Long-term results of hybrid repair techniques for Kommerell's diverticulum

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ABSTRACT

Objective: The aim of this study was to evaluate early and late results of hybrid repair techniques for Kommerell's diverticulum (KD).

Methods: All patients who underwent hybrid repair (thoracic endovascular aortic repair + supra-aortic debranching) for KD between 2009 and 2018 were included in this retrospective multicenter study (three Italian centers). A proximal landing zone (PLZ) of at least 2 cm of healthy aorta was considered adequate for the deployment of a standard thoracic stent graft. The early end points were technical success, in-hospital mortality, and cerebrovascular events. Late outcomes included survival, reintervention, and patency of supra-aortic debranching. We used an embryogenetic anomaly based aortic arch classification for PLZ evaluation to identify the most appropriate hybrid adjunct.

Results: Sixteen patients with KD were included. According to the aforementioned classification, stent graft deployment was required in six patients (37.5%) in PLZ 0, nine patients (56.3%) in PLZ 1, and one patient (6.3%) in PLZ 2. Technical success was achieved in all patients. One patient (6.3%) died in the hospital because of posterior cerebral hemorrhage after total debranching (PLZ 0). No further cerebrovascular events were observed. One patient (6.3%) had an asymptomatic left subclavian artery-right left subclavian artery bypass occlusion and required early reintervention. The 30-day secondary patency of supra-aortic debranching was 100%. Two type II endoleaks (12.5%) were detected at 1 month through computed tomography angiography. Further transient complications were found in three cases: hemidiaphragm paralysis in one patient and recurrent laryngeal nerve paralysis in two patients. At a mean follow-up of 48 months, four patients had died because of nonaortic reasons, and one RCCA-right subclavian artery bypass had lost its patency. None of the patients reported any growth of KD after hybrid repair. Ten patients (62.5%) showed aneurysmal sac shrinkage of at least 5 mm.

Conclusions: Hybrid repair is confirmed to be a safe and effective approach for KD. Operative risk is associated primarily with the invasiveness of the hybrid adjunct. (J Vasc Surg 2020;72:1213-21.)

Keywords: Kommerell's diverticulum; Hybrid repair; Thoracic endovascular aortic repair; Personalized medicine

The most common congenital variant of the aberrant subclavian artery (ASA) is a right ASA in a left-sided aortic arch, with an incidence of 0.3% to 3.0%.[1] An aberrant left subclavian artery with a right-sided aortic arch is less prevalent (0.05%). In general, the ASA is asymptomatic, but an increased risk of rupture or dissection of 19% to 53% has been reported.[2] Associated symptoms are tracheal and esophageal compression (dysphagia lusoria), which occur more frequently in patients with aneurysmal degeneration of the ASA.[3,4] Aneurysmal degeneration of the origin of the ASA is reported in 3% to 8% of patients and is known as Kommerell's diverticulum (KD).[5]

Treatment is indicated for symptomatic patients and for the prevention of complications owing to aneurysmal dilatation, aortic dissection and rupture.[6] Various surgical techniques have been described for ASA repair. Conventional surgical treatment for the ASA is performed with a thoracotomy to ligate the ASA origin and to revascularize the subclavian artery, or with the frozen elephant trunk (FET) technique through median sternotomy with arch replacement proximal to the diverticulum, supra-aortic branches reconstruction and stent graft antegrade deployment into the descending thoracic aorta in order to cover the ASA origin.[1,7]

In the past decade, because of the relatively high invasiveness of open repair, a hybrid approach to KD has been proposed. Hybrid repair consists of a partial or total debranching of arch of aorta, thereby creating a proximal landing zone (PLZ) of adequate length, followed by

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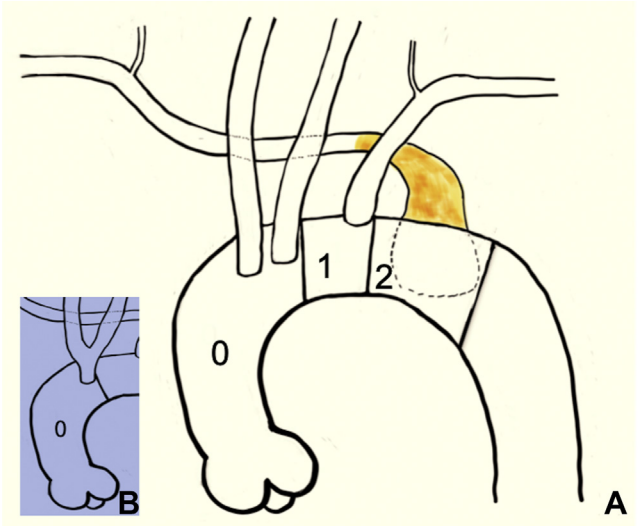

Fig 1. Modified Hishimaru aortic arch classification. Zone zero including both common carotid arteries (CCAs) **(A)** or the common carotid trunk **(B)**. Valid for normal and right-sided aortic arch, specular view.

thoracic endovascular aortic repair (TEVAR) over the aortic arch. These hybrid procedures were originally an appealing option for high-risk patients who were not candidates for open repair,[8,9] but they also represent a suitable solution for all the patients fit for surgery, depending on their anatomy and the center experience.[10]

The aim of this multicenter retrospective study was to evaluate the early and late results of debranching TEVAR for KD.

