

Predictive Factors for Iliac Limb Occlusions After Endovascular Abdominal Aneurysm Repair: Determined from Aortoiliac Anatomy, Endovascular Procedures, and Aneurysmal Remodeling

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Purpose: Iliac limb occlusion (ILO) is a serious complication of endovascular abdominal aneurysm repair (EVAR). This study aimed to identify predictive factors for ILO derived from aortoiliac morphology, endovascular procedure-related parameters, and aneurysmal remodeling characteristics.

Patients and Methods: Patient demographics, pre-EVAR anatomical characteristics of the aneurysm, endovascular procedure details, and post-EVAR aneurysmal remodeling outcomes were analyzed and compared using univariate analysis. Statistically significant factors were subsequently subjected to Cox regression and Kaplan–Meier analyses.

Results: Between January 2013 and April 2022, 66 patients were included in this study. Fourteen patients presented with ILO and were compared with 52 control patients with patent endograft limb over at least 1-year of follow-up. The tortuosity indices of the common iliac artery (CIA) and endograft iliac limb to vessel oversizing were significantly larger in the ILO group than in the patent endograft limb group. The CIA index of tortuosity ≥ 1.08 , and endograft iliac limb to vessel oversizing $\geq 18.8\%$ were independent predictors for ILO. During the follow-up of all patients, the proximal aortic neck and CIA diameters increased, aneurysm sac diameter decreased, and aortic neck and aortic length increased. The aortoiliac length increased over time in patients with patent endograft limb but not in patients with ILO. A change in the lowest renal artery–left iliac bifurcation distance ≤ 0.07 mm increased the risk of ILO.

Conclusion: ILO is predisposed to occur when the CIA index of tortuosity ≥ 1.08 and endograft iliac limb to vessel oversizing $\geq 18.8\%$ are present. Significant aortoiliac remodeling, including proximal aortic neck dilatation, neck straightening, aneurysmal sac regression, iliac artery enlargement, and aortic lengthening, occurs after EVAR. Aortoiliac elongation was observed in patients with patent endograft limb, but not in patients with ILO. ILO was associated with a change in the lowest renal artery–left iliac bifurcation from the postoperative measurements ≤ 0.07 mm.

Keywords: abdominal aortic aneurysm, endovascular abdominal aneurysm repair, iliac limb occlusion, aortoiliac anatomy, aneurysmal remodeling, oversizing, aortoiliac tortuosity

Introduction

Endovascular abdominal aneurysm repair (EVAR) is widely used to treat infrarenal abdominal aortic aneurysms. EVAR is a minimally invasive procedure, with shorter hospital stays and fewer short-term complications than open surgery.^{1,2} Iliac limb occlusion (ILO) is a well-known early or late complication of endovascular abdominal aneurysm repair (EVAR) and requires re-intervention by surgical, endovascular, or hybrid techniques in most cases.^{3–5} The short- and long-term ILO rates are still considerable, with an incidence of 5.6–5.9% in patients undergoing EVAR.^{3–5}

There are many reasons for ILO, which can be categorized as aortoiliac anatomy, graft-related causes, and aneurysmal remodeling over time. Aortoiliac anatomical factors that potentially correlate with ILO include maximum aneurysmal diameter, proximal neck measurements, distal abdominal aortic anatomy,^{6,7} common iliac artery (CIA) diameter,⁸ external iliac artery (EIA) diameter,^{3,8,9} and iliac artery tortuosity.^{10–12} Graft-related technical factors that predispose to ILO include distal landing zone in the EIA,^{3,8,9,13–15} endograft limb diameters,¹⁵ and excessive oversizing of the endograft limb.^{16,17} Aneurysmal remodeling outcomes over time are defined as dilatation of the proximal neck dilatation,^{18–23} shrinkage of the aneurysmal sac,^{18,20} aortoiliac elongation,^{18,24} and enlargement of the iliac artery.^{18,20,22,23} Endovascular graft fixation depends on the integrity and long-term structural stability of the aorta near the site of graft deployment. Aortoiliac remodeling can challenge endograft fixation and sealing. The stent graft migrates toward the aortic bifurcation, and ILO may occur if the native aorta becomes dilated or lengthened. In addition, aortoiliac conformational changes may cause limb kinking or occlusion over time. However, no study has investigated whether the remodeling outcomes of abdominal aortic aneurysms predispose to ILO after EVAR.

The aims of this study were as follows: 1) to compare patient demographics, aortoiliac anatomy, graft-related factors, and aneurysmal remodeling post-EVAR between patients with and without ILO. 2) To identify potential risk factors derived from anatomy, techniques, and aneurysmal remodeling for ILO after EVAR.

Materials and Methods

Patient Selection

A total of 593 patients underwent EVAR for infrarenal abdominal aortic aneurysm (AAA) and/or CIA aneurysm in our department between January 2013 and April 2022. The inclusion criteria for this study were elective TEVAR for asymptomatic AAA or symptomatic AAA using an infrarenal bifurcated stent graft, with iliac stent graft limbs being deployed in the CIAs or EIAs. Patients with abdominal aortic dissection, mycotic aneurysms, and traumatic pseudoaneurysms as well as those for whom postoperative computed tomography angiography (CTA) images could not be obtained were excluded. All post-EVAR and follow-up CTA were checked by two investigators to identify the ILO. Occlusion was defined as complete blockage of the lumen diameter of the stent graft, as evidenced by CT angiography, regardless of symptoms. ILO was observed in 14 patients (15 limbs). Fifty-two patients were available for CTA scans preoperatively, postoperatively before discharge, and with a minimum 1-year follow-up, and no ILO occurred until the latest CT scans. Overall, 66 patients were included in this analysis. This study was conducted in accordance with the ethical guidelines of the 1975 Declaration of Helsinki and its amendments, and the protocol was approved by the Ethics Committee of Wuhan Union Hospital (2022IEC392). Because this was a retrospective review, the requirement for written informed consent was waived, and the patient information was anonymized before analysis.

EVAR Procedures

All the procedures, including EVAR and iliac limb extension, were performed by experienced vascular surgeon. Systemic heparinization was achieved using 5000 IU of heparin. Simultaneous bilateral access to the common femoral arteries was obtained via bilateral femoral artery preparation after systemic heparinization. All endovascular stent grafts were deployed below the renal arteries, whereas the endograft limbs were deployed with a distal sealing zone in the CIAs or EIAs depending on the extent of the aneurysm. The distal landing zone of endovascular stent grafts was located in EIAs following internal iliac artery (IIA) coil embolization. Four different types of devices were used: 49 (74.2%) Talent and Endurant (Medtronic Vascular, Santa Rosa, CA, USA), two (3.0%) Cordis, six (9.1%) Microport, and nine (13.6%) Lifetech. Completion angiography to assess graft position and function was performed routinely without stiff wires in place in order to detect limb kinking that might predispose to thrombosis.

Image Analysis and Measurements

Preoperative anatomy, procedure-related data, and postoperative and long-term follow-up data were prospectively obtained from the patient records and CTA scans at different time-points. All measurements (diameter, length, and

angle) were performed with semi-automatically generated center-lumen line reconstructions on a workstation using dedicated vascular reconstruction software (AW 4.4–4.5, Advantage WorkStation, GE Healthcare). Two vascular surgeons blinded to the patient history and outcomes separately reviewed the cross-sectional and axial reconstruction of the CTA scans. These two vascular surgeons had extensive experience with workstation and centerline measurements.²⁵ If an agreement could not be reached after discrepancies were discussed, an independent investigator was consulted to reach a final consensus.

