Proximal false lumen thrombosis is associated with low false lumen pressure and fewer complications in type B aortic dissection

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ABSTRACT

Background: Improved risk stratification is a key priority for type B aortic dissection (TBAD). Partial false lumen thrombus morphology is an emerging predictor of complications. However, partial thrombosis is poorly defined, and its evaluation in clinical studies has been inconsistent. Thus, we aimed to characterize the hemodynamic pressure in TBAD and determine how the pressure relates to the false lumen thrombus morphology and clinical events.

Methods: The retrospective admission computed tomography angiograms of 69 patients with acute TBAD were used to construct three-dimensional computational models for simulation of cyclical blood flow and calculation of pressure. The patients were categorized by the false lumen thrombus morphology as minimal, extensive, proximal or distal thrombosis. Linear regression analysis was used to compare the luminal pressure difference between the true and false lumen for each morphology group. The effect of morphology classification on the incidence of acute complications within 14 days was studied using logistic regression adjusted for clinical parameters. A survival analysis for adverse aortic events at 1 year was also performed using Cox regression.

Results: Of the 69 patients, 44 had experienced acute complications and 45 had had an adverse aortic event at 1 year. The mean ± standard deviation age was 62.6 ± 12.6 years, and 75.4% were men. Compared with the patients with minimal thrombosis, those with proximal thrombosis had a reduced false lumen pressure by 10.1 mm Hg (95% confidence interval [CI], 4.3-15.9 mm Hg; $P = .001$). The patients who had not experienced an acute complication had had a reduced relative false lumen pressure (−6.35 mm Hg vs −0.62 mm Hg; $P = .03$). Proximal thrombosis was associated with fewer acute complications (odds ratio, 0.17; 95% CI, 0.04-0.60; $P = .01$) and 1-year adverse aortic events (hazard ratio, 0.36; 95% CI, 0.16-0.80; $P = .01$).

Conclusions: We found that proximal false lumen thrombosis was a marker of reduced false lumen pressure. This might explain how proximal false lumen thrombosis appears to be protective of acute complications (eg, refractory hypertension or pain, aortic rupture, visceral or limb malperfusion, acute expansion) and adverse aortic events within the first year. (J Vasc Surg 2022;75:1181-90.)

Keywords: Computational fluid dynamics; False lumen; Hemodynamics; Pressure; Thrombosis; Type B aortic dissection

Improved risk stratification for those with type B aortic dissection (TBAD) is needed to better understand the prognosis and treat patients accordingly. Clinical features, such as persistent pain and hypertension, and morphologic features, such as an increased aortic diameter, a false lumen diameter >22 mm, and a large primary entry tear, have been implicated in disease progression.[1-4] The partial false lumen thrombus

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morphology has been emerging as a predictor of complications after TBAD.[5-7] Patients with partial false lumen thrombosis have experienced worse outcomes; however, partial thrombosis has remained poorly defined and its evaluation in clinical studies has been inconsistent.[5,7] Despite these advances, predicting late complications in the vulnerable aorta remains challenging and creates uncertainty in the decision-making process.[8] Better long-term risk stratification is a key priority to improve the treatment of patients with TBAD.

Ex vivo models of TBAD have demonstrated that dissection flap anatomy and thrombus morphology affects the pressure in the false lumen measured using a pressure transducer.[9] Modern anatomic imaging and advances in computational power have enabled the creation of high-resolution aortic models from computed tomography (CT) angiograms (CTA) and the simulation of blood flow through them at scale.[10,11] The resultant computational fluid dynamic (CFD) analysis can detect intricate variations in blood flow around complex anatomic features and enable estimates of pressure within the true and false lumens.[10,12-14] Furthermore, CFD models of TBAD have been validated using various benchtop experiments.[15-18] More recently, the use of four-dimensional magnetic resonance imaging (MRI) has demonstrated the robustness of using computer modeling to study the *in vivo* hemodynamics.[19]

In the present study, we hypothesized that false lumen thrombosis would be a marker of false lumen pressure and that understanding this relationship could help predict for aorta-related clinical events. Therefore, our aim was to quantify and classify false lumen thrombosis, calculate the true and false lumen pressures, and determine whether these factors could predict the outcomes for patients with TBAD.

ARTICLE HIGHLIGHTS

- **Type of Research:** A single-center, retrospective cohort study
- **Key Findings:** In 69 patients with acute type B aortic dissection, those with proximal thrombosis of the false lumen had a 10.1 mm Hg lower false lumen pressure than those with minimal thrombosis. These patients also experienced fewer acute complications (odds ratio, 0.17) and adverse aortic events within 1 year (hazard ratio, 0.36).
- **Take Home Message:** Proximal false lumen thrombosis is a marker of reduced false lumen pressure and appears to be protective against acute complications and adverse aortic events within 1 year.

METHODS

Study design and cohort

Data from consecutive patients with new acute TBAD who had presented to Klinikum rechts der Isar, Technical University of Munich, from January 2004 to April 2019 were reviewed by vascular surgeons and collected in a prospective database.[20] The number of patients collected for analysis was 91. The most of these patients had been previously reported on by Reutersberg et al[20] in a study aimed at determining the incidence of delayed complications in patients with acute TBAD (86 patients admitted to May 2016). In contrast, in the present study, we investigated the role of false lumen thrombosis and false lumen pressure on the occurrence of complications. The patients' blood pressure was recorded on admission, immediately before CT imaging. Patients with Stanford type A aortic dissection (involvement of the ascending aorta or aortic arch), those with subacute or chronic TBAD (symptom onset ≥14 days before admission), and those randomized to the operative arm of the ADSORB (acute dissection stent grafting or best medical treatment) trial were excluded.[20] The present study was performed in accordance with the Declaration of Helsinki. The ethics committee of the medical faculty of the Technical University of Munich (Munich, Germany) approved the present study (reference no. 439/18S). The human ethics office at the University of Western Australia (Perth, Australia) approved the performance of additional computational analysis (reference no. RA/4/1/5868). A flow diagram of the patients included in the present study is shown in Supplementary Fig 1 (online only).

