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# Efficacy and Durability of Chimney Graft Technique in Urgent and Complex Thoracic Endovascular Aortic Repair

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**Abstract**

**Objective:** This study reports the early and midterm to long-term experience of chimney grafts (CGs) in urgent endovascular repair of complex lesions in the thoracic aorta.

**Methods:** Twenty-nine high-risk patients (20 men) who were unfit for open repair were treated using CG technique for ruptured (n = 14) or symptomatic (n = 15) aortic lesions engaging the aortic arch itself (n = 9), the descending aorta (n = 10), or the thoracoabdominal aorta (n = 10). Twenty-two patients (76%) were treated urgently ( $\leq 24$  hours) and seven were semiurgent ( $\leq 3$  days). Of 41 chimneys used, 24 were placed in supra-aortic branches and 17 in visceral branches. Median follow-up (interquartile range) for the entire cohort was 2 years (0.6-3.8 years), 2.5 years (1-4 years) for 30-day survivors, and 3.5 years (1.9-6.4 years) for those who were still alive.

**Results:** Four patients (14%) died  $\leq 30$  days of cerebral infarction (n = 1), visceral ischemia secondary to the initial rupture (n = 1), multiple organ failure (n = 1), or heart failure (n = 1). There were 11 late deaths (38%); however, only two deaths were related to the CG technique. The primary and secondary technical success rates were 86% (25 of 29) and 97% (28 of 29), respectively. The secondary patency rate of CGs was 98%. Seventeen (68%) of the aortic lesions shrank significantly. Three patients (10%) had primary type I endoleak and another three (10%) had secondary type I endoleak. The endoleaks were managed with Onyx (ev3 Endovascular, Inc, Plymouth, Minn) or coil embolization (n = 2), restenting (n = 1), and conversion to open repair (n = 2). One secondary endoleak is still under observation after  $>20$  months. All primary endoleaks and one secondary endoleak originated from CGs in the brachiocephalic trunk (4 of 6 [67%]).

**Conclusions:** The midterm to long-term results of the CG technique for urgent and complex lesions of the thoracic aorta in high-risk patients are promising, with low early mortality and

long durability of the CGs. More patients with longer follow-up are still needed. (J Vasc Surg 2015;61:886-94.)

**Keywords:** aortic aneurysm, thoracoabdominal aortic aneurysm, TEVAR, stent graft, chimney graft, snorkel technique, aortic lesion, aortic arch, endovascular, aorta.

## INTRODUCTION

Open repair (OR) for thoracic or thoracoabdominal aortic lesions is still the gold standard of therapy in all patients who are fit for major surgery; however, OR is associated with a high morbidity and mortality in elderly or urgent high-risk patients.<sup>1</sup> The endovascular approach is increasingly preferred for selected patients with a suitable anatomy and in the presence of suitable devices. Thoracic endovascular aortic repair (TEVAR) is relatively safe, durable, and effective when proximal and distal sealing zones are adequate.<sup>2-4</sup> Fenestrated and branched stent grafts may prove applicable in patients who do not have an adequate proximal or distal sealing zone.<sup>2</sup>

Although off-the-shelf fenestrated and branched thoracic stent grafts have recently been introduced, they are still not widely available for urgent interventions.<sup>2</sup> Open surgery therefore remains the treatment of choice for such urgent cases.<sup>1</sup> However, many of these patients are not fit for open surgery because of significant comorbidities. Thus, the chimney graft (CG) technique may currently have an important role by being the only available alternative in this setting. It may even gain acceptance for use in some elective cases.<sup>5-7</sup> The CG technique makes it possible to use standard, off-the-shelf stent grafts to instantly treat lesions with inadequate sealing zones.<sup>3</sup> CGs extend the sealing zone of an aortic stent graft while preserving blood flow to vital side branches.<sup>3,7</sup>

The CG technique is technically demanding, however. Dedicated stents do not exist yet, and the results are not always optimal. Initial reports have indicated a high (18%-50%) incidence of type I endoleak (EL-I).<sup>8-12</sup> The gutters alongside the chimney walls seem to offer a potential source for EL-I that may allow pressure transmission to the aneurysmal sac and thereby maintain the risk of bleeding or rupture. The aim of the present study was to analyze

our midterm to long-term results of patients with complex thoracic aortic lesions in whom the CG technique was used in urgent settings.

## **METHODS**

The present study is a single-center experience of the CG technique in patients treated with TEVAR after they were considered not fit for OR. Excluded were patients with aortic occlusive disease, which were presented separately.<sup>5</sup> Prospectively collected data were analyzed retrospectively. The results are presented according to the guidelines for reporting standards in TEVAR.<sup>13,14</sup> Also assessed were 30-day mortality, chimney-related mortality, procedure-related mortality, patency of CGs, primary EL-I ( $\leq 30$  days), secondary EL-I ( $> 30$  days), chimney-related reinterventions, and “favorable outcome.” Favorable outcome relates in this context only to the CGs and was defined as freedom from fatal bleeding, stroke (arch chimneys), permanent dialysis (renal chimneys) or intestinal ischemia (visceral chimneys), chimney-related death, or any related open surgery.