EMBRYOLOGIC ANATOMY OF SUPRA-AORTIC VESSELS WITH ASA

The final anatomic configuration of the aortic root is closely linked to the embryologic development of the aortic arch, with numerous embryologic variations.

The ASA always originates directly from the proximal portion of the descending thoracic aorta as the fourth vessel and crosses the midline between the esophagus and the spine to the arm. It is located not only behind the esophagus (80%), but also potentially between the esophagus and the trachea (15%) or in front of the trachea (5%).[11] In the majority of cases, the duct thoracic terminates on the left side venous system; in 2% to 3% of cases, the duct empties on the right, and bilaterally in up to 1.5% of cases.[12]

The first vessels arising from the aortic arch are usually the common carotid arteries (CCAs). A bicarotid trunk is present in 50% of cases.[13] In cases with a separate origin of CCAs, in the left-sided aortic arch, the first vessel to arise is the right CCA, followed by the left CCA, then the left non-ASA, and finally the right ASA. Usually, the average distance between the non-ASA and ASA is less than 1 cm. The left vertebral artery arises directly from the aorta in 7.7% of cases.[13] A specular anatomy is usually noted in cases of right-sided aortic arch.

ARTICLE HIGHLIGHTS

- **Type of Research:** Multicenter retrospective analysis of prospectively collected registry data from the KOmmerell DIVerticulum (KODIV) study group
- **Key Findings:** Hybrid repair of Kommerell's diverticulum provided an in-hospital mortality/stroke of 6.3% and a secondary patency of supra-aortic debranching of 100%. After a mean follow up of 4 years, there was no aortic-related mortality, stent graft migration, or type I/III endoleaks. None of the diverticula increased in size and aneurysmal shrinkage (≥5 mm) was impressively seen in 62.5%.
- **Take Home Message:** Hybrid repair for Kommerell's diverticulum is feasible and safe. An appropriate proximal landing zone and a proper supra-aortic vessel debranching strategy show good results in the long term.

METHODS

Registry data for all patients with KD treated with TEVAR and supra-aortic debranching at three Italian centers between 2009 and 2018 were prospectively collected for inclusion in this retrospective study. The study was performed in accordance with the institutional ethics committee rules, and individual consents for intervention and retrospective analysis was obtained from all patients.

An adequate preoperative assessment of patients' functional reserve was performed in all centers to estimate the operative risk. Preoperative tests for each patient were examined in a multidisciplinary manner for each center, and the operative strategy was chosen on the basis of agreement between vascular surgeons and anesthesiologists. Preoperative evaluation of computed tomography angiography (CTA) was performed for all patients at a dedicated workstation, and multiplanar reconstructions were used to evaluate the anatomic feasibility of the endovascular approach and to plan the operative strategy in terms of hybrid adjuncts. A PLZ of at least 2 cm of healthy aorta in the arch inner curve was considered adequate for the deployment of a standard thoracic stent graft. Technical success was defined as correct delivery and deployment at the intended location of the stent graft with patency of the graft and supra-aortic trunks and without any type I or III angiographically detected endoleak.[14] The follow-up scheme was based on 1-, 6-, and 12-month and then yearly CTA. The primary end points were technical success, in-hospital mortality and the occurrence of cerebrovascular events. Endoleak incidence and the need for early secondary procedures were also assessed. Late outcomes included survival,

