In Situ Laser Fenestration Is a Feasible Method for Revascularization of Aortic Arch During Thoracic Endovascular Aortic Repair

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Background—Reconstruction of the aortic major branches during thoracic endovascular aortic repair is complicated because of the complex anatomic configuration and variation of the aortic arch. In situ laser fenestration has shown great potential for the revascularization of aortic branches. This study aims to evaluate the feasibility, effectiveness, and safety of in situ laser fenestration on the three branches of the aortic arch during thoracic endovascular aortic repair.

Methods and Results—Before clinical application, the polytetrafluoroethylene and Dacron grafts were fenestrated by an 810-nm laser system ex vivo, which did not damage the bare metal portion of the endografts and created a clean fenestration while maintaining the integrity of the endografts. In vivo, 6 anesthetized female swine survived after this operation, including stent-graft implantation in the aortic arches, laser fenestration, and conduit implantation through the innominate arteries and the left carotid arteries. Based on the animal experiments, in situ laser fenestration during thoracic endovascular aortic repair was successively performed on 24 patients (aged 33–86 years) with aortic artery diseases (dissection type A: n=4, type B: n=7, aneurysm: n=2, mural thrombus: n=7). Fenestration of 3 aortic branches was performed in 2 (8.3%) patients. Both the left carotid artery and the left subclavian artery were fenestrated in 6 (25%) patients. Only left subclavian artery fenestration surgery was done in 16 (66.7%) patients. Among these patients, 1 fenestration was abandoned secondary to an acute takeoff of the innominate artery in a type III aortic arch. The average operative time was 137±15 minutes. The technical success rate was 95.8% (n=23). No fenestration-related complications or neurological morbidity occurred after this operation. During a mean postoperative 10-month follow-up (range: 2–17 months), 1 patient died of severe pneumonia, and all the left subclavian artery and carotid artery stents were patent with no fenestration-related endoleaks upon computed tomography angiography images.

Conclusions—In situ laser fenestration is a feasible, effective, rapid, repeatable, and safe option for the reconstruction of aortic arch during thoracic endovascular aortic repair, which might be available to revascularize the 3 branches. However, follow-up periods should be extended to evaluate the robustness of this technique. (***J Am Heart Assoc***. 2017;6:e004542. DOI: 10.1161/JAHA.116.004542.)

Aortic arch arteries diseases involving acute type A or type B aortic dissection and aneurysm are serious vascular challenges.[1] The morbidity and mortality of these diseases are often related to serious complications (such as visceral, renal, and limb ischemia or rupture) at clinical presentation. Thoracic endovascular aortic repair (TEVAR) of aortic arch diseases remains one of the most difficult challenges in vascular surgery because of the deep anatomic configuration of 3 major branches on aortic arches, namely, the innominate artery, left common carotid artery (LCA), and left subclavian artery (LSA).[2,3]

According to the literature, traditional surgical operations include ligation of the LSA, reconstruction of the LSA and LCA, and elective debranching before TEVAR.[4,5] These approaches are complicated and require prolonged operation time. The procedures are also difficult and can increase morbidity and mortality with a combined stroke and death.[6] However, the options in urgent or emergency situations are limited. Increased risks of complications after operations include subclavian steal syndrome, arm claudication, vertebral territory stroke, and spinal cord ischemia because the collateral blood supply to the spinal cord from the vertebral artery is obstructed.[7] According to the literatures, 54% of thoracic aortic tears locate at proximity to the LSA, eliminating the 15- to 25-mm proximal landing zone required by TEVAR.[8] If the distance between the proximal entry tear and the proximal seal zone is less than 15 mm, incomplete endografts implantation to the aortic arch always cause bird-beak configuration, which increases the risk of endoleaks during TEVAR.[9]

Branched and fenestrated endografts represent the most attractive approach to allow elderly patients with concomitant diseases to benefit from endovascular surgery.[10,11] Current delays in gaining designed devices exceed more than 6 weeks, and this latency time may be too long for critically frail patients, particularly those with varying anatomical structures. The technically difficult procedure may limit the applicability of this technology.[12] In addition, during TEVAR the operators need to repetitiously rotate the endograft to ensure that the opening is aligned with the vessel branches, which may increase the risk of stroke. In the previous study, stroke occurred in a high percentage (14%) of patients during graft stent deployment.[13]

In situ fenestration is also a potential technique for LSA and LCA revascularization.[14] Different techniques were developed to create in situ fenestrations: penetration by a needle or the sharp end of a guidewire, use of a radiofrequency probe, or laser-generated fenestration.[14–16] All these techniques present unique advantages and limitations. Both radiofrequency and laser methods are versatile and good techniques that can be used through remote access to various arteries, such as the brachial artery. Murphy et al described an in situ laser graft fenestration of a Dacron (DuPont, Wilmington, DE) endograft to revascularize the LSA during TEVAR of traumatic aortic dissection in a young patient.[17] Ahanchi et al also performed retrograde laser fenestration to revascularize the LSA.[18] As we recently reported, an 810-nm diode laser was used in the last 10 years to treat superficial venous insufficiency and congenital extratruncular venous malformations.[19,20] The diode laser was developed to obtain a more selective action against blood vessels than previous lasers, with selective tertiary hemoglobin peak, and a depth of penetration in the blood of just 0.3 mm.[20] Thus, we try to apply this diode laser to fenestrate the membrane of aortic arch grafts. This relatively simple intraoperative approach of laser-assisted endograft modification presents a rapid and feasible strategy of in situ fenestration of the endograft membrane to revascularize aortic arch branches in thoracic aortic pathologies, which shows great potential to generalize in situ fenestration into clinical application.

In this work, we modified the technical procedure and extended the application of in situ laser fenestration of thoracic aortic pathologies with an early follow-up period of patients after TEVAR.

