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Computational Fluid Dynamics of Time-Shift Changes of the Crushed Elephant Trunk in the Remote Postoperative Period

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Abstract

A 67-year-old man who had undergone total arch replacement (TAR) using the conventional elephant trunk (ET) technique for acute aortic dissection 10 years ago was admitted owing to congestive heart failure with severe aortic valve regurgitation. Mechanical ventilation and dialysis were required. Computed tomography (CT) revealed that the ET in the distal aortic arch was obstructed and the entering flow into the false lumen emerged beside the distal end of the ET, which had not been found for a decade. He underwent thoracic endovascular aortic repair (TEVAR) to relieve the cardiac afterload. The patient was discharged 20 days postoperatively, free from heart failure and renal dysfunction. We investigated the time-shift morphologic changes of ET through computational fluid dynamics (CFD) analysis. It illustrated that accelerated blood flow and wall shear stress (WSS) were effectively alleviated following TEVAR. Additionally, the accelerated flow and excessive WSS were noted at the time of the TAR procedure 10 years ago, which may have influenced the new ulcer-like projection (ULP).

Keywords: Computational fluid dynamics; Acute aortic dissection; Elephant trunk obstruction

Introduction

Although the frozen elephant trunk (ET) technique has recently flourished in treating various aortic diseases, the classical ET technique was once used to facilitate central anastomosis in two-stage surgery for the treatment of extensive aortic disease. The elephant is a freely extended arch prosthesis, and its length is recommended not to exceed 7-8 cm to prevent flexion [1]. The necessity and timing of two-step surgery exhibit case-specific variability. However, we experienced a case of crushed ET, which induced severe aortic valve regurgitation (AR) with cardiogenic shock and multiple organ failure at 10 years postoperatively. To clarify this condition, we used computational fluid dynamics (CFD) to retrospectively analyze the computed tomography (CT) images to capture the 10-year time-shifting changes in blood flow dynamics and morphogenesis.

Case Presentation

The 67-year-old man was admitted to our hospital with congestive heart failure. He had undergone total arch replacement (TAR) using the conventional ET and stepwise anastomosis technique for a DeBakey 1 thrombosed type of acute aortic dissection 10 years ago. The ET was 20 mm of woven vascular prosthesis (J-graft, Japan Lifeline Inc., Tokyo, Japan), with a 5 cm insertion length in the true lumen of the aortic distal arch. The proximal graft of TAR was 26mm (J graft, Japan Lifeline Inc., Tokyo, Japan). Transthoracic echocardiography was performed to diagnose severe aortic valve regurgitation. Non-invasive positive pressure ventilation and inotropic agents were initiated but the congestion got worse. Transesophageal echocardiography detected accelerated blood flow and stenotic lumen at the distal aortic arch. The maximum flow velocity was 4.7 cm/s and the pressure gradient was 88 mmHg, measured by the echocardiography. The enhanced CT revealed that the ET at the distal aortic arch was crushed (Figure 1), the false lumen was partially thrombosed, and the enhanced antegrade blood flow got into the false lumen beside the end of the ET graft, which had not been observed since TAR procedure performed over a decade ago (Figure 2). The ET deformation was not observed immediately following TAR. The severe stenotic ET increased the cardiac afterload and caused AR, which in turn led to impaired organ perfusion. Congestive heart failure and multiple organ failure progressed, requiring mechanical ventilation and continuous hemodialysis and filtration.

