Surgical and endovascular treatment of late postcoarctation repair aortic aneurysms: Results from an international multicenter study

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ABSTRACT

Objective: The formation of postaortic coarctation aneurysms (pCoAA) is well-described in the literature and carries a significant risk of rupture and death. Treatment strategies include open surgical, hybrid, and endovascular repair, depending on the clinical presentation, risk assessment, and anatomy. The aim of this study was to report the early and midterm results of open surgical and endovascular repair of pCoAA.

Methods: This is an international multicenter retrospective study including patients who underwent open surgical or endovascular repair for pCoAA between 2000 and 2021 at 14 highly specialized academic cardiovascular centers. The preoperative, intraoperative, and postoperative data were recorded and analyzed.

Results: A total of 74 patients (46 male; median age, 44 years; interquartile range [IQR], 35-53 years) underwent pCoAA repair. All patients had previously undergone surgical repair of aortic coarctation at a median age of 11 years for the index procedure (IQR, 7-17 years). The most common first surgical correction was synthetic patch aortoplasty in 48 patients, followed by graft interposition in 11. The median pCoAA diameter was 54 mm (IQR, 44-63 mm). The median time from the aortic coarctation repair to the pCoAA diagnosis was 33 years (IQR, 25-40 years). A total of 33 patients had symptoms at presentation, including thoracic or back pain in 8 patients. Open surgical repair was performed in 28 patients, including four frozen elephant trunk procedures and one Bentall. The remaining 46 patients underwent endovascular repair of the pCoAA. Two in-hospital deaths were observed (one frozen elephant trunk and one endovascular). After a median follow-up of 50 months (IQR, 14-127 months), there were a total of seven reinterventions.

Conclusions: This international multicenter study demonstrates that patients with pCoAA can be safely treated with either open surgical or endovascular interventions. Because the median time between the coarctation repair and the aneurysm formation was more than 30 years, life-long surveillance of these patients is warranted. (J Vasc Surg 2022;76:1449-57.)

Keywords: Aortic coarctation; Pseudoaneurysm; Descending thoracic aorta; Endovascular stent graft repair

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*A complete list of the International Rare Aortic Conditions (IRAC) Consortium is provided in the Appendix (online only).

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Aortic coarctation (CoA) is defined as a narrowing of the aorta, most often in the region of the ligamentum arteriosum adjacent to the origin of the left subclavian artery (LSA).[1,2] As a larger number of patients previously treated by open surgical repair of CoA reaches adulthood, post-aortic coarctation aneurysms (pCoAA) formation is one of the most relevant complications, with a lifetime incidence of up to 47%.[3-5] These aneurysms are often saccular, and, if left untreated, there is an increased risk of rupture and a high mortality rate.[3,4,6,7]

Important factors in the treatment of pCoAA include the specific type of aortic repair, anatomical features of the aortic arch and involvement of the supra-aortic trunks, and the longer life expectancy of this patient population.[7-9] Open surgical resection of pCoAA is challenged by the reoperative field, pulmonary adhesions, hypoplastic proximal aortic arch, hypertrophic LSA, and the proximity to the left common carotid artery.[7] Thoracic endovascular aortic repair (TEVAR) may be feasible, but it is often hampered by the patient's anatomical characteristics and may require extra-anatomic revascularization of supra-aortic vessels or custom-made endografts.[10]

Although several case series reporting the outcomes of pCoAA repair have been published in the literature, most have a small number of patients with short follow-ups. This international multicenter study reports the type of treatment and identifies concomitant conditions that might influence early and midterm results in patients with pCoAA from 14 academic high-volume aortic centers.

ARTICLE HIGHLIGHTS

- **Type of Research:** Multicenter observational nonrandomized retrospective analysis
- **Key Findings:** A total of 74 patients (46 male; median age, 44 years) underwent postaortic coarctation aneurysms (pCoAA) repair. Open surgical repair was performed in 28 patients, and the remaining underwent endovascular repair. Two in-hospital deaths were observed. After a median follow-up of 50 months, there was a total of seven reinterventions.
- **Take Home Message:** Patients with postaortic coarctation aneurysms can be treated safely with either open surgical or endovascular interventions with good early and midterm results. The late aneurysm formation after CoA repair carries anatomical peculiarities that differ from common atherosclerotic or post-traumatic isthmic aneurysms.

METHODS

Study design. This study is an international multicenter retrospective cohort study including patients treated by open surgical or endovascular repair for pCoAA between January 2000 and February 2021 at 14 academic high-volume cardiovascular centers with a special interest in aortic arch surgery (Supplementary Table I, online only). Twenty-one centers have been invited selected based on previous publications on this topic, and because they were representative centers from America, Europe, and Asia, but seven declined either because they did not treat any case during the study period or because their institutional policy did not allow them to share the data. The present study was conducted according to the locally applicable regulations and the Declaration of Helsinki, and patients gave their consent for the anonymous collection of their data on a standard consent sheet provided by each institution. Data collection was carried out in conformity with the Italian law on privacy (Art. 20-21, DL 196/2003) published in the Official Journal no. 190 of August 14, 2004, which explicitly exempts the need for ethical approval for the use of anonymous data. Institutional review board approval was not required owing to the study's retrospective design.

