

Case Report

The Effect of Left Subclavian Artery Coverage During Endovascular Repair of the Thoracic Aortic Aneurysm on Cerebral Hemodynamics: Two Cases of Flow Measurement by using 2D Phase Contrast Magnetic Resonance Imaging

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The proximity of thoracic aortic aneurysm to the left subclavian artery (LSA) has made the coverage of LSA during thoracic endovascular aortic repair (TEVAR) be essential. Despite controversy concerning the safety of LSA coverage and the indications for LSA revascularizations, the cerebral hemodynamic change after LSA coverage has not been demonstrated. We prospectively examined two patients who would undergo TEVAR with LSA coverage by using 2D cine phase contrast MR imaging. After LSA coverage, the left subclavian steal was properly compensated by the increased flow volumes of both carotid arteries and right vertebral artery, which is the major collateral supply. The total brain supply after TEVAR did not lessen, which showed good correlation with uneventful clinical outcome. Therefore, 2D phase contrast MR imaging can be recommended as a useful technique to evaluate the hemodynamic change of the LSA coverage during TEVAR and to triage the candidate for LSA revascularization.

Index words : Aortic aneurysm · Thoracic endovascular aortic repair (TEVAR) · Left subclavian artery (LSA)
2D cine phase contrast MR imaging · Subclavian steal

INTRODUCTION

Thoracic endovascular aortic repair (TEVAR) has

• Received; June 7, 2012 • Revised; August 27, 2012

• Accepted; August 28, 2012

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by Ministry of Education, Science and Technology (grant number 20119123). Otherwise, the authors have no conflicts of interests and/or disclosure.

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proven to be an effective option replacing open surgery for treating thoracic aortic lesions including aneurysm, dissection, and blunt traumatic injury (1-6). The aortic arch lesions especially of zone 2 necessitate proximal extension of the stent-graft to achieve an adequate landing zone, and the coverage of left subclavian artery (LSA) becomes essential (2-4). The antegrade flow through LSA may be critical for brain, spinal cord, and arm perfusion, and the concerns on the risk of posterior circulation stroke or vertebrobasilar insufficiency, spinal cord ischemia, and left distal arm ischemia has emerged when LSA is covered. However, the previous reports have offered conflicting data of whether LSA coverage increase risk or

preoperative LSA revascularization reduced the risk of stroke or spinal cord injury (2–6). Furthermore, the hemodynamic feature of LSA coverage has not been demonstrated systematically so far.

2D cine phase contrast MR imaging has been useful to evaluate the variety of cerebrovascular disease and their treatment response including carotid artery stenosis, moyamoya disease, and subclavian steal (7, 8). The quantitative flow data can be obtained within a few minutes of scanning in a noninvasive manner and without contrast agent injection. However, there have been no observations of 2D phase contrast MR imaging describing the hemodynamic change after LSA coverage during TEVAR. In addition, the hemodynamic change of venous drainage and the cerebrospinal fluid (CSF) flux have not been addressed until recently.

In this case report, we present cerebral hemodynamic change of intentional LSA coverage during TEVAR in patients with traumatic aortic dissection or recurrent aortic aneurysm by using 2D cine phase contrast MR imaging.

CASE REPORT

2D cine phase contrast MR imaging

The 2D cine phase contrast MR imaging was prospectively performed in two patients who were waiting for elective TEVAR by using a 1.5-T MR imaging unit (Signa, GE Medical, Milwaukee, WI,

USA) before and 2 days after TEVAR, and the detailed scanning protocols are described at Table 1. The acquisition planes for flow quantification were selected perpendicular to the presumed direction of the flow (Fig. 1). The region of interest (ROI) was manually extracted at each level by using an image processing software (ReportCARD, GE Medical, Milwaukee, WI, USA), and its flow curves of arterial, venous and CSF were generated versus time over the 30 segments of one cardiac cycle (Fig. 2). The flow volumes (FVs) of artery, vein, and CSF were recorded in mL/min, and the FVs of total cerebral blood flow (F_{VTCBFs}) were calculated as sum of both internal carotid arteries (ICA) and both vertebral arteries (VAs) at the level between first and second cervical spine (C1-2) or basilar artery (BA) at midbasilar artery (MBA) level. The arteriovenous transit time (AVTT) was defined as the difference between the time points (msec) that arterial and venous curve meet maximal slope.

Patient 1

A 76-year-old man had multiple fractures of left ribs, left scapular, left femur after bike accident. He complained of chest pain, and 3D chest CT angiography showed Stanford type B aortic dissection at arch distal to LSA origin (Fig. 3). There were left side hemothorax and hemoretroperitoneum. He had no neurologic deficit at admission. He had no previous history of hypertension or diabetes mellitus. Blood pressure was 80/50, and pulse rate was 110. Cerebral

Table 1. Scanning Parameters of 2D Cine Phase Contrast MR Imaging

	Imaging Protocol	
Scanner	A 1.5-T MR imaging unit (Signa, GE Medical, Milwaukee, WI, USA)	
Timing Points	Before and 2 days after TEVAR	
Sequence	2D fast cine phase contrast with retrospective peripheral gating	
Parameters	Echo time, Repetition time	4.4–7.1 msecs, 12.0–14.5 msecs
	Flip angle	28°
	Field-of-view	28 mm ²
	Matrix	256 × 128
	Velocity encoding	80 cm/sec for the arteries and veins 15 cm/sec for the aqueduct 5 cm/sec for the cervical subarachnoid space

Note.— TEVAR, thoracic endovascular aortic repair.

