proposed multiple vortices in the sinuses (Fig. 1A).15 In the 1990s, this hypothesis on recirculating physiological flow in the aortic root was depicted in vivo using multislice 2D phase-contrast MRI.16 The sinus vortices (Fig. 1B) are the necessary physiological flow patterns contributing to effective valve closure. Accordingly, valve-sparing root replacement with sinus prostheses might preserve near-physiological flow patterns in the aortic root and prevent altered valve function through deformed sinus vortices.17 This topic will be discussed in a later section (4D flow analysis of thoracic aortas with prosthetic graft replacement).

Counter-rotating (clockwise and counterclockwise) helices ranging from the ascending aorta to the aortic arch are known as Dean vortices and were first described mathematically by Dean in the 1920s.18 Kilner et al. successfully described the predominant secondary helical blood flow in the aortic arch in healthy patients using multislice 2D phase-contrast MRI in the 1990s.16 Kilner suggested that this flow pattern minimizes flow separation and turbulence. In the 2000s, opposing helices in the ascending aorta were visualized using 4D flow analysis (Fig. 2); these opposing helices are thought to lessen the oscillation between systolic and diastolic velocities, thereby reducing shear stress on the vessel wall.19 Through these analyses, one can assume that physiological helical flow provides favorable wall shear stress (WSS), which prevents atherosclerosis and aortopathy. The association between flow pattern and aortopathy is discussed in a later section (Pathological hemodynamics related to aneurysmal formation).

Analyses of 4D flow revealed that aortic hemodynamics in healthy subjects significantly change with age and gender.20 Stroke volume per heartbeat and forward velocities were higher in young subjects compared with elderly subjects.21 Flow conditions become increasingly disturbed with advancing age because of aortic shape factors and relative reductions in stroke volume. Thus, disturbed flow patterns are not entirely due to diseased aortas, but are also due to normal changes with aging.22 Accordingly, age- and gender-matched control cohorts are needed for assessing the impact of cardiovascular disease on aortic blood flow.

Fig. 1 Physiological vortices in the aortic root. (a) Leonardo da Vinci represented multiple physiological vortices in the aortic sinuses in the 1500s. (An image from Leonardo’s drawings re-used with permission from the Royal Collection Trust© Her Majesty Queen Elizabeth II 2021.) (b) 4D flow MRI pathline visualization depicting the recirculating vortical flows (arrowheads) accommodated by the sinuses of a healthy subject. These vortices contribute to efficient valve closure at the end of systole. AAo, ascending aorta; LVOT, left ventricular outflow tract.
Thoracic Aortic Aneurysm

Thoracic aortic aneurysm is typically a silent disease characterized by a lethal natural history. Thoracic aortic aneurysms have various etiologies, including degenerative, bicuspid aortic valve (BAV), inflammatory disease, mycotic, and congenital aneurysms.19 Risk factors for the development of thoracic aortic aneurysms include hypertension, smoking, and chronic obstructive pulmonary disease.5 Aortic aneurysms also develop in young patients with connective tissue disorders, such as the Marfan syndrome (MFS) or Ehlers-Danlos syndrome. Surgical intervention is recommended when the aortic diameter is greater than 5.5 cm (4.5–5 cm in case of BAV, MFS, or other genetic disorders), if the patient is symptomatic, or if the growth rate is greater than 0.5 cm/yr.4,5

Aortic aneurysm histopathology, termed medial degeneration, is characterized by disruption and loss of elastic fibers and increased deposition of proteoglycans.5 The aortic expansion rate generally increases with incremental increases in aortic diameter because wall tension increases with aortic radius, as dictated by Laplace’s law.23 In addition, abnormal aortic hemodynamics may induce negative remodeling, leading to the loss of elastic fibers and medial degradation.24–27 By visualizing flow patterns and quantifying vessel wall parameters, such as WSS and oscillatory shear index (OSI), 4D flow MRI can provide comprehensive information linked to aneurysm development.