Methods

Ex Vivo Laser Fenestration on Stent Grafts of Aortic Arches

Prior to clinical application, we evaluated laser fenestration on the polytetrafluoroethylene (PTFE) fabric of TAG stent grafts (W. L. Gore & Associates, Flagstaff, AZ) and Dacron fabric of Talent stent-grafts (Medtronic Vascular, Santa Rosa, CA) in a bench-top experiment model (Figure 1A). A 6F sheath (Terumo Medical Corporation, Somerset, NJ) was placed in the left carotid artery. A 4-mm balloon catheter (Mustang, Boston Scientific, MA) was passed via the sheath followed by an 810-nm optical fiber connecting to a LASEMAR Laser (Eufoton, Italy). The balloon catheter was retracted to expose the distal 0.5 cm of the laser fiber. The laser catheter directly contacts the fabric of the stent graft as perpendicularly as possible by applying energy (Figure 1A). During ex vivo laser application, the laser beam deflected off the nitinol stents of the endograft (Figure 1B). The laser system was calibrated to excite the wavelength of 810 nm with 14 to 18 W of energy and at a pulse duration of 1 s on each trigger (Figure 1C). A proximal fenestration was excited by penetrating the intimal stent toward the inflated balloon catheter (Figure 1D), which was used as a landmark for entry into the lumen. The balloon catheter was dilated to enlarge the stent tear (Figure 1E). This laser guidewire was subsequently switched to a 0.035-inch stiff guidewire, and after balloon dilatation, the fenestration was estimated by general observation to evaluate the feasibility of this method, the shape of the fenestration, the damage to the fabric membrane (Figure 1F), and the feasibility of the fenestration to safely implant a covered stent (Fluency plus; Bard Peripheral Vascular Inc, Tempe, AZ).

In Vivo Laser Fenestration on Aortic Arches After Stent Graft Implant and Image Examinations

All animal procedures were performed in accordance with the Guidelines of the Animal Experiment and Care Committee of Shanghai Jiao Tong University. Under general anesthesia,
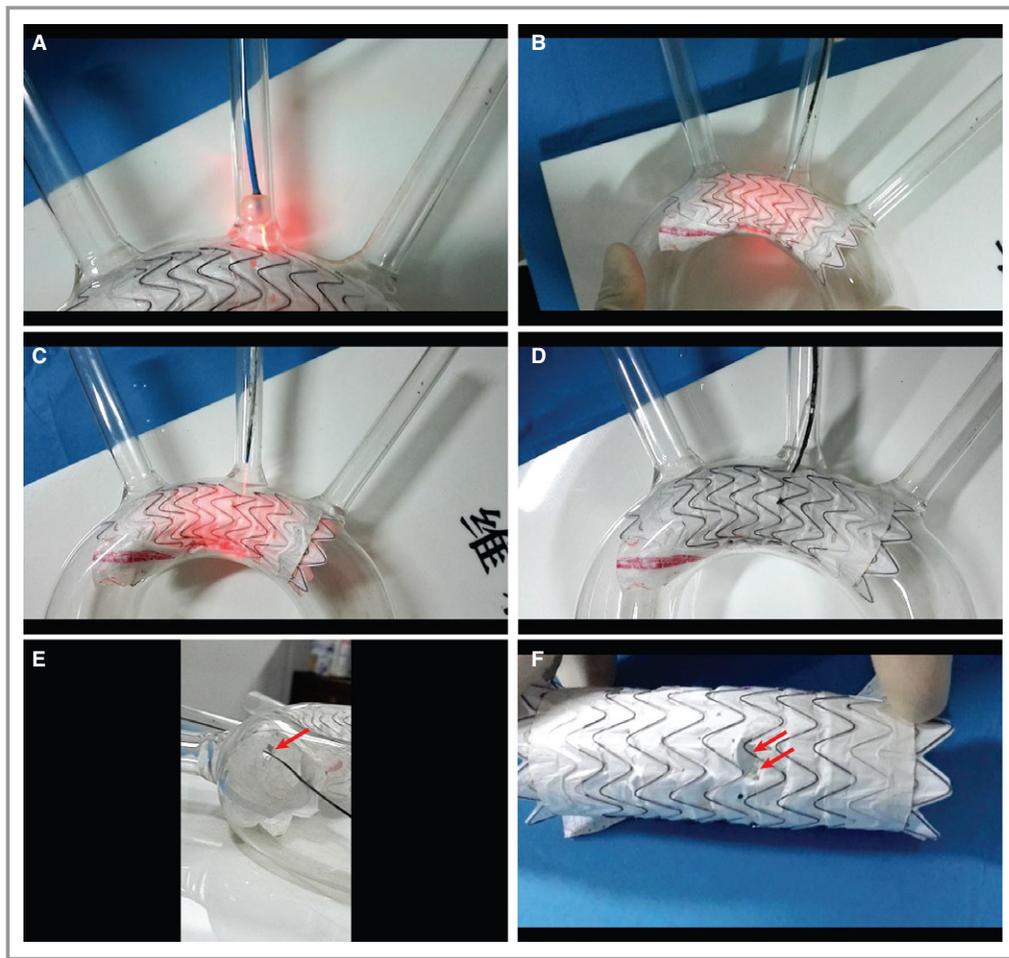
Figure 1. Ex vitro laser fenestration on stent grafts of aortic arches. A, The laser catheter directly contacts the fabric of the stent graft; (B) the laser system was calibrated to excite the wavelength of 810 nm with 14 to 18 W of energy; (C) a proximal fenestration was produced and a balloon catheter, which was used as a landmark for entry into the lumen; (D) dilated with a balloon catheter; (E) general observation of the shape of the fenestration from the side; (F) general observation of the shape of the fenestration from the front.

