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Endovascular treatment of the dissected proximal aortic arch: a systematic review

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Key question

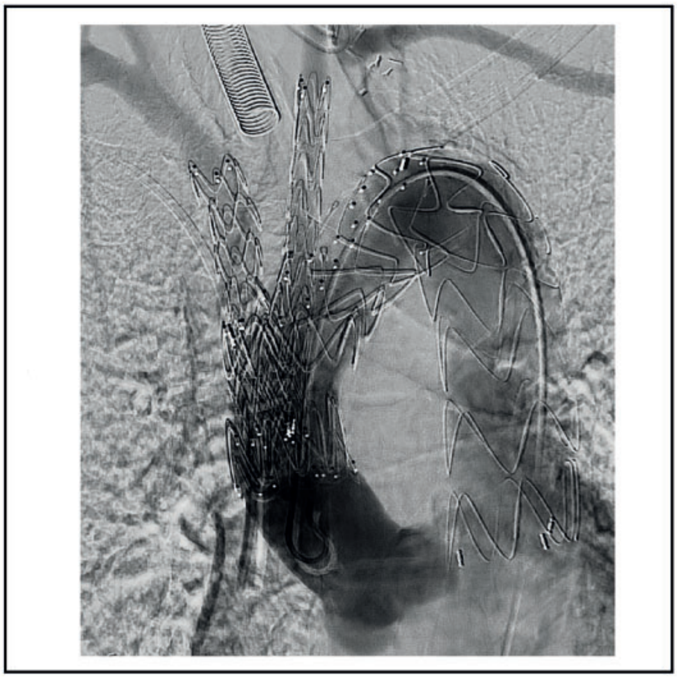
What is the current status of catheter-based treatments for the dissected proximal aortic arch?

Key finding(s)

Fifteen published reports (140 cases) showed hospital mortality 5%, stroke rate 2.8%, type-I endoleak 1.4%, late stent graft-induced new entry 2.1%, new false lumen 0.7%.

Take-home message

As an alternative treatment to standard surgery for the dissected aortic arch, the endovascular repair can be considered in selected high-risk patients.



Abstract

OBJECTIVES: Surgical repair of aortic dissection involving the proximal aortic arch is associated with higher morbidity and mortality, in particular when elderly high-risk patients are concerned. Endovascular treatments for this disease are under evaluation and some reports exist. We investigated the current use of catheter-based treatments for the dissected proximal aortic arch repair.

METHODS: We searched in PubMed and MEDLINE databases up to the end of June 2020 for studies on endovascular treatment of the dissected proximal aortic arch. Data on demographic, procedure and stent graft (SG) details, access route, mortality with cause of death, complications and follow-up were extracted. A systematic review on the employed technology, procedure and outcome was performed.

RESULTS: A total number of 15 articles (13 retrospective reports and 2 case reports) were deemed eligible and were included in the study. In total, 140 patients (mean age: 56.7 years in 106 cases) received endovascular treatments for the dissected proximal aortic arch (unspecific aortic dissection: 14; acute and subacute type A aortic dissection: 88; chronic type A aortic dissection: 23; type B aortic dissection with retrograde type A dissection: 15). The procedure strategy included unspecific thoracic endovascular aorta repair (TEVAR) ($n = 8$), TEVAR + supra-aortic debranching ($n = 2$), TEVAR + cervical bypass ($n = 8$), TEVAR + periscope SG ($n = 12$), TEVAR + chimney graft ($n = 8$), TEVAR + branched SG ($n = 21$) and TEVAR + fenestration ($n = 81$). Procedural success rate was 95.6% for 116 reported cases. Complications included endoleaks (postoperative: 2; late: 5), stroke ($n = 4$), late SG-induced new entry ($n = 3$) and new false lumen formation ($n = 1$). Hospital mortality was 5% (6 cases) in 13 reports (120 patients). The mean follow-up time was 26.2 ± 29.4 months and 2 patients died during follow-up.

CONCLUSIONS: As an alternative to surgery for high-risk patients with a dissected proximal aortic arch, the endovascular treatment seems to be promising in highly selected cases. Further studies with long-term results and specifically designed devices are required to standardize this approach.