CT angiography show no cerebral vascular abnormality. The posterior communicating artery was not seen, and the diameter of left side VA appears to be larger than that of right side. TEVAR with LSA coverage was designed in consideration of the location of aortic dissection near to LSA. A spinal catheter was inserted at third lumbar space to monitor CSF pressure to be under 10 mmHg. Heparin of 100 units per body weight (kg) was administered intravenously. Procedures were performed under general anesthesia in an operation suite equipped with a C-arm machine

(Series 9800, OEC Medical Systems, Salt Lake City, Utah, USA) having fluoroscopic and angiographic capabilities. The pig tail catheter through 5F right femoral sheath was used to monitor lesion segment and landing zone. A 24 × 110 mm-sized endovascular stent-graft (S & G biotech, Sungnam-si, Korea) through 18F right femoral access was advanced, and the distal end of stent-graft was employed to cover LSA. Preoperative LSA revascularization or coil placement to prevent retrograde flow or endoleak was not performed. On angiogram immediately after

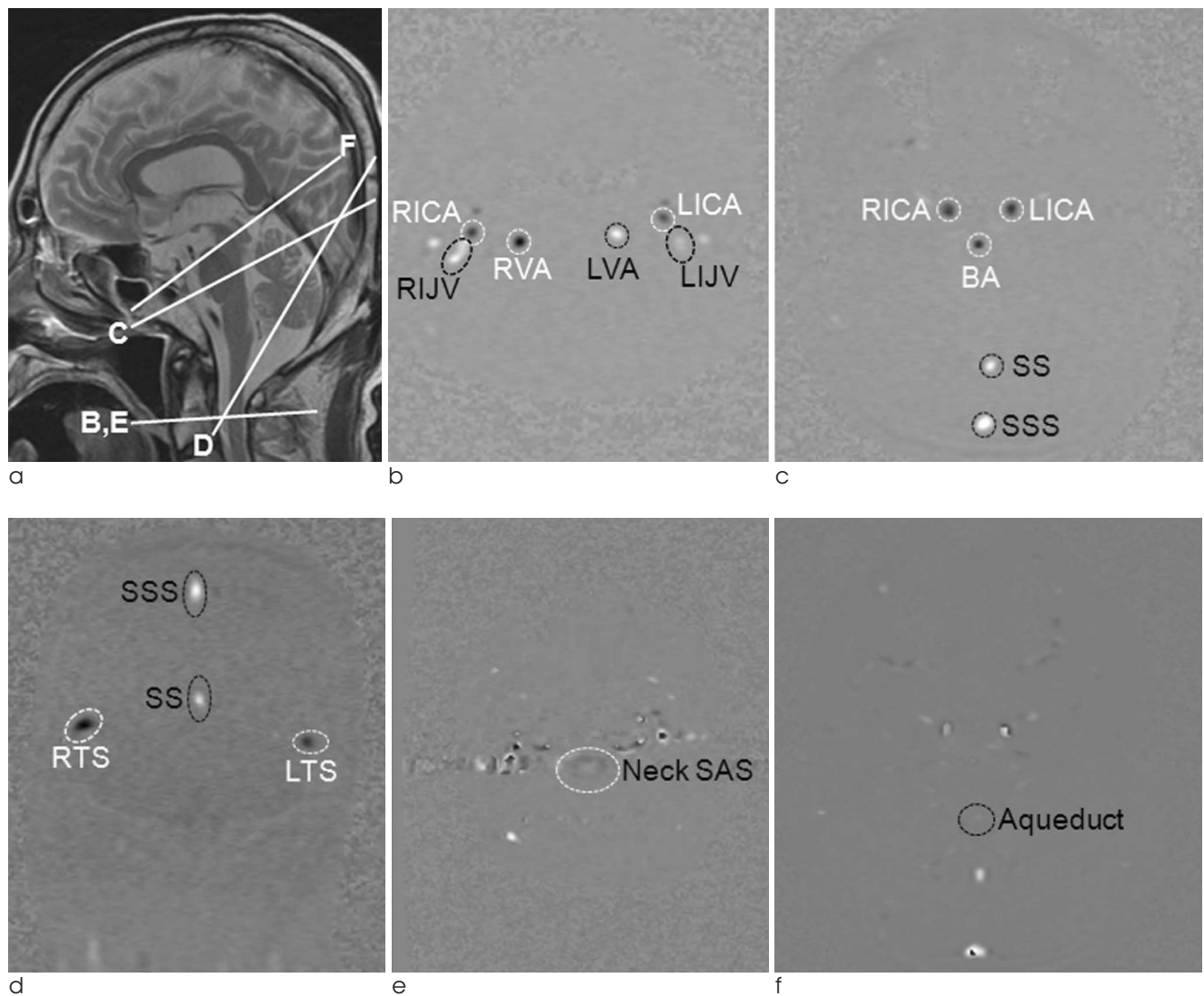


Fig. 1. Scanning protocol of 2D cine phase contrast MR imaging and data extraction. (a) T2-weighted midline sagittal scan was used as localizers to select the anatomic levels for flow quantification. Ellipsoid region of interest was drawn on each arteries and veins of C1-2 (b) and midbasilar artery level (c). The same process was done for venous drainage at coronal scan (d), for cervical subarachnoid space of C1-2 level (e), and for cerebrospinal fluid at aqueduct (f). RICA, right internal carotid artery; LICA, right internal carotid artery; RVA, right vertebral artery; LVA, left vertebral artery; RIJV, right internal jugular vein; LIJV, left internal jugular vein; BA, basilar artery; SS, straight sinus; SSS, superior sagittal sinus; RTS, right transverse sinus; LTS, left transverse sinus; SAS, subarachnoid space.