There were 253 TEVARs performed at our tertiary referral center between November 2004 and October 2012. Twenty-nine of these patients had one or several CGs. Their median age was 73 years (interquartile range [IQR], 63-74 years), and 20 (69%) were men. No patients were lost to follow-up (FU). In the current report, the term “chimney graft” denotes both chimney stent and chimney stent graft.

The CGs served to extend the sealing zone cranially into the aortic arch in 20 patients or caudally across the visceral arteries in nine. The technical aspects of CG procedure are described elsewhere.<sup>3,5,7,8</sup>

**Table I.** Clinical history and outcome of eight patients who underwent urgent thoracic endovascular aortic repair (*TEVAR*) with the chimney graft (*CG*) technique due to

	<i>Original aortic pathology</i>	<i>Previous aortic repair</i>	<i>Indications for chimney intervention</i>	<i>Time between both interventions</i>	<i>Chimney branch</i>	<i>Death related to (CG, procedure, other)</i>	<i>CG FU (y)</i>
1	AAA	FEVAR	Persistent EL-I (SMA), infection	2.5 years	SMA, RRA, LRA	CG	11
2	TAAA	FEVAR	Expanding Arch pseudoaneurysm	1 years	BT, LCCA	other	54
3	TAAA, B-dissection	TEVAR	Persistent EL-I	20 days	SMA	other	15
4	Descending aneurysm	TEVAR	Persistent EL-I	25 days	BT, LCCA	Procedure	2
5	Arch aneurysm	OR	Acute B-dissection, expanding Aneurysm	30 days	LCCA	Alive	18
6	B-dissection	OR	Acute AEF	1 years	BT	other	52
7	AAA	OR	Rupture TAA	10 years	SMA, RRA, LRA	Alive	34
8	AAA ruptured	OR	Symptomatic dissection in TAA	10 years	LSA	Alive	32

complications after a previous aortic repair

*AAA*, abdominal aortic aneurysm; *TAAA*, thoracoabdominal aortic aneurysm; *FEVAR*, fenestrated endovascular aortic repair; *RRA*, right renal artery; *LRA*, left renal artery; *BT*, brachiocephalic trunk; *TAA*, Thoracic aortic aneurysm.

The reason for selecting the CG technique was the presence of complex morphology without an adequate sealing zone or accidental overstenting of vital aortic side branches. Off-the-shelf fenestrated or branched stent grafts were unavailable or were deemed inappropriate because of unsuitable anatomy. Customized branched or fenestrated stent grafts could not be awaited. Eight patients (28%) had undergone previous aortic repair (Table I): five were in the thoracic aorta (three OR) and three in the thoracoabdominal aorta (one OR). The four chimney interventions that were secondary to previous aortic OR were prompted by complications such as dissection (n = 2), aorto-esophageal fistula (AEF; n = 1) or rupture (n = 1). Four of these reinterventions were secondary to previously failed endovascular repair with EL-I (n = 3) or pseudoaneurysm (n = 1).

Overall, the CG technique was used for aortic aneurysms (n = 11), complicated aortic dissection (n = 9), pseudoaneurysms (n = 5), accidental overstenting of the left common carotid artery (LCCA; n = 2), iatrogenic AEF (n = 1), and traumatic transection (n = 1; Table II). The chimney procedures were urgent ( $\leq 24$  hours) in 22 patients (76%), most of them were treated as emergencies ( $\leq 4$  hours), and seven (24%) were semiurgent ( $\leq 3$  days).

Fourteen of the 29 patients (48%) presented with aortic rupture, two with mycotic aneurysms, and one with graft infection. The median aneurysm diameter was 64 mm (IQR, 52-73; n = 21). Rapid expansion of the aorta (n = 11) occurred in patients with aortic dissection (n = 8), aneurysm (n = 1), and pseudoaneurysm (n = 2; Table II).

We refrained from presenting the detailed clinical course of the patients, particularly the 14 ruptured cases, because they presented with such a diverse history that a meaningful



definition of “stability” seemed difficult. All patients were temporarily resuscitated and tolerated waiting 1 to 4 hours for the emergency insertion of a stent graft. However, most had been in shock at our hospital or upon presentation at the local hospital before referral to us. The patient with an AEF was transferred 70 miles with double-inflated Sengstaken tubes after being rejected by cardiothoracic surgeons. Another patient had survived a failed attempt at open surgery at a remote university cardiothoracic clinic and was transferred by air, yet was reasonably stable upon arrival. Others (dissections) were unstable due to end-organ ischemia.

Three renal chimneys in two patients (7% [three of 44 attempted chimneys]) were impossible to insert for technical reasons. One patient had a ruptured 10-cm-large type IV thoracoabdominal aneurysm with grotesquely overstretched renal arteries that proved impossible to cannulate. This patient was excluded from the report. The other patient underwent successful implantation of a renal CG on one side but failure on the other side. He was included in the analysis.