Anatomical Measurements

Preoperative AAA anatomical measurements focused mainly on aneurysmal sac diameters, infrarenal proximal aortic neck, distal abdominal aorta, and iliac artery ipsilateral to limb occlusion. Diameter measurements were determined from outer-to-outer circumferential wall perpendicular to the long axis of the vessel. Proximal aortic neck length was defined as the distance from the lowest renal artery level to the onset of the aneurysm. The proximal aortic neck diameter was defined as the maximum diameter of the aorta 15 mm below the lowest renal artery. The proximal aortic neck angle is the most acute angle calculated between the lowest renal artery along the midline of the lumen to the origin of the aneurysm and the aortic bifurcation. The presence of mural thrombus and calcification was defined when more than half of the vascular circumference was covered with thrombi or calcification by gross measurement. The CIA index of tortuosity was calculated as the length of the CIA based on the center-lumen line from the aortic bifurcation to the origin of the internal iliac artery divided by the straight-line distance between the two landmarks. A double iliac sign was defined as the observation that the iliac arteries were visually doubled or more on an axial CTA slice. The double iliac sign was recorded as present or absent; however, no other quantitative measurements were performed.

EVAR Procedure-Related Factors

The ratio between the sum of the endograft limb diameter and the distal aorta diameter was calculated. Endograft iliac limb parameters included diameter, oversizing, and distal landing zone in the EIA. Iliac limb parameters were measured at the end of the landing zone. The degree of oversizing of the endograft iliac limb was calculated as the ratio of the iliac limb diameter to the preoperative landing zone diameter of the CIA or the EIA. The diameter of each endograft limb was measured at the level of the terminal abdominal aorta. Endograft iliac limbs with smaller diameters in the terminal abdominal aorta were defined as the smaller limb (SL) and those with larger diameters in the terminal aorta were defined as the larger limb (LL). Endograft limb extension was defined as a procedure in which the distal landing zone of the endovascular stent grafts was extended to the EIA for various reasons.

Aneurysmal Remodeling Outcomes

Baseline reference CTA images were obtained postoperatively after EVAR and before discharge. Serial follow-up CTA scans were reviewed to evaluate aneurysmal remodeling. CTA analysis consisted of measuring the proximal aortic neck angulation, the following diameters: proximal aortic neck, aneurysm sac, and CIA, and the following distances: superior mesenteric artery (SMA) to the lowest renal artery, SMA to iliac bifurcation, SMA to left iliac bifurcation, SMA to right iliac bifurcation, lowest renal to left iliac bifurcation, and lowest renal-right iliac bifurcation. The aortic diameters were measured at planes perpendicular to the central line from the adventitia to the adventitia. Standardized centerline aortic lengths were also measured. All measurements were obtained postoperative and during all follow-up CTA scans, and the changes in these measurements from the postoperative baseline to follow-up were recorded.

Statistical Analysis

Categorical variables are reported as counts and percentages. Chi-square or Fisher's exact test was used to compare categorical variables. Continuous variables are reported as mean \pm standard deviation and median (first quartile, third quartile) according to the normality of distribution. Univariate analysis between groups was performed using Student's *t*-test for variables with normal distribution and the Mann–Whitney *U*-test for independent nonparametric data. Differences among groups were analyzed using analysis of variance (ANOVA) for variables with normal distribution and the Kruskal–Wallis test for independent nonparametric data. All analyses were performed using SPSS, version 9.4

software. Cox regression analysis was performed to determine the influence of variables on ILO at follow-up. Variables with statistical significance in univariate analysis were entered into a Cox multivariate model. The results of the regression analysis are presented as hazard ratios (HR) and 95% confidence intervals (CI). Kaplan–Meier time to event analysis was used to evaluate the cumulative proportion of patients with patent endograft limb at the follow-up. Differences in ILO free survival were evaluated with a Log rank test. Statistical significance was assumed when the *p*-value was <0.05.

Results

Baseline Characteristics of Patients Enrolled in This Study

This study included 66 patients who underwent standard EVAR and regular follow-up CTA between January 2013 and April 2022. During follow-up, 52 patients presented with the bilateral patent endograft limb preoperatively, within 1 week before discharge, and during a minimum follow-up of 1 year, and 14 patients unfortunately suffered from ILO until the latest imaging examination. The patient demographics and concomitant diseases are shown in Table 1. Male patients accounted for 71.4% and 94.2% of the cases with ILO and patent endograft limbs, respectively (*p* = 0.032). Coronary artery disease was more frequently observed in patients with ILO (64.3%) than in those with patent endograft limb (26.9%) (*p* = 0.009). For the remaining factors, statistical analysis failed to show a significant difference between the ILO and patent endograft limb groups, including age, hypertension, diabetes mellitus, smoking, chronic kidney disease, cerebrovascular accident, cancer, and chronic obstructive pulmonary disease.

Clinical Pattern, Time to Occlusion, and Treatment Option of ILO

Table 2 lists the presenting symptom, time to event, the left/right or both of ILO, and treatment modalities in patients with ILO. Fourteen patients with ILO were observed until the latest follow-up CTA, including 1 patient who had ILO in both limbs. Their ages ranged from 58 to 75 years, and 10 patients (71.4%) were male. Of the 14 patients with ILO, two (14.3%) had ILO within 30 days following EVAR, and the majority of patients (12/14, 85.7%) were diagnosed with ILO within the first year of follow-up. However, two patients (14.3%) were identified as having ILO after one year of follow-up. The presenting symptoms of ILO were acute ischemia with rest pain in five patients (35.7%) and mild-to-moderate claudication in six patients (42.9%). In three patients (21.4%), the ILOs were asymptomatic and were found on follow-up CTA. ILO was located on the right side (11/14, 78.6%), left side (14.3%), or both sides (7.1%).

Three patients (21.4%) were treated with catheter-directed thrombolysis, followed by percutaneous transluminal balloon angioplasty in two patients and adjunctive stenting in one patient. Four patients (28.6%) were treated with surgical thrombectomy, followed by transluminal balloon angioplasty in four patients and adjunctive stenting in three

Table 1 Baseline Demographics and Concomitant Diseases of Patients Included in the Study

	Total Patients (n = 66)	Patients with Patent Endograft Limb (n = 52)	Patients with ILO (n = 14)	P value
Age	66.5 ± 8.5	66.6 ± 9.0	66.1 ± 6.6	0.855
Males	59 (89.4%)	49 (94.2%)	10 (71.4%)	0.032
Hypertension	37 (56.1%)	32 (61.5%)	5 (35.7%)	0.077
Diabetes mellitus	4 (6.1%)	3 (5.8%)	1 (7.1%)	1.000
Smoking	36 (54.5%)	31 (59.6%)	5 (35.7%)	0.111
Chronic kidney disease	2 (3.0%)	2 (3.8%)	0 (0%)	1.000
Coronary artery disease	23 (34.8%)	14 (26.9%)	9 (64.3%)	0.009
Cerebrovascular accident	5 (8.8%)	4 (7.7%)	1 (20.0%)	0.919
Cancer	4 (6.1%)	3 (5.8%)	1 (7.1%)	1.000
Chronic obstructive pulmonary disease	4 (6.1%)	4 (7.7%)	0 (0%)	0.571

Notes: Categorical data are shown as a number (% of each group). Continuous values are presented as mean ± standard deviation or median (first quartile; third quartile), according to the normality of distribution.

Abbreviation: ILO, iliac limb occlusion.

Table 2 Symptoms, Time and Treatment of Iliac Limb Occlusion

Case	Sex	Age	Symptoms	Time to Event	Location of Occlusion	Treatment
1	Male	58	Claudication	3 months	Right	Thrombectomy; balloon angioplasty
2	Male	63	Claudication	2 months	Right	Thrombolysis; balloon angioplasty; stent
3	Male	75	Asymptomatic	4 months	Right	Conservative
4	Female	58	Rest pain	1 hour	Right	Thrombolysis; balloon angioplasty
5	Male	65	Claudication	18 months	Right	Femorofemoral cross-over bypass
6	Male	58	Claudication	4 months	Right	Conservative
7	Male	69	Rest pain	1 month	Left	Thrombolysis
8	Female	75	Asymptomatic	3 months	Left	Conservative
9	Male	72	Rest pain	3 months	Right	Balloon angioplasty; stenting
10	Male	59	Asymptomatic	7 months	Both	Conservative
11	Female	62	Rest pain	4 months	Right	Femorofemoral cross-over bypass
12	Male	74	Claudication	4 months	Right	Thrombectomy; balloon angioplasty
13	Male	68	Rest pain	4 months	Right	Thrombectomy; balloon angioplasty; stent
14	Female	70	Claudication	16 months	Right	Thrombectomy; balloon angioplasty; stent

patients. Two patients (14.3%) were treated with femorofemoral crossover bypass. One patient (7.1%) underwent transluminal balloon angioplasty, followed by adjunctive stenting. The remaining four patients (28.6%) received conservative treatment. None of the reported patients underwent major amputation.