TEVAR, aortic dissection was successfully excluded from vascular lumen, and the origin of LSA was covered.

The FV_{TCBF} after TEVAR were 109.2% of those before TEVAR at C1-2 level and 105.9% at MBA level, respectively (Table 2). The flow direction of left VA was reversed, and the FV of right VA (FV_{RVA}) was 698.31% of those before TEVAR. The FVs of BA ($FV_{BA_{MBA}}$), right ICA ($FV_{RICA_{MBA}}$) and left ICA ($FV_{LICA_{MBA}}$) at MBA level after TEVAR was 83.03%, 111.04%, and 120.85% of those before TEVAR, respectively. The FVs of axial SS+SSS ($FV_{SS+SSS_{ax}}$), coronal SS+SSS ($FV_{SS+SSS_{cor}}$), both side TS (FV_{TS}), and both side IJV (FV_{IJV}) were 107.7%, 90.06%, 85.37%, and 134.18% of those before TEVAR, respectively. The baseline FV of CSF at C1-2 level ($FV_{CSF_{C1-2}}$) and at aqueduct ($FV_{CSF_{aqueduct}}$) showed

caudocephalad direction in averaging. The $FV_{CSF_{C1-2}}$ decrease in volume, and the $FV_{CSF_{aqueduct}}$ changed into craniocaudal direction in averaging after TEVAR. The AVTTs after TEVAR were slightly shortened as compared to the AVTTs before (the change of AVTT ≤ 100 msec; Table 3).

The patient was assessed for neurologic and left arm symptoms, and did not show sign of paraplegia or cerebral ischemia. He was uneventful for 6 months of follow-up period, and 6 months follow-up CT angiography showed stable occlusion of aortic aneurysm.

Patient 2

Type A intramural hematoma was detected in a 61-year-man with acute onset back pain and dyspnea, and graft replacement of ascending aorta was performed for it six months ago. On six months