Pathological hemodynamics related to aneurysm formation

Key references regarding 4D flow dynamics in patients with thoracic aortic aneurysms are listed and summarized in Table 1. Several abnormal flow patterns have been proposed using 4D flow MRI analyses of patients with aortic aneurysms. Figure 3 shows visualized pathline images from a patient with an ascending aortic aneurysm and from a healthy volunteer. Flow patterns with combined helices and vortices were visualized in the ascending aortic aneurysm.19 Patients with dilated aortic roots exhibit prominent vortex formations.27 Moreover, flow turbulence became more pronounced as the aortic dilatation progressed.28 Gülşan et al. proposed elevated turbulence intensity and irreversible pressure loss as complementary indicators for assessing aneurysm severity in the ascending aorta.29 Studies utilizing 4D flow MRI have also focused on WSS and OSI estimation. WSS is defined as the product of fluid viscosity and shearing velocity of the adjacent vascular wall. The OSI reflects instantaneous fluctuation of WSS and is calculated using temporal changes in the local WSS vector. A large OSI means that instantaneous WSS vectors fluctuate more compared with WSS in the mainstream direction at the calculated point during one cardiac cycle.30 Flow studies using in vitro models and computational fluid dynamics (CFD) have shown promising results in calculating consistent WSS in true patient anatomic models.31,32 Advances in postprocessing software have made WSS estimation using 4D flow MRI easier. Since then, 4D flow MRI studies revealed significant correlations of dilated ascending aortas with altered WSS and OSI.26,33,34 Both markedly increased and decreased WSS values influence vessel degeneration; thus, a WSS gradient was introduced.35 In the ascending aorta, regional increases in WSS are associated with extracellular matrix dysregulation36 and elastic fiber thinning, especially in BAV-aortopathies.37 (BAV-aortopathies are discussed in the next section.) Morphological variations in both fusiform and saccular aortic aneurysms impact WSS distribution.38 Based on these findings, WSS and OSI can be used as first-line noninvasive clinical indicators of aortic...
negative remodeling. However, technical limitations in the estimation of WSS and OSI via 4D flow MRI still exist. Reliable image-based WSS estimation requires sufficient spatial resolution, velocity to noise ratio, and pulsatile vessel wall tracking accuracy. For example, when the voxel resolution increases from 1 mm iso-voxel to 3 mm iso-voxel, the estimated WSS is underestimated by a maximum of one-third of the value calculated at 1 mm iso-voxel. These limitations hinder multicenter studies and comparisons of published studies. Dux-Santoy et al. reported that regions with low WSS and high OSI did not match those with aortic dilation in BAV patients. These discrepant results might be due to the technical difficulty of uniformly estimating WSS among research groups. Given the challenges in vessel wall segmentation, automated aortic segmentation using a deep learning model has been developed.

**Altered aortic outflow associated with bicuspid aortic valve**

In BAV disease, increased right-handed helical flow is the most common flow alteration in the ascending aorta, possibly leading to increased rotational WSS and subsequent complications. Figure 4 shows the flow patterns and WSS estimation in a BAV patient; the typical right-handed