Morphologic Characteristics of Aortoiliac Anatomy

Table 3 presents the differences between the ILO and patent endograft limb groups with respect to the aortoiliac morphology variables. The maximum aneurysm sac diameters were significantly smaller in patients with ILO (35.4 [9.6; 49.9] mm) than

Table 3 Potential Predictors from Preoperative Aorto-Iliac Anatomy for Predicting Iliac Limb Occlusion

	Patent Endograft Limb (n = 52)	ILO (n = 14)	Univariate Analysis
			P value
Maximum aneurysm sac diameters, mm	52.6 (38.9; 66.3)	35.4 (29.6; 49.9)	0.008
Infrarenal proximal aortic neck			
Proximal neck length, mm	37.3 ± 18.3	36.4 ± 14.5	0.874
Proximal neck diameter, mm	19.4 (17.3; 22.3)	17.1 (16.3; 19.9)	0.058
Proximal neck angle	33.2 ± 18.6	32.6 ± 22.8	0.992
Distal abdominal aorta			
Calcification ≥ 50% of circumference	3 (5.8%)	2 (14.3%)	0.617
Thrombus ≥ 50% of circumference	23 (44.2%)	2 (14.3%)	0.082
Distal aorta diameters, mm	27.4 (21.2; 41.3)	22.6 (17.5; 34.7)	0.117
Iliac artery, ipsilateral to limb occlusion			
CIA diameter, mm	15.3 (13.6; 19.0)	13.3 (10.8; 18.0)	0.229
EIA diameter, mm	8.5 (7.3; 9.9)	8.5 (7.5; 10.2)	0.568
Iliac calcification ≥ 50% of circumference	15 (28.8%)	5 (35.7%)	0.620
Iliac thrombus ≥ 50%	29 (55.8%)	4 (28.6%)	0.132
Double iliac sign	6 (11.5%)	6 (42.9%)	0.007
CIA index of tortuosity	1.04 (1.03; 1.07)	1.09 (1.04; 1.18)	0.016

Notes: Categorical data are shown as a number (% of each group). Continuous values are presented as mean ± standard deviation or median (first quartile; third quartile), according to the normality of distribution.

Abbreviations: CIA, common iliac artery; EIA, external iliac artery; ILO, iliac limb occlusion.

in those with patent endograft limb (52.6 [38.9; 66.3] mm) ($p = 0.008$). The CIA index of tortuosity was significantly higher in patients with ILO (1.09 [1.04; 1.18]) than in those with patent endograft limb (1.04 [1.03; 1.07]) ($p = 0.016$). One patient had ILO three months after EVAR with a tortuosity index of 1.38 (Figure 1). The double iliac sign was observed significantly more often in six patients (42.9%) with ILO than in six patients (11.5%) with patent endograft limbs ($p = 0.007$). One patient showed a double iliac sign (DIS) on preoperative CTA and developed a right ILO five months after EVAR (Figure 2).

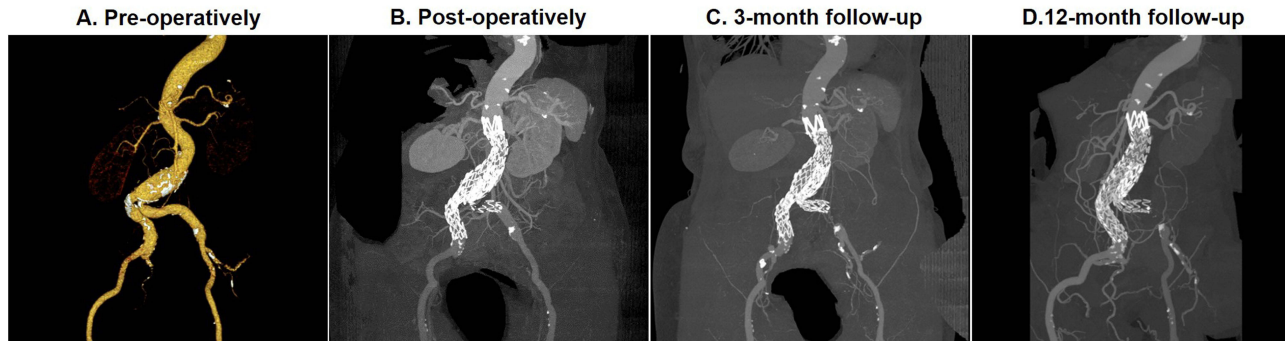


Figure 1 ILO due to tortuous CIA. (A) The preoperative CTA indicated the severe tortuosity of left CIA and tortuosity index of left CIA was calculated as 1.38. (B) Tortuous CIA resulted in limb stent-graft kinking after EVAR. (C) ILO was found at 3-month follow-up. (D) Conservative treatment was performed with significant symptom relief at 12-month follow-up.

Abbreviations: ILO, iliac limb occlusion; CIA, common iliac artery; CTA, computed tomography angiography; EVAR, endovascular abdominal aneurysm repair.