6 female swine weighing 69±10 kg were sedated (xylazine and ketamine, 5 mg/kg) and anesthetized (isoflurane). Both carotid arteries and the right femoral artery were exposed surgically under sterile conditions and catheterized with 8F sheaths (Terumo Medical Corporation, Somerset, NJ) by using the Seldinger technique. Intravenous heparin 5000 U and 30 U/min drip infusion of heparin were administered. Angiography was performed in the aortic arch artery, and the diameters of the ascending aorta and arch branches were measured. The Talent stent graft was implanted into the ascending aorta and covered the brachiocephalic trunk and the LSA.

An 8F sheath (Terumo Medical Corporation, Somerset, NJ) was placed in the left carotid artery. A 4-mm balloon catheter (Mustang; Boston Scientific, MA) was passed via the sheath followed by an 810-nm optical fiber connecting to a LASEMAR Laser (Eufoton, Italy). The balloon catheter was retracted to expose the distal 0.5 cm of the laser fiber. The laser fiber was positioned close to the intended fenestration location. The 810-nm laser system was calibrated to deliver pulses at 16 W of energy and the pulse duration time was 3 s. A proximal fenestration was created and the laser fiber penetrated into the stent graft. Then the balloon catheter was advanced into the lumen via the fiber, and after confirming the reverse blood flow and balloon dilatation, a 0.035-inch Stiff guidewire was switched. After balloon dilatation, a 7-mm stent graft (Fluency; Bard Peripheral Vascular Inc, Tempe, AZ) was introduced from the left carotid artery and implanted in the fenestration and angiography was performed by digital subtraction angiography (DSA) (Artis zee floor; Siemens Healthineers, Malvern, PA) to estimate the patency of the endograft fenestration.

In Vivo Laser Fenestration on Aortic Arches in Patients

Patient selection

Informed consent was obtained from each patient. The human operation was approved by the hospital Review Board and the Ethics Committee of the Medical Faculty at the Shanghai Jiao Tong University, China. It was a prospective study. Between April 2014 and March 2016, patients with the diagnosis of aortic artery diseases were taken into this study with critical inclusion criteria, including at least one of the aortic branches involvement and intimal tears adjacent to the LSA (less than 15 mm) or the proximal seal zone being less than 15 mm. The exclusion criteria included the following: (1) patients with cardiopulmonary and renal insufficiency who were too weak to undergo general anesthesia (the criteria according to anesthetist); (2) distance less than 15 mm between intimal tears and coronary valve; (3) coronary valve or cardiac vesicle were involved by the dissection. After surgery, technical success, operation times, clinical outcomes, number of fenestrations of the intimal flap per patient, and the complications were also assessed. Routine postoperative follow-up imaging with computed tomography angiography (CTA) was examined to evaluate TEVAR and fenestration patency, endoleaks, and dissection or aneurysm exclusion formation.

Laser fenestration procedure

With patients under general anesthesia, laser fenestration was performed on aortic arches. For the patients with involvement in the LSA only, the right femoral artery and the left brachial artery were sterilized and implanted with 8F sheaths (Terumo Medical Corporation, Somerset, NJ). For the patients with involvement of the LSA and LCA, both carotid arteries and the left or right femoral artery, the left brachial artery, or LSA were exposed surgically under sterile conditions and cannulated with 8F/9F sheaths (Terumo Medical Corporation, Somerset, NJ). Intravenous heparin 5000 U and 30 U/min drip infusion of heparin were administered. A 150-cm 4F pigtail catheter (COOK MEDICAL INC, Bloomington, IN) over a 0.035 inch stiff guidewire (Terumo Medical Corporation, Somerset, NJ) was advanced to the ascending aorta. The diameters of the ascending aorta and arch branches were measured using angiography and CTA. An 8F and 55 cm Cook sheath (COOK MEDICAL INC, Bloomington, IN) was introduced over a stiff wire to the origin of the LSA. The thoracic endograft was deployed across the LSA orifice or the carotid arteries in accordance with the preoperative assessment. Both of the catheters (COOK MEDICAL INC, Bloomington, IN) were advanced until the endograft was reached. A coaxial technique with a 7F/8F, and 55-cm double-curve guiding sheath (LifeTech Scientific Corporation, Shanghai, China) was used occasionally to achieve angulation and directional control.

Thoracic endografts were deployed by utilizing Talent or Valiant (Medtronic Inc, Santa Rosa, CA), or TAG (W. L. Gore & Associates, Flagstaff, AZ) stent grafts. After the thoracic endograft was deployed, a 4×40-mm balloon catheter (Mustang; Boston Scientific, MA) followed by an 810-nm optical fiber was gently advanced to close to the thoracic endograft. Then laser energy application was performed for 3 s with 14- to 18-W energy to create fenestration. The laser energy was activated, and an in situ fenestration was created, thus directing the flow to the carotid artery. Either the whole laser fiber or the wire was passed through the newly created fenestration. A proximal fenestration was created and the balloon catheter was advanced into the true lumen over the fiber. After confirming the reverse blood flow, balloon dilatation was performed to enlarge the fenestration. A 0.035-inch Stiff guidewire was exchanged and after endograft predilation using a 8-mm balloon (Mustang; Boston Scientific, MA), a covered stent ($10-16$ in diameter, Fluency plus; Bard Peripheral Vascular Inc, Tempe, AZ) was deployed through the fenestration into the endograft lumen and four fifths into the branch vessel. An angioplasty balloon with diameter of 10 to 16 mm was typically used to "flare" the branch stent-grafts portion. Completion DSA angiography was performed to demonstrate aortic stent and LSA or carotid fenestration patency. After the appropriate procedures, the incisions were closed. CTA was performed at 3, 6, and 12 months postsurgery to evaluate the fenestration patency, endoleaks, and aneurysm, as well as dissection exclusion.

Statistical Analysis

All of the patients underwent TEVAR with LSA or carotid fenestration as described. Patient demographics, morphologic presentation of aortic arch arteries, operation information, clinical outcomes, complications, and follow-up data were analyzed by SPSS 18.0 software. Data are expressed as mean values±SD).