Study population. Patients were eligible for this study if they underwent aortic aneurysm repair with a previous history of CoA repair. All aneurysms were classified according to the reporting standards for thoracic aortic repair.[11] pCoAA characteristics such as extent, maximum diameter, LSA involvement, treatment modalities, and complications of all patients were reviewed. Major adverse events were defined as major bleeding, stroke, paraplegia, in-hospital dialysis, or death. Aneurysm-related reinterventions were considered when a second procedure was performed related to the first intervention or to the device itself in case of endovascular repair.

Data analysis. The primary end point of this study was to assess the procedure-related mortality and morbidity at 30 days and during follow-up. Secondary end points included neurological events (stroke, transient ischemic attack, paraplegia, and paraparesis), secondary interventions, and stent graft-related outcomes such as endoleak, migration, or conversion to open repair. Data collection included demographic information, patient comorbidities, secondary recoarctation-associated reinterventions, procedure details, and patient outcome data. Data were collected retrospectively in each center from medical reports, procedure notes, and postoperative imaging examinations. All patients underwent a preoperative assessment according to each center's protocol before major thoracic aortic surgery to define surgical risk, including a high-quality thoracoabdominal computed tomography angiography performed within 6 months before the procedure.[11] Treatment strategies for the pCoAA were at the discretion of the operator in accordance with each institution's standard of care. In the case of endovascular repair, technical success was defined, according to the Society for Vascular Surgery

Table I. Preoperative patient demographics, aneurysm characteristics, and symptoms at admission of the cohort of 74 patients with postaortic coarctation aneurysm (pCoAA)[a]

Variable	Total (n = 74)	Open repair[b] (n = 28)	Endovascular repair (n = 46)
Median age, years	44 (35-53)	43 (33-51)	47 (37-54)
Male gender	46 (62.2)	15 (53.5)	31 (67.4)
Hypertension	50 (67.6)	22 (78.6)	28 (60.9)
Bicuspid aortic valve	7 (9.5)	6 (21.4)	1 (2.2)
Aortic valve replacement	5 (6.8)	5 (17.9)	0
Median age at index coarctation repair, years	11 (7-17)	9 (3-16)	12 (7-17)
Time between index procedure and pCoAA repair, years	33 (25-40)	32 (25-40)	35 (26-40)
Type of prior coarctation repair			
Synthetic patch aortoplasty	48 (64.9)	17 (60.7)	31 (67.4)
Graft interposition	11 (14.9)	4 (14.3)	7 (15.2)
Subclavian flap	7 (9.5)	2 (7.1)	5 (10.9)
End-to-end anastomosis	6 (8.1)	4 (14.3)	2 (4.3)
Endovascular repair	1 (1.4)	1 (3.6)	0
Extra-anatomic bypass	1 (1.4)	0	1 (2.2)
Secondary coarctation procedures	13 (17.6)	7 (25)	6 (13)
pCoAA diameter, mm	54 (44-63)	45 (41-65)	54 (48-62)
pCoAA with restenosis	8 (10.8)	6 (21.4)	2 (4.3)
Symptoms at admission	33 (44.6)	13 (46.4)	20 (43.5)
Thoracic or back pain	8 (10.8)	3 (10.7)	5 (10.9)
Hemoptysis	7 (9.5)	2 (7.1)	5 (10.9)
Dysphonia	5 (6.8)	1 (3.6)	4 (8.7)
Dyspnea	4 (5.4)	3 (10.7)	1 (2.2)
Uncontrolled hypertension[c]	3 (4.1)	1 (3.6)	2 (4.3)
Hemorrhagic shock	3 (4.1)	1 (3.6)	2 (4.3)
Lower limb claudication	2 (2.7)	2 (7.1)	0
Arrythmia	1 (1.4)	1 (3.6)	0
Hematemesis	1 (1.4)	0	1 (2.2)
Upper limb claudication	1 (1.4)	0	1 (2.2)

pCoAA, Postaortic coarctation aneurysm repair.
[a]Values are presented as number (%) or median (interquartile range).
[b]Including frozen elephant trunk procedures.
[c]Defined by the use of more than one anti-hypertensive drug with difficult systemic blood pressure control.

reporting standards for TEVAR,[11] as successful deployment of the endograft and aneurysm exclusion in the absence of a pressure gradient (mean <10 mm Hg) and type I and III endoleaks. Among patients treated by open repair, clinical success was defined as no in-hospital mortality and successful aneurysm repair.

Surgical procedure. The treatment of pCoAA was defined as open surgical repair in case of aortic replacement by an aortic tube graft or by frozen elephant trunk (FET). Adjunctive maneuvers, like intraoperative cardiac monitoring with transesophageal echocardiography, neurological monitoring with somatosensory and motor evoked potentials, and cerebrospinal fluid drainage were at the discretion of each institution's standard of care for open thoracic aortic surgery. In addition, in the case of LSA involvement, its revascularization was at the judgment of each operator.

Endovascular procedure. The endovascular treatment of pCoAA was defined as the exclusion of the aortic aneurysm using a tubular thoracic aortic endograft. As in open repair, adjunctive maneuvers, concomitant staged procedures, and LSA revascularization were at the discretion of each institution's standard of care for TEVAR.