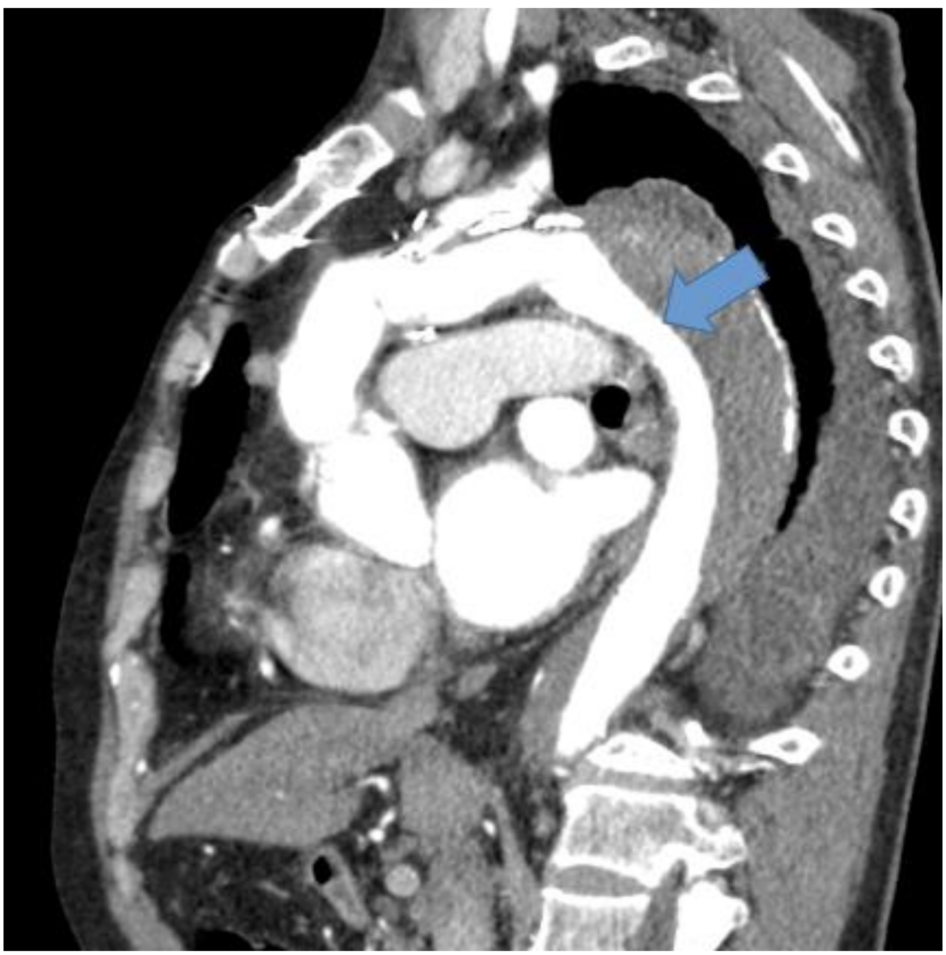

Figure 1: Computed tomography (CT) detected ET stenosis at the distal aortic arch (blue arrow).

Urgent thoracic endovascular aortic repair (TEVAR) was performed. The guide wire was delivered via the right femoral artery and ran through the ET using the pull-through technique. A 28mm conformable TAG device 150 mm in length at the proximal side and a 34mm conformable TAG device 150mm in length at the distal side (W.L. Gore & Associates, Flagstaff, AZ, USA) were deployed and fully covered the ET toward the descending aorta from zone 3. Lower extremity blood pressure and ankle-brachial index notably increased.

The patient was discharged 20 days after the surgery without evidence of heart failure and dialysis. To retrospectively investigate the morphogenetic and flow dynamic changes, we conducted the CFD for the aorta using enhanced CT at the following three phases: (1) immediately after TAR 10 years ago, (2) before TEVAR, and (3) after TEVAR (Figure 3). After TAR for the aortic dissection, the accelerated flow was generated at the distal anastomosis (Figure 3-d), which affected excessive wall shear stress (WSS) near the distal end of the ET graft (Figure 3-g). Ten years later, a new ulcer-like projection (ULP) was detected at the aortic arch, consistent with the previously described high WSS.