Results

Ex Vivo In Situ Laser Fenestration on Stent Grafts of Aortic Arches

No tearing of the fabric was observed after the dilation of the laser fenestration tear in the PTFE and Dacron stents (Figure 1). The results were replicated in our facility to demonstrate the feasibility and effectiveness of in situ laser fenestration (Figure 1). Care was taken to establish the direct contact of the laser fiber with the stent graft and as perpendicularly as possible to the stent before the laser system was calibrated to excite the wavelength of 810 nm with 14 to 18 W of energy.

During ex vivo application of the laser, the laser energy was deflected off the fabric of the endograft stents. The nitinol stents were examined after in situ laser fenestration, and their integrality and spatial structure remained intact. The results showed a round and clean tear 1 to 2 mm fenestration created within 2 to 3 s by laser energy at a wavelength of 810 nm with 14 to 18 W of energy per second. The shape, structure, and integrity of the fabric maintained the same even after balloon dilation and stent implant (Figure 1F). Our in vitro test on the PTFE and Dacron grafts demonstrated that the laser energy prevented damaging of the integrity of the fabric and the bare metal portion of the endografts, thereby creating a round and clean fenestration while maintaining the gross integrity of the endografts.

In Vivo Laser Fenestration on Aortic Arches During TEVAR and Image Examinations

Only 1 stent was implanted in each pig in the brachiocephalic trunk artery, because of the bicarotid arteries from the brachiocephalic trunk anatomy. Placement of stents was successful in all 6 pigs. DSA images demonstrated that all in situ laser fenestrations were patent in the animals (Figure 2I). All the pigs survived after the surgery with no major complications. After sacrificing the animals, the cohort of animals presented 6 possible access sites of fenestration and stent placement (Figure 2J).

Patient Demographics and Presentation

Twenty-four patients underwent in situ fenestration during TEVAR at our hospital between April 2014 and March 2016 (14 men and 10 women; 68±18 years; range, 33–86 years; type A aortic dissection in 4 patients, acute type B aortic dissection in 11 patients, thoracic aortic aneurysm in 2 patients and 7 had mural thrombus); these patients underwent endovascular total aortic arch repair via in situ fenestration TEVAR from landing zone 0 to zone 4 and then were retrospectively analyzed. Twenty patients presented hypertension, 14 had a history of smoking, 10 had diabetes mellitus, 14 had hypercholesterolemia, 10 had congestive heart failure, 18 had peripheral arteries disease, 10 had congestive heart failure, 8 showed renal insufficiency, which was detected when serum creatinine was >1.5 mg/dL, 8 had chronic obstructive pulmonary disease, and no patients had Marfan syndrome. All the patients complained of symptoms of severe chest and back pain upon admission. Sixteen of the pathological vessels extended into the LSA, 6 of the pathological vessels extended into the LCA, and 2 of the pathological vessels extended into the innominate artery. The mean maximal aortic diameter was 40±8 mm. Six patients had malperfusion, and none of the patients had

aortic valve failure, pericardial effusion, or other complications.

Our institutional TEVAR with in situ laser fenestration was successfully performed in 24 patients (14 men and 10 women, Table). All the patients underwent TEVAR with in situ laser fenestration to revascularize the LSA or LCA or the innominate artery during TEVAR in an urgent or emergency situation. The indications for TEVAR are shown in Table. Four patients had acute symptomatic type A aortic dissection, 11 patients had acute symptomatic type B aortic dissection, 2 patients presented large symptomatic thoracic aortic aneurysms, and 7 patients had intramural hematoma and aortic ulcer. Six patients had stenosis of the LSA. The mean maximal aortic diameter was 40±8 mm (range 30–48 mm).

Operative Data

TEVAR was technically successful in all 24 patients. The average of the 3 endografts (range, 2–5) was implanted during TEVAR. Multiple endografts were placed in 24 patients. Medtronic endografts were solely used in 14 patients, Gore TAG devices were solely used in 8 patients, and LifeTech Scientific Corporation endografts were placed in 2 patients.

One patient who had a bovine arch anomaly underwent zone 2 deployment with in situ LSA fenestration. A zone 2 deployment was used in 16 patients who underwent in situ laser fenestration of LSA (Figure 3). A zone 1 TEVAR placement was used in 6 patients who underwent in situ laser fenestration of LSA and LCA (Figure 4). One patient had acute type A aortic dissection and underwent TEVAR with zone 0 deployment with in situ laser fenestration of LSA and LCA and innominate artery chimney (Figure 5).

The LCA fenestration covered or bare stents ranged from 10 to 16 mm in diameter, and LSA covered stents ranged from 8 mm to 14 mm in diameter. The operative time for TEVAR with in situ laser fenestration was 135±15 minutes, and the mean contrast volume was 154±20 mL (Table). An average of 30 minutes of the total case time was required to achieve innominate artery, LCA, and brachial artery or subclavian artery access.