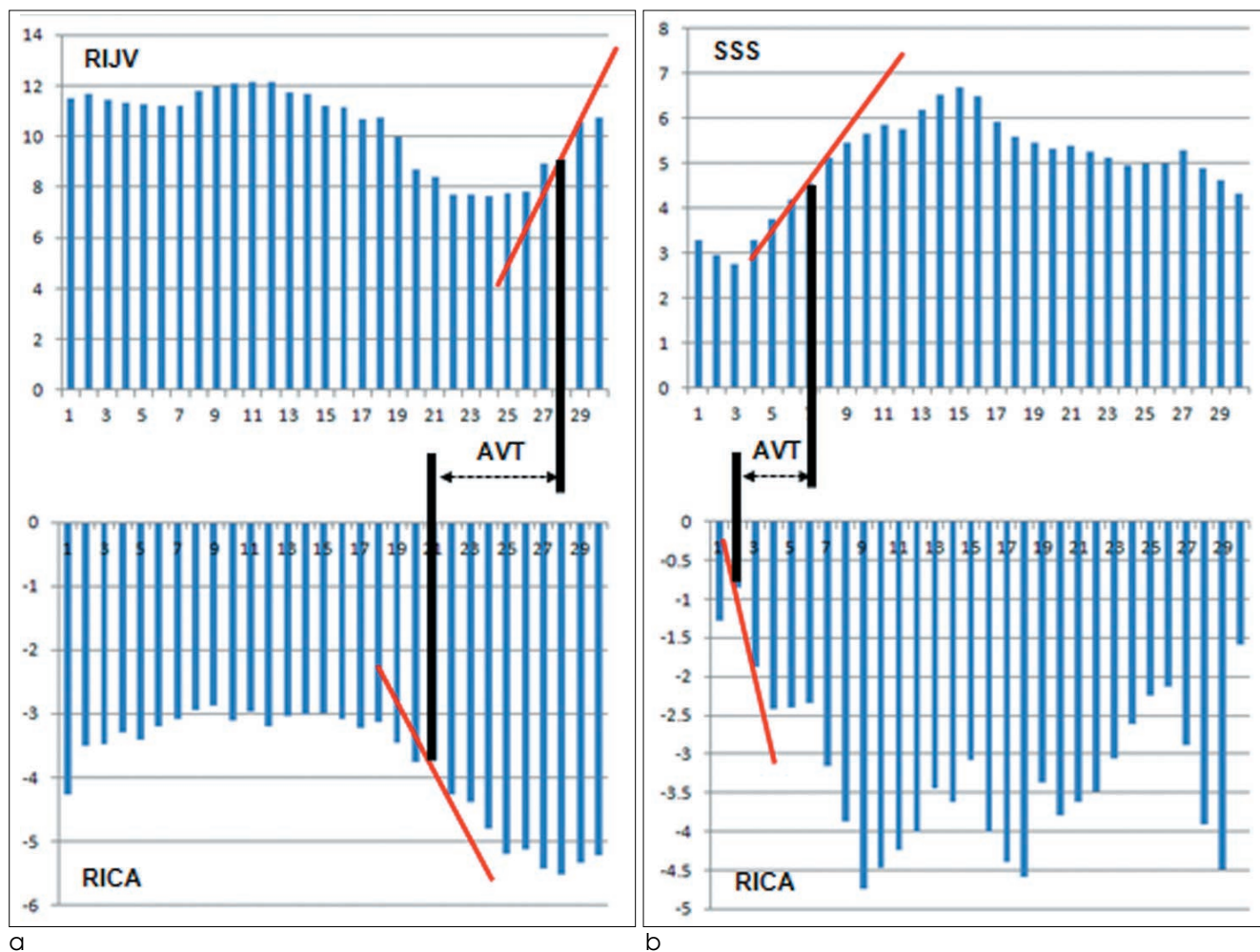


Fig. 2. Generation of time-volume curves and the definition of arteriovenous transit time (AVTT). AVTT is defined as the difference of the time points between arterial and venous curve meet its maximal slope (msec) at C1-2 level (a) and midbasilar artery level (b). RICA, right internal carotid artery; RIJV, right internal jugular vein; SSS, superior sagittal sinus.

follow-up 3D CT angiography, a 35 × 20 mm-sized aneurysmal sac was newly found at distal aortic arch (Fig. 4). Cerebral MR angiography before TEVAR revealed no significant cerebral vascular abnormality and paralleling both side VAs. He had controlled diabetes mellitus. Blood pressure was 100/70, and heart rate was 76. Under general anesthesia, a spinal catheter was placed to monitor CSF pressure. Procedures were performed in C-arm machine along with the systemic heparinization of 100 units per body weight (kg). The pig tail catheter via left femoral

access was used to measure lesion length and landing zone. A 35 × 130 mm-sized endovascular stent-graft was delivered via 18F right femoral access. The proximal and distal landing zone was confirmed on fluoroscopy with contrast injection, and the distal end of stent-graft was deployed to cover LSA. Left CCA origin was confirmed to be intact on immediate post-angiogram.

As compared to F_V TCBFs before TEVAR, the F_V TCBFs after TEVAR were 118.50% at C1-2 level and 169.19% at MBA level, respectively (Table 2). The flow direction

