Blood Flow Analysis After a Renovisceral Debranching Procedure by Four-dimensional Flow Magnetic Resonance Imaging

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Abstract: Objectives. In this study, a hybrid procedure of combined visceral reconstruction and thoracic endovascular aortic repair was performed for a thoracoabdominal aortic aneurysm. There are various methods of visceral reconstruction; we performed revascularization using a retrograde approach with a quadrifurcated graft and examined the distribution of the abdominal branch blood flow. **Methods.** Among patients undergoing the renovisceral debranching procedure, (A) 7 cases of inflow were obtained from the legs of a bifurcated vascular prosthesis; (B) 7 cases of inflow were obtained from the trunk of a bifurcated vascular prothesis; and (C) 7 cases of preoperative native blood flow were targeted. Images obtained from four-dimensional flow magnetic resonance imaging were analyzed with a cardio flow station. **Results.** In group (A), the predicted renal blood flow was 564 mL/min, and the measured blood flow was 447 mL/min. The predicted gastrointestinal (GI) blood flow was 1332 mL/min, and the measured blood flow was 1060 mL/min. In group (B), the predicted renal blood flow was 618 mL/min, and the measured renal blood flow was 524 mL/min. The predicted GI blood flow was 1294 mL/min, and the measured blood flow was 1178 mL/min. In group (C), the renal blood flow predicted from the estimated glomerular filtration rate was 648 mL/min, and the measured blood flow was 643 mL/min. The predicted GI blood flow was 1343 mL/min, and the measured blood flow was 1041 mL/min. **Conclusion.** The abdominal branch blood flow after renovisceral debranching was slightly lower than expected for both reconstruction methods. The inflow position should be close to the abdominal aortic trunk.

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Introduction

In recent years, hybrid treatment combining renovisceral debranching and thoracic endovascular aortic repair (TEVAR) has been reported as a treatment for thoracoabdominal aortic aneurysm (TAAA) in older and high-risk patients. When comparing conventional thoracoabdominal aortic replacement with this hybrid treatment, one issue with the hybrid treatment is the graft patency rate bypassed to the abdominal organs. Various methods for performing the renovisceral debranching procedure have been reported.[1-3] Several papers reported on the graft patency, with 1 finding no marked difference in the patency between antegrade and retrograde grafts.[4] Another issue is blood flow distribution to the bypassed abdominal organs. However, few reports have examined the bypass blood flow after renovisceral debranching.

At our facility, we started to perform stent grafts in 2007 and have been performing a hybrid procedure for TAAAs. The method of the renovisceral debranching procedure at our facility and the results have been reported previously.[5] Among them, there have been some cases in which kidney function declined after the renovisceral debranching procedure was performed.
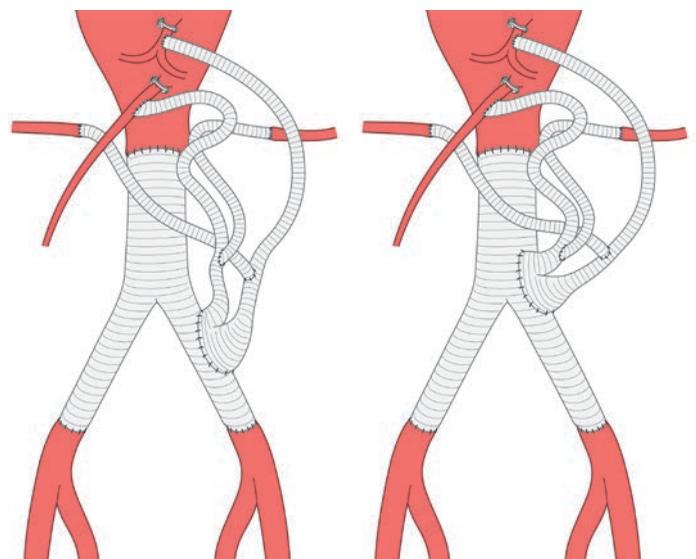

Figure 1. The renovisceral debranching procedure. **(Left)** A quadrifurcated graft to bypass the abdominal organs is anastomosed to the left leg of the bifurcated graft. **(Right)** A quadrifurcated graft to bypass the abdominal organs is anastomosed to the trunk of the bifurcated graft.