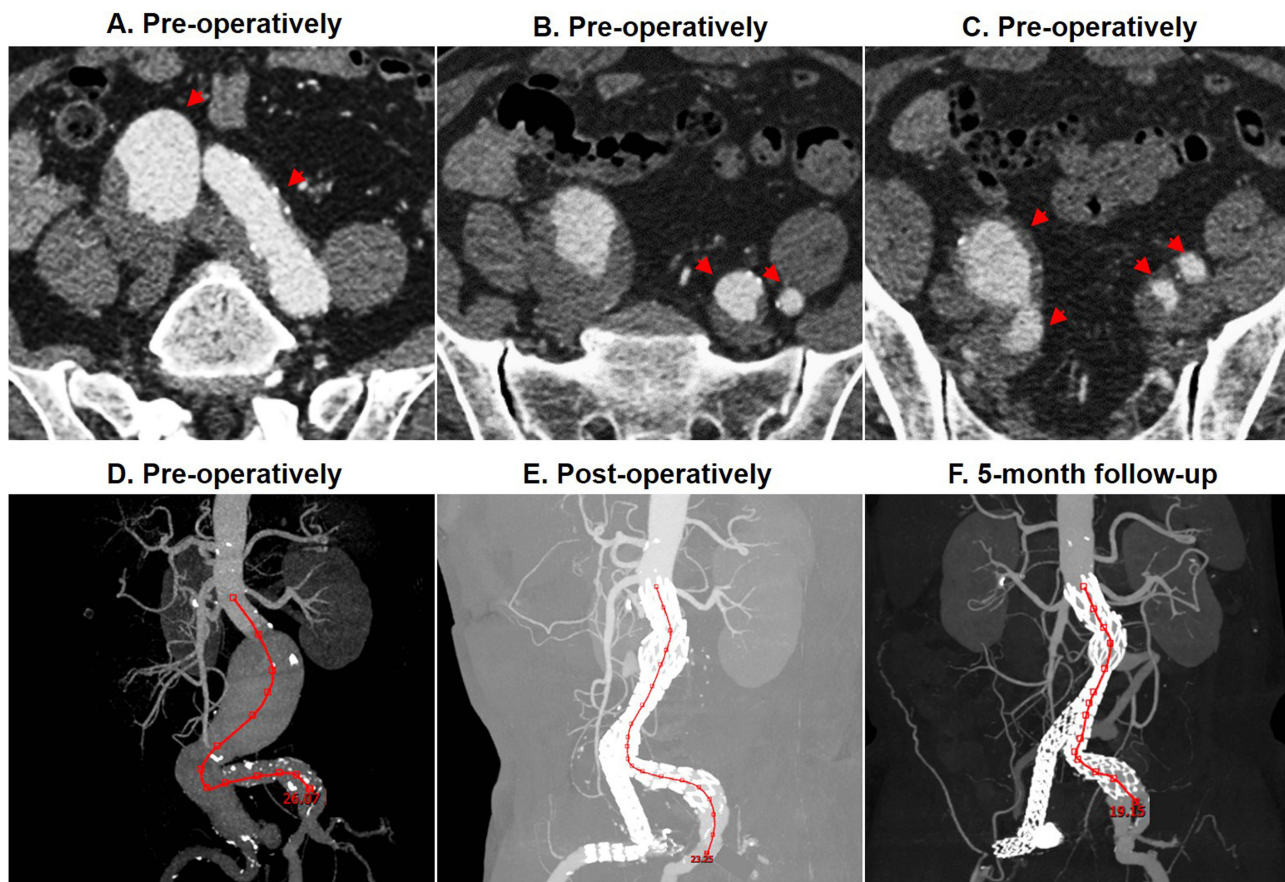


Figure 2 ILO and double iliac sign. (A–C) Double iliac sign was defined as the observation that a part of the iliac vessel within the landing zone of the graft limb was visually doubled or more on the axial CTA slice (red arrows). Double iliac sign was present on the preoperative CTA (red arrows). (D–F) Lowest renal artery–left iliac bifurcation distances were 26.1 mm, 23.3 mm, and 19.2 mm preoperatively, postoperatively, and at 5-month follow-up, respectively. Right ILO occurred at 5 months after EVAR and was associated with the significant decrease in lowest renal artery–left iliac bifurcation distance.

Abbreviations: ILO, iliac limb occlusion; CTA, computed tomography angiography; EVAR, endovascular abdominal aneurysm repair.

For the remaining factors measured in iliac artery ipsilateral to ILO, there were no significant differences between the ILO group and patent endograft limb group, on CIA diameters, EIA diameters, iliac calcification $\geq 50\%$, and iliac thrombus $\geq 50\%$ of circumference. Infrarenal proximal aortic neck measurements included diameter, length, and angle and did not differ significantly between the ILO and patent endograft limb groups. Distal abdominal aorta parameters including calcification $\geq 50\%$ of circumference, thrombus $\geq 50\%$ of circumference, and distal aorta diameter were also not significantly different between the ILO and patent endograft limb groups.

EVAR Procedure-Related Factors

Table 4 presents the EVAR procedure-related parameters of the ILO and patent endograft limb groups. The difference in diameter between the LL and SL (LL-SL) was statistically larger in patients with ILO (1.9 [0.9; 5.4] mm) than in those with patent endograft limb (1.3 [0.5; 2.5] mm) ($p = 0.048$). The SL was occluded due to compression of the LL within the distal narrow aorta 19 months after EVAR (Figure 3). Endograft-to-vessel oversizing was significantly larger in patients with ILO (20.2% \pm 6.7%) than in those with patent endograft limb (12.7% \pm 4.7%) ($p < 0.001$).

No significant difference was observed in the sum of the endograft limb diameters/distal aorta diameters and endograft iliac limb diameters between the ILO and patent endograft limb groups. Extension of the graft into the EIA was not more frequently observed in patients with ILO (42.9%) than in those with patent endograft limb (36.5%).

Aortoiliac Remodeling from Postoperative Measurement After EVAR

Table 5 presents EVAR-induced aortoiliac remodeling in patients with patent endograft limb and with ILO. Proximal aortic neck diameter increased by an average of 2.4 [0.8; 4.7] mm and 0.8 [0.5; 1.5] mm in patients with patent endograft limb and ILO, respectively (Figure 4). This change was more significant in patients with patent endograft limb than in those with ILO ($p = 0.030$). Proximal aortic neck straightened over time with angulation decreased by a mean of 0.4 \pm 9.0 degrees in patients with patent endograft limb and 0.3 \pm 11.7 degrees in patients with ILO. Aneurysm sac regression was also significant (Figure 5): decreased by a mean of 0.9 [-5.2; 1.0] mm in patients with patent endograft limb and 0.5 [-2.7; 1.0] mm in patients with ILO. CIA diameters significantly increased over time with the mean increases of 1.2 [0.2; 2.4] mm in patients with patent endograft limb and 1.5 [-0.7; 3.2] mm in patients with ILO (Figure 6).

SMA–lowest renal artery increased significantly with a lengthening of 0.4 \pm 2.0 mm in patients with patent endograft limb and 1.1 \pm 2.3 mm in patients with ILO. SMA–the top of stent graft also increased significantly with a lengthening of 1.8 \pm 3.0 mm in patients with patent endo-graft limb and 1.7 \pm 2.7 mm in patients with ILO. SMA–flow divider lengthened by an average of 4.0 [2.0; 7.8] mm in patients with patent endograft limb and 1.0 [1.0; 4.0] mm in patients with ILO. The SMA iliac bifurcation also lengthened by an average of 5.6 [1.5; 11.7] mm in patients with patent endograft limb and 2.4 (1.6; 5.3) cm in patients with ILO (Figure 7).

Table 4 Potential Predictors from Procedure-Related Technical Factors for Predicting Iliac Limb Occlusion

	Patent Endograft Limb (n = 52)	ILO (n = 14)	Univariate Analysis
			P value
Sum of endograft limb diameters/distal aorta diameters	1.1 (0.9; 1.3)	1.0 (0.8; 1.3)	0.503
Endograft limb parameters, ipsilateral to limb occlusion			
Endograft iliac limb diameters, mm	12.0 \pm 1.9	11.3 \pm 1.1	0.219
Endograft iliac limb to vessel oversizing, %	12.7 \pm 4.7	20.2 \pm 6.7	<0.001
Distal landing zone in the EIA	19 (36.5%)	6 (42.9%)	0.665
Interaction between LL and SL			
LL - SL diameter, mm	1.3 (0.5; 2.5)	1.9 (0.9; 5.4)	0.048

Notes: Categorical data are shown as a number (% of each group). Continuous values are presented as mean \pm standard deviation or median (first quartile; third quartile), according to the normality of distribution.

Abbreviations: EIA, external iliac artery; ILO, iliac limb occlusion; LL, large limb; SL, small limb.