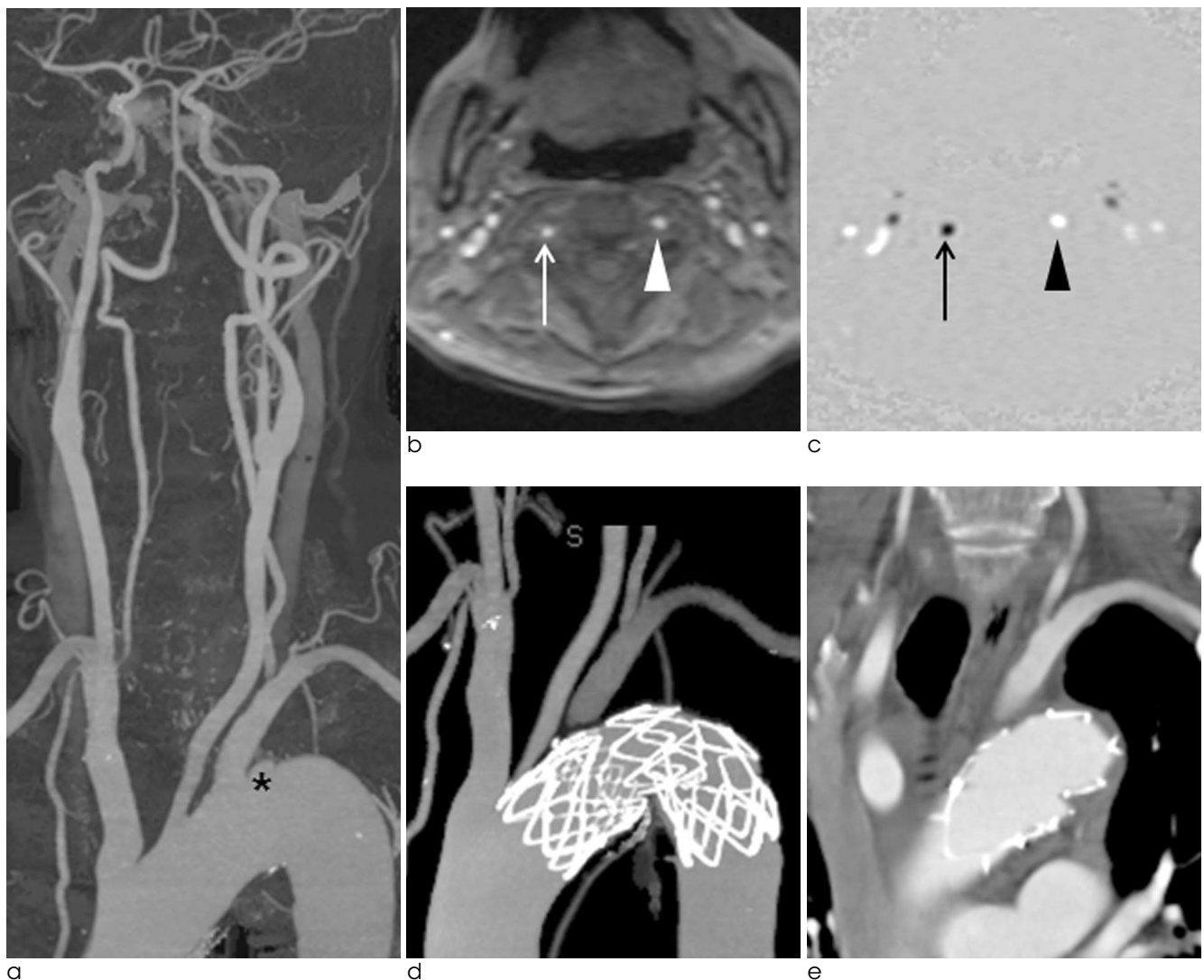


Fig. 3. A 76-year-old man (patient 1) with type B aortic dissection after bike accident. a. Iodine-enhanced CT angiography shows an 18 x 7 mm-sized focal dissecting aneurysm at arch 3 mm apart from left subclavian artery origin. There is no significant cerebral vascular abnormality. The diameter of left side vertebral artery appears to be larger than that of right side. b, c. On the 2 days after thoracic endovascular repair, axial magnitude and phase image of C1-2 level shows reversed flow at left vertebral artery (arrowhead). Arrow indicates right vertebral artery. d, e. Six months follow-up CT angiography shows covered left subclavian artery origin but visible left vertebral and subclavian arteries, suggesting development of left subclavian steal. There is no endoleak or recurrence of aneurysm.

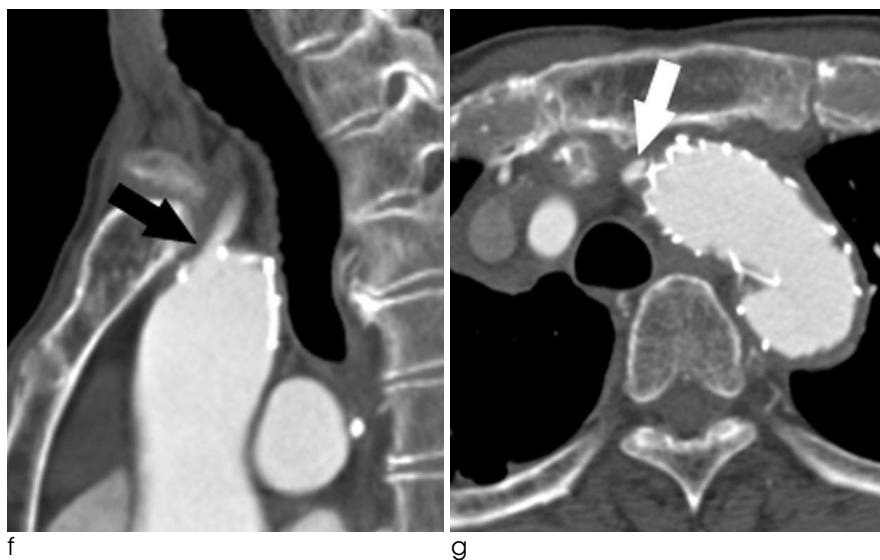


Fig. 3. f, g. The origin of left common carotid artery (arrow) is intact just in front of proximal end of stent-graft.

Table 2. Flow Volumes (FVs) Before and 2 Days after Left Subclavian Artery Coverage During TEVAR. The Each FVs of Arteries, Veins, and Cerebrospinal Fluid at C1-2 or Midbasilar Artery Level were Measured in mL/min, and the % Difference in the FVs after TEVAR in Comparison with Those Before (% Δ) were Calculated

Location	Patient 1, mL/min			Patient 2, mL/min		
	Before	After	% Δ	Before	After	% Δ
C1-2 level						
FV _{RICA_{C1-2}}	190.25	226.13	+18.86	218.18	298.93	+37.01
FV _{LICA_{C1-2}}	171.31	221.54	+29.32	295.90	379.41	+28.22
FV _{RVA_{C1-2}}	44.35	309.70	+598.31	149.58	299.09	+99.95
FV _{LVA_{C1-2}}	133.24	-168.60	-226.54	131.73	-34.90	-126.50
FV _{TCBF_{C1-2}}	539.15	588.77	+9.20	795.39	942.53	+18.50
FV _{IJV_{C1-2}}	322.07	432.15	+34.18	653.5	713.14	+9.13
FV _{CSF_{C1-2}}	-31.01*	-16.80*	-45.82	6.26	-30.00*	-579.23
Midbasilar Artery level						
FV _{RICA_{MBA}}	292.72	325.04	+11.04	190.13	354.56	+86.48
FV _{LICA_{MBA}}	155.95	188.47	+20.85	278.22	509.88	+83.27
FV _{BA_{MBA}}	167.79	139.31	-16.97	183.26	238.00	+29.87
FV _{TCBF_{MBA}}	616.46	652.82	+5.90	651.61	1102.44	+69.19
FV _{SS+SSS_{ax}}	289.35	311.62	+7.70	425.65	451.3	+6.03
FV _{SS+SSS_{cor}}	437.86	394.34	-9.94	561.49	510.02	-9.17
FV _{TS}	206.08	175.93	-14.63	461.53	504.66	+9.35
FV _{CSF_{aqueduct}}	-2.34*	3.19	-236.32	0.32	-1.38*	-531.25