Figure 2. A blood flow analysis using the Cardio Flow Station. **(Left)** Streamline of abdominal artery blood flow and measurement blood flow of each organ. **(Right)** Blood flow measurement of the left renal artery.

Insufficient renal blood flow from the bypass compared with the native renal blood flow was considered one of the causes of deterioration of the renal function.

For this reason, we performed a blood flow analysis using four-dimensional (4D) flow magnetic resonance imaging (MRI) and examined the distribution of the abdominal branch blood flow.

Patients and Methods

Operative Procedure of Renovisceral Debranching

In brief, during the renovisceral debranching procedure, the abdominal aorta is replaced with a bifurcated graft. The quadrifurcated graft is then anastomosed to the bifurcated graft, and the visceral arteries are reconstructed using the quadrifurcated graft. In our facility, the quadrifurcated graft has a size of 14 x 7 x 6 mm. The bilateral renal artery is reconstructed with a 6 mm graft. The superior mesenteric artery (SMA) and celiac trunk are

reconstructed with a 7 mm graft. Initially, the quadrifurcated graft to bypass the abdominal organs is anastomosed to the left leg of the bifurcated graft. These cases are designated as group (A) (**Figure 1, Left**). In some cases, however, the renal function was found to have deteriorated after this hybrid treatment. We suspected this to be due to a low renal blood flow. Anticipating an increase in the amount of blood flowing into the quadrifurcated graft, part of the anastomosis of the quadrifurcated graft was changed in 2018, with application switched to the trunk of the bifurcated graft. These cases have been designated as group (B) (**Figure 1, Right**).

Data Source

We performed 79 cases of hybrid treatment for TAAAs at our institution between 2007 and 2019. There were 62 patients in group (A) and 17 in group (B). Seven patients who had been regularly followed up were randomly selected from group (A), and 4D flow MRI was performed and the images

Table 1. Patient demographics and comorbidities.			
Variables	Group (A)	Group (B)	Group (C)
Patients	7	7	7
Gender			
Male	5	2	6
Female	2	5	1
Mean age (years)	70.6	71.9	74.3
Mean BSA	1.62	1.57	1.67
Mean cardiac index	3.29	3.27	3.21
Preoperative CKD			
G1 (eGFR ≥ 90)	1	2	0
G2 (60 ≤ eGFR <90)	2	1	3
G3a (45≤ eGFR < 60)	1	2	4
G3b (30 ≤ eGFR < 45)	2	1	0
G4 (15 ≤ eGFR < 30)	1	1	0
G5 (eGFR < 15)	0	0	0
Mean preoperative eGFR	56.1	60.5	60.3
CKD during MRI			
G1 (eGFR ≥ 90)	0	0	-
G2 (60 ≤ eGFR <90)	2	3	-
G3a (45≤ eGFR < 60)	3	2	-
G3b (30 ≤ eGFR < 45)	1	2	-
G4 (15 ≤ eGFR < 30)	1	0	-
G5 (eGFR < 15)	0	0	-
Mean eGFR during MRI	53.0	58.1	-

BSA = body surface area; CKD = chronic kidney disease; eGFR = estimated glomerular filtration rate; MRI = magnetic resonance imaging.

analyzed. Similarly, 7 patients who had been regularly followed up were randomly selected from group (B), and 4D flow MRI was performed and the images analyzed.

To evaluate the normal renal blood flow and gastrointestinal (GI) blood flow, 4D flow MRI was performed and the images analyzed in 7 cases before renovisceral debranching surgery was performed. These patients were designated as group (C).

This study was approved by the Institutional Review Board of Oita University Hospital, Japan, and informed consent was obtained from the relevant patients.

4D Flow MRI and Analyses

In groups (A) and (B), 4D flow MRI was performed at any time after surgery, whereas in group (C), 4D flow MRI was performed preoperatively. MRI was performed at 3:00 pm in all groups due to scheduling issues. All patients underwent noncontrast 4D flow MRI on a Magnetom Skyra 3T MRI (Siemens Medical Solutions) with an 18-channel body-phased array coil. The scan parameters were as follows: velocity encoding (cm/s), 180; repetition time (ms), 44; echo time (ms), 2.73; flip angle (°), 8; bandwidth (Hz/px), ±457;