Aortic imaging

All the patients had undergone CTA at presentation, and the same imaging studies were used for the hemodynamic assessment. The arterial phase study of the aorta was performed using a multidetector CT Somatom Sensation Cardiac 64 (Siemens Medical Systems, Erlangen, Germany), Siemens Somatom Definition AS (Siemens Medical Systems), or Phillips iCT 256 (Phillips, Amsterdam, The Netherlands). The institutional standard aortic protocol for CTA covers the entire aorta (including the aortic valve to the femoral arteries), with scanning using a 120-kV tube current modulation and 120 mA. A 0.6-mm slab thickness was reconstructed axially to 1 to 3 mm. The in-plane resolution was 0.6 to 0.8 line pairs/mm. An 80-mL bolus of iodine-based contrast (iomeprol-400) with a 30-mL bolus of sodium chloride (injection rate, 4 mL/s) was used.

Three-dimensional aortic modeling and false lumen thrombus morphology

Medical segmentation software (Mimics, version 20; Materialise, Leuven, Belgium) was used to create three-dimensional (3D) reconstructions of the true lumen, patent false lumen, and the tears connecting these regions. These reconstructions were used for the morphologic

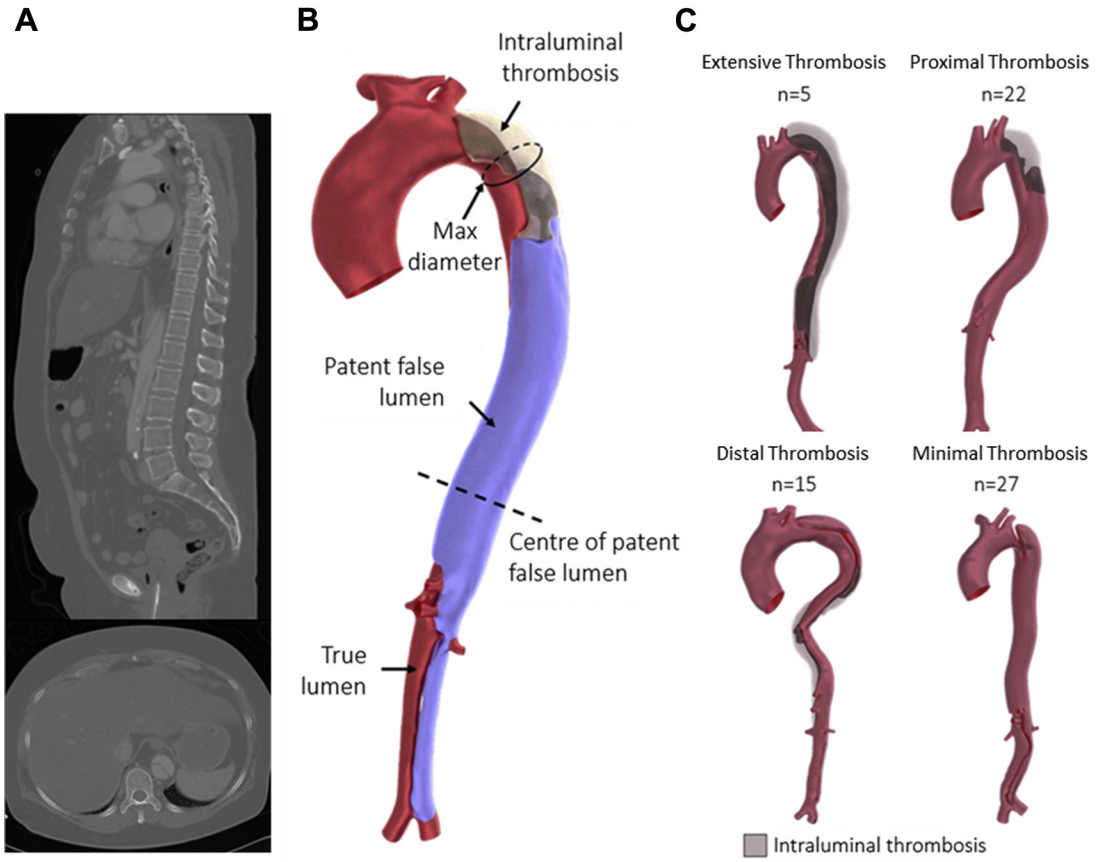

Fig 1. Imaging, reconstruction, and characterization of false lumen thrombus morphology. **A,** Sagittal and axial views from one computed tomography (CT) series used for three-dimensional (3D) reconstruction. **B,** Three-dimensional reconstruction showing the true lumen, false lumen, and intraluminal thrombus segmentations for a patient with proximal thrombosis. The maximum aortic diameter measurement and center of the patent false lumen used for morphologic categorization are also indicated. **C,** Examples of the four morphologic groups of type B aortic dissection (TBAD) identified during reconstruction.

measurements (Fig 1, *A and B*) and were the basis of the CFD model. The maximum aortic diameter was measured perpendicular to the aortic centerline within the dissected portions of the aorta. The aortic modeling team, consisting of three biomedical engineers experienced in 3D reconstruction of the vasculature and one vascular surgery trainee (L.P.P., S.R., B.J.D., B.M.), were unaware of the clinical outcomes until the hemodynamic computational assessment had been completed. The interoperator reconstruction repeatability was assessed and found to be low (Supplementary Table, online only).