Note.— TEVAR, thoracic endovascular aortic repair; % Δ = (FV after TEVAR - FV before TEVAR) / FV before TEVAR × 100 (%); C1-2, between first and second cervical vertebral level; MBA, midbasilar artery level; RICA, right internal carotid artery; LICA, left internal carotid artery; RVA, right vertebral artery; LVA, left vertebral artery; TCBF, total cerebral blood flow; IJV, internal jugular vein; CSF, cerebrospinal fluid; BA, basilar artery; FV_{SS+SSS_{ax}} or FV_{SS+SSS_{cor}}, sum of FVs at straight sinus and superior sagittal sinus measured at axial or coronal plane; FV_{TS}, sum of FVs measured at right and left transverse sinus; FV_{IJV}, sum of FVs measured at right and left internal jugular vein; FV_{CSF_{C1-2}} or FV_{CSF_{aqueduct}}, CSF flow measured at C1-2 or aqueduct; *, minus means caudocephalad direction of averaged FV_{CSF_{C1-2}} and FV_{CSF_{aqueduct}}.

Table 3. The Arteriovenous Transit Time (AVTT) Before and After TEVAR. The AVTT is Defined as the Difference between the Time Points having Maximal Slope of Arterial and Venous Time-Volume Curve

(A) AVTT of C1-2 level between Artery-right IJV/Artery-left IJV (msec)						
Location	Patient 1, msec			Patient 2*, msec		
	Before	After	% Δ	Before	After	% Δ
Right ICA	127/127	57/113	-55.11/-11.02	234	23	-90.60
Left ICA	127/127	57/113	-55.11/-11.02	134	23	-82.84
Right VA	109/109	57/113	-47.71/+3.67	67	-179	-367.17
Left VA	146/146	57/113	-60.96/-22.60	-66	-269	307.58

*Only right internal jugular vein was the reference vein because left internal jugular vein was hypoplastic.

(B) AVTT of midbasilar artery level between Artery-SS/Artery-SSS (msec)						
Location	Patient 1, msec			Patient 2, msec		
	Before	After	% Δ	Before	After	% Δ
Right ICA	281/355	207/283	-26.33/-20.28	167/167	-90/-90	-153.89/-153.89
Left ICA	**0/74	-19/57	-3.57/-22.97	134/134	112/112	-16.42/-16.42
BA	**0/74	-114/-38	-21.43/-151.35	100/100	-23/-23	-123/-123

Note.— TEVAR, thoracic endovascular aortic repair; % Δ = (AVTT after TEVAR – AVTT before TEVAR) / AVTT before TEVAR × 100 (%); ICA, internal carotid artery; VA, vertebral artery; IJV, internal jugular vein; BA, basilar artery; SS, straight sinus; SSS, superior sagittal sinus. **0, Total trigger delay at this plane was 532 msec in patient 1.

of left VA was reversed, and the FV_{RVA} was 199.95% of that before TEVAR. The $FV_{RICA_{MBA}}$, $FV_{LICA_{MBA}}$, and $FV_{BA_{MBA}}$ were 186.48%, 183.27%, 129.87% of those before TEVAR, respectively. The $FV_{SS+SSS_{ax}}$, $FV_{SS+SSS_{cor}}$, FV_{TS} , and FV_{IJV} were 106.03%, 90.83%, 109.35%, and 109.13% of those before TEVAR, respectively. The baseline $FV_{CSF_{C1-2}}$ and $FV_{CSF_{aqueduct}}$ were craniocaudal direction in averaging, but they changed into caudalcephalad direction in averaging after TEVAR. The AVTTs after TEVAR were shortened as compared to the AVTTs before (the change of AVTT ≤ 200 msec; Table 3).

The patient was uneventful for 6 months of follow-up period, and 6 months follow-up CT angiography showed stable occlusion of aortic aneurysm. Left CCA origin was spared, and the origin of LSA was covered without endoleak.

DISCUSSION

The proximity of thoracic aortic aneurysm or dissection to the LSA, especially located at landing zone 2, has occasionally required intentional coverage (2–4). Controversy continues concerning the safety of LSA

coverage and the indications for LSA revascularizations, with the importance of antegrade flow through the LSA for brain and spinal cord perfusion. The stroke and spinal cord ischemia associated with the intentional LSA coverage during TEVAR have been reported to be developed in 3.1–8.6% and in 2.5–2.8% of the patients, respectively (4–6). However, the primary revascularization of LSA did not offer protective effect against stroke, considering that the stroke rate between the revascularization and non-revascularization groups was not different (4, 5). Interestingly, the most strokes were embolic and occurred in the anterior circulation (5). The distal end of devices, wires, and catheters are likely to increase atheroma manipulation at arch, which can subsequently dislodge embolic material at the orifices of the great vessels. Our study results are consistent with these in that coverage of the LSA origin is usually well tolerated as a result of the collateral flow via the right VA (3–5). In our two patients, the total brain supply after TEVAR did not lessen despite subclavian steal, being actually 105.9–169.19% of that before TEVAR, which were well correlated with uneventful clinical outcome. Among them, the FV of right VA was most significantly increased among other arteries.