field of view (mm), 340; slice thickness (mm), 4; slice/slab, 26. The scan time for each acquisition was 15 to 20 min. 4D flow MRI provides sets of 3D volumes over time. Each 4D volume contains 1 magnitude volume and 3 phase-difference volumes encoded in the 3 directions of space (x, y, z). Raw data are uploaded to Cardio Flow Station software (Cardio Flow Design Inc.). Blood flow in the aorta and its branches is plotted. When all have been plotted, they are finally visualized in a streamlined manner (**Figure 2, Left**). The blood flow is obtained at cross sections (**Figure 2, Right**). In groups (A) and (B), the blood flow in the graft bypassed to the bilateral renal arteries, SMA, and celiac trunk was measured. In group (C), the blood flow in the bilateral renal arteries, SMA, and celiac trunk was measured.

The blood flow distribution to each organ at rest was reported by Hall.[6] The GI blood flow at rest is 25% of the cardiac output (CO), and the renal blood flow at rest is 20%. The CO is required to calculate the organ blood flow, but the CO cannot be simultaneously measured during MRI. Therefore, the CO during MRI was calculated based on a cardiac index (CI) at rest. The resting CI was calculated by the following formula from the previous report by Katori et al[7]: y (L/min/m^2) = 4.703 − 0.020 x (y: CI; x: age). Although the renal blood flow is 20% of the CO, the renal blood flow is also thought to be affected by the renal function. A normal renal function was defined as an estimated glomerular filtration rate (eGFR) of 100 mL/min/1.73 m^2. This eGFR was reflected when the predicted renal blood flow was calculated. The predicted renal blood flow (mL/min) = CI (L/min/m^2) x BSA (m^2) x 1000 x 1/5 x eGFR during MRI (mL/min)/100.

Statistical Analyses

All data were analyzed retrospectively. Continuous variables were expressed as the mean ± standard deviation. Categorical variables were presented as the number and percentage. The Mann-Whitney U test was used to compare 2 groups and the Kruskal-Wallis test was used to compare 3 groups, while the Shirley-Williams multiple comparison approach was also used. All analyses were performed using the Excel statistical software package (Ekuseru-Toukei 2015; Social Survey Research Information Co).

Results

Patient Demographics

The patient demographics are summarized in **Table 1**. In group (A), 5 patients were male. The mean patient age was 70.6 ± 8.9 years. The mean body surface area (BSA) was 1.62 ± 0.10 m^2. The mean CI was 3.29 ± 0.18 L/min/m^2. In group (B), 2 patients were male. The mean patient age was 71.9 ± 15.5 years. The BSA was 1.57 ± 0.27 m^2. The mean CI was 3.27 ± 0.31 L/min/m^2. In group (C), 6 patients were male. The mean patient age was 74.3 ± 6.5 years. The BSA was 1.67 ± 0.15 m^2. The mean CI was 3.21 ± 0.13 L/min/m^2.

Patients with chronic kidney disease (CKD) ≥ grade 3 (eGFR

Table 2. Renal blood flow for each group.

Group (A)

	Age	Gender	CI	eGFR	Predicted RBF (mL/min)	Measured RBF (mL/min)	Rt. RA (mL/min)	Lt. RA (mL/min)	Satisfaction rate of measured RBF (%)
1	85	M	3.00	29.6	286	381	208	173	133.1
2	68	M	3.34	39.4	440	313	157	155	71.1
3	72	M	3.26	55.4	582	515	264	252	88.5
4	73	F	3.24	73.1	716	453	243	210	63.3
5	64	M	3.42	48.2	564	490	216	273	86.8
6	55	F	3.60	69.3	734	530	243	287	72.2
7	77	M	3.16	56.2	626	445	275	170	71.1
Mean SD	70.6 8.9		3.29 0.18	53.0 14.3	564 146	452 68	229 37	217 50	83.7 21.8

Group (B)

	Age	Gender	CI	eGFR	Predicted RBF (mL/min)	Measured RBF (mL/min)	Rt. RA (mL/min)	Lt. RA (mL/min)	Satisfaction rate of measured RBF (%)
1	53	F	3.64	88.2	1022	892	467	425	87.3
2	84	F	3.02	30.7	223	251	131	120	112.7
3	45	M	3.80	73.9	1135	690	394	296	60.8
4	70	M	3.30	32.7	402	330	199	131	82.1
5	88	F	2.94	45.9	400	395	204	191	98.1
6	81	F	3.08	46.7	429	451	272	179	105.1
7	82	F	3.06	88.3	714	657	306	351	92.0
Mean SD	71.9 15.5		3.27 0.31	58.1 23.1	618 322	524 212	282 109	242 108	91.3 15.8