The intraluminal thrombus was reconstructed, and the proportion of false lumen thrombosis was calculated relative to the total false lumen volume (thrombus volume divided by the total false lumen volume). The participants with <10% thrombosis of the false lumen were categorized as having minimal thrombosis and those with thrombosis of >90% of the false lumen were categorized as having extensive thrombosis. For patients with 10% to 90% thrombosis of the false lumen, the longitudinal midpoint of the false lumen was used to designate the thrombosis as proximal or distal, depending on which region had the greater thrombus burden (Fig 1, *B*). Therefore, we defined four groups according to the thrombus classification: (1) minimal thrombosis, (2) extensive thrombosis, (3) distal thrombosis, and (4) proximal thrombosis (Fig 1, *C*). All the patients had had at least one communicating tear between the true and false lumens.

Calculation of true and false lumen pressure

The simulation methods used to calculate the pressure in the true and false lumen are outlined in detail in the Supplementary Methods (online only), including a mesh independence study (Supplementary Fig 2, online only). The pressure was calculated by simulating the systolic pressure as the surface average across the entire patent false lumen surface and corresponding true lumen. The luminal pressure difference was then calculated as the difference between the false and true lumen pressures.

Clinical classification and outcome

The participants were considered to have complicated aortic dissection if they had met the criteria defined by the European Society of Vascular Surgery guidelines[21]: malperfusion, aortic expansion >4 mm in diameter, aortic rupture, refractory pain, and/or refractory hypertension.[20,22] These definitions are consistent with the categories termed "high-risk" and "complicated" TBAD in the more recent Society for Vascular Surgery and Society of Thoracic Surgeons reporting standards for TBAD.[23] The patients were considered to have experienced an acute complication if the complication had occurred within 14 days of presentation.

In addition to acute complications, the cases were categorized using a second, unique clinical endpoint, adverse aortic events. Adverse aortic events were a composite of aortic rupture, aortic repair, and/or aorta-related death within the first year (inclusive of the acute phase). The adverse aortic event group was distinct from the acute complication group and focused on the patient outcomes at 1 year, regardless of the specific complications that had occurred in the acute phase.

Statistical analysis

The patient characteristics, aortic morphology, and false lumen pressures were compared between the four false lumen thrombus morphology groups. A χ^2 test was performed to compare the categorical variables. The continuous variables were assessed for homogeneity, and analysis of variance was used to compare them between the groups.

Study 1: cross-sectional study analysis of aortic morphology at presentation. In the initial analysis, we investigated the false lumen pressure after acute TBAD in relation to the aortic morphology derived from the admission CTA. The false lumen pressure was investigated as the dependent variable in a linear regression model adjusted for the aortic diameter and the patient's age.

Study 2: longitudinal analysis of clinical events. In the second analysis, we investigated the effects of thrombus morphology and false lumen pressure on the clinical events. First, the acute complications that had occurred within 14 days of presentation were studied using a logistic regression model to identify the contributing clinical features. This model was adjusted for patient age, sex, aortic diameter, blood pressure, and false lumen thrombus morphology. Second, the adverse aortic events at 1 year were investigated in relation to the thrombus morphology using Kaplan-Meier log-rank and Cox regression analyses. The Cox regression model was adjusted for patient age, sex, aortic diameter, and blood pressure. The false lumen thrombus morphology was added to this model to determine its prognostic value.

Statistical analysis was performed in the *R* environment, version 3.5.2 (R Foundation for Statistical Computing, Vienna, Austria). A *P* value of .05 was considered statistically significant.

RESULTS

Patient characteristics. Of the 91 patients admitted with acute TBAD, 22 were excluded because the CT imaging studies did not have adequate contrast perfusion in the false lumen for aortic modeling and hemodynamic analysis owing to the presence of complete thrombosis. Of the 69 remaining study participants, the mean ± standard deviation age was 62.6 ± 12.6 years and 75.4% were men. The cohort was well matched between the false lumen thrombus morphology groups (Table I). However, patients with extensive thrombosis had had a larger diameter relative to the remaining cohort ($P < .001$). In contrast, those with proximal thrombosis of the false lumen had increased diastolic blood pressure ($P = .04$). The mean thrombosis burden was greater in those with proximal thrombosis than in those with distal thrombosis (57.1% ± 24.0% vs 39.6% ± 20.6%; $P = .02$). We did not observe any difference in the shear stress, low and oscillatory shear, or oscillatory shear index between the thrombosis groups (Supplementary Fig 3, online only).

Acute complication occurred in 44 of the 69 patients and included refractory hypertension (n = 6), aortic rupture (n = 5), visceral or limb malperfusion (n = 21), acute expansion (>4 mm; n = 9), and refractory pain (n = 10). Seven patients had had more than one acute complication. Within the first 14 days, 34 of the 69 patients had undergone thoracic endovascular aortic repair. At 1 year, 45 of the 69 patients had experienced an adverse aortic event, including aortic rupture (n = 5), aortic repair (n = 44), and aorta-related death (n = 5). Of the 24 patients without a reported adverse aortic event, 10 had been last seen for follow-up at <1 year from presentation.

Study 1: cross-sectional analysis of aortic morphology at presentation. The pressure difference between the true and false lumens differed in relation to the false lumen thrombus morphology (Fig 2, *A and B*). Patients with distal thrombosis of the false lumen had had an increased false lumen pressure relative to the true lumen. In contrast, patients with proximal thrombosis had had a reduced relative false lumen pressure.