From this viewpoint, the primary LSA revascularization is not mandatory before TEVAR, but should be considered in selected patients. Indications for primary LSA revascularization included a patent left internal mammary artery-left anterior descending artery bypass, a functioning dialysis fistula in the left arm, need for long segment aortic coverage, and prior or concomitant infrarenal aortic replacement. The secondary revascularization can be performed in patients that became symptomatic or present vertebrobasilar insufficiency after LSA coverage (3).

An atretic or stenotic right VA may increase risk for spinal cord ischemia, provided that the anterior spinal artery is partly formed from branches of the thyrocervical trunk. Therefore, cerebral CT or MR angiography before TEVAR should be recommended to visualize both vertebral and the basilar arteries and to exclude concomitant VA trauma or anomaly (9). Duplex ultrasound may be helpful to evaluate the patency of the extracranial circulation especially of the right VA and presence of subclavian steal (10). 2D phase contrast MRI may be useful in identifying candidate of

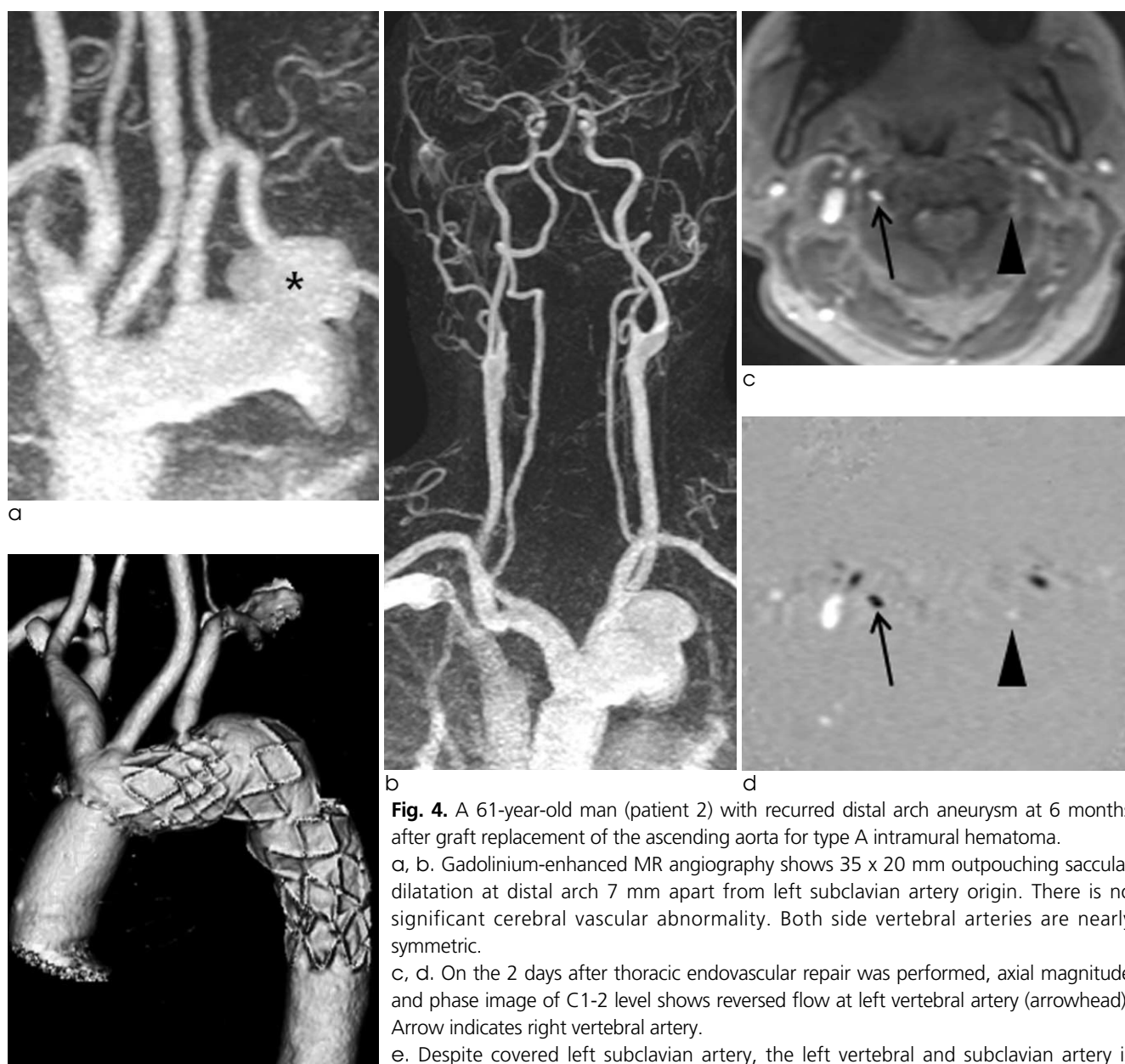


Fig. 4. A 61-year-old man (patient 2) with recurred distal arch aneurysm at 6 months after graft replacement of the ascending aorta for type A intramural hematoma. a, b. Gadolinium-enhanced MR angiography shows 35 x 20 mm outpouching saccular dilatation at distal arch 7 mm apart from left subclavian artery origin. There is no significant cerebral vascular abnormality. Both side vertebral arteries are nearly symmetric. c, d. On the 2 days after thoracic endovascular repair was performed, axial magnitude and phase image of C1-2 level shows reversed flow at left vertebral artery (arrowhead). Arrow indicates right vertebral artery. e. Despite covered left subclavian artery, the left vertebral and subclavian artery is demonstrated possibly due to left subclavian steal on 6 months follow-up CT angiography. There is no endoleak or recurrence of aneurysm.