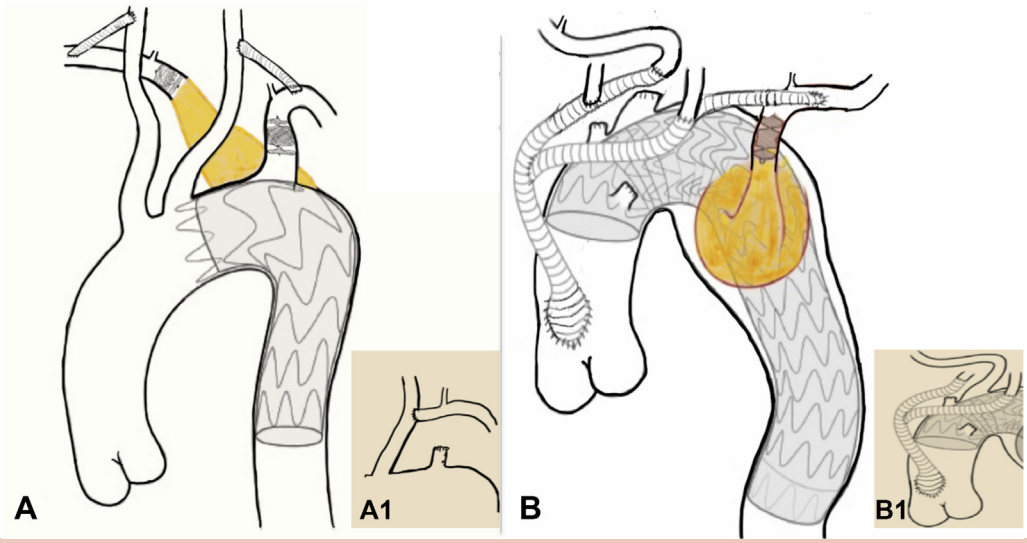

Fig 2. Partial debranching in left side arch for proximal landing zone (PLZ) 1, bilateral carotid-subclavian bypass **(A)** or transposition **(A1)**. Total debranching from the ascending aorta in right side arch for PLZ 0, a Y bypass to the subclavian artery and carotid arteries replantation **(B)** or a Y bypass for the carotid arteries **(B1)** with extrathoracic subclavian revascularization. (Modified from Criado.[15])

Table I. Clinical and demographic characteristics (N = 16)

Baseline characteristics	No.	Percent
Male gender	11	68.8
Age, years, mean ± SD	70.4 ± 7.5	Range, 55-80
Smoking	5	31.3
Hypertension	13	81.3
CAD	2	12.5
Previous CABG	0	0
Previous PCI	0	0
COPD	4	25
Diabetes mellitus	2	12.5
Dyslipidemia	8	50
CRF	0	0
Aortic arch aneurysm	7	43.8
Aortic dissection	1	6.3
Connective tissue disorders	0	0
Previous open aortic repair	2	12.5
Previous endo aortic repair	0	0
Bicarotid trunk	4	25
Right-sided aortic arch	2	12.5
Symptoms	6	37.5
Dysphagia	3	18.8
Dysphonia	2	12.5
Peripheral embolism	1	6.3
Median KD diameter, mm (IQR)	43 (28-59)	Range, 24-80
Median aortic arch diameter, mm (IQR)	40 (38-69)	Range, 32-145

CABG, Coronary aortic bypass graft; *CAD*, coronary artery disease; *COPD*, chronic obstructive pulmonary disease; *CRF*, chronic renal failure; *IQR*, interquartile range; *KD*, Kommerel diverticulum; *PCI*, percutaneous coronary intervention; *SD*, standard deviation.

the need for late reintervention, and the patency of supra-aortic debranching. The measured values are reported as percentages and mean ± standard deviation or medians and interquartile range (IQR). Statistical analyses were performed in version 21 of SPSS software (IBM Statistics Inc, Armonk, NY).

Classification. According to the availability of at least 2 cm of healthy aorta for the PLZ, we proposed a modified Hishimaru aortic arch classification to determine the most appropriate strategy and stratify the patients according to the type of hybrid adjunct used (Fig 1) as follows:

Zone 0: Ascending aorta including both separated ostia of CCAs or, if they had a common origin, the ostium of the bicarotid trunk
Zone 1: Aortic arch including the origin of the non-ASA
Zone 2: Aortic arch including only the origin of the ASA

In the case of a right-sided aortic arch, the view and the classification were specular.

RESULTS

Population and procedural data. Sixteen patients underwent elective hybrid repair for KD (Fig 2), five (31.3%) of whom were female. The three centers contributed 7, 5, and 4 patients. The mean patient age was 70.4 ± 7.5 years (range, 55-80 years). In seven cases (43.8%), there was a concomitant aortic aneurysm of the distal aortic arch and the first part of the descending thoracic aorta, not influencing the operative strategy. The median diameter of the KD was 43 mm (IQR, 28-59 mm; range, 24-80 mm). The median diameter of the aortic

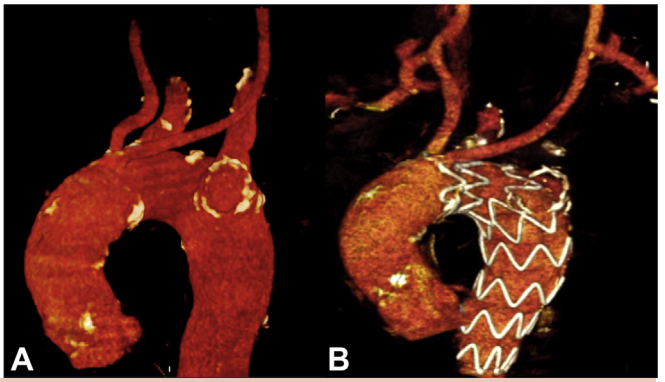

Fig 3. Volume rendering view of Kommerel diverticulum in left site arch before **(A)** and after partial debranching with bilateral carotid-subclavian bypass with thoracic endovascular aortic repair (TEVAR) in proximal landing zone (PLZ) 1 **(B)**.