**Table II.** The presentation and operative indication of 29 patients with complex aortic lesions, who were urgently treated with CG technique and TEVAR

<i>Patients Nr (%)</i>	<i>Indicative Pathology</i>	<i>Clinical presentation and operative indication</i>						<i>outcome</i>
		<i>Rupture</i>	<i>Rapid expansion</i>	<i>Ischemia</i>	<i>EL-I of previous TEVAR</i>	<i>infection</i>	<i>Urgent</i>	
11 (38%)	Aneurysms	9	1	0	2	1	9	2
9 (31%)	Dissection	1	8	5	1	0	6	2
5 (17%)	Pseudoaneurysms	1	2	0	0	2	4	2
2 (7%)	Accidental overstenting	1	0	0	0	0	1	0

1 (3%)	Transection	1	0	0	0	0	1	0
1 (3%)	Aorto-esophageal fistula	1	0	0	0	0	1	0

**Table III.** A chimney-branch related outcome for 29 patients with different complex aortic lesions who were urgently treated with CG technique and TEVAR

<i>CG Location</i>	<i>BT</i>	<i>LCCA</i>	<i>LSA</i>	<i>CT</i>	<i>SMA</i>	<i>RRA</i>	<i>LRA</i>	<i>Total</i>
No	7	13	4	1	9	3	4	41
CG Occlusion	0	0	0	0	0	0	1	1(2%)
Primary EL-I	3	0	0	0	0	0	0	3 (10%)
Secondary EL-I	1	2	0	0	0	0	0	3 (10%)
Sacrificed branches	0	0	10	7	0	1	0	18

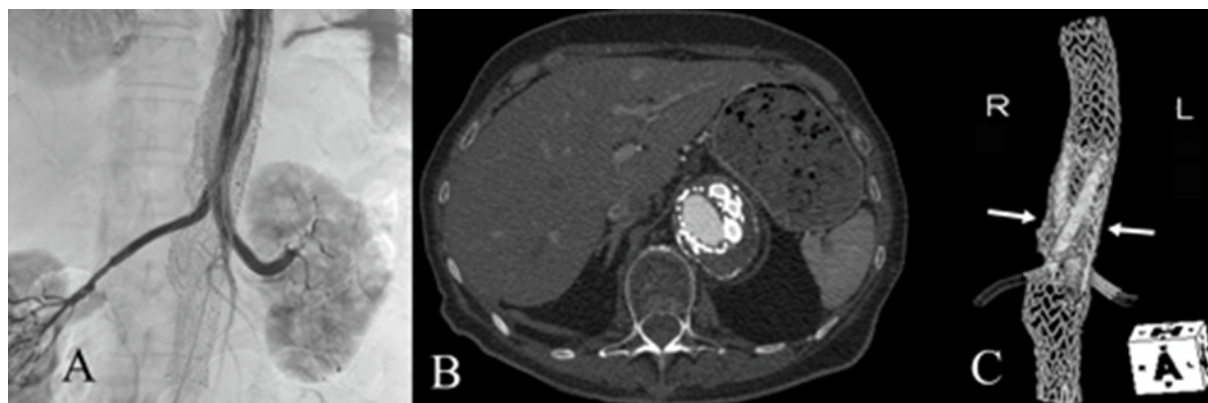
*BT*, brachiocephalic trunk; *RRA*, right renal artery; *LRA*, left renal artery.

**CGs.** The 29 patients received 41 CGs composed of 83 stents. Twenty-four CGs were implanted in supraaortic branches and 17 in visceral aortic branches (Table III). The composition, frequency, and distribution of the used CGs are summarized in the [Supplementary Table](#) (online only). The median length of CGs was 90 mm (IQR, 53.5-120 mm), with a median diameter of 10 mm (IQR, 8-12 mm). The sandwich graft technique<sup>15</sup> was applied in four patients (Fig 1). The reversed (periscope) CG technique<sup>9</sup> was used in six patients; one of whom was part of the sandwich technique.

Intentional sacrifice of aortic side branches by overstenting was part of the procedure in 18 patients: 10 left subclavian arteries (LSAs), seven celiac trunks, and one right renal artery.

**Statistical methods.** Data are presented as numbers, percentages, medians, and IQRs. Kaplan-Meier estimate was used to construct outcome curves. IBM SPSS 20 software (IBM Corp, Armonk, NY) was used for these analyses.

**Ethical approval.** The Ethical Advisory Board approved the study, and informed consent was obtained from all patients. No human identity or privacy was involved, and the treatment provided to this cohort of patients was the standard care of our department.



**Fig 1.** A mycotic thoracoabdominal aneurysm was managed with the sandwich technique and chimney grafts (CGs) to the superior mesenteric artery (SMA), right renal artery (RRA), and left renal artery (LRA). The celiac trunk was embolized. **A**, Intraoperative angiography shows patent SMA and renal CGs. **B**, Follow-up (FU) computed tomography (CT) angiography (CTA) shows obliterated aneurysm with three open CGs. No reinfection or other complications were seen during 3 years of FU. **C**, A three-dimensional reconstructed CT scan illustrates the positions of the three CGs between the proximal thoracic and inner abdominal aortic stent grafts. The white arrows point to the distal end of the proximal thoracic stent graft.

## RESULTS

**Early findings.** The 30-day mortality was 14% (n = 4), and all deaths were in emergency cases. Three of these patients received CGs to the supra-aortic vessels (two in the LCCA and one in the LSA), and one patient had CG in the superior mesenteric artery (SMA). Two of the early deaths were hemodynamically unstable patients with ruptures; one was 81 years old and had a complicated type B dissection with irreversible visceral ischemia despite a functioning periscope graft. The fourth patient died of cardiac failure on day 14.