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
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<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hope et al.</td>
<td>2007</td>
<td>13</td>
<td>Dilation of the ascending aorta skews the normal flow in the ascending aorta, changing retrograde, and helical flow patterns.</td>
</tr>
<tr>
<td>Weigang et al.</td>
<td>2008</td>
<td>6</td>
<td>Patients with ascending aortic aneurysms exhibited altered flow patterns with combined helical and vortical flows.</td>
</tr>
<tr>
<td>Hope et al.</td>
<td>2010</td>
<td>45</td>
<td>Abnormal helical systolic flow in the ascending aorta was depicted in patients with BAV, including those without aneurysm, or aortic stenosis.</td>
</tr>
<tr>
<td>Bieging et al.</td>
<td>2011</td>
<td>11</td>
<td>Dilated ascending aortas had increased WSS during diastole, reduced pulsatility in WSS values over the cardiac cycle, and delayed onset of WSS in systole.</td>
</tr>
<tr>
<td>Hope et al.</td>
<td>2011</td>
<td>46</td>
<td>Abnormal, eccentric flow in the ascending aortas of BAV patients is associated with elevated and asymmetric WSS, which may cause aneurysmal degeneration.</td>
</tr>
<tr>
<td>Bürk et al.</td>
<td>2012</td>
<td>33</td>
<td>Increased ascending aortic diameter correlated with helix and vortex formation, decreased systolic WSS, and increased OSI.</td>
</tr>
<tr>
<td>Bissell et al.</td>
<td>2013</td>
<td>95</td>
<td>The severity of flow abnormalities and aortic dilations differ depending on BAV fusion types.</td>
</tr>
<tr>
<td>Mahadevia et al.</td>
<td>2014</td>
<td>60</td>
<td>The presence and type of BAV fusion were associated with changes in regional WSS distribution, systolic flow eccentricity, and expression of BAV-aortopathies.</td>
</tr>
<tr>
<td>von Spiczak et al.</td>
<td>2015</td>
<td>3</td>
<td>2D and 3D metrics for the quantification of vortical blood flow in the thoracic aorta are linked to distinct patterns of ascending aortic aneurysm morphology.</td>
</tr>
<tr>
<td>Kari et al.</td>
<td>2015</td>
<td>31</td>
<td>Irrespective of aortic valve morphology and function, ascending aortic blood flow patterns are linked to distinct patterns of ascending aortic aneurysm morphology.</td>
</tr>
<tr>
<td>Natsume et al.</td>
<td>2017</td>
<td>100</td>
<td>Saccular aneurysms with higher sac depth/neck width ratios (exceeding 0.8) exhibit low WSS regardless of diameter, which may explain their malignant outcomes.</td>
</tr>
<tr>
<td>Ha et al.</td>
<td>2017</td>
<td>80</td>
<td>Flow skewness was associated with aortic dilatation in patients with aortic stenoses.</td>
</tr>
<tr>
<td>Bollache et al.</td>
<td>2018</td>
<td>27</td>
<td>Increased aortic valve-mediated WSS is significantly associated with elastic fiber thinning in patients with BAV.</td>
</tr>
<tr>
<td>Guala et al.</td>
<td>2019</td>
<td>198</td>
<td>BAV and non-BAV patients have similar stiffness in the aorta, whereas MFS patients have a stiffer aorta. Aortic stiffness strongly depends on dilation severity.</td>
</tr>
<tr>
<td>Kauhanen et al.</td>
<td>2019</td>
<td>20</td>
<td>Aortic dilation associates with flow displacement and increased circumferential WSS in patients without aortic stenosis.</td>
</tr>
<tr>
<td>Dux-Santoy et al.</td>
<td>2020</td>
<td>46</td>
<td>Regions with low WSS and high OSI do not match those with the highest prevalence of dilation in patients with BAV.</td>
</tr>
<tr>
<td>Shiina et al.</td>
<td>2021</td>
<td>22</td>
<td>Echo planar imaging 4D flow MRI may be useful for risk stratification for aortopathy after arterial switch operation.</td>
</tr>
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BAV, bicuspid aortic valve; MFS, Marfan syndrome; OSI, oscillatory shear index; WSS, wall shear stress.
helices and increased WSS can be seen. These marked abnormal helices are observed not only in the dilated ascending aorta with a stenotic BAV but also in those without aneurysms or aortic stenoses.43 The current clinical guidelines recommend that an ascending aortic aneurysm with BAV should be surgically treated in the lower threshold of diameter (4.5 cm).4,5 This is because the altered aortic outflow patterns in patients with BAV affect the aortopathies and increase the risk of aortic complications at relatively small aortic diameters.44 An alternative theory for aortic dilation postulates that a genetic or developmental abnormality in the proximal aortic tissue leads to weakening of the aortic wall with a BAV.45 Given the controversy of whether BAV-aortopathy results from intrinsic abnormal mechanical properties of the aorta wall or altered systolic outflow, Guala et al. also reported that aortic stiffness in BAV patients was similar to stiffness in non-BAV patients, suggesting that flow alteration rather than intrinsic mechanical properties cause BAV-associated aortopathies.46 BAV-related eccentric systolic blood flow had an asymmetrically elevated WSS.47 The flow skewness (a ratio of the sum of forward and retrograde systole flow to the net systole flow rate) and the presence of BAV were also associated with aortic dilation.48 Furthermore, the presence and type of BAV leaflet fusion altered the regional WSS distribution, the systolic outflow asymmetry, and the development of BAV-aortopathy.49 An ex vivo flow study using an MRI-compatible pulsatile flow circulation system also revealed that the bicuspid symmetry and the position of the smaller leaflet in BAV were determinant factors of the characteristics of the aortic valvular outflow jet.50 These flow-based findings regarding BAV-related aortopathy suggest that the altered flow pattern is not secondary to a dilated aorta but participates in the pathogenesis of aneurysm formation. Future prospective studies are warranted to evaluate the impact of BAV morphology and the associated hemodynamic alterations in determining the risk for aortopathy development and progression.49