Keywords: Thoracic endovascular aorta repair • Catheter-based techniques • Aortic dissection • Proximal aortic arch

ABBREVIATIONS

FET	Frozen elephant trunk
IA	Innominate artery
RTAD	Retrograde type A dissection
SG	Stent graft
TEVAR	Thoracic endovascular aorta repair
TAAD	Type A aortic dissection

INTRODUCTION

Type A aortic dissection (TAAD) is a life-threatening condition associated with high mortality. While in TAAD the primary entry tear is usually located in the ascending aorta, in retrograde type A dissection (RTAD) the tear is either in the arch or in the descending thoracic aorta. Therefore, the proximal arch is often involved by the dissection in most TAAD and RTAD cases. The treatment for the dissected arch remains a clinical and technical challenge and the open repair, including prosthetic arch replacement with or without frozen elephant trunk (FET), represents the standard of care. It offers the advantage of a complete repair with a low likelihood of late reintervention. However, the procedure requires the use of cardiopulmonary bypass and hypothermic circulatory arrest and, despite all anaesthesiological and surgical progresses, it remains associated with a higher mortality and morbidity. In a multicentre study by Urbanski *et al.* [1], the FET technique showed a hospital mortality of 12% and a stroke rate of 17%, despite the mean age of 64 years. Another systematic analysis reported surgical mortality of 5.3%, permanent stroke rate of 3.4%, transient neurologic deficit of 5.2% and permanent spinal cord injury of 0.6% [2].

Recently, the endovascular repair of the diseased ascending aorta has been proposed as an alternative for high-risk patients, and successful procedures for selected cases of TAAD or other ascending aorta disease have been reported [3, 4]. The thoracic endovascular aorta repair (TEVAR) of the dissected arch is a challenge given the necessity of simultaneously exclude the entry tear, preserve the supra-aortic vessels patency and protect the aorta from further dilatation, in particular when the proximal arch is concerned (corresponding to zone 0C of the Ishimura classification). The aim of this review is to investigate the current use of endovascular techniques for the treatment of the proximal aortic arch dissection presenting or not with a primary entry tear in the ascending aorta.

METHODS

This systematic review was performed and reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement [5]. We searched in PubMed and MEDLINE (https://www.ncbi.nlm.nih.gov/pubmed/) with time point set to end of June 2020 using medical subject headings and text words supplemented by scanning the bibliographies of recovered articles. We combined 'endovascular treatment' and 'aortic arch' using the Boolean operator 'AND'. We used similar search strategies using the terms 'endovascular repair', 'endovascular stent grafting', 'endograft repair', 'endovascular stent grafts' and 'proximal aortic arch', 'proximal aortic arch dissection', 'aortic arch dissection', 'arch dissection', 'dissected aortic arch'. Two co-authors (CW and LVS) reviewed and selected relevant articles for inclusion. Differences were resolved in consensus discussions. All titles, abstracts and full papers were sequentially reviewed against predefined inclusion criteria prior to attempted data extraction. Additional hand searching was undertaken.

Inclusion criteria

The predefined inclusion criteria were cases receiving the implantation of an endovascular stent graft (SG) for the treatment of a confirmed dissected proximal aortic arch with or without additional procedures including surgical debranching of supra-aortic vessels, chimney graft implantation and fenestration. Language was limited to articles written in English. Only papers in which we could extract the exact number of cases with dissected proximal aortic arch from the total amount of reported cases were included.

Exclusion criteria

All studies or cases reporting the treatment of non-dissected proximal aortic arch diseases (aortic arch aneurysm, pseudoaneurysm, penetrating ulcer and thrombosis) were excluded. The cases in which the zone 0 of the aortic arch was healthy and not dissected, but was used as the extended proximal landing zone