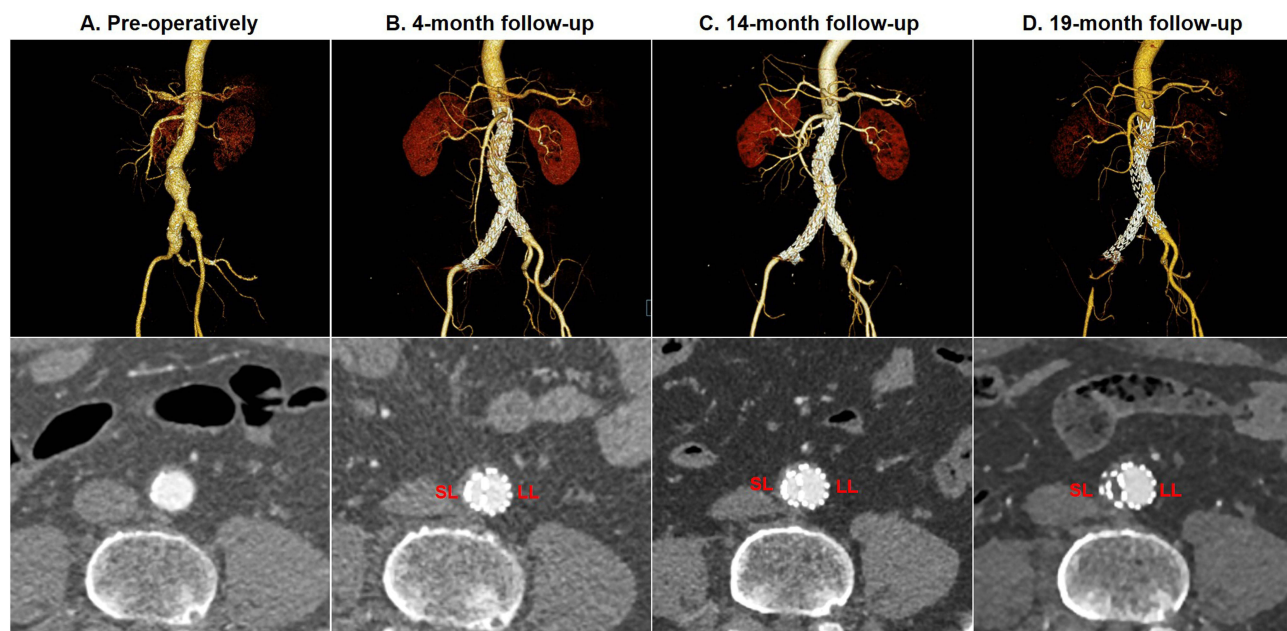


Figure 3 ILO due to the interaction between LL and SL within the distal narrow aorta. **(A)** The preoperative CTA showed the terminal narrow aorta diameter of 16.5 mm. **(B and C)** LL interacted with SL within the narrow terminal aorta, and a large difference in diameter between LL and SL was created at 4-month and 14-month follow-up. **(D)** SL was subsequently occluded at 19-month follow-up.

Abbreviations: ILO, iliac limb occlusion; CTA, computed tomography angiography; LL, large limb; SL, small limb.

Aortoiliac lengthening was obvious in patent endograft limb group with an average increase of 2.9 ± 15.7 mm in SMA–left iliac bifurcation, 1.7 ± 10.8 mm in SMA–right iliac bifurcation, $2.6 [-1.8; 11.1]$ mm in lowest renal artery–left iliac bifurcation, and $4.4 [-1.9; 9.8]$ mm in lowest renal artery–right iliac bifurcation. Conversely, the average length of aortoiliac segments was shortened in the ILO group with an average decrease of 6.3 ± 18.5 mm in SMA–left iliac bifurcation, 3.1 ± 9.9 mm in SMA–right iliac bifurcation, $0.6 [-9.6; 3.2]$ mm in lowest renal artery–left iliac bifurcation,

Table 5 Potential Factors from Aortic Aneurysm Remodeling After EVAR for Inducing Iliac Limb Occlusion

	Patent Endograft Limb (n = 52)	ILO (n = 13)	Univariate Analysis
			P value
Proximal landing zone-aortic neck changes			
Proximal aortic neck diameter, mm	2.4 (0.8; 4.7)	0.8 (0.5; 1.5)	0.030
Proximal aortic neck angulation, degrees	-0.4 ± 9.0	-0.3 ± 11.7	0.397
Aneurysm sac diameter changes			
Aneurysm sac diameter, mm	$-0.9 (-5.2; 1.0)$	$-0.5 (-2.7; 1.0)$	0.480
Distal landing zone-iliac artery changes			
CIA diameter, mm	1.2 (0.2; 2.4)	1.5 (-0.7; 3.2)	0.876
Aortic neck length changes			
SMA - lowest renal artery, mm	0.4 ± 2.0	1.1 ± 2.3	0.595
SMA - top of stent graft, mm	1.8 ± 3.0	1.7 ± 2.7	0.993
Aortic length changes			
SMA - flow divider, mm	4.0 (2.0; 7.8)	1.0 (1.0; 4.0)	0.115
SMA - iliac bifurcation, mm	5.6 (1.5; 11.7)	2.4 (1.6; 5.3)	0.213

(Continued)

Table 5 (Continued).

	Patent Endograft Limb (n = 52)	ILO (n = 13)	Univariate Analysis
			P value
Aortoiliac length changes			
SMA- left iliac bifurcation, mm	2.9 ± 15.7	-6.3 ± 18.5	0.067
SMA- right iliac bifurcation, mm	1.7 ± 10.8	-3.1 ± 9.9	0.136
Lowest renal - left iliac bifurcation, mm	2.6 (-1.8; 11.1)	-0.6 (-9.6; 3.2)	0.031
Lowest renal - right iliac bifurcation, mm	4.4 (-1.9; 9.8)	-1.6 (-9.5; 6.2)	0.153

Notes: Categorical data are shown as a number (% of each group). Continuous values are presented as mean ± standard deviation or median (first quartile; third quartile), according to the normality of distribution. A negative number means shrinking or shortening.

Abbreviations: CIA, common iliac artery; EVAR, endovascular aneurysm repair; ILO, iliac limb occlusion; SMA, superior mesenteric artery.

and 1.6 [-9.5; 6.2] mm in lowest renal artery–right iliac bifurcation. The lowest renal artery–left iliac bifurcation showed a statistically significant difference between the patent endograft limb and the ILO groups ($p = 0.031$).

Risk Factors for Iliac Limb Occlusion After EVAR

The results of Cox regression analysis for ILO are presented in Table 6. CIA index of tortuosity ≥ 1.08 (HR = 1.584, 95% CI = 1.073–2.339; $p = 0.021$) and endograft to vessel oversizing $\geq 18.8\%$ (HR = 1.347, 95% CI = 1.150–1.577; $p < 0.001$) were identified as independent risk factors for ILO. Kaplan–Meier analysis confirmed a significantly lower ILO-free survival when the CIA index of tortuosity was ≥ 1.08 (47.6% vs 87.1%; Figure 8A) or when the endograft-to-vessel oversizing was $\geq 18.8\%$ (31.1% vs 94.0%; Figure 8B). Moreover, the presence of one risk factor was associated with a relatively lower ILO-free survival rate compared with none of the two predictors (75.0% vs 96.3%; Figure 8C). Change of lowest renal artery–left iliac bifurcation from postoperative measurement ≤ 0.07 mm (HR = 0.543, 95% CI = 0.333–0.886; $p = 0.015$) increased the risk for ILO after EVAR. Kaplan–Meier analysis indicated a significantly lower ILO-free survival when changes in lowest renal–left iliac bifurcation from postoperative measurements ≤ 0.07 mm (66.8% vs 86.8%; Figure 8D).

Discussion

We previously reported that ILO following EVAR contributes to tortuous iliac arteries. A CIA index of tortuosity ≥ 1.08 was identified as an independent risk factor for ILO. This is consistent with two previous studies,^{10–12} which indicated that the angulation and tortuosity of the CIA were indicators of ILO after EVAR. Long and tortuous iliac arteries were more likely to be associated with endograft limb compression and/or kinking and thrombosis after deployment. When we

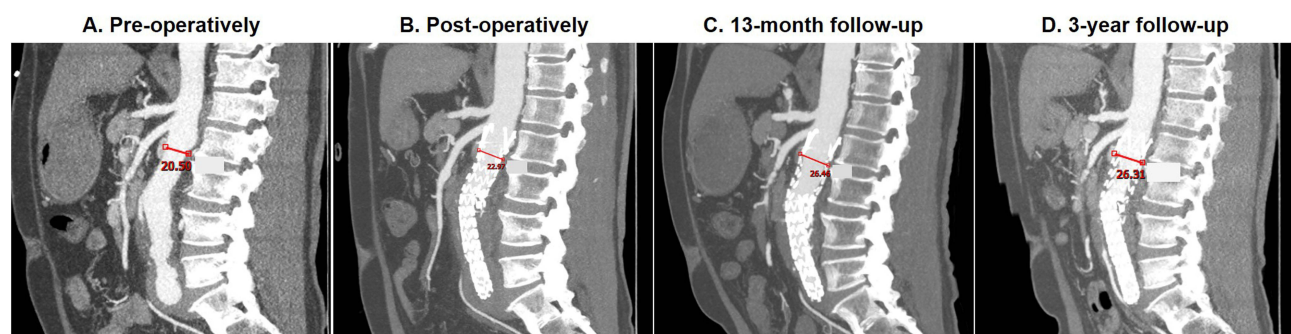


Figure 4 Proximal aortic neck dilatation over time following EVAR. (A, B) Proximal aortic neck diameters were 20.5 mm and 23.0 mm on preoperative and postoperative CTA, respectively. (C and D) The sagittal CTA scans obtained at 13 month and 3 years after EVAR showed aortic neck dilatation of 26.5 mm and 26.3 mm.