No perioperative strokes, myocardial infarction, transient ischemic attacks, cerebral infarction, or other neurologic complications occurred. One patient died of severe pneumonia during the postoperative period, leading to the in-hospital mortality rate of 5%. The range of hospital stay was 6 to 33 days. The follow-up time was 2 to 17 months (mean, 10 months). No endoleak was discovered, false lumen thrombosis and subsequent positive remodeling of the aorta were evidenced, and all the in situ laser fenestrated arteries were patent by postoperative follow-up CTA imaging, combined with clinical symptoms.
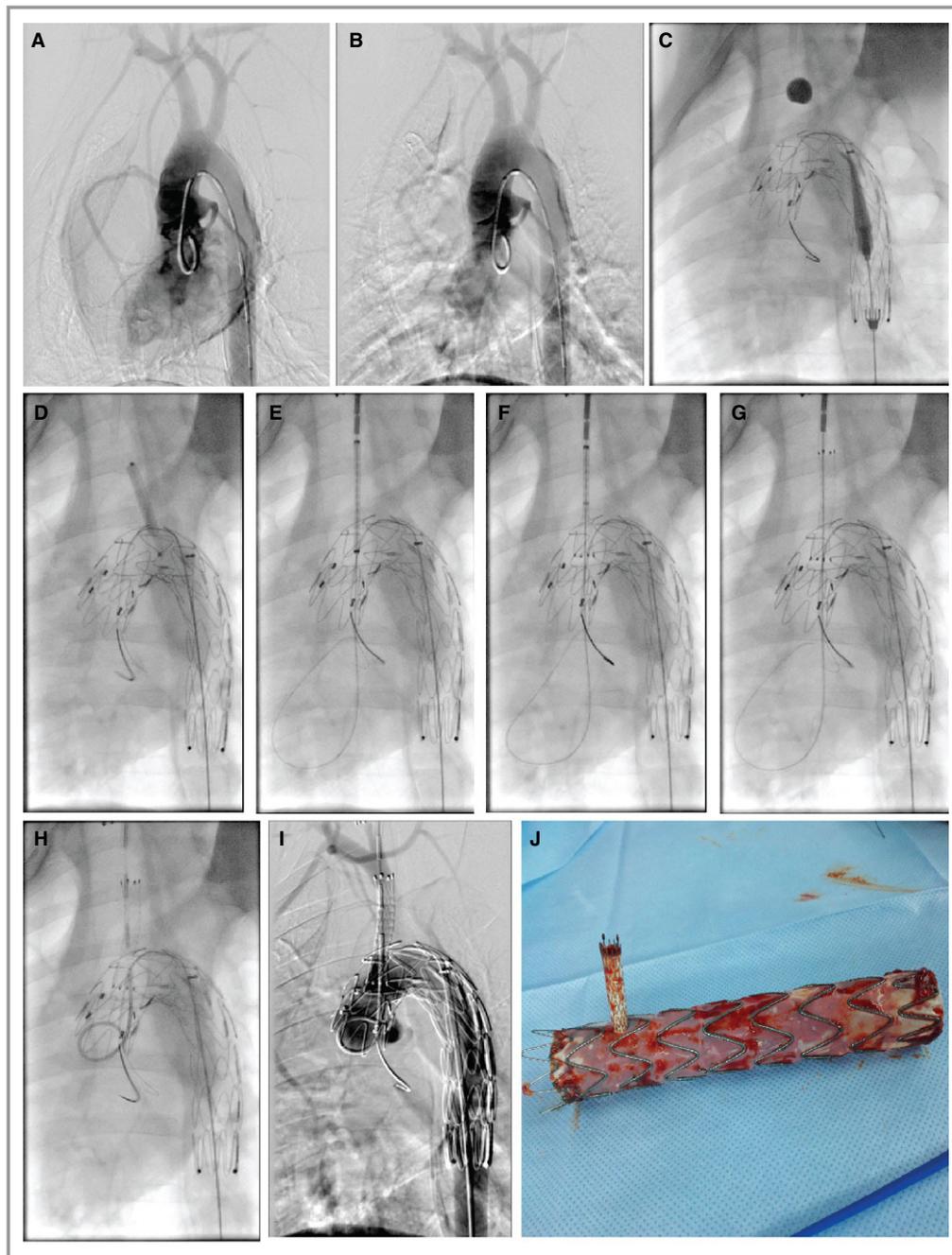
Figure 2. In vivo laser fenestration on aortic arches during TEVAR in pigs. A, aortic angiography in AP view; (B) aortic angiography in left-anterior oblique view; (C) 1 stent was implanted in the aortic arch and in situ laser fenestration; (D) balloon dilatation was performed to enlarge the fenestration; (E) a 0.035-inch Stiff guidewire was exchanged; (F) position of the stent; (G) placement of a stent; (H) pigtail catheter was advanced to the ascending aorta; (I) aortic angiography showed the patency of the aortic arch branches; (J) after sacrificing the animals, the cohort of animals presented possible access sites of fenestration and stent placement. AP indicates anterior-posterior; TEVAR, thoracic endovascular aortic repair.

Discussion

Based on the initial experience of Murphy et al,[17] laser-assisted in situ fenestration during TEVAR was characterized as a treatment for a variety of thoracic aortic pathologies, and our experience showed at least 4 advantages. First, the laser provides a rapid and repeatable method of in situ fenestrating of the endograft membrane. In our in vitro and in vivo experiments, the PTFE and Dacron grafts showed that the laser prevented damage to the integrity of the fabric and the

Table. Baseline Characteristics and Operative Details of 24 Patients With In Situ Laser Fenestrations During TEVAR

Baseline Characteristics	
Age, y	68 (33–86)
Men	14 (58.3%)
Women	10 (41.7%)
Hypertension	20 (83.3%)
Smoking	14 (58.3%)
Diabetes mellitus	10 (41.7%)
Coronary/peripheral artery disease	18 (75%)
Renal insufficiency	8 (33.3%)
Congestive heart failure	10 (41.7%)
COPD	6 (25%)
Operative details	
Proximal diameter, mm	40±8
Proximal landing zone 0/1/2/3	2/6/16/0
Adjacent to the LSA	16 (66.7%)
LSA+LCA	6 (25%)
Three branches	2 (8.3%)
Percutaneous brachial access	83.3%
Fenestrations branch covered stent diameter, mm	10 to 16
Endoleak	0
Operative time, min	135±15
Contrast, mL	154±20
Length of stay, days	17 (6–33)
Stroke	0
Death	4.2%

COPD indicates chronic obstructive pulmonary disease; LCA, left carotid artery; LSA, the left subclavian artery; TEVAR, thoracic endovascular aortic repair.