The results from the linear regression analysis estimated that the false lumen pressure was 10 mm Hg (95% confidence interval [CI], 4.3-15.9 mm Hg) lower for the patients with proximal thrombosis compared with those with minimal luminal thrombosis, after adjusting for aortic diameter and patient age ($P < .001$). Neither the aortic diameter nor patient age was significantly associated with the false lumen pressure difference (Table II).

Table I. Patient characteristics

Characteristic	Overall (n = 69)	False lumen thrombus morphology				*P* value
		Minimal thrombosis (n = 27)	Extensive thrombosis (n = 5)	Distal thrombosis (n = 15)	Proximal thrombosis (n = 22)	
Male sex	52 (75.4)	21 (77.8)	5 (100.0)	11 (73.3)	15 (68.2)	.50
Age, years	62.6 ± 12.6	58.6 ± 13.9	66.4 ± 7.8	63.9 ± 13.2	65.9 ± 10.3	.18
Weight, kg	87.1 ± 17.5	90.5 ± 17.3	94.0 ± 18.2	84.8 ± 20.0	82.7 ± 16.1	.53
Height, m	1.76 ± 0.09	1.77 ± 0.08	1.81 ± 0.10	1.80 ± 0.08	1.72 ± 0.08	.08
Systolic blood pressure, mm Hg	151 ± 33.8	142 ± 29.0	139 ± 11.3	154 ± 44.8	162 ± 31.1	.22
Diastolic blood pressure, mm Hg	78 ± 19.1	72 ± 15.3	71 ± 13.4	77 ± 25.8	88 ± 16.4	.04
Aortic diameter, mm	41.15 ± 6.1	38.22 ± 4.6	49.57 ± 7.8	41.59 ± 6.9	42.53 ± 4.4	<.001
Dissection fenestrations	4.6 (2.8)	5.7 (3.1)	4.0 (2.4)	2.8 (1.6)	4.4 (2.4)	.01

Data presented as number (%) or mean ± standard deviation.

Study 2: longitudinal analysis of clinical events. Acute complications within the first 14 days from presentation were common (n = 44; 63.8%). Patients with proximal thrombosis were less likely to develop acute complications than the remaining cohort were ($P = .01$; Table III). The patients who had not developed complications had a lower relative false lumen pressure compared with those who had experienced acute complications (mean, −6.35 ± 12.05 mm Hg vs −0.62 ± 8.91 mm Hg; $P = .03$).

Proximal thrombosis of the false lumen was the only significant predictor of acute complications on adjusted logistic regression analysis (Table IV). Patients with proximal thrombosis had a reduced likelihood of acute complications compared with patients with distal thrombosis (odds ratio, 0.13; 95% CI, 0.02-0.56; $P = .01$).

Adverse aortic events had occurred in 45 patients (65.2%) within the first year of follow-up (Table III). Patients with proximal thrombosis had experienced fewer adverse aortic events compared with the remaining cohort (log-rank $P = .03$; Fig 2, *C*). The presence of proximal false lumen thrombus was the only significant predictor that was protective against adverse aortic events within the first year after adjusting for age, sex, aortic diameter, and blood pressure (odds ratio, 0.36; 95% CI, 0.16-0.80; $P = .01$; Table IV).

DISCUSSION

In the present retrospective study, we aimed to characterize the hemodynamic pressure in patients with TBAD and determine how the pressure relates to the false lumen thrombus morphology and clinical events. We found that patients with predominantly proximal false lumen thrombus had significantly lower false lumen perfusion pressures ($P < .001$), were less likely to develop acute complications within the first 14 days ($P = .01$), and were also less likely to experience adverse aortic events, including aortic rupture, aortic repair, or aorta-related death within the first year ($P = .01$). Furthermore, we used a classification system that is easy to use in routine clinical practice with 3D reconstruction and CTA data analysis. Identifying easily accessible clinical and radiologic factors from the CTA findings that influence the false lumen pressure difference might improve our ability to risk stratify patients with acute TBAD.

False lumen thrombosis after TBAD has received much attention as a potential predictor of complications,[5,7,24] including the recent Society for Vascular Surgery/Society of Thoracic Surgeons reporting standards for TBAD.[23] These guidelines, however, have assumed homogeneity for the effects of different false lumen thrombus patterns. However, our findings have shown that it is important to characterize the false lumen thrombosis by location and burden because these will influence the false lumen pressure, which contributes to false lumen expansion, true lumen compression, and, ultimately, further dissection.[9] Thrombosis occurs in areas of disturbed and low-flow states encountering newly damaged thrombogenic aortic media. A self-propagating cycle of thrombosis can partially occlude fenestrations within the dissection flap. Reduced inflow from the proximal thrombosis of the false lumen will decrease the perfusion pressure. In contrast, distal false lumen thrombosis can result in stenosis of the outflow channels, thus increasing the false lumen perfusion pressure.[9,12]

Of the variables considered in the present study, our initial analysis revealed that the false lumen thrombus morphology was the strongest and only independent clinical predictor of the false lumen pressure difference. The mean thrombus burden was greater in cases of proximal false lumen thrombosis compared with distal thrombosis, with a greater variance. This is a possible reason for the similarly high variance observed in the