Aortic Dissection

Aortic dissection is a life-threatening vascular disease resulting from an injury in the aortic wall. Aortic dissection leads to the creation of a true lumen (TL) and a false lumen (FL) separated by an intimal flap with multiple communicating tears between the lumina. Emergent graft replacement is indicated for acute type A aortic dissection (TAAD), while the treatment strategy for acute type B aortic dissection (TBAD) depends on the classification of complicated TBAD or uncomplicated TBAD. Complicated TBAD refers to malperfusion syndrome, rupture or impending rupture, uncontrolled hypertension, persistent abdominal or chest pain, or findings of rapid expansion on CT imaging. An emergent thoracic endovascular aortic replacement (TEVAR) should be considered for complicated TBAD because the above-mentioned conditions result in a high risk of early death if left untreated. On the other hand, uncomplicated TBAD have traditionally been managed nonoperatively with aggressive blood pressure control in its acute phase. However, patients with TBAD are chronically at risk of aortic complications during follow-up periods. The 3-year mortality rate is up to 25% according to the International Registry of Acute Aortic Dissection.51,52 Prophylactic surgical intervention is a potential option to improve survival. However, a randomized trial that compared preemptive TEVAR and optimal medical treatment alone reported that preemptive TEVAR caused a higher incidence of neurological adverse events and failed to improve 2-year survival and complication rates.53 Therefore, identifying patients at higher risk of aortic complication and selectively providing prophylactic intervention in the early phases of the disease is the most desirable treatment strategy to improve the late prognosis.
Previous clinical investigations revealed that aortic growth and the incidence of late death are significantly higher in patients with a patent FL compared to an occluded FL.11,54,55 This crucial finding indicates that flow dynamic abnormalities in the patent FL influence FL pressurization and degeneration, ultimately determining the late outcomes.51,56–58 Accordingly, flow-based risk stratification through imaging modality might enable clinicians to predict the expansion of FL more sensitively than the current morphology-based risk stratification, including a large initial diameter (> 40 mm), large primary entry (> 10 mm), or partially thrombosed FL. The characteristics of flow dynamics in the FL are complex and differ according to the location and size of the intimal tears.58,59 4D flow MRI is a powerful tool for assessing aortic flow dynamics by accurately quantifying blood flow volume and velocity, and for visualizing velocity-encoded 3D pathlines.14,60,61 This emerging imaging modality permits reliable evaluation of dissected aorta in a patent FL.52,63 When common flow characteristics were characterized by quantitative flow analyses of dissected aortas, the blood flow volume and velocity were significantly dampened in the FL as compared with those in the TL, and the transit time of blood through the FL was markedly prolonged, with significant blood flow reversal.56,63,64 In other words, high-velocity antegrade flow in the TL and low-velocity retrograde flow in the FL can coexist in dissected aortas. To accurately capture both the high- and low-velocity blood flow, multivelocity encoding (multi-VENC) 4D flow MRI with a wide dynamic range of target blood flow velocity has been proposed.63,65–68
Perioperative evaluation of dissected aortas using 4D flow MRI

In suitable survivors of TBAD, elective TEVAR is considerable for reducing delayed mortality and disease progression. To uncover the patient-specific flow characteristics of dissected aortas before TEVAR, 4D flow MRI can be used. Small fenestrations and their hemodynamic characteristics were detected. 4D flow MRI also revealed complex bidirectional flow patterns in multichanneled aortic dissections before TEVAR. The flow dynamics inside the FL were uncovered before and after the entry closure via TEVAR. The combined use of 4D flow MRI and CFD could predict the post-TEVAR flow dynamics from pre-TEVAR flow data. Patient-specific analysis using flow visualization and quantification may aid in planning treatment. Future work should be focused on the endovascular strategy for individual-specific morphologies of dissected aortas.

Risk prediction of chronic aortic dissection

In patients with chronic aortic dissection with a patent FL, a previous landmark morphological study based on CT and echocardiography identified several parameters, including baseline maximum aorta diameter, proximal location of the entry tear, and entry tear size, as predictors of dissection-related adverse events, whereas the adjusted hazard ratios based on these parameters were not high (1.32, 1.84, and 1.13, respectively). Flow analysis based on 4D flow MRI is desired to discover more reliable and independent predictors of poor outcomes among these patients.