Figure 3. In situ laser fenestration of LSA during TEVAR. A, CTA showed 1 patient had mural thrombus and ulcer; (B) aortic angiography in left-anterior oblique view; (C) 1 stent was implanted in the aortic arch and in situ laser fenestration; (D) balloon dilatation was performed to enlarge the fenestration and a 0.035-inch Stiff guidewire was exchanged; (E) placement of a stent and aortic angiography showed the patency of the aortic arch branches; (F and G) postoperative CTA presented possible access sites of fenestration and stent placement; (H) cross section of CTA showed that the in situ laser fenestrated LSA were patent. CTA indicates computed tomography angiography; LSA, left subclavian artery; TEVAR, thoracic endovascular aortic repair.

bare metal portion of the endografts, and created a round and clean fenestration while maintaining the gross integrity of the grafts. Second, the diode laser was developed to obtain a more selective action against blood vessels and penetrated ≈0.3 mm into tissues, which expanded TEVAR application with stable and safe procedures. Third, the laser fiber is soft and can pass through various kinds of complex aortic arch anatomy. In situ laser fenestration is a rapid and simple method for the endotreatment of acute aortic lesions involving the branch of the arch. Fourth, no perioperative strokes, myocardial infarction, transient ischemic attacks, cerebral infarction, or other neurologic complications occurred and no endoleak was observed, and all the in situ laser fenestrated arteries were patent either clinically or by postoperative follow-up CTA imaging.

In situ fenestrations were employed for the arch arteries and were reported in both experimental and clinical
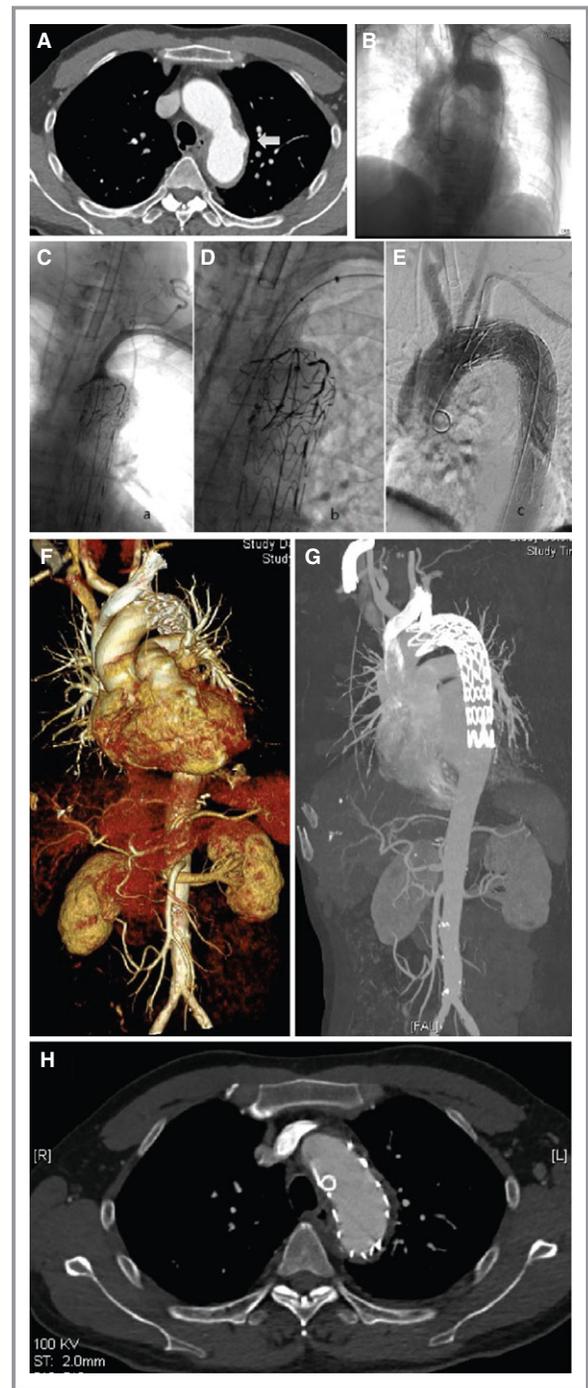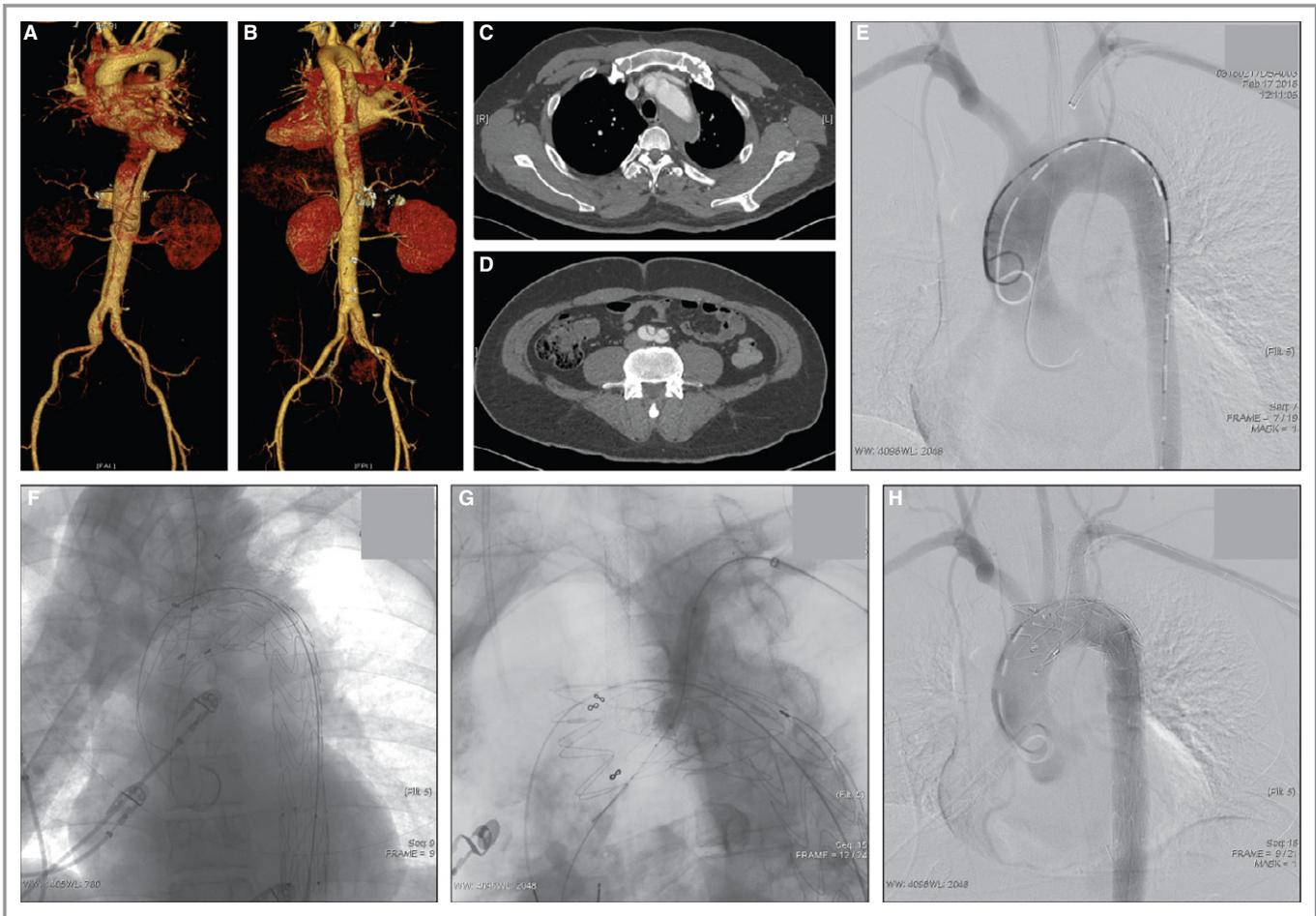
Figure 4. In situ laser fenestration of LCA and LSA during TEVAR. A, CTA showed that 1 patient had aortic dissection involved the LCA and LSA; (B) CTA images in back-anterior oblique view; (C) cross section of CTA showed that the tear involved the LCA and LSA; (D) cross section of CTA showed aortic dissection involved the bilateral iliac artery; (E) aortic angiography in left-anterior oblique view; (F) 1 stent was implanted in the aortic arch and in situ laser fenestration of LCA; (G) LCA stent placement and balloon dilatation was performed to enlarge the fenestration and a 0.035-inch Stiff guidewire was exchanged in LSA; (H) aortic angiography showed the patency of the aortic arch branches. CTA indicates computed tomography angiography; LCA, left carotid artery; LSA, the left subclavian artery; TEVAR, thoracic endovascular aortic repair.