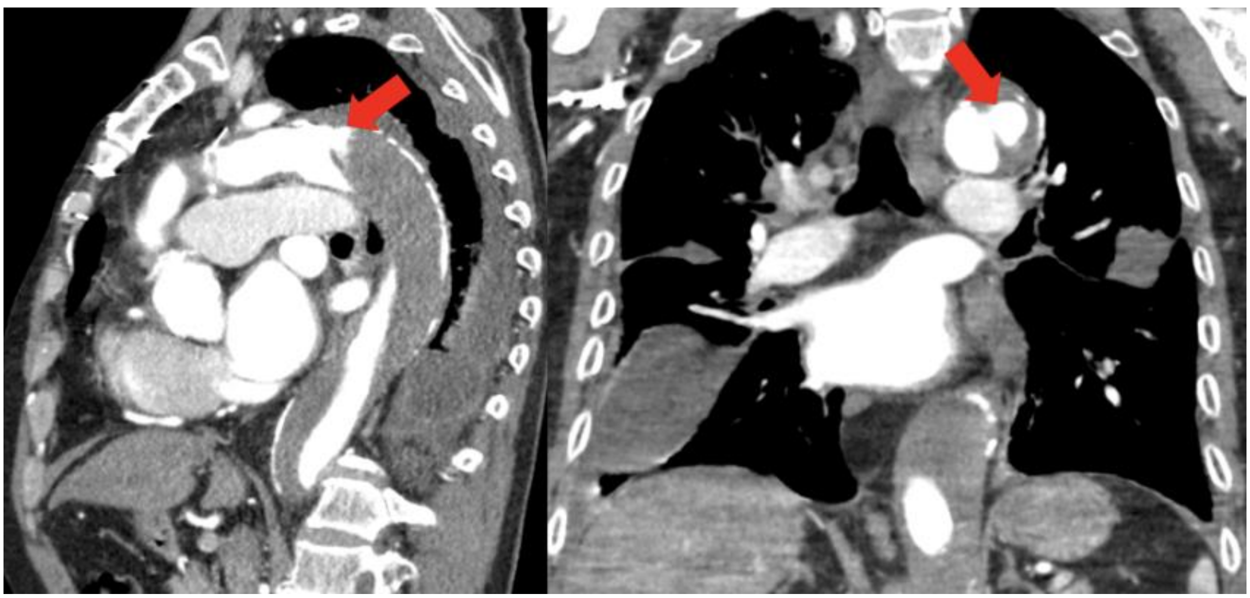

Figure 2: A new ulcer-like projection was detected beside the distal end of ET before TEVAR, which had not been found for 10 years (red arrow).

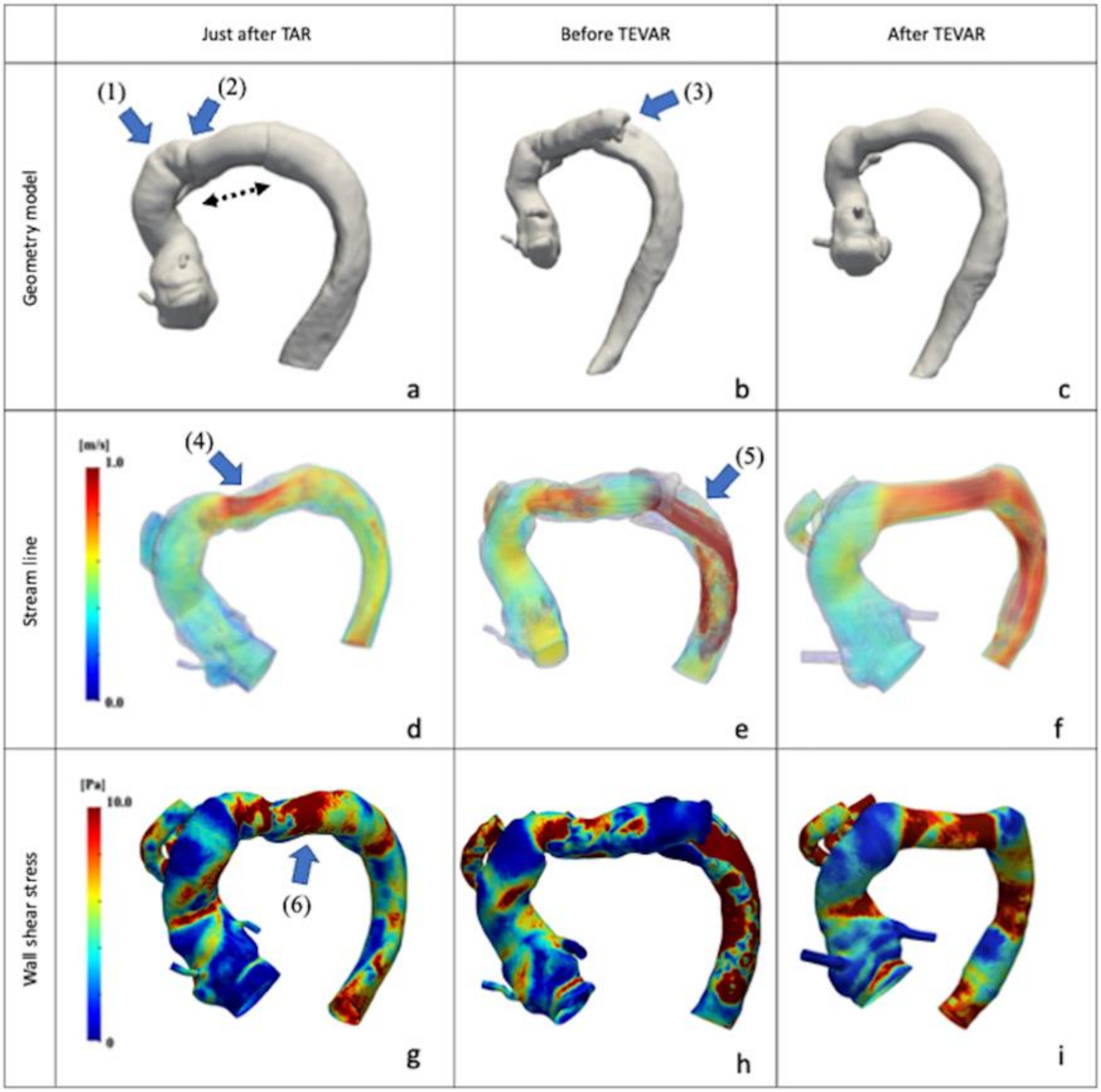

Figure 3: Three perioperative phases are shown with computational fluid dynamics: after TAR 10 years ago (a, d, g), before TEVAR (b, e, h), and after TEVAR (c, f, i). The first row represents the geometry model (a-c), the second shows the streamline (d-f), and the third indicates the wall shear stress. (a) The dotted arrow indicates the ET length. (1) is the graft-graft anastomosis, and (2) is the distal anastomosis. (b) Entering flow into the false lumen emerges near the end of the ET ((3)). (d) High-velocity flow is found at the distal anastomosis line ((4)). (e) The outflow of the ET forward the descending aorta is accelerated ((5)). (g) High wall shear stress is observed at the end of ET ((6)) and is very close to (3).