Abbreviations: EVAR, endovascular abdominal aneurysm repair; CTA, computed tomography angiography.

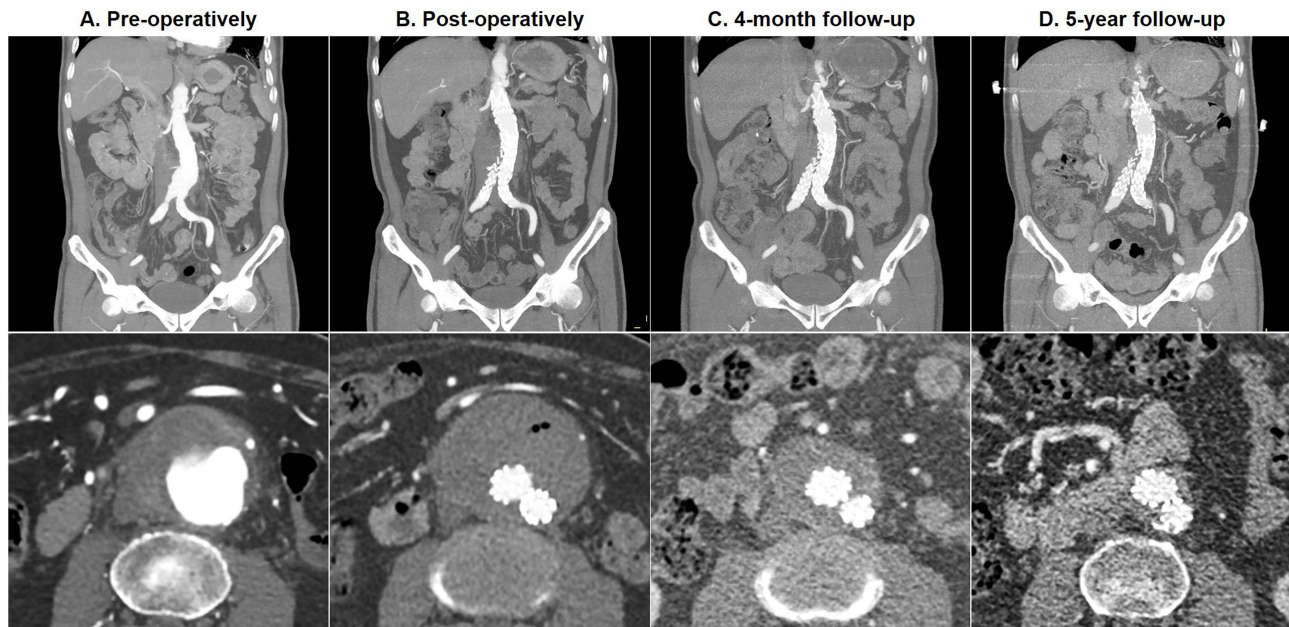


Figure 5 Aneurysmal sac regression over time following EVAR. (A and B) The axial CTA scans obtained preoperatively and postoperatively before discharge showed the maximum aneurysmal sac diameter of 70.8 mm and 69.4 mm. (C) The 4-month axial CTA scans indicated the aneurysmal sac regression of 54.9 mm. (D) The 5-year axial CTA scans demonstrated a total regression of the aneurysmal sac due to the remodeling of aneurysmal mural thrombus.

Abbreviations: EVAR, endovascular abdominal aneurysm repair; CTA, computed tomography angiography.

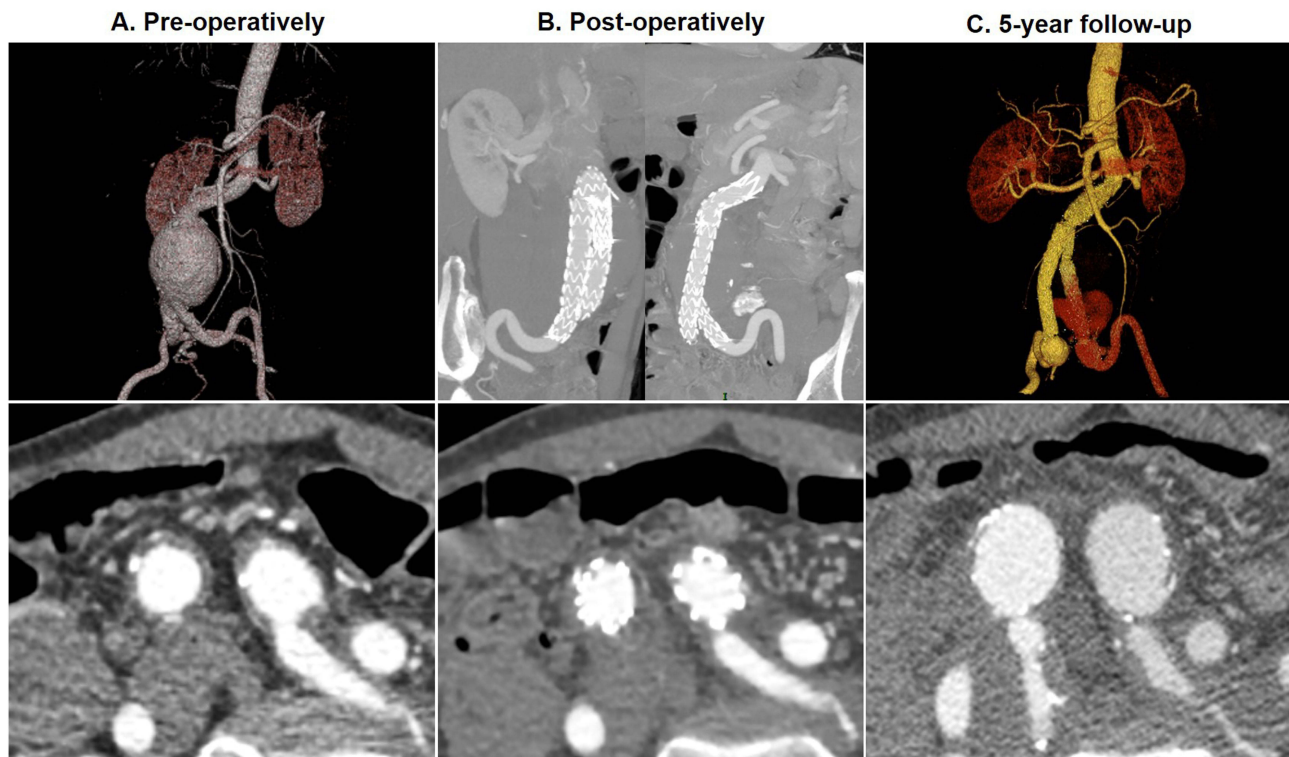


Figure 6 Common iliac artery enlargement over time following EVAR. (A) The axial and reconstructed CTA scans obtained preoperatively showed the right and left CIA diameter of 15.9 mm and 20.7 mm at the iliac bifurcation. (B) The axial and reconstructed CTA scans obtained postoperatively before discharge indicated the right and left CIA diameter of 16.1 mm and 20.8 mm at the iliac bifurcation. (C) The 5-year axial and reconstructed CTA scans demonstrated the aneurysmal dilatation of bilateral CIA nearby the iliac bifurcation and the right and left CIA diameters of 31.41 mm and 33.94 mm.