The median hospital stay was 7 days (IQR, 4-17 days), including any subsequent stay at other departments during the same admission.

The primary technical success rate, according to the reporting standards for TEVAR,<sup>14</sup> was 86% (25 of 29). One patient who was operated on for a ruptured thoracoabdominal aneurysm with the sandwich technique required retrograde stenting of the kinked SMA-chimney via a laparotomy and extension of the aortic stent graft for an EL-I. The implantation of one of her renal CGs had failed. This patient subsequently died of multiple late complications although her CGs remained patent. Another patient with patent CGs also required laparotomy for a guidewire perforation of the SMA. Two patients had continued EL-I that required open arch reconstruction (n = 1) and coil-embolization (n = 1). The secondary technical success was 97% (28 of 29). One patient was excluded, as aforementioned, because the attempted CG implantation failed.

Primary EL-I occurred in three patients (10%). All were related to supra-aortic CGs in the brachiocephalic trunk (Table III). Two of the primary EL-I were evident on the final operative angiography. One was successfully coil-embolized on postoperative day 5 (Fig 2). Another minor leak was detected on postoperative day 2 and was successfully sealed with a transthoracic thrombin injection. However, this patient died 45 days later of esophageal perforation, possibly caused by iatrogenic trauma during transesophageal echocardiography or, alternatively, due to esophageal erosion from the adjacent large aneurysm. Onyx (ev3 Endovascular, Inc. Plymouth, Minn) embolization of the chimney gutters failed in the third primary EL-I. This patient underwent open aortic arch reconstruction.

**Midterm to long-term results.** The median FU for the entire cohort was 2 years (IQR, 0.6-3.8 years), 2.5 years (IQR, 1-4 years) for 30-day survivors, and 3.5 years (IQR, 1.9-6.4 years) for those patients who were still alive. No patients were lost to FU. There were two

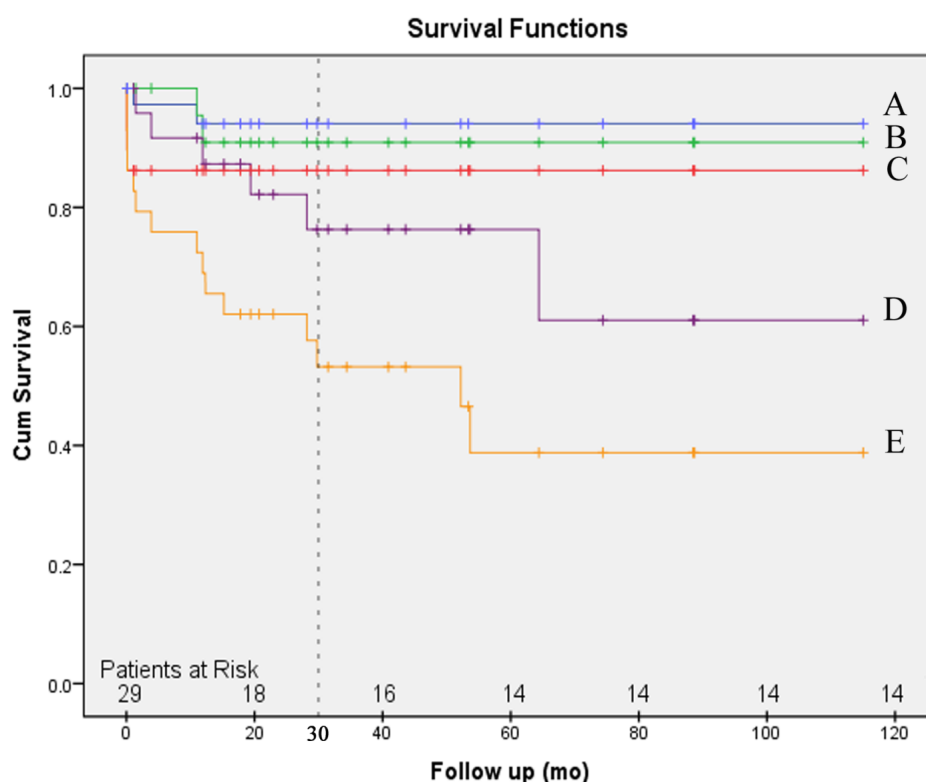


**Fig 2.** Transverse and sagittal views of three consecutive computed tomography angiographies (CTAs) demonstrate the aortic arch with a contained rupture of a pseudoaneurysm (arrows) with hematoma (arrowheads) that was treated with thoracic endovascular aortic repair (TEVAR), chimney to the brachiocephalic trunk, and a carotid-to-carotid bypass. The left subclavian artery (LSA) was sacrificed. **A**, Preoperative CTA with the ruptured pseudoaneurysm. **B**, Proximal type I endoleak (EL-I), seen as continued opacification of the pseudoaneurysm (arrow) on postoperative day 4. **C**, The leak was successfully coiled, and the pseudoaneurysm was obliterated, with complete resorption of the hematoma seen on CT at the 2-year follow-up (FU).

chimney-related deaths (7%) and six procedure-related deaths (21%). The all-cause mortality rate at the latest time (30 postoperative months), when the standard error was <10%, was 12 of 29 (41%; Fig 3). Survival curves are presented in Fig 3. Patient survival at the first, second, and third year was 69% (20 of 29), 62% (18 of 29), and 55% (16 of 29), respectively, and the overall survival was 48% (14 of 29).