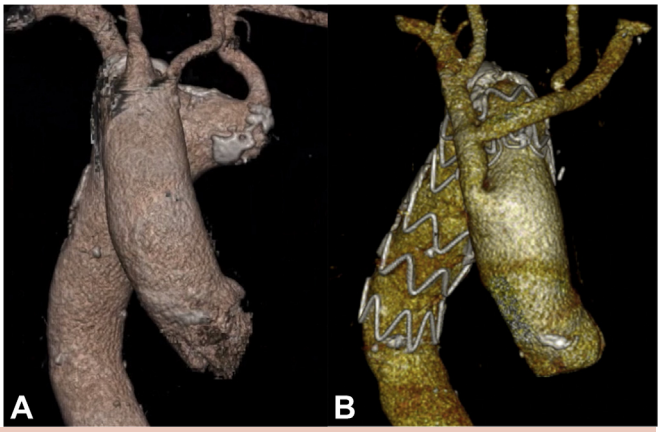

Fig 4. Volume rendering view of Kommerel diverticulum in the right side arch before **(A)** and after total debranching with Y bypass for subclavian arteries and common carotid arteries (CCAs) reimplantation with thoracic endovascular aortic repair (TEVAR) in proximal landing zone (PLZ) 0 **(B)**.

arch was 40 mm (IQR, 38-69 mm; range, 32-145 mm). None of the patients had any evidence of connective tissue disorders. A concomitant chronic type B dissection was noted in one case (6.3%). Further baseline characteristics of the population are reported in Table I. In six patients (37.5%), the KD was a cause of dysphagia (3), dysphonia (2), and peripheral embolism (1). Two patients (12.5%) presented a right-sided aortic arch with aneurysmal origin of the aberrant left subclavian artery, whereas four patients had a bicarotid trunk. In no cases did the operative strategy include the sacrifice of subclavian arteries. Debranching inflow was provided by carotid arteries in ten patients (62.5%; Fig 3), including a right axillary artery-left axillary artery bypass owing to the small diameter of the right CCA, and by the ascending aorta in the remaining six patients (37.5%; Fig 4). According to the aforementioned classification, stent graft deployment was required in 6 patients (37.5%) in PLZ 0, 9 patients (56.3%) in PLZ 1, and 1 patient (6.3%) in PLZ 2. Details of the debranching technique are summarized in Table II. A staged approach was used in five patients (31.3%), in case of bilateral carotid-subclavian bypass for PLZ 1 sealing, with a median interval of 9 days (IQR, 7-30 days; range, 6-60 days) between the stages, without any significant difference compared to the one-staged procedure. Near-infrared spectroscopy monitoring was used in all the cases. In 10 patients (62.5%), the stent graft was deployed under a hypotensive regimen established by rapid cardiac pacing. An aortic conduit for thoracic stent graft insertion was needed in one patient (6.3%). The common femoral artery was used as the main access point for the remaining 15 patients, five of whom had percutaneous access. Thoracic stent grafts were provided by Cook (Cook Medical, Bloomington, Ind) in 6 cases (37.5%), Bolton (Terumo Aortic, Glasgow, UK) in 5 cases (31.3%), Gore (W. L. Gore & Associates, Flagstaff, Ariz) in 3 cases (18.8%), and Medtronic (Medtronic Inc. Santa Rosa, Calif) in 2 cases (12.5%). The median fluoroscopy time was 22 minutes (IQR, 17-25 minutes; range, 12-28 minutes), and the median volume of contrast media used was 110 mL (IQR, 90-138 mL; range, 60-160 mL). No significant differences were observed in the baseline and procedural data among the patients according to PLZ.

Early results. Technical success was achieved in all patients. The median hospitalization time was 10 days (IQR, 8-12 days; range, 6-22 days), including a median intensive care unit stay of 1 day (IQR, 1-2 days; range, 0-8 days). One patient (6.3%) died in the hospital because of posterior cerebral hemorrhage after total debranching and TEVAR in PLZ 0. No further cerebrovascular event was registered. One patient (6.3%) had an asymptomatic right axillary artery-left axillary artery bypass occlusion and required reintervention on the sixth postoperative day for flow restoration. The 30-day secondary patency of supra-aortic debranching was 100%. Two type II endoleaks (12.5%) were detected at the 1-month CTA; there was no evidence of type I or III endoleaks. Other transient early complications were observed in three patients (hemidiaphragm paralysis in one patient and recurrent laryngeal nerve paralysis in two patients) after debranching and TEVAR in PLZ 0. No cases of myocardial infarction, renal insufficiency, spinal cord ischemia, retrograde dissection, or other major complications were observed. No differences were noted among patients according to PLZ regarding early outcomes. The early results are summarized in Table III.