Follow-up. Follow-up protocols were at the discretion of each treating physician and in accordance with each center's standard of care. All patients had a follow-up in their respective institutions, and data were collected by medical charts, phone calls, and postoperative imaging

Table II. Procedural details with open and endovascular postaortic coarctation aneurysm (pCoAA) repair

Variable	Number (%)
Open surgical approach (including FET)	28 (37.8)
DTA interposition	17 (23.0)
DTA interposition graft with left subclavian bypass	6 (8.1)
FET	4 (5.4)
Bentall	1 (1.4)
Endovascular procedures (TEVAR)	46 (62.2)
Landing zone (Ishimaru)	
Zone 1	2 (2.7)
Zone 2	12 (16.2)
Zone 3	32 (43.2)
TEVAR	32 (43.2)
TEVAR with left carotid-subclavian bypass	11 (14.8)
TEVAR with left subclavian to carotid artery transposition	1 (1.4)
TEVAR with carotid-carotid-subclavian bypass	2 (2.7)

DTA, Descending thoracic aorta; *FET*, frozen elephant trunk; *TEVAR*, thoracic endovascular aortic repair.

analysis. Carotid-subclavian bypass grafts were assessed by duplex ultrasound examination when necessary. Endovascular outcomes are reported in accordance with the most recent reporting standards document for TEVAR.[11]

Statistical analyses. Continuous variables were presented as median with interquartile range (IQR), and categorical variables were expressed as counts and percentages. Spearman test was used to calculate the trend over time. Statistical analyses were performed with GraphPad Prism 9.1.1 (GraphPad Software, Inc., San Diego, CA) on a MacOS.

RESULTS

All consecutive patients undergoing aortic aneurysm repair with a prior history of CoA repair were included in this study, with a total of 74 patients (median age, 44 years; IQR, 35-53 years; 46 men_ from 14 vascular centers. Twenty-eight patients were treated with open surgical repair, and the remaining 46 had an endovascular approach. Patients' characteristics are shown in Table I.

All patients had previously undergone CoA repair (Supplementary Fig 1, online only) at a median age of 11 years (IQR, 7-17 years) for the index procedure. The most common index surgical technique for CoA correction was a synthetic patch aortoplasty in 48 patients (64.9%). A secondary procedure was performed in 13 patients (17.6%) owing to recurrent restenosis or anastomotic aneurysmal degeneration at a median age of 22 years (IQR, 14-47 years). Among the 13 patients who underwent a secondary intervention, 5 were treated for recurrent coarctation. All surgical techniques performed for CoA repair are detailed in Table I.

The median diameter of the pCoAA was 54 mm (IQR, 44-63 mm). Aneurysm sac morphology was not recorded. Symptoms at admission were present in 33 patients (44.6%), with a median aneurysm diameter of 55 mm (IQR, 41-68 mm). The most common symptom presentation was thoracic or back pain, observed in eight of the 33 patients. Two patients with large aneurysms (80 and 113 mm) presented with aneurysm rupture. Both patients were treated emergently by endovascular aortic repair in zone 2, which required left carotid-subclavian bypass. One patient who presented with a pCoAA complicated by type B dissection was treated by FET but died during recovery. All symptoms at admission are listed in Table I. The remaining 41 of these 74 patients were asymptomatic at the time of presentation, and the diagnosis was made during routine imaging surveillance (computed tomography angiography, magnetic resonance imaging, and echocardiography) or as an incidental finding. No significant difference regarding maximum pCoAA aneurysm diameters was found between symptomatic and asymptomatic patients (55 mm [IQR, 41-68 mm] vs 53 mm [IQR, 45-57 mm]; $P = .522$).

Surgical outcomes. Twenty-eight patients (median age 43 years; IQR 33-51 years; 15 males) were treated for pCoAA by redo open surgical repair, including four FET procedures and one Bentall procedure (Table II). Clinical success was 96%, with one in-hospital death. One patient underwent a FET procedure and distal implantation of a thoracic endograft. Seventeen patients (23%) underwent aneurysmectomy followed by thoracic graft interposition (Fig 1, *A-D*). The LSA was revascularized by graft interposition in six patients (Fig 1, *E-H*). One patient presenting with concomitant pCoAA and recurrent coarctation after Dacron patch aortoplasty was treated by aneurysmectomy followed by thoracic graft interposition and stenting of the anastomosis; owing to the persistence of a pressure gradient, an adjunctive ascending aorta to the descending thoracic aorta (DTA) bypass (side-to-side anastomosis) was performed.

The endovascular patients (median age, 47 years; IQR 37-54 years; 31/46 males) included TEVAR in thoracic aortic arch Ishimaru zones 1, 2, and 3 (Table II). Technical success was 92.5%. Two patients had a type IA endoleak, which required open conversion and endograft removal in one and proximal thoracic endograft extension in the other. One patient was treated with a custom-made thoracic device owing to the large difference between the proximal and distal aortic diameters. Left carotid-subclavian bypass and carotid-carotid-left subclavian bypass was performed in 11 and 2 of the 46 patients, respectively. Proximal subclavian artery retrograde embolization was performed in all patients submitted to left carotid-subclavian bypass. One patient,