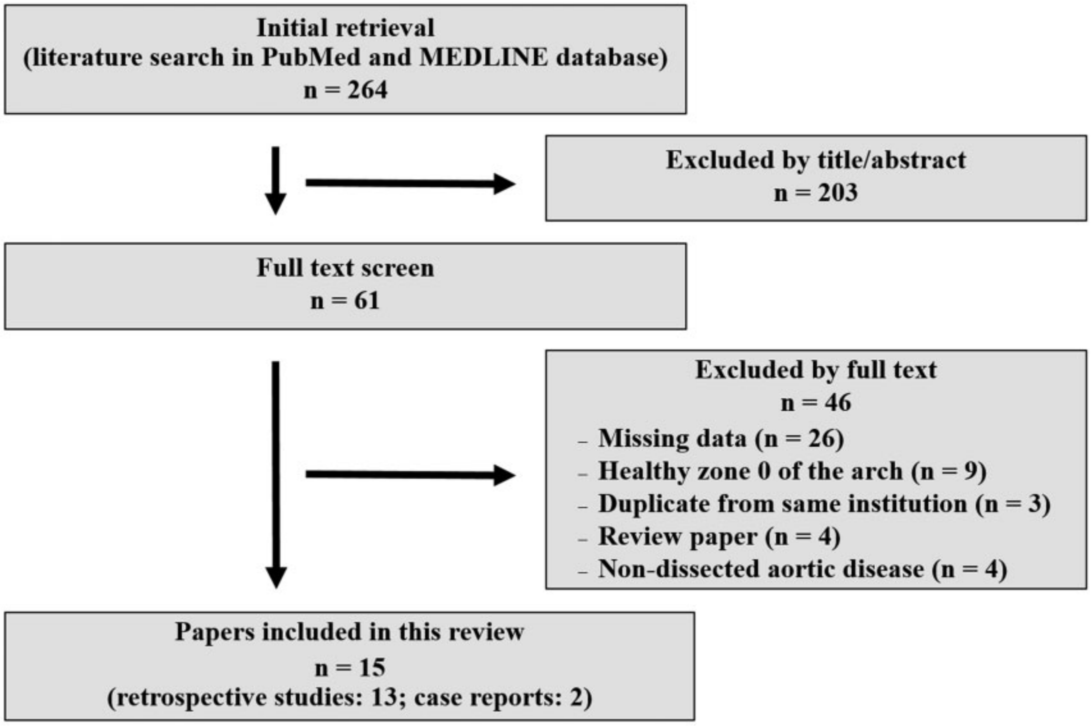


Figure 1: Flow diagram illustrating the identification, selection and exclusion of articles included in this review.

for distal TEVAR were also excluded. Correspondences, expert opinions and reviews were not included, too.

Data extraction

We collected data on study design (retrospective study or case report), age, gender, number of patients, type of dissection (acute or chronic, TAAD or RTAD), preoperative risk score (EuroSCORE, Society of Thoracic Surgery score, American Society of Anaesthesiologists score), SG and procedural details, access route, hospital mortality, cause of death, complications, reinterventions, follow-up length and outcome.

The risk of bias was assessed at the study level using Cochrane's Collaboration Tool [6]. Through 6 domains, this tool evaluates the risk of bias and categorizes each study as high risk, low risk or unclear risk.

Statistical analysis

Data collected were organized on an Apple Numbers spreadsheet (version 6.6.2). Descriptive statistics was used to describe demographic data and SG details. Continuous variables were described using the mean ± standard deviation while dichotomous variables were expressed as absolute number with percentage.

RESULTS

The literature search yielded 264 publications that were screened by title/abstract and full text. Finally, 15 publications focusing on transcatheter endovascular treatment of the dissected proximal aortic arch were identified from the English literature and included in the present analysis (Fig. 1). All data are described in Table 1. There were 13 retrospective reports and 2 case reports [7–21]. Only 5 papers strictly focused on the dissected proximal aortic arch pathology. In the other 10 reports, we extracted the qualifying cases from the TAAD or type B aortic dissection case pools, but sometimes data on age, gender, in-hospital mortality, complications and follow-up could not be accurately extracted because mixed with other cases. Concerning the choice of performing TEVAR instead of surgery, we identified the following reasons: patients with high-risk surgical profile [7–9, 11, 12, 14–16, 18, 19]; patients refusing surgery [17, 20]; and not specified [10, 13, 21].

A total number of 140 patients were included in the study. The mean age was 56.7 years (range: 33–78 years) for 106 reported cases. In the full group, 71 patients were male, 35 were female and 34 were not specified. Concerning the disease, a generic 'aortic dissection' was reported in 14 cases (10%), TAAD (including 10 residual TAAD) in 111 cases (79.3%), type B aortic dissection in 10 cases (7.1%) and RTAD in 5 cases (3.6%).