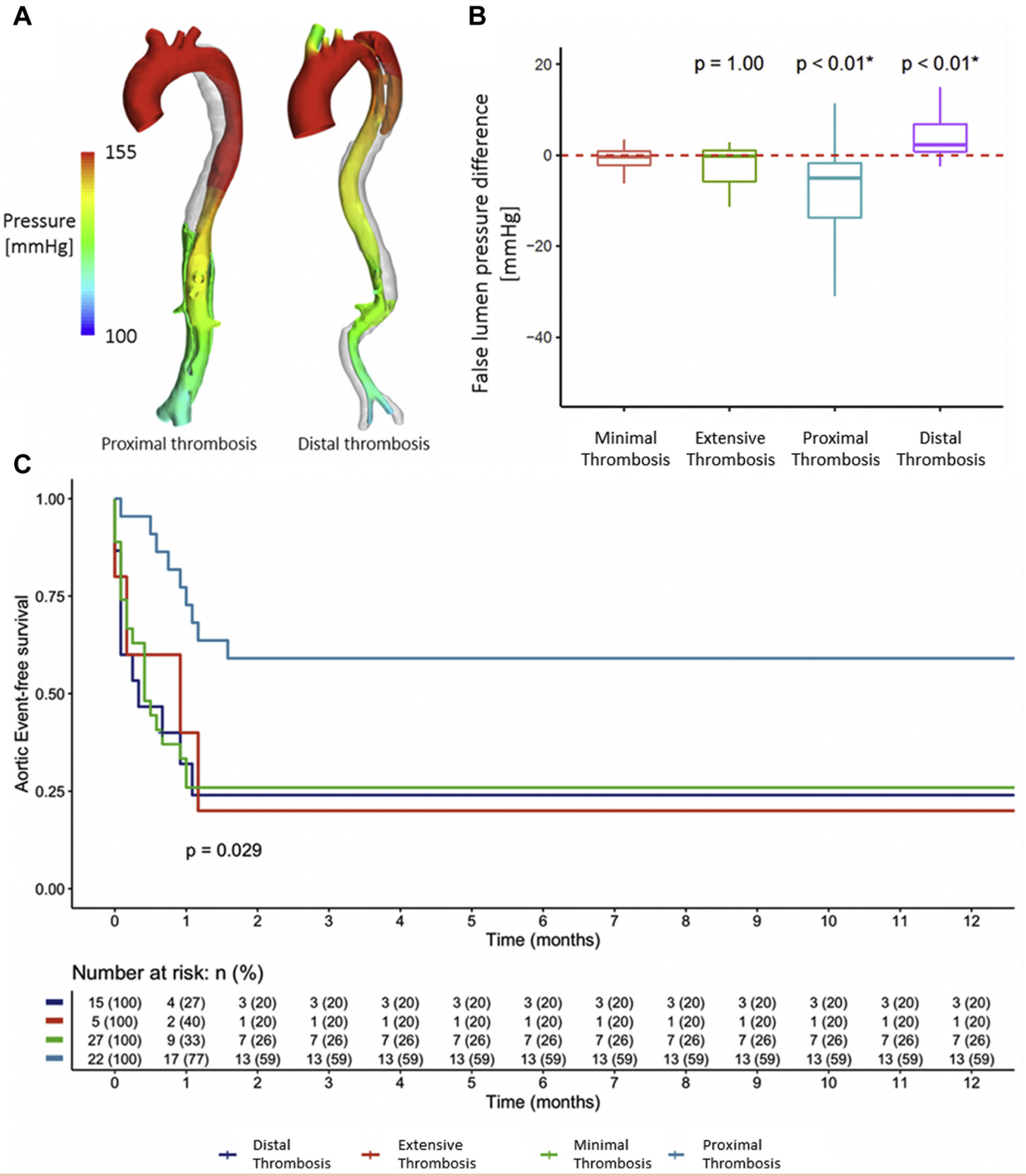

Fig 2. False lumen pressure after acute type B aortic dissection (TBAD). **A,** Three-dimensional contours of pressure for cases from the proximal and distal thrombosis groups. The surface average pressure for the proximal and distal thrombosis cases was 125 and 150 mm Hg for the false lumen and 151 and 141 mm Hg for the true lumen, respectively. Thrombus is shown in *gray*. **B,** Proximal thrombosis resulted in a significantly reduced luminal pressure difference between the false and true lumens. In contrast, the relative false lumen pressure was increased in patients with distal thrombosis. **C,** Aortic event-free survival after acute type B aortic dissection (TBAD) stratified by false lumen thrombus morphology. Adverse aortic events were defined as aortic repair, aortic rupture, or aorta-related death. Patients with proximal false lumen thrombosis experienced fewer adverse aortic events (log rank $P = .03$).

Table II. Factors influencing luminal pressure difference between false and true lumens[a]

Variable	Luminal pressure difference, mm Hg	95% CI	*P* value
False lumen thrombus morphology[b]			
Extensive thrombosis	−5.53	−15.94 to +4.89	.29
Distal thrombosis	+2.94	−3.31 to +9.19	.35
Proximal thrombosis	−10.10	−15.87 to −4.34	.001
Aortic diameter (per 5-mm increase)	+1.56	−0.78 to +3.89	.19
Age (per 10-year increase)	−0.06	−2.09 to +1.96	.95

CI, Confidence interval.
[a]Linear regression analysis adjusted for false lumen thrombus morphology, aortic diameter, and age.
[b]Compared with minimal thrombosis group.