TAR: Total arch replacement; TEVAR: Thoracic endovascular aortic repair; ET: Elephant trunk

Discussion

Conventional ET has played a significant role in aortic surgeries since Borst and colleagues introduced this technique in 1983 [1]. ET technique in TAR is the placement of an inverted graft into the descending aorta from the distal anastomosis line. To treat the extensive aortic aneurysm and aortic dissection in a single-stage procedure, the replacement of the ascending aorta, aortic arch, and descending aorta requires multiple incisions and prolonged extracorporeal bypass time and aorta clamp time, thereby resulting in high morbidity and mortality. Otherwise, treating these lesions in a stepped surgical approach has the advantage of procedural simplicity for the aorta clamp and graft-graft anastomosis in the second surgical graft replacement [2]. Furthermore, secondary TEVAR is also beneficial following the ET technique. Although TAR with frozen ET is feasible for a single complete treatment of extensive thoracic aortic lesions, intraoperative complications related to frozen ET have been reported, including intimal injuries called stent graft-induced new entry tear [3], spinal cord ischemia [4], and incomplete expansion of the frozen ET [5].

ET in the postoperative course of TAR has been reported to develop stenosis, but most cases are in the early to midterm postoperative phase. Sekine reported ET stenosis-induced hemolytic anemia at five months following TAR for the aortic dissection [6]. The distal anastomosis was removed, and the descending thoracic aortic replacement was performed via left thoracotomy. Anegawa documented a case of ET stenosis on the 83rd postoperative day of TAR, wherein the left ventricular ejection fraction was severely reduced to 10 % owing to increased cardiac afterload [7]. A small native aorta, a relatively large ET graft, and inappropriate anastomotic handling are considered the causes of ET stenosis [6].

Stenosis is rarely detected in the remote period, particularly 10 years later, as in this case. The last contrast-enhanced CT was at 6 months postoperatively following TAR for aortic dissection. At that time, CT did not show communicating blood flow from the true lumen into the false lumen at the aortic arch. Thereafter, plain CT was regularly checked as an outpatient examination for 10 years without aortic dilatation and adverse events.

CFD, an imaging evaluation tool for blood flow hemodynamics, generates equations of fluid dynamics using patient-specific vascular geometries and physiological flow or pressure conditions [8]. It can provide blood flow streamline, pressure in the specific area, and WSS, a well-known parameter of the progression of arterial endothelial degeneration [9]. As the geometric model is developed from the CT image data, CT at the present and the past phases are feasible for image analysis. Therefore, CFD analysis is highly beneficial for evaluating aortic remodeling following aortic surgery as flow dynamics can be investigated over time.

This CFD finding in the present case suggests that the small size of the ET graft diameter may cause high-velocity flow at the exit of the ET, resulting in excessive WSS at the aortic arch wall beside the distal end of the ET (Figures 3-d,3-g). Ten years later, a new ULP emerged distally in the ET, proximal to the aortic segment that previously exhibited elevated WSS (Figures 3-b, 3-g). The ULP at this tear may have increased the false lumen pressure and compressed the ET in the true lumen. In addition, the distal end of the ET was located at the aortic arch curvature, which may have contributed to the WSS development. The larger and longer ET graft or the translocation of the distal anastomosis line to locate the end of the ET in the descending aorta could have prevented ET stenosis in the remote postoperative period.

It is not clear when the ULP came out at the aortic arch. The patient who had undergone surgical treatment for aortic dissection, especially TAR with ET, should be followed up for a long time during the postoperative period with contract-enhanced CT performed at least once a year as aortic findings following aortic dissection surgery may change in the remote period as in the present case. Furthermore, the experience of CFD analysis in this case is anticipated to guide future studies in determining the optimal size and length of the ET for aortic morphology.

Conclusion

We experienced a case of ET obstruction in the remote postoperative period. The stenosis was successfully relieved by TEVAR, leading to the treatment of congestive heart failure with AR. CFD can analyze images retrospectively using previous CT images and provide temporal changes in blood flow dynamics alongside morphologic information.

Acknowledgment

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