Key publications regarding flow dynamic predictors of enlarging dissected aortas are listed in Table 2. Flow analysis might predict late complications of dissected aorta beyond standard anatomic risk factors, such as the aortic diameters. In 2000, the correlation between flow volume inside the FL and aortic enlargement was revealed using 2D phase-contrast MRI. Owing to the subsequent development of 4D flow imaging techniques up to the present, aortic flow dynamics can be accurately assessed by quantifying blood flow volume, velocity, and 3D pathlines in the dissected aorta. Figure 5 shows the flow alterations in the FLs of chronic aortic dissection patients using 4D flow MRI. 4D flow analyses revealed that the following unique factors predict poor outcomes in patients with chronic aortic dissection. Amano et al. demonstrated intelligible flow visualization of the dissected thoracic aorta, depicting rapid jet flow at the entry and slower helical flow in the FL with disease progression. Stroke volume, velocity, and the degree of flow turbulence in the FL are also associated with a more rapid aortic expansion or late complications. Trojan et al. detected significant alterations of contrast dynamics within the FL of expanding aortic dissections. FL ejection fraction, defined as the ratio of retrograde flow rate at the dominant entry tear during diastole over the antegrade systolic flow rate, was an independent predictor of aortic growth. The combined use of 4D flow MRI and CFD could predict the post-TEVAR flow dynamics from pre-TEVAR flow data. Patient-specific analysis using flow visualization and quantification may aid in planning treatment. Future work should be focused on the endovascular strategy for individual-specific morphologies of dissected aortas.

**Table 2  Prior literature regarding flow dynamic predictors of enlarging dissected aortas**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Number of patients</th>
<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inoue et al.</td>
<td>2000</td>
<td>21</td>
<td>2D phase-contrast MRI* revealed that the rate of flow volume in the FL compared with the total flow volume in the TL and FL correlated with the rate of enlargement.75</td>
</tr>
<tr>
<td>Amano et al.</td>
<td>2011</td>
<td>16</td>
<td>Slower helical flow after rapid entry jet was observed in the FL of patients with disease progression.62</td>
</tr>
<tr>
<td>Clough et al.</td>
<td>2012</td>
<td>12</td>
<td>Stroke volume, velocity, distal dominant entry tears, and helical flow in the FL are related to the rate of aortic expansion.56</td>
</tr>
<tr>
<td>François et al.</td>
<td>2013</td>
<td>12</td>
<td>Flow patterns were significantly altered in association with the extent of disease, vessel dilatation, and posttherapeutic anatomy.64</td>
</tr>
<tr>
<td>Trojan et al.</td>
<td>2017</td>
<td>20</td>
<td>3D time-resolved contrast-enhanced MRA* detected alterations in contrast dynamics within the FL of expanding aortic dissections.79</td>
</tr>
<tr>
<td>Burris et al.</td>
<td>2020</td>
<td>18</td>
<td>FL ejection fraction, defined as the ratio of retrograde flow rate at the dominant entry tear during diastole over the antegrade systolic flow rate, was an independent predictor of aortic growth.57</td>
</tr>
<tr>
<td>Takahashi et al.</td>
<td>2021</td>
<td>33</td>
<td>Patients with high-volume turbulent flow in their FL are at higher risk of late complications.78</td>
</tr>
</tbody>
</table>

* These flow analyses were derived from other than 4D flow MRI. FL, false lumen; TL, true lumen.
4D Flow Analyses of Thoracic Aortas with Prosthetic Graft Replacement

Several recent 4D flow MRI studies focused on flow-based analyses in patients who underwent aortic graft replacement. One of the biggest concerns in this field is the preservation of postoperative physiological flow dynamics after aortic valve-sparing root replacement. In general, the standard surgery for dilated aortic roots is the Bentall procedure, which replaces both the root and valve cusps with a composite prosthesis. Another option is valve-sparing root replacement for aortic root aneurysms, which involves the replacement of the aortic root with an artificial graft, while the normal or minimally diseased aortic valve cusps are preserved.80 This procedure retains aortic root dynamism and restores near-normal flow characteristics, which has been confirmed using combined CFD and phase-contrast MRI.81 The efficacy of anatomically shaped sinus prostheses in preserving flow dynamism to near normal has been reported.82 Compared to the conventional tube graft, sinus prostheses positively impact lower WSS and flow pattern organization.35,83 Thus, graft replacement with a sinus prosthesis may be advantageous in terms of aortic valve function and durability.83 This topic needs confirmation in larger-cohort studies with prospective follow-ups.

