Anatomic and hemodynamic investigation of an occluded common carotid chimney stent graft for hybrid thoracic aortic aneurysm repair

Rosamaria Tricarico, PhD,* Yong He, PhD,b,c Roger Tran-Son-Tay, PhD,a,d Liza Laquian, MD,c
Adam W. Beck, MD,* and Scott A. Berceli, MD, PhD,a,b,c Gainesville, Fla; and Birmingham, Ala

ABSTRACT

We examined the possible reasons for common carotid artery chimney stent graft occlusion through computational fluid dynamics analyses of follow-up imaging of a patient-specific aortic configuration reconstructed from computed tomography aortography. Anatomic and hemodynamic parameters were extracted for the bilateral common carotid and subclavian arteries before and after endograft placement. Results suggested that postoperative reduction in lumen diameter within the chimney stent graft combined with an increased flow rate led to complex hemodynamics with high wall shear stress, probably resulting in high-shear thrombogenesis and chimney stent graft occlusion 2.6 years after the primary repair. Early postoperative duplex ultrasound imaging might help identify at-risk conditions. (J Vasc Surg Cases and Innovative Techniques 2019;5:187-194.)

Keywords: Chimney stent graft; Common carotid artery; Postoperative stent graft occlusion; TEVAR; Hybrid thoracic aortic aneurysm repair

The chimney stent graft technique has been increasingly used to treat thoracic aortic aneurysms or dissection involving arch great vessels.1-7 Despite the potential benefits, chimney stent graft failure is a common complication.8,9 Among the mechanisms of failure, stent graft collapse or occlusion has been observed.10 We present analyses of a failed left common carotid artery (LCCA) chimney stent graft performed in conjunction with thoracic endovascular aortic repair (TEVAR), examining the patient-specific anatomic and hemodynamic parameters associated with chimney stent graft thrombosis. Consent for publication was obtained from the patient.

METHODS

Clinical data. The patient, a 68-year-old woman, is a tobacco user with a history of coronary artery disease, chronic obstructive pulmonary disease, and hypertension. She initially presented with an asymptomatic 4.8-cm-diameter descending thoracic aneurysm. After 2.5 years, she developed a 6-cm-diameter aneurysm with acute chest pain.

Preoperative computed tomography angiography (CTA) identified a proximal landing location just distal to the innominate artery origin. Therefore, a TEVAR procedure involving coverage of the left subclavian artery (LSA) and LCCA, with an LCCA chimney stent graft and LCCA to LSA bypass, was performed. The aneurysm was repaired with two Gore CTAG devices (45 × 200 mm and 45 × 150 mm; W. L. Gore & Associates, Flagstaff, Ariz). The bypass used an 8-mm knitted Dacron graft. A Viabahn stent graft (7 × 50 mm; W. L. Gore & Associates) was used as the LCCA chimney stent graft and supported with an Atrium iCAST device (8 × 38 mm; Atrium Medical, Hudson, NH). The stent graft overlap was 1.5 cm in length and located 2 cm distal to the LCCA origin. LSA embolization was performed with an Amplatzer II device (10 mm; Abbott, Redwood City, Calif) by direct puncture of the LCCA to LSA graft. The distal landing zone was proximal to the celiac artery. Completion aortography demonstrated successful cessation of flow into the aneurysm and no evidence of LCCA stenosis. She awoke neurologically intact and was stable. One-year CTA confirmed patency of the chimney stent grafts and bypass. A 2.6-year visit showed occluded LCCA stent graft. LCCA (Supplementary Fig 1), and LCCA to LSA bypass with retrograde flow from the left vertebral artery to the LSA. However, she had no significant symptoms, and no additional interventions were warranted. At 3.5 years, she was admitted to the hospital with dizziness, which resolved without intervention. The last CTA study was performed at 4 years, and she continues to be...
asymptomatic with a stable aneurysm diameter and no endoleak. LCCA revascularization has been discussed but not pursued, given a lack of significant symptoms.