For 88 reported cases (63%), the TEVAR was performed in an acute or subacute TAAD. For 13 patients only we extracted and recorded history of previous cardiac or aortic operation. The American Society of Anaesthesiologists score was reported III, IV and V in 2 studies while the mean EuroSCORE-II was reported as 11.4 ± 3.2% (range: 5–17%) in 1 study. Mean hospital mortality was 5% (6 cases) in 13 papers (120 patients). The cause of death was multiple organ failure ($n = 2$), new distal aortic dissection and rupture 2 days after the procedure ($n = 1$), intraprocedural cardiac tamponade ($n = 1$), pneumonia ($n = 1$) and gastrointestinal haemorrhage ($n = 1$). Four reports documented in-hospital complications: 4 strokes and 2 type I endoleaks.

The anatomic characteristics of the dissected ascending aorta and arch were not available in the revised articles. Procedural success rate was 95.6% for 116 reported cases and the details of the devices and procedures are listed in Table 2. The most

Table 1: Case series summary of endovascular treatment of the dissected proximal aortic arch

Author	Article types	Year of publication (period of treatment)	Number of patients (.../total)	Age (years)	Gender (M/F)	Aortic disease	Previous cardiac or aortic operation	Risk score	Hospital mortality (%)	Cause of hospital death	Complications	Re-intervention	Follow-up (months)	Late complication	Later death
Verscheure *et al.* [7]	Retrospective study	2019 (2011–2018)	6/70	NA	NA	TAAD (C: 6)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Zhang *et al.* [8]	Retrospective study	2019 (2009–2014)	7/51	NA	NA	TAAD (C: 7)	NA	NA	0	none	None	None	NA	NA	NA
Clough *et al.* [9]	Retrospective study	2018 (2010–2017)	14/30	NA	NA	Unspecified AD (C: 14)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Li *et al.* [10]	Retrospective study	2020 (2017–2019)	9/148	57.6 ± 10.9	8/1	TAAD (A or subacute: 8, C: 1)	NA	NA	1 (11.1%)	new distal dissection and rupture 2 days later	Stroke: 1	NA	NA	NA	0
Kuo *et al.* [11]	Retrospective study	2019 (2016–2017)	11/13	62.1 ± 12.1 (range: 42–78)	8/3	TAAD (A: 1) TBAD: 10	Open grafting, or hybrid operation	ASA score III: 7 IV: 3 V: 1	0	none	None	None	Mean: 20	Type Ib EL: 2 SINE: 3 (infected: 1) New false lumen: 1 (all treated with redo-TEVAR)	2
Xiang *et al.* [12]	Retrospective study	2019 (2016–2017)	3/37	NA	NA	RTAD: 3	NA	NA	0	-	NA	NA	NA	NA	NA
Qin *et al.* [13]	Retrospective study	2019 (2014–2018)	58	58 (range: 33–67)	32/26	TAAD (A: 21, subacute: 37)	None	NA	2 (3.4%)	Intra-procedural cardiac tamponade (1) Pneumonia (1)	Stroke: 2	NA	10.6 ± 5.4	Type Ia EL: 2 Type II EL: 1	NA
Wang *et al.* [14]	Retrospective study	2018 (2016–2017)	1/7	57	0/1	TAAD (A: 1)	Ascending aorta and aortic valve replacement	NA	0	none	None	None	NA	NA	NA
Gao *et al.* [15]	Retrospective study	2017 (2013–2016)	12	54 ± 9.6	10/2	TAAD (A: 12)	None	EuroSCORE-II: 11.4 ± 3.2% (range: 5–17%)	2 (16.7%)	MOF (2)	None	None	17 ± 14.5 (range: 2–42)	None	None
Wang *et al.* [16]	Retrospective study	2017 (2009–2016)	2/23	56, 60	2/0	RTAD (C: 2)	None	NA	0	none	None	None	36, 36	None	NA
Liang *et al.* [17]	Case report	2017	1	63	1/0	TAAD (A: 1)	None	NA	0	none	None	None	12	None	None
Voskresensky *et al.* [18]	Retrospective study	2017 (2002–2015)	4/27	NA	NA	TAAD (C: 4)	NA	NA	0	none	NA	NA	NA	NA	NA
Ozcan *et al.* [19]	Case report	2015	1	50	1/0	TAAD (A: 1)	Ascending aorta replacement for TAAD	NA	0	none	None	None	NA	NA	NA
Ye *et al.* [20]	Retrospective study	2011 (2001 – 2009)	10/45	51 (range: 41–71)	9/1	TAAD (A: 6, C: 4)	None	NA	1 (10%)	gastrointestinal haemorrhage	Type I EL: 1 Stroke: 1	Right axillary right external iliac artery bypass	35.5 ± 5.4 (4–112)	NA	NA