The two chimney-related deaths occurred >11 months. The first patient died of a late complication (bleeding, ischemia, infection, and multiorgan failure) resulting from a

guidewire perforation of a peripheral SMA branch during the index operation. The other patient died of intestinal ischemia (according to the autopsy findings) and multiple organ failure 3 days after an open arch reconstruction to seal a chimney-related secondary EL-I (Fig 4).



**Fig 3.** Twenty-nine patients with complex aortic lesions were urgently treated with the chimney graft (CG) technique and thoracic endovascular aortic repair (TEVAR). The Kaplan-Meier outcome curves estimate the freedom from CG occlusion (*A*), chimney-related mortality (*B*), 30-day mortality (*C*), type I endoleak (EL-I) (*D*), and all-cause mortality (*E*).

Three patients (10%) had a secondary proximal EL-I. The first patient had a type B dissection combined with pseudocoarctation of the aorta. He was treated with TEVAR, CG to the LCCA, and left carotid-to-subclavian bypass. A computed tomography angiography

(CTA) 2 months after the intervention revealed a proximal EL-I that was watched for 1.5 years until a significant aortic dilatation (10 mm) was noted. Restenting of the LCCA reduced the leak but did not seal it completely. The temptation of further coiling was resisted because of the risk of cerebral embolization. The EL-I persisted for another 1.5 years, until the patient was advised to undergo open conversion, which he refused. Since then, the EL-I sealed spontaneously, and the patient is doing well in his fifth postoperative year.

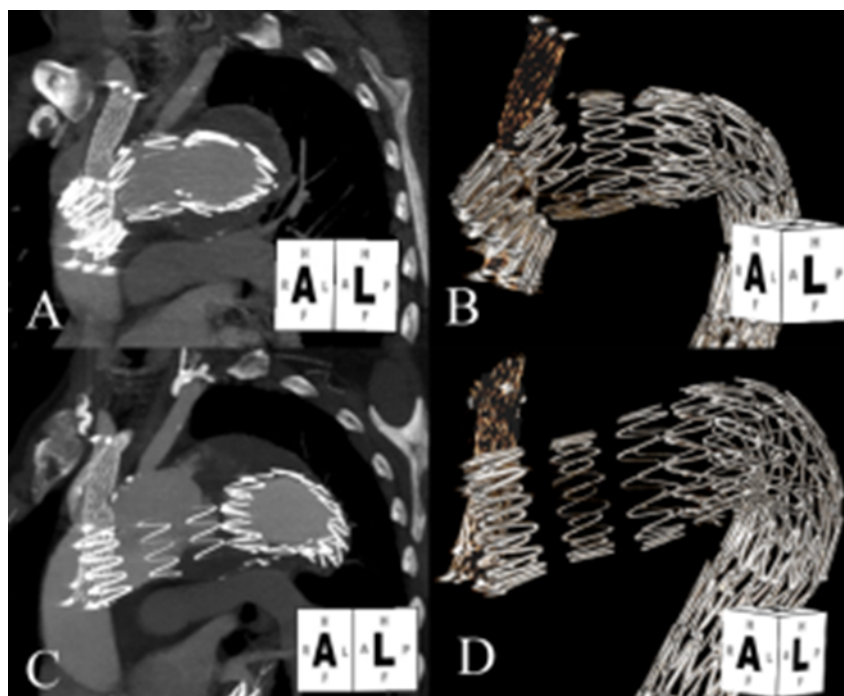
The second patient (Fig 4) presented with a type B dissection with a severely compromised true lumen. She was treated urgently with TEVAR, CG to the brachiocephalic trunk, and carotid-to-carotid bypass. On postoperative day 2, a pre-existing abdominal aortic aneurysm ruptured and EVAR was performed. The proximal EL-I was noted at 8 months and was associated with a 9-mm increase in sac diameter. She was observed for another 4 months before she underwent open arch reconstruction with an interposition graft to replace the CG in the brachiocephalic trunk. Postoperatively, her vital signs deteriorated rapidly, and she died on postoperative day 3 of multiorgan failure, possibly due to colon ischemia (according to the autopsy findings).

The third patient presented with a ruptured arch aneurysm and underwent acute TEVAR with CG to the LCCA and sacrifice of the LSA. An EL-I was identified 5 months postoperatively. The aneurysm sac diameter decreased by 4 mm (from 58 to 54 mm) at 12 months, and no further intervention was undertaken. After 20 months, the sac remained stable although the EL-I persisted.

Sacrifice of the celiac trunk (n = 7) or the LSA (n = 10) was well tolerated, except by one patient with a sacrificed LSA who developed transient paraparesis, which was reversed by



spinal drainage. The patient with a sacrificed renal artery developed a progressive rise in serum creatinine that ultimately led to chronic renal failure.