primary or secondary LSA revascularization with an inadequate collateral vertebral circuit (7–9). In our patients, the direction of left VA flow changed to retrograde fashion after LSA coverage. The amount of FV of retrograde left VA seems to be dependent upon pre-TEVAR VA dominance, as seen from 168.60 mL/min at dominant left VA of patient 1 and 34.90 mL/min at equal both side VAs of patient 2. The subclavian steal behaves like an arteriovenous shunt requiring supplies for left VA flow as well as basilar flow, which was compensated by the increased FV of other cerebral arteries including both ICAs and contralateral VA. The right VA is a major collateral supply, and the degree of increasing % of the patient 1 with non-dominant right VA was as high as 6 times that of the patient 2 with equally dominant both VAs. It seems that non-dominant right VA may be rather insufficient to compensate the reversed dominant contralateral VA, although it became enlarged remarkably to supply collateral flow, as seen from that the FV_{BA} after TEVAR of patient 1 (non-dominant right VA) and patient 2 (equally dominant VA) was 83.03% and 129.87% of FV_{BA} before TEVAR, respectively.

To the best of our knowledge, this is the first report to measure prospectively the FV changes of patients who undergone LSA coverage by using 2D cine phase contrast MR imaging. Even in a few literatures on the flow measurement of VA in the patients with subclavian steal by using Doppler ultrasound or 2D phase contrast MR imaging (7, 8, 10), the direct and quantitative measurement of venous and CSF has not been made. In comparison to arterial FVs, the venous FVs after TEVAR showed rather inconsistent results. The $FV_{SS+SSS_{ax}}$ after TEVAR were 106.03–107.70% of those before TEVAR, but the $FV_{SS+SSS_{cor}}$ after TEVAR were 90.06–90.83% of those before TEVAR. The FV_{IJV} and FV_{TS} after TEVAR were 109.13–134.18% and 85.37–109.35% of those before TEVAR, respectively. Different angle and location of the scanning plane, and anatomical complexity of venous drainage might be considered. We could not find any consistent trend in the change of FV_{CSF} . AVTT seemed to be shortened with varying degree, and the order of arterial and venous peak was sometimes reversed, which remains to be further investigated.

In terms of limitation, as being case report of two

patients, the method of analysis depends only upon the comparison between before and after TEVAR. Whether preoperative evaluation of the vertebrobasilar system would allow selective LSA revascularization remains to be further investigated in a future prospective study of larger population. The patients were clinically observed during 6 months period, but there was no available 6 months follow-up 2D phase contrast MR imaging, although the chronic hemodynamic feature at 6 months may be different from that of immediate post-TEVAR.

In summary, the total brain supply after TEVAR is properly compensated despite subclavian steal, most significantly by increased FV of right VA, which shows good correlation with favorable clinical outcomes. 2D phase contrast MR imaging can be recommended as a useful technique to evaluate the hemodynamic change of the LSA coverage during TEVAR and to triage the candidate for LSA revascularization.

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흉부대동맥류의 혈관내치료 도중 좌측 쇄골하동맥 폐색이 뇌혈류역동에 미치는 효과: 2차원 위상차 대조 자기공명영상을 이용한 혈류 측정 2례 보고

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흉부대동맥류는 좌측 쇄골하동맥에 가까이 위치해 있어서 흉부대동맥내치료를 시행할 때 좌측 쇄골하동맥의 폐색이 불가피한 경우가 많다. 좌측 쇄골하동맥 폐색의 안전성과 좌측 쇄골하동맥 재생술의 필요성에 대해 논란이 계속되고 있음에도 불구하고, 좌측 쇄골하동맥의 폐색후 뇌혈류역학적인 변화에 대한 기존의 체계적인 연구는 없었다. 저자들은 좌측 쇄골하동맥폐색을 동반한 흉부대동맥내치료를 대상이 되는 2명의 환자에서 치료 전후의 2차원 위상차 대조 자기공명영상을 시행하였다. 좌측 쇄골하동맥의 폐색 후 좌측 쇄골하도주가 발생하였으며, 이로 인한 뇌혈류의 소실을 양측 경동맥과 주된 부행혈류인 오른쪽 추골하동맥이 적절하게 보상하였다. 전체 뇌혈류는 감소하지 않았으며 이는 임상적으로 뇌졸중이나 척수마비의 증상이 나타나지 않은 것과 잘 일치하였다. 2차원 위상차 대조 자기공명영상은 좌측 쇄골하동맥 폐색을 동반한 흉부대동맥내치료를 뇌혈류역학적인 평가와 좌측 쇄골하동맥 재생술이 필요한 환자의 선별에 유용할 것으로 사료된다.

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