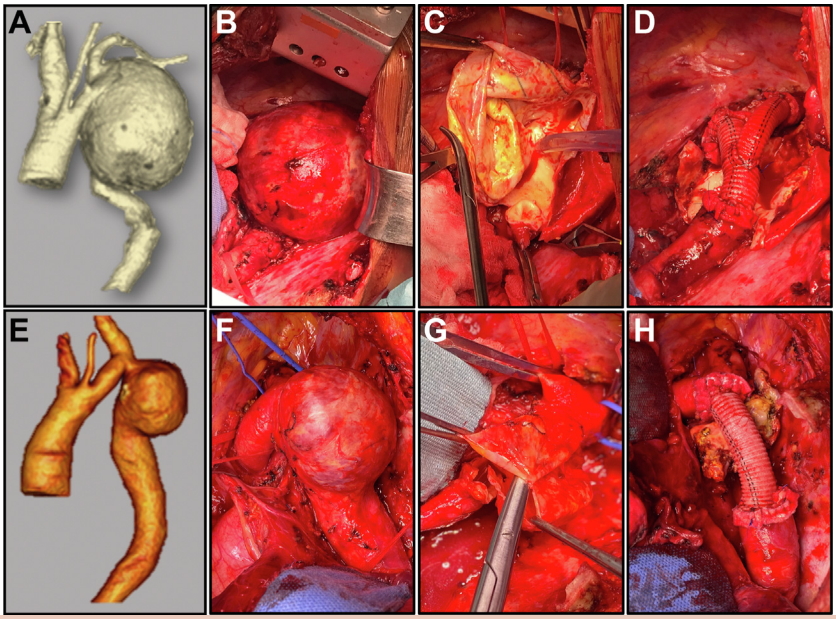

Fig 1. Open surgical repair of a postaortic coarctation aneurysm (pCoAA). **(A)** Preoperative three-dimensional computed tomography angiography (3D-CTA) reconstruction of the aorta showing pCoAA in an angulated hypoplastic aortic arch, and a hypertrophic left subclavian artery (LSA). Intraoperative findings. **(B)** Aneurysmal aortic degeneration after Dacron patch aortoplasty. **(C)** Magnified view of the aortic wall and the Dacron patch, highlighting the thin aneurysmal wall. **(D)** Result of aneurysmectomy and thoracic graft interposition with a Dacron tube without involvement of the subclavian artery origin. **(E-H)** Involvement of the LSA in a larger pCoAA. **(E)** Preoperative 3D-CTA reconstruction demonstrating a pCoAA with involvement of the LSA. Intraoperative findings. **(F)** Aneurysmal aortic degeneration in patient previously submitted to Dacron patch aortoplasty. **(G)** Magnified view of the internal aneurysmal wall, showing the Dacron patch. **(H)** Aortic reconstruction and LSA revascularization with Dacron tube.

who underwent TEVAR in zone 2, underwent a left subclavian-carotid transposition and left proximal subclavian artery ligation. In cases of left carotid-carotid-subclavian bypass, retrograde embolization of the LSA was performed in one and proximal ligation in the other (Fig 2). No retrograde endoleaks were observed in the patients who underwent supra-aortic vessel bypass. Two patients presented with a symptomatic aortic recoarctation associated with focal dissection and a saccular aortic aneurysm.

Early and follow-up outcomes. Primary and secondary outcomes are summarized in Table III. There were two in-hospital deaths (2.7%), including the patient treated by FET for complicated type B dissection. This patient developed acute kidney injury and respiratory failure, and was out on dialysis and extracorporeal membrane oxygenation; however, the patient died on postoperative day 17. A second patient with hematemesis owing to an aortoesophageal fistula underwent attempted endovascular repair, but the patient died on postoperative day 1. The in-hospital major adverse events rate was six patients (8.1%). There was no paraplegia reported. One patient treated by TEVAR in Ishimaru zone 3 developed an ischemic left hemispheric (anterior and posterior) nondisabling stroke. Five of the 74 patients underwent in-hospital secondary reinterventions (Table III).

During a median follow-up of 50 months (IQR, 14-127 months), one patient presented with occlusion of the left brachial artery and underwent mechanical thrombectomy with a Fogarty catheter and LSA stenting 27 months after the index procedure. Aneurysm sac growth was observed only in one patient in the endovascular group (1/46) owing to a type IB endoleak; the patient underwent an additional procedure with distal thoracic endograft relining after 110 months of follow-up (Table III). In all the other cases, aneurysm sac was reported as stable or shrinkage. Type II endoleak from intercostal arteries was reported in two patients, without the need for reintervention, owing to the aneurysm size stability reported after 75 and 84 months of follow-up. No type III endoleaks requiring reintervention were reported. There were no differences between the open and endovascular groups regarding early and long-term outcomes (Table III).

DISCUSSION

Open surgical repair of CoA is tailored to each patient using a variety of well-described techniques in the literature such as end-to-end anastomosis, subclavian flap aortoplasty, synthetic patch aortoplasty, and graft interposition.[3,12] The risk of pCoAA formation is associated mostly with patch aortoplasty technique ranging from 8.7% to 51.0%, followed by graft interposition up to 6%