Late results. The mean follow-up was 48 months (range, 1-121 months). In addition to the patient who died in the hospital, four patients died during follow-up, all for nonaortic reasons. Except for a patient who required

Table II. Procedural details (N = 16)

Procedural details	No.	%
Landing zone 0	6	37.5
Ascending aorta—bisubclavian bypass + CCAs reattachment	3	18.8
Ascending aorta—bicarotid bypass + SAs reattachment	2	12.5
Ascending aorta-BCT-LCCA-LSA bypass	1	6.3
Landing zone 1	9	56.3
Bilateral CCA-SA bypass	8	50
RCCA-LCCA-LSA bypass + LAX-RAX bypass	1	6.3
Landing zone 2	1	6.3
RCCA-RSA bypass	1	6.3
Staged	5	31.3
Median interval between the stages, days (IQR)	9 (7-30)	Range, 6-60
NIRS monitoring	16	100
Rapid cardiac pacing	10	62.5
Femoral access for SG	15	93.7
Iliac access for SG	1	6.3
Median fluoroscopy time, minutes (IQR)	22 (17-25)	Range, 12-28
Median volume of contrast media, mL (IQR)	110 (90-138)	Range, 60-160

BCT, Bicarotid trunk; *CCAs*, common carotid arteries; *IQR*, interquartile range; *LAX*, left axillary artery; *LCCA*, left common carotid artery; *LSA*, left subclavian artery; *NIRS*, near infrared spectroscopy; *RAX*, right axillary artery; *RCCA*, right common carotid artery; *RSA*, right subclavian artery; *SAs*, subclavian arteries; *SG*, stent graft.

Table III. Early procedural results (N = 16)

Early results	No.	%
Technical success	16	100
In-hospital mortality	1	6.3
Cerebrovascular complications	1	6.3
Posterior stroke after LSA dissection	1	6.3
Retrograde dissection	0	0
Endoleak	2	12.5
Type I	0	0
Type II	2	12.5
Type III	0	0
Early secondary procedures	1	6.3
LAX-RAX redo bypass	1	6.3
30-Day secondary debranching patency	16	100
Median hospitalization time, days (IQR)	10 (8-12)	Range, 6-22
Median ICU stay, days (IQR)	1 (1-2)	Range, 0-8

ICU, Intensive care unit, *IQR*, interquartile range; *LAX*, left axillary artery; *LSA*, left subclavian artery; *RAX*, right axillary artery.

Table IV. Late results in the follow-up (N = 15)

Late results	No.	%
Mean follow-up, months	48	Range, 1-121
Late mortality	4/15	26.6
Nonaortic reason	4/15	26.6
Cerebrovascular complications	0/15	0
Debranching patency		
Primary	13/15	86.7
Secondary	14/15	93.3
Renal insufficiency	0/15	0
Endoleak	3/15	20
Type I	0/15	0
Type II	3/15	20
Type III	0/15	0
Secondary procedures	1/15	6.7
Open TAAA repair at 22 months	1/15	6.7
Sac shrinkage >5 mm	10/15	62.5
Sac growth	0/15	0
Symptoms regression	6/6	100
Total	5/6	83.3
Partial	1/6	16.7

TAAA, Thoracoabdominal aortic aneurysm.

open thoracoabdominal aneurysm repair 22 months after the initial procedure, no other late reintervention was needed. A right CCA-right subclavian artery bypass lost its patency without symptoms during follow-up, resulting in an overall primary and secondary patency rate for supra-aortic debranching of 87.5% and 93.8%, respectively. No patient showed any renal function deterioration or other late major complications. Three type II endoleaks from bronchial artery were noted in late CTAs. However, no sac enlargement was found.

Table V. Comparative literature results of debranching thoracic endovascular aortic repair (TEVAR) for Kommerell's diverticulum (KD)

		Early outcomes			
Study	Pt, No.	Mortality	Stroke	SCI	Nerve injury
van Bogerijen et al[20]	12	1 (8.3)	1 (8.3)	1 (8.3)	0
Idrees et al[2]	10	0	1 (10)	0	0
Verzini et al[29]	15	1 (6.6)	0	0	0
Wooster et al[10]	10	0	0	0	0
Tinelli et al (current report)	16	1 (6.3)	1 (6.3)	0	3 (19.7)

EL, Endoleak; *SCI*, spinal cord ischemia.

There were no new-onset type I or III endoleaks or stent graft migration. Ten patients (62.5%) showed aneurysmal sac shrinkage of at least 5 mm, and no patients reported any growth (Table IV).

DISCUSSION

Aneurysmal degeneration of ASA is known as KD and is associated with a high tendency toward rupture and dissection. Austin and Wolfe[16] reported a rate of rupture of 19%, whereas Cinà et al[4] reported a rate of rupture of 6% and a rate of either dissection or rupture of 53%. Indications for treatment include symptomatic organ compression, aneurysmal dilatation, and aortic dissection or rupture. The threshold above which intervention is recommended in asymptomatic patients remains a matter of debate. Cinà et al[4] recommend surgery in good-risk patients for diverticula of greater than 3 cm.

Currently, there are no guidelines regarding KD management. The standard treatment for KD had been conventional open surgery (OS) until the advent of the endovascular and hybrid era.[1,17] The largest series of KD open repair was published by Kieffer et al[1] and included 17 patients. In that series, the mortality rate was 23.5%, and no central neurologic complications were observed. Other series regarding OS have been published by Esposito et al,[18] Cinà et al,[4] and Kouchoukos and Masetti,[19] who reported a mortality rate of 18%, 9% and 10%, respectively.