works.[21,22] Different fenestration techniques were reported: radiofrequency probes,[15] the use of needles or sharp guide wire,[13,14,23] in situ retrograde fenestration,[24] and laser.[25] All the techniques demonstrated advantages and disadvantages. A needle or radiofrequency probes work effectively if the distance from the access site to the fenestration site is straight and short, such as a surgically exposed LCA. However, this application is limited for LSA, which often exhibits an acute angle between the origin and the aortic arch.

Alternatives to LSA or LCA coverage including elective bypass to or transposition of the LSA/LCA or implant of branched and chimney grafts.[26] Open LSA and LCA revascularization usually requires longer operative time and presents more risks for artery ischemic attacks, nerve injury, or other neurologic complications. Because branch stent-grafts and patient-customized grafts often require extensive design,

precise intraoperative DSA imaging, and refined manipulation, this application is limited.[27] Furthermore, these modified grafts are often not available for patients with acute thoracic aortic pathologies. Therefore, intraoperative fenestration shows great potential for the revascularization of aortic branches.

Our group was careful in adopting in situ laser fenestration into clinical practice. Both bench and animal experiments characterized in situ fenestration and optimized the techniques. Our data showed that in situ laser fenestrations did not present perioperative strokes, myocardial infarction, transient ischemic attacks, cerebral infarction, or other neurologic complications and no endoleak was observed. Therefore, we assume that this method is sufficiently safe unlike the chimney graft, which can cause gutter endoleaks.
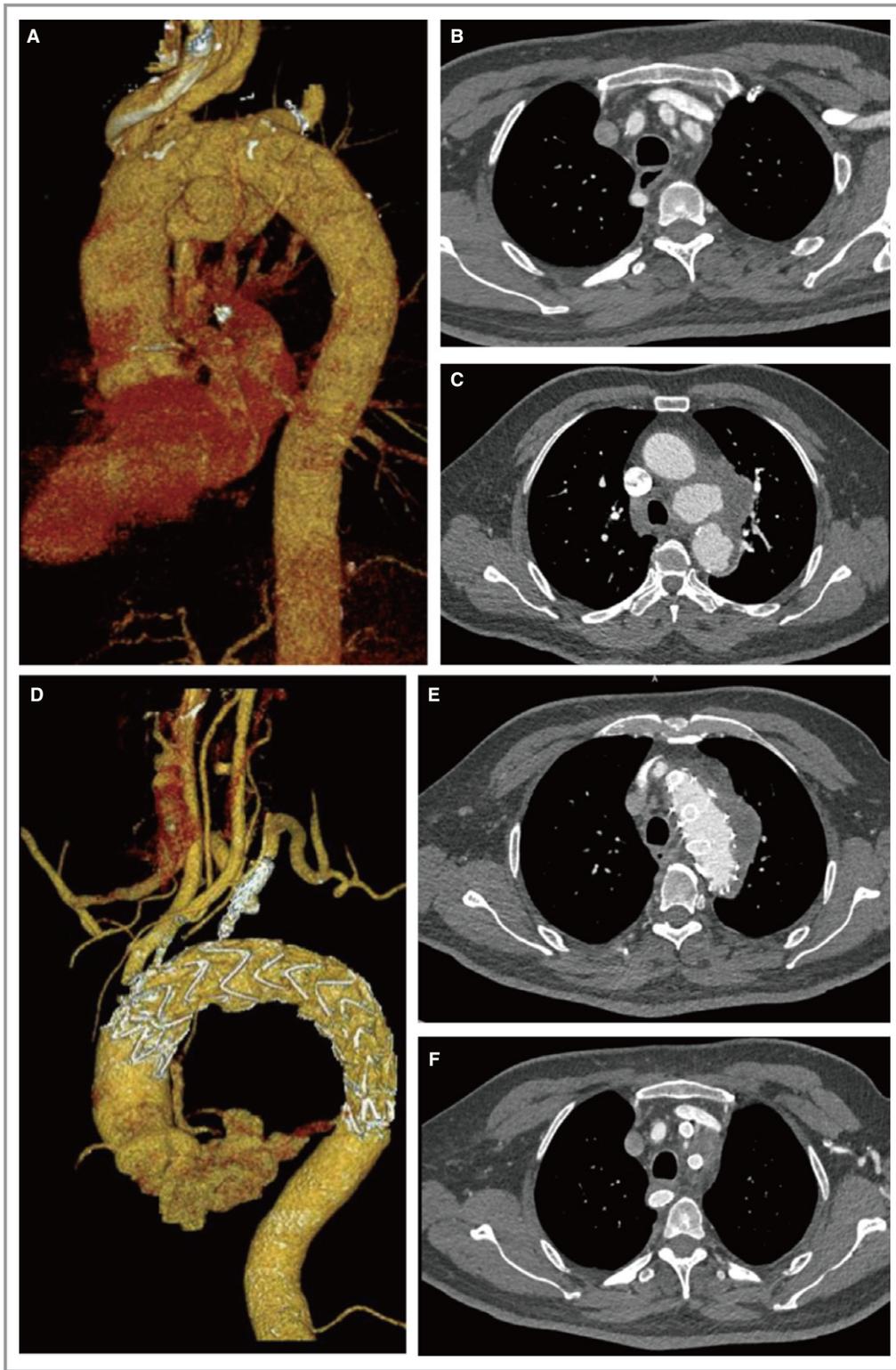
Figure 5. In situ laser fenestration of the innominate artery, LCA, and LSA during TEVAR. A, CTA showed that 1 patient had aortic dissection that involved the innominate artery, LCA, and LSA; (B and C) cross section of CTA showed that the tear involved the innominate artery, LCA, and LSA; (D) postoperative CTA presented possible access sites of 3 branches of fenestration and stent placement; (E and F) cross section of postoperative CTA showed that the in situ laser fenestrations of the 3 branches were patent. CTA indicates computed tomography angiography; LCA, left carotid artery; LSA, left subclavian artery; TEVAR, thoracic endovascular aortic repair.

For cerebral artery ischemia, in the cases of innominate artery and LCA reconstruction, the procedure of the fenestration time is ≈90 s on average. We think this ischemic time is acceptable, as recent research demonstrated cerebral blood flow can be safely interrupted for 5 minutes at room temperature.[22,28] In our procedure, carotid artery occlusion that lasted for 60 s was probably safe.