**Fig 4.** One of the secondary type I endoleak (EL-I) patients was a 63-year-old woman who presented with extensive aortic dissection and distal ischemia due to an acutely compromised true lumen. **A** and **B**, She was operated on urgently with thoracic endovascular aortic repair (TEVAR) and chimney graft (CG) to the brachiocephalic trunk. **C**, After 8 months, an EL-I occurred due to **(D)** distal migration of the main aortic stent graft relative to the CG. The patient was observed for another 4 months before she was converted to open arch reconstruction, but died on postoperative day 3 of acute intestinal ischemia and multiorgan failure.

Secondary patency of the CGs was 98%. One renal CG occluded (Table III), and one SMA CG was significantly stenosed and restented. The aneurysm sac shrank in 17 of 25 patients (68%), and the general outcome was considered favorable in 18 (62%). Serum creatinine remained stable or decreased in 16 of 26 patients (62%). However, it increased in three of the four patients with renal CGs, including the patient with one sacrificed renal artery and another patient with a crushed renal CG, which became occluded.

Seven patients (24%) required chimney-related reinterventions (Table IV), and five reinterventions were successful. The median interval between the index procedure and the first chimney-related reintervention was 5 days (IQR, 1-356 days), and the median number of reinterventions was one (IQR, 1-3). The indications for reinterventions were primary EL-I (n = 3), secondary EL-I (n = 2), the aforementioned bleeding in an SMA due to a guidewire perforation, and bleeding in another SMA due to erosion by a kinked stent. The reinterventions involved coil embolization (n = 2; Fig 2), Onyx embolization (n = 1), transthoracic thrombin embolization (n = 1), restenting of the CG (n = 2), and laparotomy after unsuccessful restenting (n = 1). The Onyx embolization failed, and the patient required open arch reconstruction.

## **DISCUSSION**

This study focuses specifically on the feasibility, safety, and midterm to long-term durability of the CG technique in urgent and complex thoracic lesions in high-risk patients. Not surprisingly, the late overall mortality of this cohort was significant, reaching 52% at 9 years. Although this seems discouraging, it is not entirely different from reports of other groups of aortic patients, such as those patients who were treated with a fenestrated abdominal stent graft.<sup>16</sup> However, the 30-day mortality in our complex and high-risk group of thoracic cases was merely 14%, which highlights the minimally invasive nature and technical feasibility of this type of treatment. Furthermore, the secondary patency was 98%, and only two late deaths were attributable to the CG technique itself, suggesting a promising long-term durability of the CGs. Considering all this, the CG technique for complex lesions of the thoracic aorta in high-risk patients seems encouraging.

**Table IV.** Chimney graft (CG)-related reinterventions among 29 patients who were treated with the CG technique and thoracic endovascular aortic repair (TEVAR) for urgent and complex aortic lesions

<i>Pat ien t</i>	<i>Chimney branches</i>	<i>Time to reinterventio n (d)</i>	<i>Indication for reintervention</i>	<i>Type of reintervention</i>	<i>Nr of reinterv entions</i>	<i>Success of reinterven tion (y, n)</i>	<i>Cause of failure</i>
1	BT	5	EL-I-early -BT	Coil-embolization of distal SMA branch and Laparotomy x2	1	y	
2	BT	356	EL-I-late-BT	Converted to OR	1	n	Persistent EL-I
3	BT, LCCA	13	EL-I-early-BT	Onyx embolization and converted to OR	2	y	
4	BT, LCCA	2	EL-I-early-BT	Embolization with Transthoracic thrombin injection	1	y	
5	LCCA	531	EL-I-late-LCCA	chimney restenting	1	y	
6	CT,SMA,L RA	1	Bleeding-internal	Laparotomy x3	3	n	Persistent bleeding, death after a month
7	RRA,LRA, SMA	1	Bleeding of distal SMA branch	coil-embolization and Laparotomy x2	3	y	

*BT, Brachiocephalic trunk; CT, celiac trunk; EL-I, type I endoleak; LCCA, left common carotid artery; LRA, left renal artery; OR, open repair; RRA, right renal artery; SMA, superior mesenteric artery.*

TEVAR is an important alternative to OR, particularly in the increasing elderly population, which tolerates open surgery poorly.<sup>1,17,18</sup> However, not all thoracic aortic patients with a high risk for OR are good candidates for standard TEVAR. Fenestrated or branched TEVAR is

often not applicable,<sup>5,11</sup> or there may not be time to wait for a customized graft because a large proportion of TEVAR cases are emergencies.<sup>2,7</sup> The CG technique offers an opportunity to treat such patients without delay. It allows proximal or distal extension of the main aortic endograft in patients with inadequate landing zones. Furthermore, the CG technique may improve the conformability between the main stent graft and a gothic arch.<sup>19</sup>

The results of CGs used in the urgent setting have encouraged several investigators to use this technology also as a primary therapeutic option for elective cases.<sup>5-7</sup>

The risk of EL-I has been a major concern with the CG technique since its introduction. Previous studies reported various frequencies of EL-I ranging from 0% to 50%.<sup>6,7,11,12,18,20</sup> EL-I was present in 21% (10% primary and 10% secondary EL-I) of our patients. The main reason for the wide range is probably different inclusion criteria, length of the CGs, and obtained sealing zone. We used relatively long CGs, with a median length of 90 mm (Supplementary Table, online only). A small sample-size and varying diagnostic sensitivity or image interpretation may also explain the wide range of reported ELs.