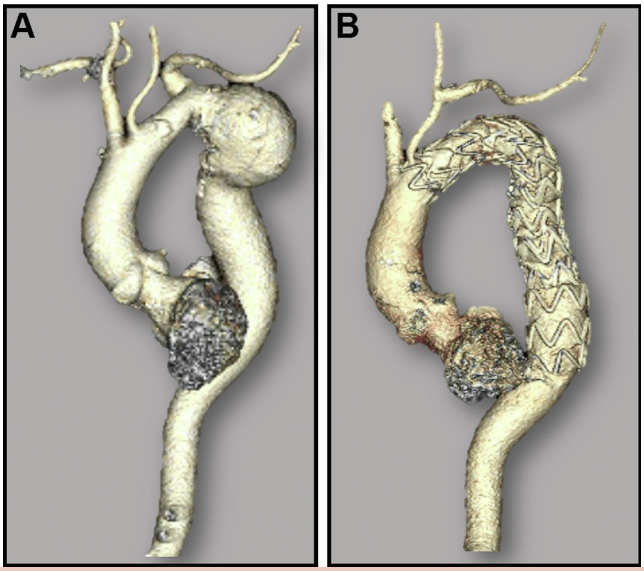

Fig 2. Endovascular treatment of a postaortic coarctation aneurysm (pCoAA) in a patient previously submitted to Dacron patch aortoplasty. **(A)** Preoperative three-dimensional computed tomography angiography (3D-CTA) reconstruction. **(B)** Postoperative 3D-CTA reconstruction showing implantation of two thoracic endografts (28 mm × 174 mm proximally, and 34 mm × 182 mm distally) in the distal aortic arch and descending thoracic aorta (DTA), with a left subclavian-carotid transposition, and complete aneurysm exclusion.

and end-to-end anastomosis up to 3%.[3,4,9,12] Chen et al[13] demonstrated that patients with patch repair have a more than four-fold increased risk of developing pCoAA compared with patients with subclavian flap repair.[13] Advanced age at the time of CoA repair is an independent risk factor for repair site dilatation.[6] In the literature, the mean age reported of pCoAA presentation is 36 years.[7,12,14] In the present cohort, because the median time between index procedure and pCoAA repair was 33 years (IQR, 25-40 years), lifelong monitoring with strict follow-up might be appropriate.

Dacron patch aortoplasty became popular in the mid-1960s because it avoids sacrificing the LSA and intercostal arteries and minimizes restenosis by eliminating circumferential suture lines.[15] However, the technique fell into disfavor in the mid-1980s owing to a higher incidence of late aneurysm formation (≤51%).[3,12,15] In this series, aneurysmal formation was associated with prior synthetic patch aortoplasty in 48 of the 74 patients (64.9%). The progressive degeneration of the aortic wall opposite to the side of the patch and the creation of an area with decreased compliance and decreased distensibility could progress to aortic wall dilatation.[3,6,8] The degeneration of the Dacron patch fibers is thought to play a role in late pCoAA formation.[3,8] However, in an immunohistochemically Dacron graft patch analysis explanted from a 48-year-old male patient who developed a pCoAA pseudoaneurysm 27 years after the index procedure, no disruption of the Dacron structure was described, but significant cellular infiltration, showing endothelialization.[16] In this series, histological evaluation was consistent with the findings (Fig 3).

Pathological abnormalities reported in the aortic wall with congenital CoA include increased stiffness and decreased distensibility, medial cystic necrosis, and decreased smooth muscle cells in the prestenotic segment.[17] Also, endothelial function, inflammatory process, and intima-media thickness and distensibility of the large arteries were examined in normotensive patients 12.0 ± 2.9 years after coarctation repair: significantly increased levels of proinflammatory cytokines and adhesion molecules, and abnormal structural and functional properties of the upper body circulation were observed.[18] These findings provided evidence that such alterations might be permanent; that is, they may occur many years after CoA repair.[18] These underlying features may result in alterations in aortic wall elastic properties and might play a role in the development of the pCoAA.

Currently, endovascular repair with either balloon angioplasty or stent placement (bare or covered stent) is being commonly preferred in larger children and adults.[19,20] Although the endovascular approach seems to be safe and effective in maintaining long-term aortic obstruction relief, the rate of pCoAA formation is not negligible.[20,21] The Coarctation of the Aorta Stent Trial (COAST I) and the Covered Cheatham-Platinum Stents for Prevention or Treatment of Aortic Wall Injury Associated With Coarctation of the Aorta Trial (COAST II), which enrolled 248 patients, reported a pCoAA cumulative incidence of 6.3% at 48 to 60 months of follow-up.[19-21] Moreover, the stent fracture and the reintervention rates were, respectively, 2.9% and 5.1% at 12 months and 24.4% and 21.3% at 48 to 60 months of follow-up.[19-21] In our series, we report one patient who previously underwent endovascular repair for CoA.

The natural course of these late aortic aneurysms seems to be more malignant than atherosclerotic ones, regardless of the maximum diameter. Cramer et al[3] reported in their cohort of coarctation repair a 47% rate of aneurysm formation, of which 31% presented with ruptured aneurysms carrying a mortality rate of 78%. Knyshov et al[4] reported a 100% rate of spontaneous aneurysm rupture in 15 years of follow-up of untreated patients with pCoAA. Based on this malignant course, the American Heart Association/American College of Cardiology guidelines for adults with congenital heart disease recommend evaluation of the repair site by instrumental imaging by magnetic resonance imaging or a computed tomography scan at least every 5 years.[1] The optimal timing for elective surgical repair remains unclear owing to the lack of data showing a clear association between diameter and risk of rupture.[3,7] Cramer et al[3] recommend elective

Table III. Early and follow-up outcomes with open and endovascular postaortic coarctation aneurysm repair (pCoAA)