Anatomic and hemodynamic investigation. Patient-specific aortic geometries were reconstructed from preoperative and postoperative (1 year and 2.6 years) CTA scans to characterize the anatomic and hemodynamic changes (Fig 1, A). The hemodynamics preoperatively and at 1 year postoperatively was investigated because a corresponding duplex ultrasound study provided flow rate boundary conditions of the aortic arch branches for computational fluid dynamics (CFD) analysis (Fig 1, B). The flow rate of ascending aorta was not measured, and therefore it was estimated from the patient’s body surface area. The hemodynamics were simulated in ANSYS Fluent software (ANSYS Inc, Canonsburg, Pa) under rigid wall conditions. Flow was assumed to be laminar and pulsatile; additional details of CFD simulations and the methodology of parameter extraction have been reported previously. Distribution of total pressure and wall shear stress (WSS)-related parameters are presented in this study. Maximum WSSs were analyzed to detect areas at risk of high-shear.
thrombogenesis. Conversely, large relative residence time, the combination of high oscillatory shear index (OSI) and low time-averaged WSS, identifies a low-velocity recirculation region at risk of low-shear thrombogenesis.

RESULTS
The total measured blood flow to the upper body (as the sum of bilateral common carotid artery, subclavian artery, and vertebral artery flow rates) increased 10% from preoperatively to 1 year postoperatively (Supplementary Table). Whereas the total blood flow to the right carotid and subclavian arteries decreased 14%, the total blood flow to the left carotid and subclavian arteries increased 45% from preoperatively to 1 year postoperatively despite the increased local resistance of the LCCA proximal to the bypass anastomosis. Compared with preoperative measurements, the LCCA showed a 75% decrease of cross-sectional area at 1 year (Fig 2, A) because of overlapping layers of stent graft within the LCCA or reduced LCCA stent graft expansion secondary to compression of the overlying aortic stent graft. In contrast, the right common carotid artery (RCCA; Fig 2, B) and subclavian arteries (Supplementary Fig 2) demonstrated no appreciable change in cross-sectional areas through 1 year. She was taking aspirin 81 mg before TEVAR and was prescribed clopidogrel (Plavix) after the procedure. No new medications were started when the narrowed stent graft was identified.

Such variations in anatomy and flow distribution were associated with major changes in the 1-year postoperative hemodynamics. The presence of the carotid-subclavian bypass resulted in increased flow through the proximal LCCA chimney stent graft compared with the native LCCA before repair. In combination with the reduction of cross-sectional area, this created a 7.7-fold higher peak systolic total pressure drop from preoperatively (1.4 mm Hg) to 1 year postoperatively (12.2 mm Hg) throughout the proximal stented LCCA segment (Fig 3, A). Correspondingly, the LSA showed a lower pressure at 1 year postoperatively compared with preoperatively secondary to the larger pressure drop across the LCCA chimney bypass graft circuit (Supplementary Fig 3, A). In comparison, the total pressures along the RCCA and right subclavian artery were fairly stable (Fig 3, B; Supplementary Fig 3, B).

Notable changes in the LCCA and LSA biomechanical forces were observed at 1 year postoperatively. Maximum WSS within the LCCA reached a peak of 50 Pa locally (Fig 4, A) compared with lower values observed in the RCCA and bilateral subclavian arteries. Whereas low OSI values were observed in the bilateral common carotid arteries and LSA, the larger OSI (>0.2; Fig 4, B) along the right subclavian artery was caused by the high diastolic flow reversal in this artery (Fig 1). Conversely, large areas of high relative residence time (>10 1/Pa; Fig 4, C) were found in the left vertebral artery origin because of diameter enlargement and flow recirculation. WSS-based parameters along the common carotid and subclavian arteries are provided in Supplementary Fig 4.