Although OS remains an effective option for KD repair, currently, the treatment paradigm has shifted toward hybrid techniques.[20,21] These hybrid strategies include two-stage conventional elephant trunk (cET) with endovascular completion, FET, zone 0 TEVAR with intrathoracic total debranching, and TEVAR combined with different types of extrathoracic partial debranching.[2,22]

A large systematic review by Cao et al,[23] which included more than 1800 patients, showed that FET and cET performed for aortic arch aneurysm or dissection are associated with a perioperative mortality rate of 9.8% and 13.2%, respectively, and a stroke rate of 6.2% and 10.9%, respectively. Idrees et al[2] reported excellent results in seven patients treated with cET with endovascular completion (n = 4) and FET (n = 3) for KD repair: no in-hospital or late mortality, no perioperative neurological events and no reintervention (mean follow-up, 1.8 ± 1.5 years). Nevertheless, despite the advances in surgical and perioperative management, these procedures remain demanding because they require a midsternotomy and circulatory arrest, similar to open repair. Thus, they should not be considered the first choice in patients deemed unfit for OS, especially when a suitable PLZ allows for a less invasive hybrid procedure to be performed. FET might be the best option when KD is associated with a thoracic aortic aneurysm extending into the ascending aorta.[20]

Hybrid procedures with stent graft deployment into the aortic arch or the ascending aorta and partial or total supra-aortic vessel debranching are valid alternatives to FET, cET, and OS in the treatment of KD, especially in patients with high surgical risk. Many authors have published case reports and small case series regarding this topic, but no large series with long-term follow-up are available.[2,10,17,20,24-29]

There are three main aspects that must be considered when performing debranching TEVAR for KD: (1) the suitability of access vessels; (2) limited tortuosity of the aorta and the ASA; and (3) the availability of safe proximal and distal landing zones. More precisely, to ensure correct apposition of the stent graft, the PLZ must be at least 2 cm in the inner curve.[8] The availability of a suitable PLZ is the key factor enabling hybrid treatment of KD. Thus, as mentioned, we proposed a modification to Hishimaru classification to help surgeons identify the most appropriate strategy for each patient. Henceforth, we refer to our modified classification.

Overstenting of the ASA requires at least a unilateral carotid-subclavian transposition/bypass and ASA proximal occlusion through plugs, coils, or primary ligation. The choice between transposition and bypass techniques should be made according to the patient's anatomy and the operator's preference. This procedure is very similar to zone 2 TEVAR for thoracic aortic aneurysm. Unfortunately, in patients with KD, zone 2 is often very short

Table V. Continued.

Long-term outcomes						
				EL		
Mean follow-up, months	Survival	Secondary patency	Stable/shrinkage	I	II	Reintervention
36	9/11 (81.8)	11/11 (100)	10/11 (90.9)	0/11	3/11 (27)	2/11 (18)
22	10/10 (100)	9/10 (90)	10/10 (100)	0/10	2/10 (20)	3/10 (30)
30	(12/14) 85.7	14/14 (100)	–	1/14 (7.1)	1/14 (7.1)	–
2-41	10/10 (100)	7/7 (100)	7/7 (100)	0/7	0/7	–
48	11/15 (74)	14/15 (93.3)	15/15 (100)	0/15	3/15 (20)	1/15 (6.7)

(average length of 5.4 mm), especially in the presence of a growing aneurysm[13]; thus, stent graft apposition is generally not feasible.[10] In our experience, this procedure was possible only in one patient (6.3%) who presented a suitable PLZ 2. Four other cases of zone 2 TEVAR for treatment of KD have been described in the literature.[20,24,29] In contrast, Wooster et al[10] reported no cases of stent graft deployment in zone 2, because they preferred to routinely cover the ostia of both subclavian arteries.

Patients with KD most commonly have a suitable PLZ 1 (56.3% in our experience). After including the hybrid subgroup that was included in two other studies, this percentage is even higher (87% and 92%).[20,29] Compared with Hishimaru zone 1 TEVAR for aortic arch disease, which is increasingly avoided because of its shortness and angled configuration, zone 1 in the presence of an ASA anomaly is often long enough to ensure stent graft sealing and is often horizontally oriented. Settembre et al[13] analyzed 180 CT scans of patients with right ASA and reported that the distances between the ASA and the left CCA and between the ASA and the bicarotid trunk was more than 2 cm in the inner curve in 97.1% and 59.2% of patients, respectively. Stent graft deployment in zone 1 with coverage of both subclavian artery ostia is associated with bilateral carotid-subclavian reimplantation/bypass and proximal occlusion of both subclavian arteries. The surgical technique is the same used for unilateral cervical debranching, but exposure of all supra-aortic vessels through double cervicotomy may potentially increase the risk of complications, such as stroke, dysphonia, and diaphragm paralysis. Thus, like other authors, we suggest considering a staged approach for this procedure.[10,20] In patients who present challenging anatomic conformations or have undergone previous surgeries, different types of supra-aortic vessel reconstruction might be considered.