Variable	Total (n = 74)	Open repair [a] (n = 28)	Endovascular repair (n = 46)
30-Say mortality	2 (2.7)	1 (3.6)	1 (2.2)
Stroke	1 (1.4)	0	1 (2.2)
Prolonged ventilation (>48 hours)	3 (4.1)	2 (7.1)	1 (2.2)
Postoperative hemodialysis	2 (2.7)	1 (3.6)	1 (2.2)
Vocal cord paralysis	2 (2.7)	2 (7.1)	0
Pulmonary embolism	1 (1.4)	1 (3.6)	0
Arrhythmia	2 (2.7)	2 (7.1)	0
Access complications (pseudoaneurysm)	1 (1.4)	1 (3.6)	0
In-hospital reintervention	5 (6.8)	3 (10.7)	2 (4.3)
Cause for reintervention			
Bleeding	3 (4.1)	3 (10.7)	0
Type IA endoleak	2 (2.7)	NA	2 (4.3)
Type of reintervention			
TEVAR	1 (1.4)	0	1 (2.2)
Open surgical conversion	1 (1.4)	NA	1 (2.2)
Length of stay, days	6 (5-8)	8 (7-12)	5 (4-7)
Reintervention during follow-up	2 (2.7)	1 (3.6)	1 (2.2)
Cause for reintervention			
Type IB endoleak with aneurysm growth	1 (1.4)	NA	1 (2.2)
Left brachial artery thrombosis	1 (1.4)	1 (3.6)	0

NA, Not applicable; *TEVAR*, thoracic endovascular aortic repair.
Values are presented as number (percentage) or median (interquartile range).
[a] Including frozen elephant trunk procedure.

surgical repair at the time of diagnosis in almost all cases if the maximum diameter exceeds 45 mm. In smaller cases, it is advisable to adhere to strict follow-up every 6 months.[3] In our series, 17 patients were treated with a maximum diameter smaller than 45 mm (8 were symptomatic).

The pCoAA open surgery faces several anatomical challenges owing to the nature of the original pathology.[9] Patients usually have some degree of hypoplasia of the aortic arch, which implies a fragile aortic wall and a significantly smaller diameter in comparison with the DTA, which is often dilated and conical. The transition from the aortic arch to the aneurysm often presents an acute angle, which might be very close to a hypertrophic LSA, and reimplantation with graft interposition might be required. Intraoperative complications include nerve lesions, stroke, and spinal cord ischemia. Although the spinal cord ischemia rates after DTA repair as high as 20% have been reported in the literature,[22] in this specific group of patients, these rates are much lower. Young age, the short extent of aortic resection, proximal DTA lesion, and a highly developed collateral network might have a protective role, even though regression of such vascular network after CoA repair is well-known.

Over the last decades, a shift toward aortic endovascular treatment has been evident (Supplementary Table II, online only). In contrast, a trend toward a specific type of repair for pCoAA was not identified in this study over time ($r_s = 0.63$; $P = .36$), despite the increasing observed proportion of overall treatment over the last two decades (Supplementary Fig 2, online only). As regards endovascular repair, the technical evolution of thoracic stent grafts and the possibility to access custom-made devices, allowing to overcome the anatomical challenges of this pathology, have made this approach an attractive alternative.[23] Although pCoAA endovascular repair has been reported in the literature with favorable outcomes,[7,14,23] it may be challenging for several factors. The acute arch angulation and relatively small aortic diameter in younger patients may lead to inadequate apposition of the stent-graft in the inner aortic curvature or bird's beak. The presence of a hypoplastic aortic arch often requires a smaller proximal stent-graft diameter or a customized stent graft. Finally, coverage of the LSA is not recommended, particularly in younger patients and in those with CoA, who have a greater likelihood of arm claudication than older patients.[23] Idrees et al[9] advocate that purely endovascular repair is not ideal in cases of a hypoplastic arch owing to the lack of adequate proximal landing zone. In these cases, a hybrid repair, such as an FET procedure, may offer the benefits of both open and endovascular approaches.[9]

The anatomical complexity of a pCoAA aneurysm is related to a relevant rate of endovascular reintervention,

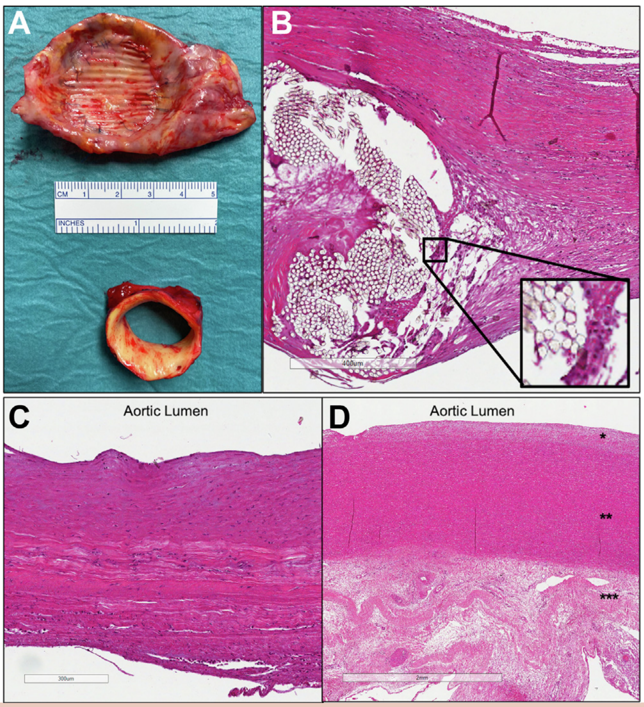

Fig 3. Histological findings. **(A)** Macroscopic segments of the explanted Dacron graft, luminal side up, and non-aneurysmatic aorta segment resected, distally of the aneurysm. **(B)** Hematoxylin and eosin-stained section of showing fibrous tissue overgrowing the Dacron graft with infiltration of foreign body giant cells. Scale bar, 400 microns. **(C)** Hematoxylin and eosin-stained section of aorta adjacent to graft showing diffuse fibrosis effacing normal vascular microscopic architecture and thickness. Scale bar, 300 microns. **(D)** Hematoxylin and eosin-stained section of distal aorta showing maintained vascular microscopic architecture and thickness. Scale bar, 2 mm. *Intima layer; **media layer; ***adventitia layer.