Group (C)

	Age	Gender	CI	eGFR	Predicted RBF (mL/min)	Measured RBF (mL/min)	Rt. RA (mL/min)	Lt. RA (mL/min)	Satisfaction rate of measured RBF (%)
1	74	M	3.22	53.9	580	486	190	296	83.8
2	65	M	3.40	74.7	904	655	435	220	72.5
3	82	F	3.06	68.3	552	494	379	115	89.5
4	65	M	3.40	64.9	776	953	430	523	122.8
5	76	M	3.18	56.6	616	944	471	473	153.3
6	76	M	3.18	53.6	590	546	313	233	92.6
7	82	M	3.06	49.8	518	422	262	160	81.5
Mean SD	74.3 6.5		3.21 0.13	60.3 8.5	648 129	643 204	354 95	289 143	99.4 26.4

CI = cardiac index; eGFR = estimated glomerular filtration rate; RA = renal artery; RBF = renal blood flow; SD = standard deviation.

< 60 mL/min/1.73 m^2) before renovisceral debranching surgery accounted for 57.1% of each group. Preoperative eGFR was 56.1 ± 22.3 mL/min/1.73 m^2, 60.5 ± 24.1 mL/min/1.73 m^2, and 60.3 ± 8.5 mL/min/1.73 m^2 in groups (A), (B), and (C), respectively. Patients with CKD grade ≥ 3 at the time of postoperative MRI accounted for 71.4% of group (A) and 57.1% of group (B). The eGFR at that time was 53.0 ± 14.3 mL/min/1.73 m^2 and 58.1 ± 23.1 mL/min/1.73 m^2 in groups (A) and (B), respectively. Among all 79 patients who had the renovisceral debranching procedure between 2007 and 2019, 51 (64.6%) had a renal function of CKD grade ≥ 3.

Renal Blood Flow Analyses

The predicted renal blood flow was compared with the measured renal blood flow. The predicted renal blood flow was calculated by considering the eGFR of each patient at the time of MRI data acquisition. The data are shown in **Table 2**. In group (A), the mean eGFR at the time of MRI was 53.0 mL/min/1.73 m^2. The mean renal blood flow predicted from the eGFR value was 564 ± 146 mL/min. The mean renal blood flow obtained by the 4D flow analysis was 447 ± 71 mL/min. The measured renal blood flow corresponded to 83.7% of the expected blood flow. In group (B), the mean eGFR at

Table 3. Gastrointestinal blood flow for each group.

Group (A)					
	Predicted GIBF (mL/min)	Measured GIBF (mL/min)	SMA (mL/min)	Celiac trunk (mL/min)	Satisfaction rate of measured GIBF (%)
1	1290	1037	495	542	85.8
2	1396	1219	559	660	87.3
3	1313	706	377	330	53.8
4	1224	909	408	501	74.3
5	1463	1020	466	554	69.7
6	1324	1111	311	800	83.9
7	1392	1419	903	516	102.0
Mean SD	1332 86	1060 209	503 180	567 143	79.5 14.2
Group (B)					
	Predicted GIBF (mL/min)	Measured GIBF (mL/min)	SMA (mL/min)	Celiac trunk (mL/min)	Satisfaction rate of measured GIBF (%)
1	1448	1176	672	504	81.2
2	907	751	324	427	82.8
3	1921	2076	926	1150	108.1
4	1536	1502	584	918	97.8
5	1089	1125	436	689	103.3
6	1148	882	422	460	76.8
7	1011	737	737	occlusion	72.9
Mean SD	1294 331	1178 444	586 194	691 265	89.0 12.8
Group (C)					
	Predicted GIBF (mL/min)	Measured GIBF (mL/min)	SMA (mL/min)	Celiac trunk (mL/min)	Satisfaction rate of measured GIBF (%)
1	1345	767	286	481	57.0
2	1513	1026	489	540	68.0
3	1010	897	897	occlusion	88.8
4	1495	1876	687	1189	125.5
5	1360	956	410	546	70.3
6	1375	801	167	634	58.3
7	1300	961	410	551	73.9
Mean SD	1343 154	1041 351	478 227	563 321	77.4 22.0