Among the 41 implanted CGs, 7 were in the brachiocephalic trunks, 13 in the LCCA, 4 in the LSA, and 9 in the SMA (Table III); however, the brachiocephalic trunk was the only source of all primary plus one secondary EL-I (4 of 6 [67%]). Complications associated with CG stenting of a brachiocephalic trunk seems to be frequent (four of seven [57%]). A recent meta-analysis reported that 44% of complications were attributed to CGs in the brachiocephalic trunk.<sup>21</sup> Its alignment with the ascending aorta (straight course), large diameter, and proximity to the heart (with higher pressure, increased arterial wall movement, and less sealing zone) could be postulated as parts of the underlying cause. Compared with that, it is notable that the longest five FU periods (range, 5.3- 9.5 years) in this cohort were for

patients with a CG in the LCCA (n = 4) or LSA (n = 1). All of them are still alive and without a related complaint.

An EL-I needs not to be a major complication. Two of the primary EL-I were treated promptly and were successfully sealed, one with coils (Fig 2) and the other with thrombin. However, the third primary EL-I that we attempted to embolize with Onyx 2 weeks postoperatively eventually had to undergo open arch repair. Other investigators have suggested that high-flow EL-I should be sealed promptly.<sup>20</sup>

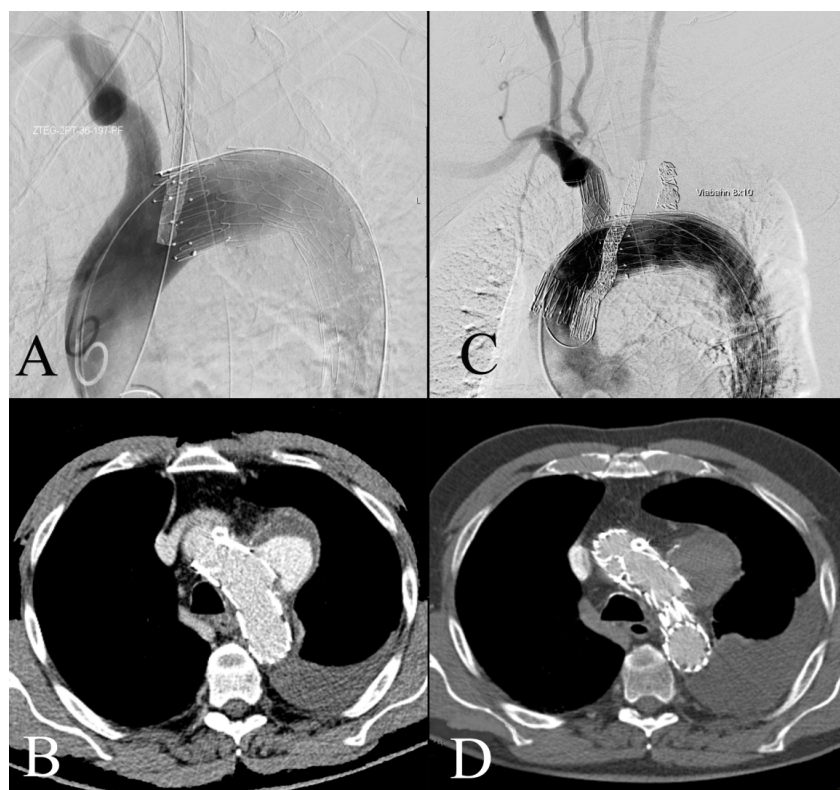
The three secondary EL-I were managed less urgently. One was observed for 1.5 years before it was successfully sealed by restenting. Since then, it has been observed for another 4 years without evidence of recurrence. The second patient was managed conservatively for 1 year until she underwent open arch repair and died 3 days postoperatively. The third patient remains well, with a stable sac diameter, after 2 years of conservative management.

The limited number of cases does not allow us to define which EL-I may safely be treated conservatively, but that none of the patients ruptured during conservative management of a secondary EL-I is noteworthy.

Can we predict a secondary EL-I? The normal aorta dilates with age,<sup>22</sup> and there is a tendency of the aneurysmal neck to dilate after EVAR,<sup>23</sup> particularly if the neck is large. Furthermore, we observed that one patient was taking prednisolone and methotrexate for autoimmune disease. Steroids and some chemotherapeutic agents are known to affect the collagen of the arterial wall, potentially causing additional dilatation of the sealing zone.<sup>24,25</sup>

The third potential factor for EL-I that we observed was distal migration of the main aortic stent graft. Traditionally, most CGs are short and are only used to allow an aortic stent graft to protrude just beyond the orifice of a vital aortic side branch.<sup>26</sup> The overlap between the CG and the aortic stent graft is thereby short and sensitive to any dislocation or dilation of the

components. It follows that the corresponding gutters are short and poorly suited to provide a seal. Fig 4 illustrates a case of a short overlap between the aortic stent graft and the CG where a minor distal migration disrupted the seal and caused a secondary EL-I. It seems that CGs need to be significantly longer to allow a longer sealing zone with longer gutters and less tendency for leakage. A greater portion of the aorta should probably be used to provide a seal in the arch. Indeed, we have been able to seal a leaking arch stent graft by extending it into the ascending aorta (Fig 5).