Abbreviations: EVAR, endovascular abdominal aneurysm repair; CTA, computed tomography angiography; CIA, common iliac artery.

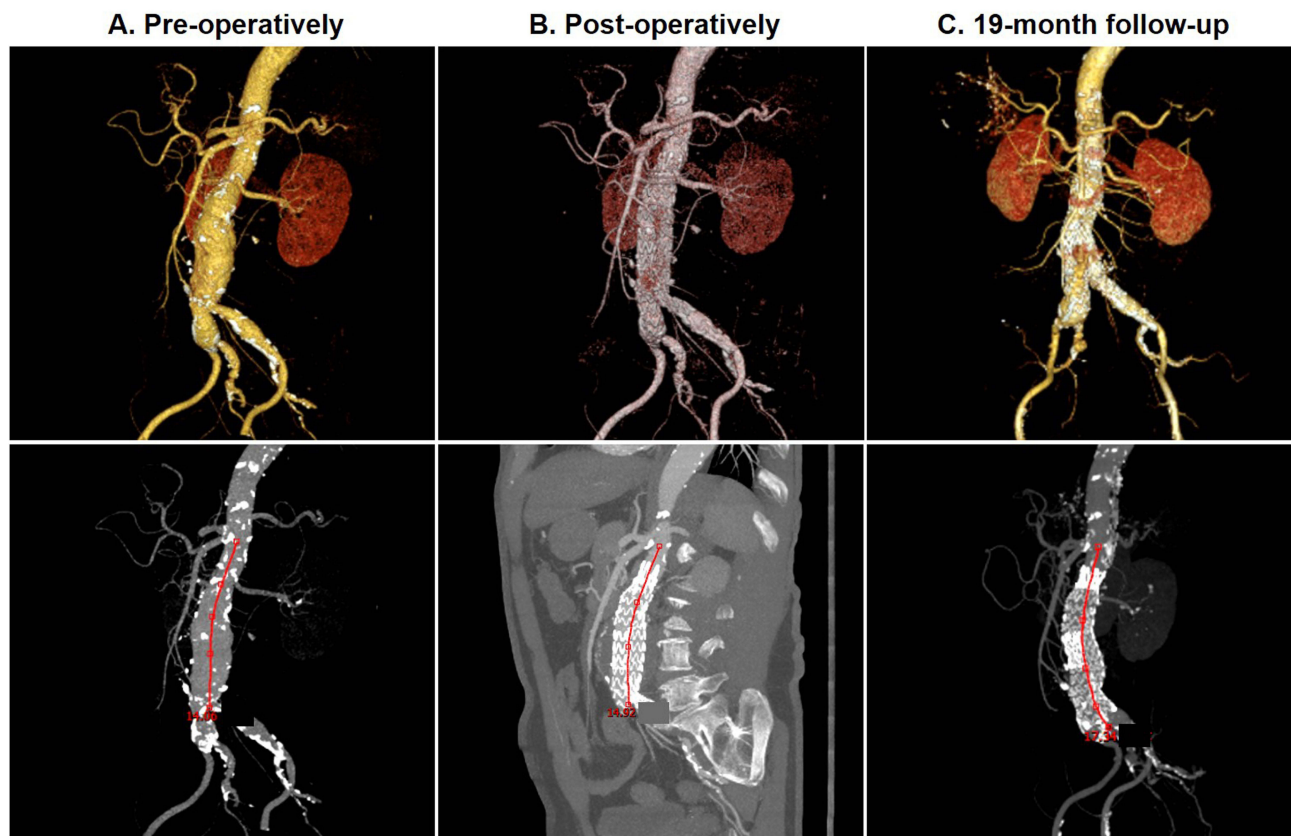


Figure 7 Aortoiliac elongation over time following EVAR. **(A and B)** The axial and reconstructed CTA scans obtained preoperatively and postoperatively before discharge showed the SMA–iliac bifurcation distance of 14.1 mm and 14.9 mm. **(C)** The 19-month CTA scans showed the SMA–iliac bifurcation lengthening of 17.3 mm. **Abbreviations:** EVAR, endovascular abdominal aneurysm repair; CTA, computed tomography angiography; SMA, superior mesenteric artery; EVAR, endovascular abdominal aneurysm repair.

reviewed the reconstructed CT images in 14 cases with demonstrated ILO following EVAR, endograft kinking occurred in the most angulated CIA in two patients. When tortuosity is located at the CIA close to the iliac bifurcation or distal EIA, it is helpful to avoid endograft limb deployment into the iliac arterial segment of the abrupt transition. When aortoiliac angulation resulted in kinking of the endograft iliac limb, the adjunctive iliac stent in the endograft limb increased resistance against kinking and significantly reduced the risk of postoperative ILO.^{26,27}

Table 6 Multivariable Proportional Hazards Analysis of Variables Affecting the Risk for Iliac Limb Occlusion

	Multivariable Analysis		
	HR	95% CI	P value
Female	0.608	0.129–2.858	0.528
Coronary artery disease	2.901	0.689–12.221	0.146
Preoperative maximum aneurysm diameters, mm	0.986	0.923–1.043	0.662
Double iliac sign	1.313	0.273–6.318	0.734
CIA index of tortuosity	1.584	1.073–2.339	0.021
Endograft to vessel oversizing	1.347	1.150–1.577	<0.001
LL - SL diameter, mm	1.122	0.837–1.505	0.440
Proximal aortic neck diameter changes from Postoperative measurements, mm	0.962	0.780–1.186	0.715
Lowest renal - left iliac bifurcation from Postoperative measurements, cm	0.543	0.333–0.886	0.015

Abbreviations: CI, confidence interval; CIA, common iliac artery; HR, Hazard Ratio; LL, larger limb; SL, smaller limb.