Table III. Clinical sequelae of patients presenting with acute TBAD

Variable	Overall (n = 69)	False lumen thrombus morphology				*P* value
		Minimal thrombosis (n = 27)	Extensive thrombosis (n = 5)	Distal thrombosis (n = 15)	Proximal thrombosis (n = 22)	
Acute complications						
Refractory hypertension	6 (8.7)	2 (13.3)	0 (0.0)	3 (11.1)	1 (4.5)	.67
Aortic rupture	5 (7.2)	3 (20.0)	0 (0.0)	1 (3.7)	1 (4.5)	.19
Visceral or limb malperfusion	21 (30.4)	7 (46.7)	1 (20.0)	9 (33.3)	4 (18.2)	.29
Acute expansion (>4 mm)	9 (13.0)	2 (13.3)	2 (40.0)	2 (7.4)	3 (13.6)	.27
Refractory pain	10 (14.5)	2 (13.3)	3 (60.0)	3 (11.1)	2 (9.1)	.03
Composite	44 (63.8)	12 (80.0)	4 (80.0)	20 (74.1)	8 (36.4)	.01
One-year outcomes						
Aortic rupture	5 (7.2)	1 (3.7)	0 (0.0)	3 (20.0)	1 (4.5)	.10
Aortic repair	44 (63.8)	20 (74.1)	4 (80.0)	11 (73.3)	9 (40.9)	.02
Aorta-related death	5 (7.2)	1 (3.7)	0 (0.0)	2 (13.3)	2 (9.1)	.53
Adverse aortic event (composite)	45 (65.2)	20 (74.1)	4 (80.0)	11 (73.3)	10 (45.5)	.03

TBAD, Type B aortic dissection.
Data presented as number (%).

false lumen pressure difference for this group. The false lumen thrombus morphology was also associated with clinical events, such that proximal thrombosis of the false lumen appeared to be protective against both acute complications at 14 days and adverse aortic events at 1 year. Hence, the distribution of false lumen thrombus at presentation is an important clinical predictor. Our hemodynamic analysis of the false lumen pressure difference offers a potential mechanism of how the difference might affect the outcomes. In the case of distal thrombosis, entry tears to the false lumen will likely remain open. In contrast, distal tears will be obstructed, causing an increase in the false lumen pressure. However, proximal thrombosis is more likely to obstruct these entry tears, reducing the false lumen pressure.

The magnitude and nature of shear stress in the false lumen were quantified using time-averaged wall shear stress and oscillatory shear index. These are known to affect the endothelium and have been related to the outcomes for abdominal aortic aneurysms.[25,26] Our analysis showed no significant relationship between the false lumen oscillatory shear index or time-averaged wall shear stress and outcomes, suggesting such a relationship might not exist for TBAD.

Nearly one half of all patients with acute complications had experienced visceral or limb malperfusion and one third experienced either rapid aortic expansion or aortic rupture (Table III). These hard endpoints are well-established markers of complicated TBAD and account for most of the interventions required within the first year. In our cohort, adverse aortic events had occurred within the first 2 months after presentation, supporting the findings that most of these will occur in the acute (14 days) or subacute (90 days) phase.[27] With few late

Table IV. Clinical predictors of acute complications and 1-year adverse aortic events after acute TBAD

Variable	Likelihood ratio	95% CI	*P* value
Acute complications (14 days; logistic regression analysis)	OR		
Proximal thrombosis	0.17	0.04-0.60	.01
Age (per 10-year increment)	0.91	0.53-1.54	.73
Male sex	1.10	0.27-4.39	.89
Aortic diameter (per 5-mm increment)	1.30	0.71-2.64	.43
Systolic blood pressure (per 10-mm Hg increment)	0.91	0.68-1.23	.55
Diastolic blood pressure (per 10-mm Hg increment)	1.03	0.61-1.69	.92
Adverse aortic events (1-year; Cox proportional hazard model)	HR		
Proximal thrombosis	0.36	0.16-0.80	.01
Age (per 10-year increment)	1.00	0.97-1.03	.79
Male sex	1.45	0.65-3.26	.37
Aortic diameter (per 5-mm increment)	1.00	0.95-1.05	.93
Systolic blood pressure (per 10-mm Hg increment)	0.99	0.98-1.01	.51
Diastolic blood pressure (per 10-mm Hg increment)	1.01	0.98-1.04	.57

CI, Confidence interval; *HR*, hazard ratio; *OR*, odds ratio; *TBAD*, type B aortic dissection.

complications in the present study, a larger cohort is required to assess the value of thrombus classification in predicting late complications.

An increasing aortic diameter is an important indicator for intervention of TBAD.[28-30] However, aortic dissections are dynamic conditions and, unlike aortic aneurysms, the causes of adverse outcomes are multifactorial, beyond the aortic diameter alone. In our cohort, an increasing aortic size at presentation was associated with the occurrence of acute complications. However, the difference did not reach statistical significance. The aortic diameter as used in clinical practice is a unidimensional metric that fails to capture the full extent of aortic expansion and how unique TBAD morphology creates different hemodynamic loads on the false lumen wall. A need exists for more tailored risk prediction beyond the aortic size alone. Our data suggest that considering the thrombosis patterns of the false lumen could improve risk prediction beyond the use of conventional clinical parameters and the aortic diameter alone.