Continued

Table 1: Continued

Author	Article types	Year of publication (period of treatment)	Number of patients (.../total)	Age (years)	Gender (M/F)	Aortic disease	Previous cardiac or aortic operation	Risk score	Hospital mortality (%)	Cause of hospital death	Complications	Re-intervention	Follow-up (months)	Late complication	Later death
Bernardes *et al.* [21]	Retrospective study	2014 (2007–2012)	1/7	58	0/1	TAAD (C: 1)	None	ASA 3	0	none	Type I EL	Corrected with device extension	3.5	None	None
Summary	Retrospective studies: 13 Case reports: 2	2001–2018	140/530 (26.4%)	Mean for 106 patients: 56.7 (range: 33–78)	71/35 (NA = 34)	Unspecified AD: 14 TAAD (C: 23, A and sub-acute: 88) TBAD: 10 RTAD: 5	13/97 (13.4%) (NA = 43)	ASA score in 2 reports; EuroSCORE-II in 1 report	6/120 (5%) (NA = 20)	Cardiovascular: 2 Non-cardiovascular: 4	Stroke: 4 Type I EL: 2	2 reported	Mean for 95 patients: 26.2 ± 29.4 (range: 2–112)	EL: 5 SINE: 3 New false lumen formation: 1	2

Values are expressed as numbers and % or mean ± standard deviation.

A: acute; AD: aortic dissection; ASA: American Society of Anaesthesiologists; C: chronic; EL: endoleak; MOF: multiple organ failure; NA: not available; RTAD: retrograde type A dissection; SINE: stent graft-induced new entry; TAAD: type A aortic dissection; TBAD: type B aortic dissection; TEVAR: thoracic endovascular aorta repair.

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Table 2: The details of the devices and combined procedure in thoracic endovascular aorta repair for proximal dissected aortic arch