GIBF = gastrointestinal blood flow; SD = standard deviation; SMA = superior mesenteric artery.

the time of MRI was 58.1 mL/min/1.73 m². The mean renal blood flow predicted from the eGFR value was 618 ± 322 mL/min. The mean renal blood flow obtained by the 4D flow analysis was 524 ± 212 mL/min. The measured renal blood flow corresponded to 91.3% of the expected blood flow. In group (C), the mean eGFR at the time of MRI was 60.3 mL/min/1.73 m². The mean renal blood flow predicted from the eGFR value was 648 ± 129 mL/min. The mean renal blood flow obtained by the 4D flow analysis was 643 ± 204 mL/min. The measured renal blood flow corresponded to 99.4% of the expected blood flow. Regarding the renal blood flow,

although there was no significant difference (P=.29) among the 3 groups, the flow tended to be slightly lower than usual in both reconstruction methods. Although there was no significant difference (P=.31) between groups (A) and (B), group (B) tended to have a higher renal blood flow than group (A).

GI Blood Flow Analyses

The data for each group are shown in **Table 3**. The GI blood flow was shown as the sum of SMA blood flow and celiac trunk blood flow. In group (A), the mean predicted GI blood flow was 1332 ± 86 mL/min. The mean GI blood flow

obtained by the 4D flow analysis was 1060 ± 209 mL/min. This represented 79.5% of the expected amount. In group (B), the mean predicted GI blood flow was 1294 ± 331 mL/min. The mean GI blood flow obtained by the 4D flow analysis was 1178 ± 444 mL/min. This represented 89.0% of the expected amount. In group (C), the mean predicted GI blood flow was 1343 ± 154 mL/min. The mean GI blood flow obtained by the 4D flow analysis was 1041 ± 351mL/min. This represented 77.4% of the expected amount. Regarding the GI blood flow, although there was no significant difference (P=.30) among the 3 groups, the flow tended to be lower than the expected amount in all groups. Although there was no significant difference (P=.31) between groups (A) and (B), group (B) tended to have a higher GI blood flow than group (A). Normally, the blood flow in the celiac trunk tended to be higher than that in the SMA. Obstruction of the celiac trunk was observed in 2 patients, involving occlusion of the graft in one and occlusion of the native celiac trunk in the other. In these cases, when the celiac trunk was occluded, it seemed that the SMA was supplying a sufficient blood flow to supplement it.

Discussion

Hybrid treatment that combines renovisceral debranching and thoracic endovascular aortic repair has been widely reported as a treatment for thoracoabdominal aortic aneurysm in high-risk patients. Treatment with total endovascular has not yet become a common treatment due to anatomical difficulties. We have been performing this hybrid treatment at our hospital since 2007. With this approach, there have been some cases in which there was no bypass occlusion to the renal artery in the remote period, but deterioration of the renal function was observed. Initially, the quadrifurcated graft to bypass the abdominal organs is anastomosed to the leg of the bifurcated graft. However, Wen et al reported that computer simulations showed that visceral revascularization from the distal aorta maintained proper organ perfusion, but visceral revascularization from the iliac artery reduced the renal blood flow.[8] Yuan et al reported that bifurcated graft reconstruction from the bilateral common iliac arteries preserved the renal artery blood flow but reduced the blood flow in the celiac trunk and SMA compared with reconstruction with a quadrifurcated graft.[9] Therefore, part of the inflow of the renovisceral debranch was switched from the leg to the body of the bifurcated graft. However, to secure a TEVAR landing zone, the quadrifurcated graft could not be anastomosed solely to the body of the bifurcated graft. Instead, the graft was anastomosed across the body and leg of the bifurcated graft. 4D flow MRI was performed to measure the blood flow in each organ to confirm changes in the organ blood flow due to differences in inflow locations. In recent years, blood flow evaluations by ultrasonography have become common, but it is considered difficult to measure the celiac trunk and SMA due to the anastomotic site of the artificial graft. With 4D flow MRI, the blood flow can be measured repeatedly at the

same time without any time lag; therefore, the blood flow was evaluated by 4D flow MRI.