Study limitations. First, although, to the best of our knowledge, the present study is the largest computational hemodynamic study of TBAD to date, a larger study is still required to generalize our findings in a wider cohort. Second, 10 patients without a reported adverse aortic event were last seen for follow-up <1 year from presentation. It is possible that some of these patients could have presented to another center because of an event. Third, CTA has previously been shown to overestimate the thrombus volume compared with delayed-phase MRI.[31] However, MRI is rarely performed for patients with acute aortic dissection owing to the limited availability and lengthy image acquisition times required. Hence, despite the overestimation of thrombus burden, CTA remains the most readily accessible imaging technique for early risk stratification after acute aortic dissection. Overestimation of the thrombus burden does not influence categorization of false lumen thrombus morphology. The sensitivity of our reconstruction methods to the imaging phase (arterial and venous) was low. The thrombus reconstructions from both phases for three patients had a mean difference of 9% by volume. Fourth, for the patients with complete thrombosis of the false lumen, no contrast perfusion could occur in the false lumen (22 patients). Thus, the false lumen could not be reconstructed, and although some pressurization of the thrombosed false lumen could have been present, a comparison between the true and false lumen pressures was not possible. Patients with full thrombosis, however, are considered hemodynamically stable and are not generally considered for repair. Fifth, a number of assumptions were required for our CFD models, ranging from rigid aortic walls to experimental validation. These aspects have been discussed in detail in the Supplementary Methods. Sixth, because these patients had presented to a tertiary referral center, some bias could have been present toward complicated cases of TBAD. Seventh, the anticoagulation status of the patients was not recorded but could have feasibly affected the presence of false lumen thrombosis. Finally, 1 year of follow-up is insufficient to capture the medium- and long-term outcomes after TBAD. It is possible that longer follow-up will reveal further prognostic relationships between the hemodynamic metrics, aortic morphology, and clinical events.

CONCLUSIONS

To the best of our knowledge, the present study is the largest to assess aortic hemodynamics after acute TBAD and the first to describe the potential mechanism by which false lumen thrombus morphology influences the clinical events. Classifying partial thrombosis of the false lumen as either proximal or distal thrombosis was associated with the hemodynamic assessment results and clinical risk prediction. The presence of proximal false lumen thrombosis at presentation has emerged as the strongest clinical predictor of both reduced perfusion pressure in the false lumen and favorable short-term and 1-year outcomes. A reduction in false lumen pressure, which occurs in patients with proximal false lumen thrombosis, appeared protective against acute complications and adverse aortic events at 1 year. We believe that false lumen thrombosis should be studied in greater detail to better understand the patient-specific prognosis of TBAD.

The data underlying the present study are available on reasonable request to the corresponding author.

AUTHOR CONTRIBUTIONS

Conception and design: LP, BR, BM, NS, HE, PN, BD
Analysis and interpretation: LP, BR, BM, LK, NS, HE, PN, BD
Data collection: LP, BR, MS, SR
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Critical revision of the article: LP, BR, MS, BM, SR, LK, NS, HE, PN, BD
Final approval of the article: LP, BR, MS, BM, SR, LK, NS, HE, PN, BD
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Overall responsibility: LP, BD

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SUPPLEMENTARY METHODS (online only).

Computational fluid dynamics simulation details. The computational meshes were constructed using previously reported methods[1] and were tested for numerical accuracy using the grid convergence index (GCI).[2,3] The patient-specific heart rate, height, and weight data were used to adjust the inlet waveform for each patient. The body surface area was calculated from the height and weight and used to calculate the expected cardiac output.[4,5] The generalized waveform was then scaled to reflect the calculated cardiac output.[6] For cases for which this information was not available, the average aortic flow for the entire cohort was applied. Windkessel models were applied to mimic the effect of the distal arterial bed at all outlets, and patient-specific systolic and diastolic blood pressure measurements were used to calculate the pressure waveforms. The renal arteries were assigned unique Windkessel parameters to account for the lack of retrograde flow observed.[7] Blood was modeled as a non-Newtonian fluid using a Carreau-Yasuda rheological model.[8] Data were automatically extracted from predefined regions of interest for each geometry (Supplementary Fig 2, online only).

With the exception of surface seven, all GCI values were <2%, indicating that the values obtained from the finest mesh (6M cells) approached the asymptotic solution (Supplementary Fig 2, online only). The GCI for surface 7 was <10%, likely owing to its close proximity to the boundary. These results were still within a reasonable range of the theoretical exact solution. Any resulting inaccuracies in the shear stress calculations were negligible, given that all observations were made about the false lumen and true lumen as a whole. The GCI for the lumen surface as a whole was 1.08%. The wall shear stress over the cardiac cycle, oscillatory shear index, low and oscillatory shear, and false lumen pressure were extracted from the models.

Limitations to computational fluid dynamics. Our computational fluid dynamics model required certain assumptions. First, modeling an elastic structure such as the aorta is challenging in this scenario because incorporating the aortic material properties and wall thickness to the model adds complexity and additional unknown variables to the analysis. Thus, we opted to simplify our model by treating the aortic wall and dissection flap as a rigid wall using previously well-established techniques.[9-12] Furthermore, we did not perform experiments to directly validate our computer model, because this work had been performed previously by several independent groups in the context of type B aortic dissection. Each group found good agreement between the computer models and physical experiments[13-16] and, recently, four-dimensional magnetic resonance imaging.[17] It is not known how the agreement between rigid wall CFD and experimental or imaging results might differ across morphologic groups. However, before adopting the use of the false lumen thrombosis as a prognostic marker of outcome, it would be worthwhile to measure the false lumen pressure during an interventional procedure for comparison with the CFD predictions. However, attempts at such measurements were not possible in our retrospective study.

Thrombus reconstruction from arterial and venous imaging phases. We quantified the variability in thrombus reconstruction when using the arterial and venous phases of computed tomography angiography for three patients. The thrombus volumes obtained from the arterial and venous phases were 40,311 mm^3, 58,477 mm^3, and 21,658 mm^3 and 43,242 mm^3, 42,063 mm^3, and 24,491 mm^3, respectively, for a mean difference of 9% across the three patients. This was not a consistent over- or underestimation. For all three patients, the morphologic categorization using thrombus location and amount was unaffected.