reported to be up to 33%.[14] In this multicenter study, a total of 3 of 46 reinterventions were observed in the endovascular group, mostly caused by type IA or IB endoleaks. The use of custom-made devices or tapered stent grafts might explain the better results obtained in the setting of a hypoplastic arch in comparison with that found in the literature. Despite the promising results, long-term durability remains in question. In this multicenter series, satisfactory midterm results were recorded, especially in terms of reinterventions and aneurysm recurrence, both in the surgical and endovascular groups.

A limitation of this study is the incomplete data collection regarding postoperative acute kidney injury, which is an important variable for the outcomes in such complex procedures. Owing to its retrospective design, a standardized classification for postoperative acute kidney injury was not used in all centers. Therefore, to avoid any misinterpretations, only the need for hemodialysis was reported. Although this study is limited by the retrospective design over an extended time period, the heterogeneous patient population, the methodological shortcomings, and the relatively limited sample size of our cohort, to our knowledge, this is the largest series published so far, with 74 cases. Any recommendation regarding the best approach for pCoAA based on this cohort is difficult to be defined owing to the rarity of this pathology. However, our data suggest that patients with a previous history of CoA repair should have close life-long surveillance, and these repairs should be performed in specialized centers.

CONCLUSIONS

This international multicenter study carried out at highly specialized academic aortic centers showed that patients with pCoAA can be treated safely with both surgical and endovascular interventions, with good early and midterm results. The late aneurysm formation after CoA repair carries anatomical peculiarities that differ from common atherosclerotic or post-traumatic isthmic aneurysms. The endovascular approach is a good alternative when anatomically feasible, which is demonstrated to be effective during midterm follow-up. Because the mean time between the CoA repair and the aneurysm formation was more than 30 years, life-long surveillance of these patients is warranted. The decision on the type of treatment should be tailored to each patient, and long-term outcomes need further studies, especially for endovascular repairs, because the long-term durability of stent grafts and adverse side effects on the entire cardiovascular system, especially in young patients, remain unknown.

AUTHOR CONTRIBUTIONS

Conception and design: GM, VB
Analysis and interpretation: GM, LC, DP, VB, YE, AO, VR, LP, GO, AE, BV, NT, JB, FV, AA, MC
Data collection: GM, LC, DP, VB, YE, AO, VR, LP, GO, AE, BV, NT, JB, FV, AA, MC
Writing the article: GM, LC, VB, YE, AO, VR, LP, GO, AE, BV, NT, JB, FV, AA, MC
Critical revision of the article: GM, LC, DP, VB, YE, AO, VR, LP, GO, AE, BV, NT, JB, FV, AA, MC
Final approval of the article: GM, LC, DP, VB, YE, AO, VR, LP, GO, AE, BV, NT, JB, FV, AA, MC
Statistical analysis: GM, VB
Obtained funding: Not applicable
Overall responsibility: GM

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Additional material for this article may be found online at www.jvascsurg.org.

APPENDIX (online only).

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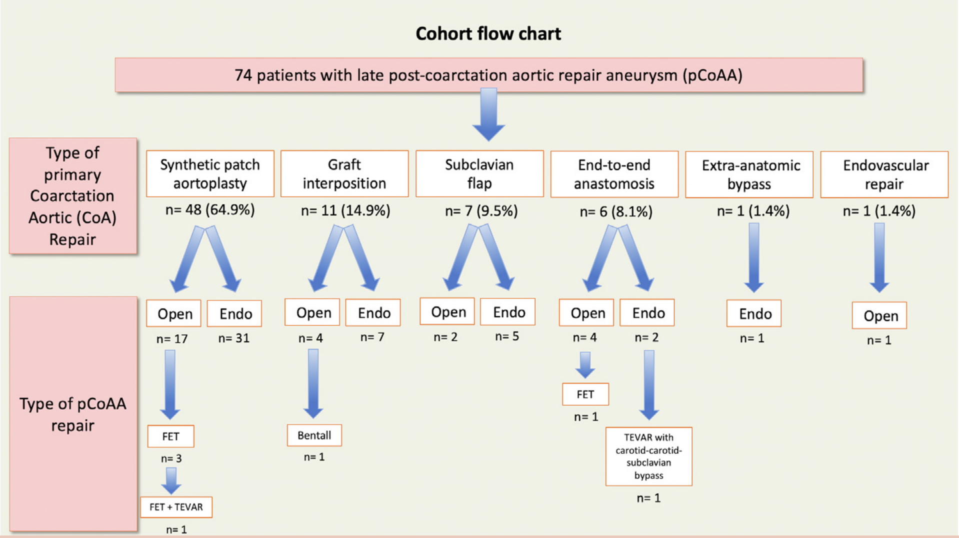
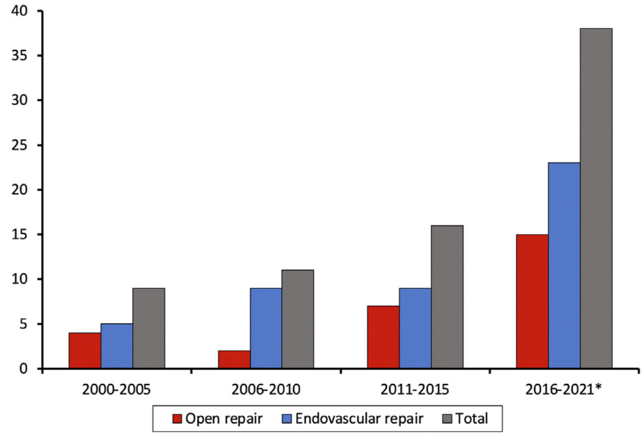