Author	Number of patients (1/total)	Devices	Aorta SG diameter (mm)	IA SG diameter (mm)	Aorta SG length (mm)	IA SG length (mm)	SG selection (oversize)	Access route	Procedure	Technical success rate (%)
Verscheure *et al.* [7]	6	CMD Inner-branched SG (Cook)	NA	NA	NA	NA	NA	Multiple access (FA, RCCA, LCCA)	TEVAR + cervical bypass	NA
Zhang *et al.* [8]	7	CMD Branched SG (MicroPort)	NA	NA	NA	NA	NA	Multiple access (brachial or carotid artery)	TEVAR (branched SG)	100
Clough *et al.* [9]	14	CMD Inner-branched SG (Cook)	NA	NA	NA	NA	NA	Multiple access (brachial or carotid artery)	TEVAR (branched SG)	NA
Li *et al.* [10]	9	OTS (Valiant, C-TAG, Zenith, etc)	NA	NA	NA	NA	NA	Multiple access	TEVAR + fenestration (*in situ*)	100
Kuo *et al.* [11]	11	CMD (Cook TX2, Valiant Captivia)	NA	NA	NA	NA	20% (12.9–26.8%)	Multiple access (FA, IA, LCCA, LSA)	TEVAR + fenestrated	100
Xiang *et al.* [12]	3	OTS (cTAG, valiant, Ankura)	NA	NA	NA	NA	NA	Multiple access (FA, IA, LCCA, LSA)	TEVAR + fenestration (*in situ*)	100
Qin *et al.* [13]	58	OTS (aortic SG: TAG or cTAG; IA SG: Fluency)	NA	13.5	NA	40	NA	Multiple access (FA, LCCA, RCCA, left brachial artery)	TEVAR + fenestration (*in situ*)	91.3
Wang *et al.* [14]	1	OTS (C-TAG, Viabahn)	NA	NA	NA	NA	NA	Multiple access	TEVAR + chimney graft	100
Gao *et al.* [15]	12	OTS (TAG, Viabahn)	37–40	11–13	150	100	NA	Multiple access	TEVAR + periscope graft	100
Wang *et al.* [16]	2	OTS (aortic SG: Ankura, Valiant; IA SG: Fluency)	40	12	200	60	Aorta: 15% Chimney: 5%	Multiple access	TEVAR + chimney graft	100
Liang *et al.* [17]	1	OTS (aortic SG: TAG; IA SG: Viabahn)	45	13	200	100	NA	Multiple access (FA, LCCA, bilateral brachial artery)	TEVAR + chimney graft	100
Voskresensky *et al.* [18]	4	OTS (aortic SG: Zenith TX2; IA SG: Viabahn)	NA	NA	NA	NA	Aorta: 0–10% IA: 10–20%	Multiple access	TEVAR + chimney graft	NA
Ozcan *et al.* [19]	1	OTS (E-vita Thoracic)	28	NA	170	NA	15%	FA	TEVAR + supra-aortic debranching	100
Ye *et al.* [20]	10	OTS (Medtronic and Cook)	30–42	NA	60–80	NA	5–10%	Multiple access	TEVAR with (2) or without (8) cervical bypass	100
Bernardes *et al.* [21]	1	OTS (Medtronic Valiant)	36	16	200	95	NA	Multiple access	TEVAR + supra-aortic debranching + IA chimney graft	100
Total	140	CMD = 38 (27.2%) OTS =102 (72.8%)	37.3 ± 5.8 (range: 28–45)	13 ± 1.7 (range: 11–16)	151.4 ± 59 (range: 60–200)	79 ± 27.5 (range: 40–100)	–	–	–	95.65 (for 116 cases)

Values are expressed as numbers and % or mean ± standard deviation.

CMD: custom-made device; FA: femoral artery; IA: innominate artery; LCCA: left common carotid artery; LSA: left subclavian artery; NA: not available; OTS: off-the-shelf; RCCA: right common carotid artery; SG: stent graft; TEVAR: thoracic endovascular aortic repair.

Table 3: Procedural strategies and outcome of endovascular treatment of the dissected proximal aortic arch

Procedural strategy	Number of cases	Period	Complications	Hospital mortality
TEVAR only	8	2001–2009	0	0
TEVAR + supra-aortic debranching	2	2007–2012	Endoleak: 1	0
TEVAR + cervical bypass	8	2001–2018	Endoleak: 1; stroke: 1	1 (12.5%)
TEVAR + periscope SG	12	2013–2016	0	2 (16.7%)
TEVAR + chimney SG	8	2002–2017	0	0
TEVAR + branched SG	21	2009–2017	0	0
TEVAR + fenestration (*in vitro*)	11	2016–2017	0	0
TEVAR + fenestration (*in situ*)	70	2014–2019	Stroke: 3	3 (4.3%)

SG: stent graft; TEVAR: thoracic endovascular aorta repair.

common arterial access was the multiple one, including femoral artery, carotid artery, innominate artery (IA), left subclavian artery and/or brachial artery. A total of 140 aortic SGs were used in TEVAR procedure, including 38 (27.2%) custom-made and 102 (72.8%) 'off-the-shelf' SGs. The average diameter of the aortic SG was 37.3 ± 5.8 mm (range: 28–45 mm) with a mean length of 151.4 ± 59mm (range: 60–200 mm) in 27 reported cases. In most cases, the details of the SGs used for the collateral branches were not reported. The average diameter of the IA graft was 13 ± 1.7 mm (range: 11–16 mm), with a mean length of 79 ± 27.5 mm (range: 40–100 mm) in 74 reported cases. In 5 reports, the selection for the main graft was based on an oversize of the true lumen diameter of 0–26.8%, while the IA SG selection was based on a 5–20% oversize.