Repeatability of three-dimensional reconstructions. Despite the complexity of the type B aortic dissection geometries, we found good repeatability of the volume and surface area measurements from our three-dimensional reconstructions (Supplementary Table, online only) indicating low interanalyst differences.

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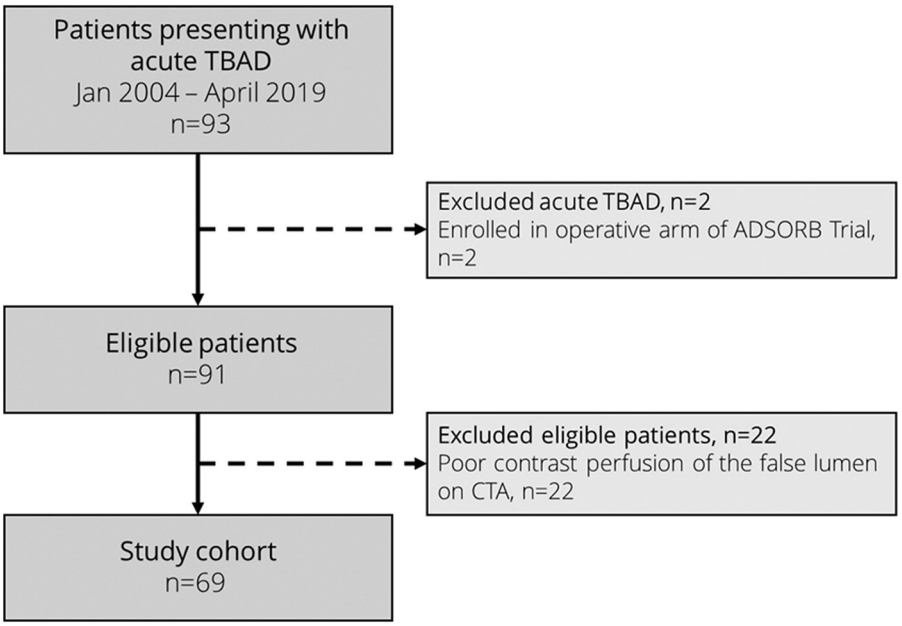
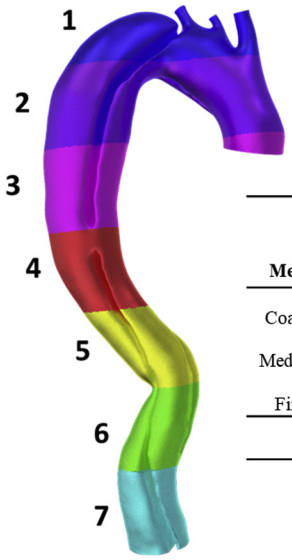
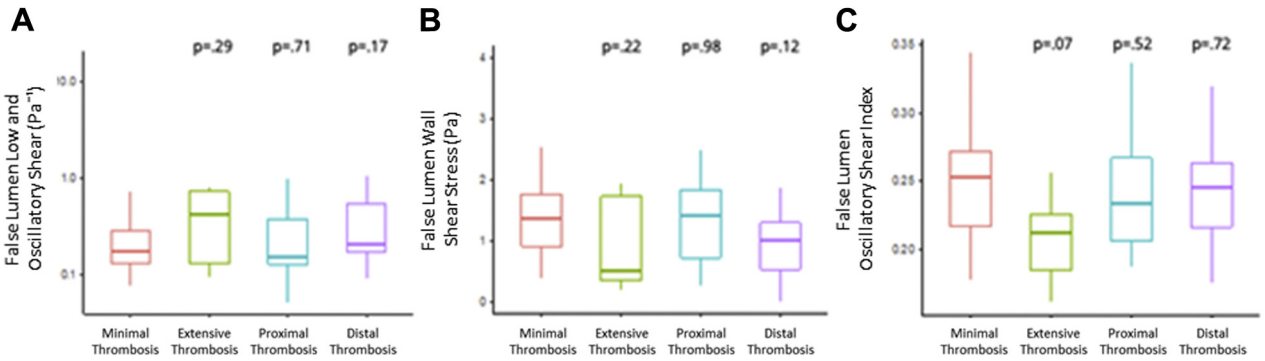


Supplementary Fig 1 (online only). Flow diagram of the patients included in the study. *ADSORB,* Acute Dissection Stent Grafting or Best Medical Treatment; *CTA,* computed tomography angiography; *TBAD,* type B aortic dissection.



		Surface							Whole
Mesh	Cells	1	2	3	4	5	6	7	Surface
Coarse	1,783,208	13.36	9.01	7.29	8.95	7.24	12.72	7.09	9.69
Medium	3,489,343	13.64	9.35	7.56	9.17	7.51	12.89	7.40	9.98
Fine	6,053,992	13.56	9.30	7.47	9.20	7.58	12.93	7.26	9.88
	GCI (%):	0.39	0.11	1.21	0.05	0.32	0.11	9.59	1.08

Supplementary Fig 2 (online only). Mesh independence study. *GCI,* Grid convergence index.



Supplementary Fig 3 (online only). Difference in hemodynamic metrics. Low and oscillatory shear **(A)**, time averaged wall shear stress **(B)**, and oscillatory shear index **(C)** in the false lumen of each group.

Supplementary Table (online only). Reconstruction repeatability (results for three reconstructions of same case by three different analysts)

Analyst	Volume, mm^3	Error, ϵ %	Surface area, mm^2	Error, ϵ %
1	417,340	2.19	81,519	1.05
2	349,755	14.36	74,334	7.86
3	458,137	12.18	86,165	6.81
Average	408,410	9.57	80,672	5.24