DISCUSSION
This study suggests that postoperative narrowing of the lumen and the resulting complex hemodynamics might have contributed to local activation of the high-shear thrombogenesis pathways and led to the occlusion of the LCCA chimney stent graft. This speculation is supported by a study reporting that WSS higher than 18 Pa, such as that detected along the stented LCCA, induces platelet activation and local thrombus formation. Moreover, a multivariate analysis of chimney endovascular aneurysm repair shows that occlusion rates increase with small target vessels, such as in this LCCA chimney case, in which the chimney stent graft might have been undersized and contributed to its failure. In our previous publication, we examined a series of juxtarenal endovascular aneurysm repairs to identify specific geometric and hemodynamic parameters that are associated with chimney stent graft occlusion. We
believe that similar parameters may be beneficial in predicting future failure; however, the number of available aortic arch cases is currently insufficient to develop validated parameters for such predictions.

CONCLUSIONS
The challenging anatomy of an aortic arch chimney stent graft, particularly coupled with procedures such as common carotid-subclavian artery bypass grafting, can result in complex hemodynamics not observed in the normal vasculature. We propose that careful evaluation through postoperative CTA and duplex ultrasound imaging, supported by hemodynamic analysis, may pre-emptively detect sites at risk for future occlusion. With technologic evolution and new solving algorithms, CFD analyses will be able to provide predictive data for optimizing surgical TEVAR strategies.

REFERENCES
1. Hiraoka A, Chikazawa G, Tamura K, Totsugawa T, Sakaguchi T, Yoshitaka H. Clinical outcomes of different approaches to aortic arch disease. J Vasc Surg 2015;61:88-95.
2. Lioupis C, Abraham CZ. Results and challenges for the endovascular repair of aortic arch aneurysms. Perspect Vasc Surg Endovasc Ther 2011;23:202-13.

3. Pecoraro F, Lachat M, Cayne NS, Pakeliani D, Rancic Z, Puippe G, et al. Mid-term results of chimney and periscope grafts in supra-aortic branches in high risk patients. Eur J Vasc Endovasc Surg 2017;54:295-302.

4. Seike Y, Matsuda H, Fukuda T, Inoue Y, Omura A, Uehara K, et al. Total arch replacement versus debranching thoracic endovascular aortic repair for aortic arch aneurysm: what indicates a high-risk patient for arch repair in octogenarians? Gen Thorac Cardiovasc Surg 2018;66:263-9.

5. Mangialardi N, Serrao E, Kasemi H, Alberti V, Fazzini S, Ronchey S. Chimney technique for aortic arch pathologies: an 11-year single-center experience. J Endovasc Ther 2014;21:312-23.

6. Ohrlander T, Sonesson B, Ivancev K, Resch T, Dias N, Malina M. The chimney graft: a technique for preserving or rescuing aortic branch vessels in stent-graft sealing zones. J Endovasc Ther 2008;15:427-32.

7. Voskresensky I, Scali ST, Feezor RJ, Fatima J, Giles KA, Tricarico R, et al. Outcomes of thoracic endovascular aortic repair using aortic arch chimney stents in high-risk patients. J Vasc Surg 2017;66:9.e1-9.

8. Scali ST, Feezor RJ, Chang CK, Waterman AL, Berceli SA, Huber TS, et al. Critical analysis of results after chimney endovascular aortic aneurysm repair raises cause for concern. J Vasc Surg 2014;60:865-73; discussion: 873-5.

9. Pecoraro F, Veith FJ, Puippe G, Amman-Vesti B, Bettex D, Rancic Z, et al. Mid- and longer-term follow up of chimney and/or periscope grafts and risk factors for failure. Eur J Vasc Endovasc Surg 2016;51:664-73.

10. Xue Y, Sun L, Zheng J, Huang X, Guo X, Li T, et al. The chimney technique for preserving the left subclavian artery in thoracic endovascular aortic repair. Eur J Cardiothorac Surg 2015;47:623-9.