In all cases, the proximal landing zone was in the proximal ascending aorta that was not dissected and did not presented the primary entry tear. Due to the entry tear mostly located near to the IA (limited data on revised paper about the location of the entry tear in the arch or distally) and the implication of the cervical branches, the majority of the distal landing zones were located distally to the IA origin, thus requiring additional procedures performed. The procedural strategy included unspecific TEVAR only ($n = 8$), TEVAR + supra-aortic debranching ($n = 2$), TEVAR + cervical bypass ($n = 8$), TEVAR + periscope SG ($n = 12$), TEVAR + chimney grafts ($n = 8$), TEVAR + branched SG ($n = 21$), TEVAR + fenestration (*in situ*) ($n = 70$) and TEVAR + fenestration (*in vitro*) ($n = 11$). Where required, the *in situ* and *in vitro* fenestration was performed indifferently in custom-made and 'off-the-shelf' SGs.

Half of procedures were TEVAR combined with an *in situ* fenestration, followed by TEVAR and branched SG. To guarantee the brain protection during the *in situ* fenestration, TEVAR procedures combined with *in situ* fenestrations were supported either by an extracorporeal bypass through the vascular shunt connection of bilateral sheaths between the right and left carotid artery or by using a cardiopulmonary bypass. Three death cases happened in TEVAR combined with *in situ* fenestration, 2 in TEVAR combined with periscope SG and 1 in TEVAR combined with cervical bypass. The procedural details and related issues are displayed in Table 3.

In this literature investigation, the mean follow-up time was 26.2 ± 29.4 months (range: 2–112) for 95 patients, and 8 papers did not provide late outcome. Two patients died during the follow-up and the cause was not reported. Only 2 papers documented late complications during the follow-up, including endoleak ($n = 5$), SG-induced new entry ($n = 3$) and new false lumen formation ($n = 1$), but none of the revised papers included in this review showed data on vascular or endovascular reintervention.

DISCUSSION

The aortic dissection involving the aortic arch remains a serious disease requiring a surgical ascending aorta repair combined (or not) with total arch replacement and FET, under cardiopulmonary bypass, cardioplegic arrest and hypothermic circulatory arrest. However, despite the surgical approach is still considered the golden standard treatment for the dissected aorta, and despite the surgical and the anaesthesiological techniques have greatly improved over the last years, the mortality and the neurological complications rate remains significantly high especially when high-risk patients and elderly patients are concerned [22]. In particular, in the subgroup of the octogenarians, the emergency surgery for TAAD is associated with relatively high intraoperative mortality (14.9%) with a 30-day survival rate of 61.2% [23].

Compared with the traditional open surgery, the endovascular technique features the advantage of a less body trauma with a faster recovery for the elderly ill patient, but technical limits and absence of long-term results calm the enthusiasms for a spread use of this disrupting technology and strategy. Nevertheless, since the first reported case of an endovascular TAAD repair by Dorros *et al.* in 2000, the endovascular treatment of the type A dissection was proposed as an alternative to open surgery in very selected high-risk or inoperable patients, with satisfactory preliminary results [3, 24].

Similarly, the present review also suggests a satisfactory outcome for patients with dissected proximal aortic arch receiving TEVAR treatments but the indication and the durability of such technique are still questionable and only patients with a too high risk for surgery can be good candidates. In 13 reports, 6 out of 120 patients (5%) died in hospital, 4 patients had a stroke and in 2 patients a type I endoleak was detected. Qin *et al.* [13] reported a large series of 58 patients with acute or subacute TAAD involving the aortic arch and treated with TEVAR in combination with an *in situ* fenestration: the procedural success was fully achieved in 53 patients (91.4%), while a late endoleak occurred in 3 patients and a favourable aortic remodelling was noted during the follow-up. Another retrospective analysis of 12 patients (mean EuroSCORE-II: 11.4 ± 3.2%; range 5–17%) treated with TEVAR combined with periscope grafts reported by Gao *et al.* [15] also showed no SG thrombosis, stroke or peripheral artery embolism after a mean follow-up time of 17 ± 14.5 months.

These preliminary results suggest that the endovascular treatment for the dissected proximal aortic arch has an acceptable early mortality and stroke rate compared to the results of the open surgery in very selected cases, but still the long-term efficacy and the indication in lower-risk patients remain questionable key points for the widespread use of this technology.