Several flow studies in patients with aortic prosthetic graft showed significantly higher levels of secondary flow patterns relative to healthy volunteers.35,83,84 These flow patterns were related to the surgically altered aortic geometry with noncompliant artificial grafts or graft kinking.84 Figure 6 shows an example of helicity distal to the replaced ascending aorta. These patients are at increased risk for distal vessel wall remodeling. Hope et al. reported an MFS patient with prior aortic root replacement, who exhibited more pronounced altered flow patterns and hemodynamic stresses in the thoracic aorta than other cohorts.85 This patient subsequently developed a new aortic dissection during the prospective follow-up period. Also, kinked prosthetic grafts, resulting from intrinsic pressurization and curvature, are at risk of unphysiological flow patterns, development of pressure gradients, and nonuniform stress distributions.86 Surgically repaired TAADs with replaced grafts showed flow acceleration and elevated kinetic energy in the TL relative to the TBAD.87 Mechanical hemolytic anemia due to aortic arch graft kinking is a rare but well-known complication, showing significant flow turbulence with elevated energy loss inside the graft during 4D flow analysis.88 Figure 7 shows flow turbulence due to graft kinking and a stenosed proximal anastomosis site. Preserving the natural undisturbed curvature and the physiological flow conditions should be the aims when replacing thoracic aortas.

Drawback of 4D Flow MRI Acquisition

4D flow MRI has several drawbacks. First is a concern about the time-consuming image acquisition. In general, for the whole coverage of the thoracic aorta, para-sagittal 4D flow MRI acquisition with approximately 140-mm slice thickness has been needed. In addition, the combined use of electrocardiography and respiratory gating further prolongs the scan time of 4D flow MRI, usually > 10 min.89 Recently, however, the scan time has been reported to become drastically shortened within a few minutes owing to the development of acceleration techniques.90,91
gadolinium enhancement is preferable in the acquisition of 4D flow MRI to improve both the contrast between the blood and the surrounding tissues, and the SNR linked to the velocity-to-noise ratio. This may hamper the clinical use for patients with renal dysfunction. Noncontrast 4D flow MRI can be also clinically useful. Without the need for an external contrast agent, its inherent contrast nature as T1 weighted image enables it to generate a phase-contrast magnetic resonance angiogram (PC-MRA), which discriminates the vessel component from the surrounding tissues. Care should be taken such that the Ernst angle of blood is different between noncontrast and contrast 4D flow MRI. The flip angle should be tailored for scanning with or without contrast agent injection. Third, the aortic vessel pulsation (moving) during the cardiac cycle is a critical issue in the accurate estimation of WSS in 4D flow MRI. Most of the previous studies used only peak WSS with the vessel segmentation of time-averaged or time-maximum intensity projection PC-MRA. This approach makes sense because its boundary condition represents the wall location in systole. However, if we examine WSS in the diastolic phase or OSI, which requires the WSS value over the cardiac cycle, accurate vessel segmentation is mandatory through the entire cardiac cycle. Further development of the post-processing software for vessel tracking from time-resolved PC-MRA and validation would be needed. As an alternative to the calculation of near-wall parameters, such as WSS and OSI, calculation of flow parameters inside the lumen, such as energy loss, might be feasible.
Conclusion

The assessment of thoracic aortic diseases in vivo has been significantly improved by 4D flow MRI for the following reasons. First, 4D flow MRI depicts flow alterations, which may cause aneurysm formation. In particular, patients with BA V disease exhibit remarkably altered aortic outflow patterns. Second, accurate assessment of aortic flow dynamics can be accomplished in dissected aortas using 4D flow MRI. Quantitative flow dynamics and visualized flow alterations in the FL are potential predictive factors for delayed complications. Third, 4D flow MRI provides detailed hemodynamic information of surgically replaced thoracic aortas that show flow alterations with an increased risk of vessel wall remodeling.

Future work should focus on the validation of predictive values of the new parameters obtained by 4D flow MRI. Since nearly all research to date involved cross-sectional observational studies based on single-point 4D flow evaluations in advanced aortic disease, the clinical predictive relevance of the 4D flow MRI analysis remains a matter of speculation. To understand the causal relationship between flow dynamics and clinical prognoses, prospective data in a large cohort are essential; therefore, 4D flow MRI application is expected to become widely used.

Conflicts of Interest

All authors declared that they have no conflict of interests related to this article.

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18. Dean WR. Note on the motion of fluid in a curved pipe. Philos Mag. 1927; 4:208.