11. de Simone G, Devereux RB, Daniels SR, Mureddu G, Roman MJ, Kimball TR, et al. Stroke volume and cardiac output in normotensive children and adults. Assessment of relations with body size and impact of overweight. Circulation 1997;95:1837-43.

12. Tricarico R, He Y, Laquian L, Scali ST, Tran-Son-Tay R, Beck AW, et al. Hemodynamic and anatomic predictors of renovisceral stent-graft occlusion following chimney endovascular repair of juxtarenal aortic aneurysms. J Endovasc Ther 2017;24:880-8.

13. He Y, Terry CM, Nguyen C, Berceli SA, Shiu YT, Cheung AK. Serial analysis of lumen geometry and hemodynamics in human arteriovenous fistula for hemodialysis using magnetic resonance imaging and computational fluid dynamics. J Biomech 2013;46:165-9.

14. Casa LD, Deaton DH, Ku DN. Role of high shear rate in thrombosis. J Vasc Surg 2015;61:1068-80.

15. Himburg HA, Grzybowski DM, Hazel AL, LaMack JA, Li XM, Friedman MH. Spatial comparison between wall shear stress measures and porcine arterial endothelial permeability. Am J Physiol Heart Circ Physiol 2004;286:H1916-22.
**Supplementary Fig 1.** Ultrasound imaging at 2.6 years. On duplex ultrasound examination, no flow was detected into the left common carotid artery (LCCA) at the middle location and minimum and disturbed flow rate was detected at the distal location because of thrombosed artery. No blood flow was detected into the bypass.

**Supplementary Fig 2.** Cross-sectional area in the subclavian arteries. **A,** Left subclavian artery (LSA). **B,** Right subclavian artery (RSA). The blue line indicates values along the bypass (BYP) length. **Post-op1,** At 1 year postoperatively; **Post-op2,** at 2.6 years postoperatively. **Pre-op,** preoperatively.
**Supplementary Fig 3.** Total pressure analysis. Absolute values of total pressure along the brachiocephalic and subclavian arteries. **A,** Left subclavian artery (LSA). **B,** Brachiocephalic artery (BCA)-right subclavian artery (RSA). The gray line indicates values along the BCA length. *BYP,* Bypass; *Post-op1,* at 1 year postoperatively; *Post-op2,* at 2.6 years postoperatively. *Pre-op,* preoperatively.

**Supplementary Fig 4.** Hemodynamic outcomes at preoperative and postoperative times. **A,** Maximum wall shear stress (MAX WSS); **B,** oscillatory shear index (OSI); and **C,** relative residence time (RRT) are shown as circumferential averages along bilateral common carotid and subclavian arteries. The left common carotid artery (LCCA) and left carotid-subclavian bypass occluded at 2.6 years postoperatively (Post-op2). The blue line indicates values along the bypass (BYP) length. *LSA,* Left subclavian artery; *RCCA,* right common carotid artery; *RSA,* right subclavian artery. *Pre-op,* preoperatively; *Post-op1,* at 1 year postoperatively.
### Supplementary Table. Flow rate distribution into the arteries of interest during the analyzed time window

| Artery  | Preoperatively, mL/min | Postoperatively at 1 year, mL/min |
|---------|------------------------|----------------------------------|
| RCCA    | 445                    | 359                              |
| RSA     | 317                    | 119                              |
| RVA     | 19                     | 191                              |
| LCCA    | 279                    | 382                              |
| LSA     | 204                    | 342                              |
| LVA     | 66                     | 72                               |
| Estimated CO | 4626              |                                   |

CO, Cardiac output; LCCA, Left common carotid artery; LSA, left subclavian artery; LVA, left vertebral artery; RCA, right common carotid artery; RSA, right subclavian artery; RVA, right vertebral artery.

*The cardiac output was estimated from patient-specific body surface area.*