In the proximal dissected aortic arch, the cervical branches are always partially or completely involved, especially the IA.Therefore, the major concern of the endovascular treatment is how to manage the conflict of simultaneously exclude the entry tear and preserve the patency of cervical branches. At the time being, there is no consensus or criteria guiding the choice for the most appropriate additional procedure aiming at maintaining the perfusion of the supra-aortic arteries during the procedure.

In the early phase, TEVAR alone was used as a palliative method in much selected cases but nowadays, and according to our investigation, several endovascular or surgical procedures are used in addition to the index TEVAR in order to improve the outcome [20]. These combined procedures include supra-aortic surgical debranching, cervical bypass, endovascular periscope or chimney SG, branched SG and fenestration and can be summarized into 2 major techniques: the hybrid technique and the complete endovascular technique.

During the last years, the fenestration technique, in particular the *in vitro* one, has become the most widely used method in combination with TEVAR and has contributed to the development of the complete endovascular technique for the treatment of complex arch anatomies [10–13]. The *in situ* fenestration requires the support of a cardiopulmonary bypass and for this reason is not considered a full endovascular therapy but still a hybrid operation. In this review, more than half of the cases underwent TEVAR with fenestration, including both the *in situ* and *in vitro* techniques. The additional procedures are not without risks and the hybrid technique still needs a thoracic or cervical incision with cross-clamping of collateral branches and carries the risk of prosthetic graft infection. Similarly, stroke, endoleak and migration of the SG are the most common complications of the complete endovascular technique.

SG selection of both aortic SG and branches SG is crucial in TEVAR for dissected proximal aortic arch. Currently available SGs do not fully address the unique feature of the ascending aorta and aortic arch anatomy. The novel branched endografts are still under development and are not readily available, especially in emergent circumstances [14]. Another finding of this review is that the majority of the endografts used in TEVAR were 'off-the-shelf' endografts (72.8%). The other 27.2% of cases were performed with custom-made SGs or standard endoprosthesis modified by the surgeon. The development of specifically designed endovascular devices for the ascending aorta and for aortic arch replacement is imminent. However, this will be a challenge not only because of the complex anatomy and physiology of the region but also because healthy aortic segments for a safe sealing and fixation are not always available in proximal and distal dissected tissues.

With regard to the procedural success rate of published reports, we found a 95.6% rate for 116 reported cases. Twelve out of 85 patients (14%) suffered from late complications including endoleak, SG-induced new entry and new false lumen formation during the follow-up.

Most of the reports concluded that the endovascular treatment was a minimally invasive effective method to treat TAAD involving cervical branches in high-risk inoperable patients and showed good clinical short- and mid-term results. However, the long-term results need to be closely monitored and randomized controlled studies are still missing. The improvement and the innovation of the endovascular technology with newly designed devices more suitable for the complexity of the ascending aorta and the arch will help to improve the long-term results of patients with dissected proximal aortic arch.

Limitations

This study presents some limitations. This is a review of published endovascular technologies for the treatment of the dissected proximal aortic arch. All included publications are retrospective studies and case reports, and thus, the present report is affected by all limitations inherent these type of publications. Next, there could be a risk of publication bias because some important data in the revised articles are missing or present a mixture of different pathology, techniques, strategies and outcome. There is also a certain degree of heterogeneity in the indications, SG selection, procedural details and outcome that limit the possibility of developing a certain degree of standardization for this technique. Therefore, a general conclusion from a solid statistical analysis with adequate samples is lacking.

CONCLUSION

The available literature on endovascular treatment for the dissected proximal aortic arch still consists of small case series from a limited amount of studies describing the indication, the procedural details and the short-term outcome of selected patients. The endovascular treatment is suggested as an alternative technique for the treatment of dissected proximal aortic arch in patients at high-risk for surgery. The development of specific strategies and newly designed devices for the dissected ascending aorta and arch may further improve the outcome and spread the use of this technique.

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Author contributions

Changtian Wang: Data curation; Methodology; Writing—original draft. **Ludwig Karl von Segesser:** Conceptualization; Data curation; Methodology; Writing—review & editing. **Denis Berdajs:** Data curation; Writing—review & editing. **Enrico Ferrari:** Data curation; Methodology; Supervision; Validation; Writing—original draft.

Reviewer information

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