Supplementary Fig 1 (online only). Flow chart of participants in cohort study illustrating the type of primary coarctation aortic repair and type of postcoarctation aortic aneurysm repair (*pCoAA*). *FET*, frozen elephant trunk; *TEVAR*, thoracic endovascular aortic repair.



Supplementary Fig 2 (online only). Trends in the type of pCoAA approach over time. *Until February 2021.

Supplementary Table I (online only). Clinical site information

Institution	Country	No. of patients
Arnaud de Villeneuve Hospital, Montpellier	France	17
Azienda Ospedaliero-Universitaria di Bologna, Bologna	Italy	16
"Vita-Salute" San Raffaele University School of Medicine, Milan	Italy	9
The Barts Heart Centre, William Harvey Research Institute, Queen Mary University of London, St Bartholomew's Hospital, London	United Kingdom	5
Mayo Clinic, Jacksonville, Florida	United States of America	5
Hospital de Santa Maria, Lisbon	Portugal	4
CardioVascular Institute, Hospital Clinic, University of Barcelona	Spain	4
McGovern Medical School, The University of Texas Health Science Center at Houston, Texas	United States of America	3
Institute of Cardiac & Aortic Disorders (ICAD), Aortic Aneurysm Center, SIMS Hospitals, Chennai	India	3
Hospital of the Ludwig-Maximilians-University (LMU), Munich	Germany	2
Johns Hopkins Hospital, Baltimore	United States of America	2
Turin University, A.O.U. Città della Salute e della Scienza, Molinette Hospital, Turin	Italy	2
Cedars-Sinai Medical Center, Los Angeles, California	United States of America	1
University Heart Center Freiburg, Albert-Ludwigs-University of Freiburg, Freiburg	Germany	1
Total		74

Supplementary Table II (online only). Literature review of surgical and endovascular postaortic coarctation aneurysm (*pCoAA*) repair with follow-up

Study (year)	No. of patients with pCoAA/ total of CoA repairs	Age at CoA Repair, years (mean)	Age at pCoAA presentation, years (mean)	Type of prior repair	Mean diameter, mm	Elective/emergency pCoAA	Open repair	Endovascular repair	Follow-up
Knyshov et al (1996)[4]	48/891	NR	NR	43 SPA 4 ETE 1 TGI	NR	26/4	30	0	NR
Bogaert et al (2001)[24]	16/85	6.9	17-37	16 SPA	47.1	16/0	16	0	54.1 mo
von Kodolitsch et al (2002)[12]	25	19	31	5 ETE 14 SPA 6 TGI	65	13/12	25	0	NR
Ince et al (2003)[25]	6	25	49 ± 12	SPA	NR	6/0	0	6	11-47 mo
Napoleone et al (2003)[26]	13/195	NR	NR	SPA	NR	13/0	13	0	51.8 mo
Kutty et al (2008)[7]	9	NR	36	4 SPA 5 unknown	63	7/2	0	9	24 mo
Botta et al (2009)[27]	11	20.2	45.7 ± 13.6	9 SPA 2 TGI	43.6 ± 8.3	11/0	4	7	44.5 mo
Brown et al (2010)[28]	11/130	1.4	32 ± 24	NR	NR	NR	7	1	NR
Roselli et al (2012)[29]	25	NR	NR	NR	57 ± 14	23/2	NR	NR	1 death
Cramer et al (2012)[3]	29/63	NR	NR	29 SPA	NR	20/0	20	0	7 deaths
Idrees et al (2013)[9]	14	NR	45 ± 13.5	NR	59 ± 15	13/1	14 hybrid repairs		26 mo/1 death
Juszkat et al (2013)[30]	7/37	8.1 ± 4.9	31.1 ± 5.4	SPA	56.9 ± 7.1	7/0	0	6	26 mo
Preventza et al (2013)[5]	53	Median 23-y interval	39.9 ± 11.3	20 SPA 10 TGI 4 ETE 1 SFA 2 Asc. to DTA 3 Endo.	NR	53/0	42	11	40 mo
Alsafi et al (2014)[31]	3	NR	NR	NR	39, 32, 35	3/0	0	3	NR
Kotelis et al (2016)[14]	11	NR	NR	9 SPA 2 SFA	56	7/4	0	11	60 mo
Lescan et al (2019)[23]	3	1,6,1	35,33,33	1 SPA 1 SFA 1 TGI	NR	3/0	0	3	3.4-12.9 mo

Asc. to DTA, Ascending to descending bypass; *CoA*, aortic coarctation; *ETE*, end-to-end anastomosis; *NR*, not reported; *SFA*, subclavian flap aortoplasty; *SPA*, synthetic patch aortoplasty; *TGI*, tube graft interposition.