When zone 1 is unsuitable, zone 0 TEVAR with intrathoracic total debranching might be an appropriate treatment option. We included both CCAs in PLZ 0, given their very close origin (<1 cm), which is not suitable for an adequate sealing.[13] Zone 0 TEVAR with total debranching is performed through a midsternotomy and does not require circulatory arrest. A variety of total debranching techniques have been described in the literature.[30] We performed this procedure in six patients by using two different types of reconstruction: aortobicarotid bypass with a Y-graft with bilateral carotid-subclavian transposition/bypass, and aortobisubclavian bypass with a Y-graft with carotid reimplantation (Supplementary Video, online only). Hybrid arch repair involving zone 0 presents a significantly higher rate of perioperative mortality and stroke than other PLZ ($P = .021$) and thus, it should be performed only in high-volume centers by a multidisciplinary team.[23]

Our study demonstrated that hybrid procedures with both extrathoracic or intrathoracic debranching are feasible and safe options for treatment of KD, because they can be performed with limited morbidity and mortality. The early mortality rate in our series was 6.3%: one patient died because of cerebral hemorrhage after zone 0 debranching. This result is in line with those from the three other most relevant studies regarding this topic. In the series by Verzini et al,[29] Van Bogerijen et al,[20] and Wooster et al,[10] the mortality rates were 6.6%, 8.3%, and 0%, respectively. The rates of stroke, spinal cord ischemia, and early bypass occlusion were also similar to those published by these authors. Notably, our rate of nerve injuries was higher, possibly because we performed more zone 0 debranchings than were performed in the other studies.

The present study reports the longest mean follow-up period among the studies on the same topic (48 months; range, 1-121 months). The overall long-term survival was lower (74%) than that in other studies; however, no death was KD related. We observed one late bypass occlusion and three type II endoleaks, which did not require reintervention. No aneurysmal sac growth was reported. A reintervention was needed in only one patient because of distal extension of the aneurysm. No significant differences were detected between the debranching groups in terms of early and late outcomes. The rates of bypass patency, sac modification, endoleaks, and reintervention were similar to those reported in the other studies. All the compared

results are listed in Table V.[10,20,29] The main difference between the present study and previous studies is the higher number of zone 0 debranchings. In the absence of a suitable PLZ 1 or 2, we preferred to achieve proximal sealing in the ascending aorta, whereas other authors have opted for OS, FET, or cET.[2,20]

This study has two main limitations. First, although it is one of the largest series regarding hybrid treatment of KD, the sample size is too small for drawing strong conclusions. Second, the multicenter and retrospective nature of this study may have increased the heterogeneity in data collection. A larger prospective study might aid in comparing the early and late outcomes of different strategies for treatment of KD.

CONCLUSIONS

Hybrid repair is a feasible and safe approach for treatment of KD. Although complex supra-aortic bypass reconstructions are often needed because of anatomic constraints, the operative stroke and death rates remain more acceptable. Furthermore, pushing the repair to a more PLZ when needed may be beneficial in the long term, with no late aneurysm-related deaths, type I endoleaks, or migrations in our study. Further studies with larger sample sizes and longer follow-up times are needed to confirm these results.

AUTHOR CONTRIBUTIONS

Conception and design: GT, PC, YT
Analysis and interpretation: GT, CF, MF, GP, PC, YT
Data collection: GT, CF, RG
Writing the article: GT, CF, MF
Critical revision of the article: GT, CF, RG, GP, PC, YT
Final approval of the article: GT, CF, RG, MF, GP, PC, YT
Statistical analysis: CF, RG, MF
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REFERENCES