**Fig 5.** A 75-year-old man presented with a ruptured arch aneurysm. **A**, The implanted chimney graft (CG) to the left common carotid artery (LCCA) was too short to seal the aneurysm, and **(B)** a proximal type I endoleak (EL-I) was seen on the immediate postoperative computed tomography angiography (CTA). **C**, The aortic stent graft and the CG were subsequently extended into the ascending aorta, adding another CG in the brachiocephalic trunk. **D**, The final CTA demonstrates successful exclusion of the sac without recurrence for >2 years of follow-up (FU).

Different subclassifications of EL-I have been suggested.<sup>10,11,20,27</sup> Each type may have a different etiology and require another therapeutic approach.<sup>18,20,27,28</sup> A subclassification based on postoperative timing and flow rate seems to be management oriented. A primary high-flow EL-I requires prompt reintervention, whereas a secondary low-flow EL-I may perhaps seal spontaneously under watchful conservative management. However, there is yet no standardized definition of low-flow vs high-flow EL. It remains a subjective estimation based on contrast appearance in the arterial-phase vs late-phase CTA.<sup>20</sup> The midterm to long-term patency rate of the CGs was as aforementioned 98%, which reflects a satisfactory durability of this technique. This high patency rate has also been reported by other investigators<sup>11,18</sup> and is fully comparable to competing technologies such as the fenestrated and branched stent grafts.<sup>16</sup> The patency of CGs may depend on several factors, such as the length, diameter, and type of the stent used, in addition to the coagulation profile of the blood.<sup>6,20</sup> Statistical analysis with more patients is required to confirm this hypothesis.

Any arch surgery, open or endovascular, is associated with a significant risk for stroke. Stroke occurred in only one patient in our series. This patient presented as an emergency with a ruptured arch aneurysm and was hemodynamically unstable. He had a stenosed LCCA but, unfortunately, he also had a concomitant unrecognized occlusion of the right internal carotid artery. Urgent temporary overstenting of the LCCA stabilized the patient but caused a fatal stroke before the LCCA was revascularized by a CG. Similar experience has been reported earlier<sup>17</sup> and may emphasize the importance of including the cerebral vessels in the preoperative CTA.

This study has some limitations. More patients with longer FU are needed to allow a statistical analysis that would clarify the influence of each stent characteristic on the results. We still do not know if the type (bare or covered, self-expanding or balloon expandable), length, and diameter of the CGs affect the outcome. Our results are also affected by the high

comorbidity of the patients and complications that were not related to the CG technique. A randomized study seems difficult to perform, and neither the indication nor the operative technique has been standardized.

## CONCLUSIONS

The present results with a 30-day mortality of 14% in a high-risk cohort of urgent patients indicate a possible future applicability of the CG technique in the thoracic aorta. The analysis also confirms an acceptable midterm to long-term durability and safety of the thoracic CGs with a 7% chimney-related mortality. This suggests that the CG technique may even become an alternative for certain elective cases. Secondary proximal ELs were infrequent and seem preventable. Further experimental research and more patients with longer FU are required to define the role of CG technology.



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**Supplementary Table (online only).** The distribution, dimension, and patency of 41 chimney grafts (CGs) that were used with thoracic endovascular aortic repair (TEVAR) in 29 patients with urgent and complex aortic lesions

<i>Stents</i>	<i>Brachiocephalic trunk</i>	<i>Left common carotid artery</i>	<i>Left subclavian artery</i>	<i>Celiac trunk</i>	<i>Superior mesenteric artery</i>	<i>Left renal artery</i>	<i>Right renal artery</i>	<i>Total</i>
Stents/CGs	14/7	20/13	10/4	3/1	19/9	12/4	5/3	83/41
Self-expanding	6	3	0	1	4	3	2	19(46%)
Balloon expandable	1	6	0	0	2	0	0	9(22%)
Combined	0	4	4	0	3	1	1	13(32%)
Bare stent	3	5	3	0	3	0	0	14(34%)
Covered stent	2	4	0	0	3	2	1	12(29%)
Combined	2	4	1	1	3	2	2	15(37%)
No. of stents per CG								
1 stent	2	6	0	0	2	1	0	11(27%)
2 stent	3	7	3	0	4	2	1	20(49%)
3 stent	2	0	0	1	3	1	1	8(19%)
4 stent	0	0	1	0	0	1	0	2(5%)
No. of CGs per patient								
Single	3	9	4	0	5	0	0	21(51%)

Double	4	4	0	0	0	0	0	8(20%)
Triple	0	0	0	1	4	4	3	12(29%)
Chimney dimensions (median) (mm)								
Estimated length <sup>a</sup>	80	40	70	174	92	97	92	90
Diameter	14	9	12	8	10	7	7	10

*BT*, Brachiocephalic trunk; *CT*, celiac trunk; *LCCA*, left common carotid artery; *LRA*, left renal artery; *LSA*, left subclavian artery; *RRA*, right renal artery; *SMA*, superior mesenteric artery.

<sup>a</sup>Most of the chimneys included multiple stents. The length of each chimney was estimated, taking into consideration the overlap between its various components/stents.