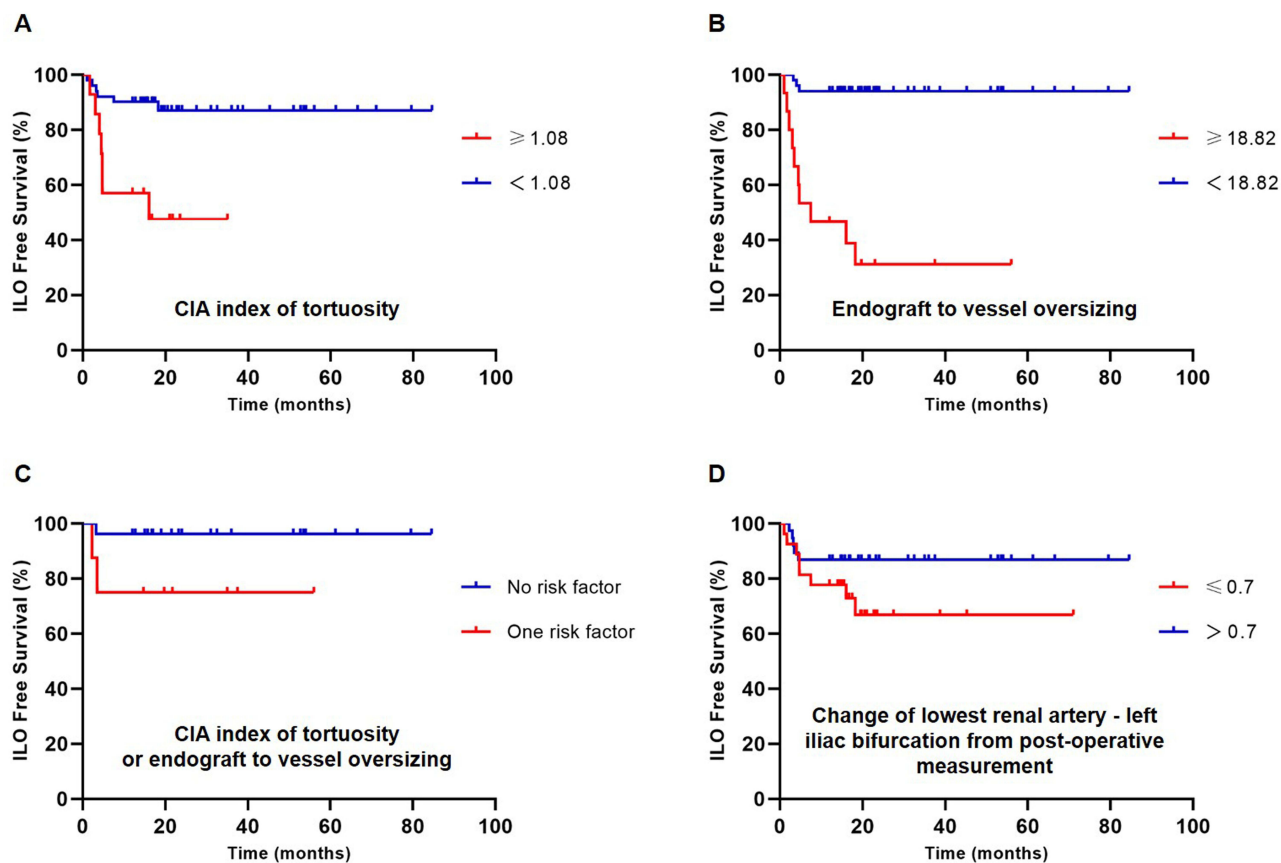


Figure 8 Kaplan-Meier analysis of ILO-free survival. **(A)** tortuosity index of CIA ≥ 1.08 or < 1.08 , **(B)** endograft iliac limb to vessel oversizing $\geq 18.8\%$ or $< 18.8\%$, **(C)** neither tortuosity index of CIA ≥ 1.08 nor endograft iliac limb to vessel oversizing $\geq 18.8\%$ or one risk factor, **(D)** change of lowest renal artery-left iliac bifurcation from postoperative measurement ≤ 0.07 mm.

Abbreviations: ILO, iliac limb occlusion; CIA, common iliac artery.

Endograft limb oversizing $\geq 18.82\%$ was recognized as a predisposing factor for ILO in this study. This is in line with two previous studies, which reported that a $>15\%$ oversized endograft in the iliac arteries appeared to be an independent predictor of ILO after EVAR.^{16,17} Excessive oversizing of the endograft may lead to bunching of the endograft limb into relatively small-sized vessels. Radial force of the distal iliac endograft limb in the vessel lumen can result in stenosis and obstruction. In contrast, the extension of the endograft limb into the EIA did not prove to be a significant risk factor for ILO. This is consistent with a study by Mantas et al,¹⁶ which indicated that an endograft into the EIA did not impact the ILO. However, previous studies have identified endograft extensions to the EIA as a risk factor for ILO.^{3,8,9}

Significant aortoiliac remodeling, including proximal aortic neck dilation, neck straightening, aneurysm sac regression, aortoiliac elongation, and iliac artery enlargement, occurs after EVAR. Proximal aortic neck dilation may relate to the oversizing and radial force of the stent graft, especially during the early months.¹⁸ Dilation in the long term may be due to the natural progression of an aneurysmal wall degeneration.¹⁸ The probability of aortic neck dilation rates was reported to be $59\% \pm 6.1\%$ at 4 years after EVAR.¹⁹ Proximal aortic neck dilatation was more rapid at the first postoperative month and at the third postoperative year (24–36 months).²⁰ In the study of Vukovic et al,²¹ proximal aortic neck diameter expanded by 2 to 4 mm within 1 year. Proximal aortic neck diameter 15 mm below the lowest main renal artery increased from 23.5 ± 2.5 mm at 1 month to 27.3 ± 2.8 mm at 5 years.²² Proximal aortic neck dilatation appeared to be more marked at the level closest to the aneurysm than at the level of the renal arteries.²³ Neck angulation changes after EVAR are well documented in the literature.^{18,22} Proximal aortic neck angulation straightening occurred after EVAR, with a decrease of 0.6 ± 7 degrees from 1 month to 5 years.²² A reduction of aneurysm sac diameter was reported after EVAR with a greater regression rate during the first six postoperative months and at 2 years postoperative interval.²⁰ Significant aortoiliac elongation was observed up to 5 years after EVAR, and aortic measurements included

SMA–top of stent graft, SMA–flow divider, SMA–iliac bifurcation, and top of stent graft–iliac bifurcation.²⁴ An expansion of CIA at the distal landing zone was more prominent in the first six postoperative months.^{18,20} Between 1 month and 5 years, iliac artery diameter at the attachment zone increased from 13.0 ± 3.1 mm to 14.6 ± 3.4 mm and from 13.4 ± 3.4 mm to 16.3 ± 3.8 mm on the right and left sides, respectively.²² The increase at the level of the iliac arteries was distally more marked than at its origin.²³

Significant aortic lengthening was observed in the aortoiliac segments over the study period but not in the iliofemoral segments.²⁴ This is in agreement with the results of our study. A recent study demonstrated that aortic elongation occurred after EVAR and did not differ between the patent endograft limb and ILO groups. Aortic elongation was determined by measuring the SMA–lowest renal artery, SMA–top of the stent graft, SMA–flow divider, SMA–and the iliac bifurcation. Aortoiliac measurements were obtained with a focus on the iliofemoral arterial length, including the SMA–left iliac bifurcation, SMA–right iliac bifurcation, lowest renal–left iliac bifurcation, and lowest renal–right iliac bifurcation. This study found an average increase in aortoiliac measurements in patients with patent endograft limb; nevertheless, an average decrease in aortoiliac midline distances was observed in patients with ILO. The change in the distance between the lowest renal artery and the left iliac bifurcation was statistically lower in patients with ILO than in patients with patent endograft limb, and this change ≤ 0.07 was identified as an independent predictor of ILO after EVAR. It is presumed that aortoiliac tortuosity might result in a decrease in the distance between the lowest renal artery and left iliac bifurcation after EVAR.

This study has several limitations. First, retrospective studies exhibit inherent drawbacks in terms of missing data and selection bias owing to a lack of randomization. Patients with ILO may have been missed, particularly those who developed only mild or no symptoms. The study showed an imbalance in the number of cases treated with each endograft type as well as the total follow-up duration. Second, the number of patients enrolled in the study was sixty-six and relatively small, with a low ILO event rate; 14 patients were diagnosed with ILO after EVAR. Their experience was also limited to only four types of endografts, with no data on ILO with other types of devices. Third, the total number of 527 patients excluded owing to incomplete or inadequate follow-up CT image quality was relatively high and may have biased the reported results.

Conclusion

The tortuosity index of CIA ≥ 1.08 on preoperative CTA serves as a reliable predictor of ILO after EVAR. Endograft iliac limb-to-vessel oversizing $\geq 18.8\%$ increased the risk of ILO after EVAR. Aortoiliac remodeling after EVAR involves the expansion of the proximal aortic neck, reduction of the aortic neck angulation, regression of the aneurysm sac diameter, expansion of the iliac arteries, and aortic elongation. Aortoiliac shortening is present in patients with ILO, but not in patients with patent endograft limb. The change in the lowest renal artery to the left iliac bifurcation ≤ 0.07 between the postoperative and follow-up CT images was independently related to the occurrence of ILO.

Abbreviations

AAA, abdominal aortic aneurysm; CTA, computed tomography angiography; CI, confidence interval; CIA, common iliac artery; EIA, external iliac artery; EVAR, endovascular abdominal aneurysm repair; HR, hazard ratio; IIA, internal iliac artery; ILO, Iliac limb occlusion; LL, larger limb; SL, smaller limb; SMA, superior mesenteric artery.

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Disclosure

The authors report no conflicts of interest in this work.

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