1. Kieffer E, Bahnini A, Koskas F. Aberrant subclavian artery: surgical treatment in thirty-three adult patients. J Vasc Surg 1994;19:100-9; discussion: 110.
2. Idrees J, Keshavamurthy S, Subramanian S, Clair DG, Svensson LG, Roselli EE. Hybrid repair of Kommerell diverticulum. J Thorac Cardiovasc Surg 2014;147:973-6.
3. Backer CL, Mavroudis C, Rigsby CK, Holinger LD. Trends in vascular ring surgery. J Thorac Cardiovasc Surg 2005;129:1339-47.
4. Cinà CS, Althani H, Pasenau J, Abouzahr L. Kommerell's diverticulum and right-sided aortic arch: a cohort study and review of the literature. J Vasc Surg 2004;39:131-9.
5. Davidian M, Kee ST, Kato N, Semba CP, Razavi MK, Mitchell RS, et al. Aneurysm of an aberrant right subclavian artery: treatment with PTFE covered stentgraft. J Vasc Surg 1998;28:335-9.
6. Myers JL, Gomes MN. Management of aberrant subclavian artery aneurysms. J Cardiovasc Surg (Torino) 2000;41:607-12.
7. Suzuki K, Sezai A, Unosawa S, Tanaka M. Frozen elephant trunk technique for Kommerell's diverticulum with right-sided aortic arch and aberrant left subclavian artery. J Card Surg 2018;33:21-3.
8. Czerny M, Weigang E, Sodeck G, Schmidli J, Antona C, Gelpi G, et al. Targeting landing zone 0 by total arch rerouting and TEVAR: midterm results of a transcontinental registry. Ann Thorac Surg 2012;94:84-9.
9. Holt PJ, Johnson C, Hinchliffe RJ, Morgan R, Jahingiri M, Loftus IM, et al. Outcomes of the endovascular management of aortic arch aneurysm: implications for management of the left subclavian artery. J Vasc Surg 2010;51:1329-38.
10. Wooster M, Back M, Sutzko D, Gaeto H, Armstrong P, Shames M. A 10-year experience using a hybrid endovascular approach to treat aberrant subclavian arterial aneurysms. Ann Vasc Surg 2018;46:60-4.
11. Guzman ED, Eagleton MJ. Aortic dissection in the presence of an aberrant right subclavian artery. Ann Vasc Surg 2012;26:860.e13-8.
12. Ilahi M, Ilahi TB. Anatomy, thorax, thoracic duct. StatPearls. Treasure Island (FL): StatPearls Publishing; 2019.
13. Settembre N, Saba C, Bouziane Z, Jeannon F, Mandry D, Malikov S. Hybrid treatment of the aberrant right subclavian artery (arteria lusoria): feasibility study on 180 angio-CTs. Ann Vasc Surg 2017;44:229-33.
14. Fillinger MF, Greenberg RK, McKinsey JF, Chaikof EL; Society for Vascular Surgery Ad Hoc Committee on TEVAR Reporting Standards. Reporting standards for thoracic endovascular aortic repair (TEVAR). J Vasc Surg 2010;52:1022-33. 1033.e15.
15. Criado FJ. Taking a new look at Kommerell: recent insights on aortic diverticula. Vasc Dis Manag 2016;13:E156-65.
16. Austin EH, Wolfe WG. Aneurysm of aberrant subclavian artery with a review of the literature. J Vasc Surg 1985;2:571-7.
17. Kopp R, Wizgall I, Kreuzer E, Meimarakis G, Weidenhagen R, Kühnl A, et al. Surgical and endovascular treatment of symptomatic aberrant right subclavian artery (arteria lusoria). Vascular 2007;15:84-91.
18. Esposito RA, Khalil I, Galloway AC, Spencer FC. Surgical treatment for aneurysm of aberrant subclavian artery based on a case report and a review of the literature. J Thorac Cardiovasc Surg 1988;95:888-91.
19. Kouchoukos NT, Masetti P. Aberrant subclavian artery and Kommerell aneurysm: surgical treatment with a standard approach. J Thorac Cardiovasc Surg 2007;133:888-92.
20. van Bogerijen GH, Patel HJ, Eliason JL, Criado E, Williams DM, Knepper J, et al. Evolution in the management of aberrant subclavian arteries and related Kommerell diverticulum. Ann Thorac Surg 2015;100:47-53.
21. Knepper J, Criado E. Surgical treatment of Kommerell's diverticulum and other saccular arch aneurysms. J Vasc Surg 2013;57:951-4.
22. Yang C, Shu C, Li M, Li Q, Kopp R. Aberrant subclavian artery pathologies and Kommerell's diverticulum: a review and analysis of published endovascular/hybrid treatment options. J Endovasc Ther 2012;19:373-82.
23. Cao P, De Rango P, Czerny M, Evangelista A, Fattori R, Nienaber C, et al. Systematic review of clinical outcomes in hybrid procedures for aortic arch dissections and other arch diseases. J Thorac Cardiovasc Surg 2012;144:1286-300.
24. Odero A, Bozzani A, Pirrelli S. Endovascular treatment of acute type B dissection and Kommerell's diverticulum. Ann Thorac Surg 2007;84:1736-8.
25. Bosma J, van Swijndregt AD, Vahl AC. Hybrid treatment of a ruptured diverticulum of Kommerell. J Endovasc Ther 2010;17:762-6.
26. Corral JS, Zúñiga CG, Sánchez JB, Guaita JO, Basail AM, Gimeno CC. Treatment of aberrant right subclavian artery aneurysm with endovascular exclusion and adjunctive surgical bypass. J Vasc Interv Radiol 2003;14:789-92.

27. Vucemilo I, Harlock JA, Qadura M, Guirgis M, Gowing RN, Tittley JG. Hybrid repair of symptomatic aberrant right subclavian artery and Kommerell's diverticulum. Ann Vasc Surg 2014;28:411-20.
28. Rosu C, Dorval JF, Abraham CZ, Cartier R, Demers P. Single-stage hybrid repair of right aortic arch with Kommerell's diverticulum. Ann Thorac Surg 2017;103:e381-4.
29. Verzini F, Isernia G, Simonte G, De Rango P, Cao P; Italian AARSA Collaborative Group. Results of aberrant right subclavian artery aneurysm repair. J Vasc Surg 2015;62:343-50.
30. Andrási TB, Grossmann M, Zenker D, Danner BC, Schöndube FA. Supra-aortic interventions for endovascular exclusion of the entire aortic arch. J Vasc Surg 2017;66:281-97.e2.

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