Patient selection is paramount for in situ fenestrations. A type I arch anatomy exhibits a better approach with a laser fiber located perpendicularly to the graft. This arch decreases the chance that the laser fiber will slip forward proximally from the graft to the aortic arch.[29] According to Riga et al, the quality of in situ fenestrations correlated with a more perpendicular approach.[29] Redlinger et al noted that a type III arch should be better deployed with a chimney graft.[25] The chimney technique can save time for aortic arch type III, compared with laser fenestration to reconstruct the carotid artery. Thus, it was used in 1 patient with the aortic arch type III at the beginning to decrease the risk, when laser fenestration was not so skilled. In the following cases, this problem was solved when laser fenestration was skilled, and an in vitro bypass system was invented and used to ensure cerebral perfusion. An in vitro bypass system will be reported by us in future articles. Our study shows that the use of a balloon-expandable catheter is important for decreasing the chance that the laser fiber may slip forward proximally from the graft to the aortic on type II or III arch anatomy.

The choices of wavelength, energy range, and pulse interval of laser excitation were related to the type and size of the target arteries and graft fabric.[25] Previous researchers have used only 10 W.[30] We suggest that it may be necessary to use 14 to 18W. High laser energy levels can destroy the PTFE and Dacron fabrics completely, which might limit the potential ischemia time to <2 minutes during operations. The diode laser was used to treat superficial venous insufficiency and congenital extratruncular venous malformations, as we recently reported.[19,20] The diode laser was developed to obtain a more selective action against blood vessels than previous lasers, which operate at wavelengths of 940 or 810 nm, with selective tertiary hemoglobin peak, and a depth of penetration in the blood of just 0.3 mm.[31,32] An 810-nm diode laser beam will penetrate ≈0.3 mm into tissues. Thus, we applied this approach to fenestrate the membrane of aortic arch grafts. In situ laser fenestration offers many potential benefits over surgical operation, and no major complications, such as perioperative strokes, transient ischemic attacks, or other neurologic complications, were observed. In summary, in situ laser fenestration represents a breakthrough in treating the complicated aortic pathologies, and further research is under way with our collaborators to confirm its long-term safety and patency.

Conclusion

This study demonstrates that in situ laser fenestration is a feasible, effective, rapid, repeatable, and safe technique for the reconstruction of the branches on aortic arch during TEVAR in complicated and emergency patients with a spectrum of thoracic aortic pathologies, even for the 3 branches. The high technical success, low morbidity and mortality, and good early patency expanded this application to more patients with stable and safety procedures. Our experience demonstrates that in situ laser fenestration is an effective and safe approach when patients are selected appropriately. Future prospective studies, including standardized clinical procedures, DSA and CTA imaging follow-up data, and fluid mechanics change will be useful in further evaluating the role of this modification in treating aortic arch arteries during TEVAR.

Sources of Funding

Disclosures

None.

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