Regarding the renal blood flow, considering the relationship between the renal function and renal blood flow, the renal blood flow is considered to decrease as the renal function decreases.[10] In general, the renal function declines with age. Imai et al reported that the renal function in patients with GFR < 50 mL/min/1.73 m^2 tends to decline more than twice as fast with age. In addition, hypertension, proteinuria, and a low GFR were shown to be significant risk factors for a rapid decline in GFR.[11] The renal blood flow is a physiologic indicator that decreases significantly with age.[12] Assuming that the renal blood flow at age 30 is 100%, the flow is said to decrease linearly with age, reaching about 50% by age 80.[13] Given the above, the renal blood flow is not 20% of the cardiac output at any age or renal functionality. It makes sense to perform correcting using the eGFR value to calculate the predicted renal blood flow. In the present study, the measured renal blood flow was slightly lower than that predicted for both reconstruction methods. However, the renal blood flow tended to be higher when the inflow position was closer to the main trunk of the abdominal aorta. This is consistent with the report by Wen et al.[8] As an intraoperative factor that affects the renal function, renovisceral debranching surgery requires renal artery clamping for renal artery reconstruction. Chong et al reported that suprarenal cross-clamping is associated with postoperative renal dysfunction.[14] In addition, Dubois et al reported that postoperative transient renal dysfunction is associated with renal ischemia time and left renal vein division.[15] Sugimoto et al reported that preoperative CKD grade ≥ 3 was a risk factor for long-term renal dysfunction.[16] In our surgical procedure, the renal artery was clamped just before reconstruction, and the clamp time itself was considered minimal. Regarding the preoperative patient background characteristics, more than 50% of patients had CKD grade ≥ 3, and most of them had hypertension. These data suggest that the decrease in renal function we experienced after surgery might be related to the decrease in the renal blood flow to some extent, and the long-term deterioration in the renal function was largely due to these issues.

The GI blood flow was below the predicted value in all groups. However, when comparing the 2 reconstruction methods, the GI blood flow tended to be higher when the inflow position was closer to the abdominal aortic trunk than otherwise, a finding similar to that noted with the renal blood flow. The GI blood flow increases with meal intake, and it peaks between 30 and 90 min after meal ingestion and gradually decreases.[17] Because no contrast medium was used for the MRI scans obtained in this study, no dietary restrictions were applied. Therefore, the abdominal visceral blood flow may be affected depending on the intake time, amount, and morphology of the meal. In this result, the GI blood flow was lower than the predicted value, but none of the postoperative patients complained of any abdominal pain after eating. Therefore, the GI blood flow after meals was considered to have sufficiently increased as expected.

There are 3 requirements that must be met for this hybrid treatment to be able to be applied to not only high-risk patients but also younger patients. First, additional treatment for endoleak must be avoided. Second, long-term patency of the renovisceral debranching graft must be ensured. Third, adequate blood flow to the debranched abdominal organs must be maintained. Endoleak will remain a challenge as long as stent graft treatment is performed, especially concerning the prevention of long-term retreatment due to type II endoleak. Regarding graft patency, we previously reported a patency rate of over 90% in the remote period.[5] Regarding maintaining an adequate blood flow to the debranched abdominal organs, our results showed that the measured renal and GI blood flow were slightly less than the predicted values. As such, we concluded that this surgery is not yet superior to open surgery.

Several limitations associated with the present study warrant mention. First, the exact CO during MRI is unknown. Therefore, to express the CO at rest, the value was calculated using a previously reported approximate formula. However, some patients may have a higher or lower CO. Second, the timing of the MRI must be considered. We performed 4D flow MRI at 3:00 pm due to scheduling issues. In patients who ate lunch before this point, the meal may have influenced the distribution of the blood flow to various organs. The GI blood flow is increased by meal intake.[18] However, the renal blood flow is thought to be decreased due to the renal vasoconstriction caused by meal intake.[19,20] Therefore, it is possible that the renal blood flow was underestimated and the GI blood flow was overestimated, depending on the timing of meal intake before MRI.

Conclusion

The abdominal branch blood flow after renovisceral debranching was slightly lower than expected for both reconstruction methods. However, the abdominal branch blood flow tended to be higher when the inflow was anastomosed to the body of the abdominal aorta. The inflow position should be close to the abdominal aortic trunk. In such cases, it is necessary to ensure that the landing zone is secured for the next TEVAR procedure. ∎

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