Advanced Endovascular Approaches in the Management of Challenging Proximal Aortic Neck Anatomy: Traditional Endografts and the Snorkel Technique

Jon G. Quatromoni, MD, MSTR¹ Ksenia Orlova, MD, PhD¹ Paul J. Foley III, MD¹

¹ Division of Vascular Surgery, Department of Surgery, University of Pennsylvania School of Medicine, Philadelphia, Pennsylvania

Semin Intervent Radiol 2015;32:289–303

Address for correspondence Paul J. Foley III, MD, Division of Vascular Surgery, Department of Surgery, University of Pennsylvania School of Medicine, 4 Silverstein Building, Hospital of the University of Pennsylvania, 3400 Spruce Street, Philadelphia, PA 19104 (e-mail: foileyp@uphs.upenn.edu).

Abstract

Keywords

- endovascular aneurysm repair
- juxtarenal and pararenal aortic aneurysms
- snorkel technique
- chimney technique
- endoleak
- interventional radiology

Advances in endovascular technology, and access to this technology, have significantly changed the field of vascular surgery. Nowhere is this more apparent than in the treatment of abdominal aortic aneurysms (AAAs), in which endovascular aneurysm repair (EVAR) has replaced the traditional open surgical approach in patients with suitable anatomy. However, approximately one-third of patients presenting with AAAs are deemed ineligible for standard EVAR because of anatomic constraints, the majority of which involve the proximal aneurysmal neck. To overcome these challenges, a bevy of endovascular approaches have been developed to either enhance stent graft fixation at the proximal neck or extend the proximal landing zone to allow adequate apposition to the aortic wall and thus aneurysm exclusion. This article is composed of two sections that together address new endovascular approaches for treating aortic aneurysms with difficult proximal neck anatomy. The first section will explore advancements in the traditional EVAR approach for hostile neck anatomy that maximize the use of the native proximal landing zone; the second section will discuss a technique that was developed to extend the native proximal landing zone and maintain perfusion to vital aortic branches using common, off-the-shelf components: the snorkel technique. While the techniques presented differ in terms of approach, the available clinical data, albeit limited, support the notion that they may both have roles in the treatment algorithm for patients with challenging proximal neck anatomy.

Objectives: Upon completion of this article, the reader will be able to discuss the concept of hostile aortic aneurysm neck morphology, the rationale and available alternative endovascular approaches to difficult proximal necks, and the clinical data for and against these techniques.

Accreditation: This activity has been planned and implemented in accordance with the Essential Areas and Policies of the Accreditation Council for Continuing Medical Education (ACCME) through the joint providership

of Tufts University School of Medicine (TUSM) and Thieme Medical Publishers, New York. TUSM is accredited by the ACCME to provide continuing medical education for physicians.

Credit: Tufts University School of Medicine designates this journal-based CME activity for a maximum of **1 AMA PRA Category 1 Credit™**. Physicians should claim only the credit commensurate with the extent of their participation in the activity.

Issue Theme Endovascular Aortic Aneurysm Repair; Guest Editor, S. William Stavropoulos, MD, FSIR

Copyright © 2015 by Thieme Medical Publishers, Inc., 333 Seventh Avenue, New York, NY 10001, USA.
Tel: +1(212) 584-4662.

DOI <http://dx.doi.org/10.1055/s-0035-1558825>.
ISSN 0739-9529.

Endovascular aneurysm repair (EVAR) has revolutionized the management of abdominal aortic aneurysms (AAAs) in patients with suitable anatomy.^{1,2} The overall success of endovascular repair depends largely upon adequate proximal fixation of the endograft to the aortic wall, which serves to prevent type Ia endoleaks and stent migration.³ Aortic neck anatomy is the most pivotal morphological characteristic of aortic aneurysms to determine successful sealing of the endoprosthesis.^{3,4} Numerous studies report on specific aortic neck features that negatively impact proper stent placement and subsequently lead to poor patient outcomes. These include aortic neck angulation,^{4,5} long aortic neck length,^{6–8} large diameter of the proximal seal zone,⁹ percentage of calcified neck circumference,¹⁰ intramural thrombus,⁴ and conical aortic neck morphology.^{11,12}

Strict anatomic criteria are provided by each stent graft manufacturer in the instructions for use (IFU). With an increasing trend toward utilization of endovascular, as opposed to open surgical, techniques for the treatment of infrarenal aneurysmal disease, many interventionalists are treating an increasing number of patients with unfavorable or “hostile” neck anatomy. Although some anatomic features are deemed more important in the prevention of type IA endoleaks (►Fig. 1) and stent graft migration, a “hostile aortic neck” is defined as one in which the anatomy is beyond the scope of the specific IFU.¹¹ Specifically, most manufacturers define favorable neck anatomy by an aortic neck diameter of equal to or less than 32 mm, aortic neck length of at least 10 to 15 mm, and aortic angulation of equal to or less than 60 degrees (►Fig. 2, ►Table 1). Difficult or hostile aortic neck anatomy is defined as neck length of less than 15 mm, neck angulation greater than 60 degrees, greater than 50% calcification of the aortic circumference, and a reverse taper morphology.¹¹

Based on these criteria, ~20 to 30% of patients presenting with AAAs are deemed ineligible for standard EVAR because

Fig. 1 Intraoperative angiogram of a type I (proximal) endoleak (arrow).

Fig. 2 Determining the suitability of EVAR for AAAs. Diagram depicting the measurements necessary for EVAR planning. a, aortic neck diameter; b, aortic neck diameter 15 mm distal to the lowest renal artery; c, aortic neck length; d, aneurysm diameter; e, lowest renal artery to aortic bifurcation length; f, aortic bifurcation diameter; g, right common iliac artery diameter; h, left common iliac artery diameter; i, right external iliac artery diameter; j, left external iliac artery diameter; k, lower renal to right internal iliac artery length; l, lower renal to left internal iliac artery length; m, right iliac artery sealing lengths; n, left iliac artery sealing lengths. †, aortic neck angle (in red). (Reprinted, with minor adaptations, with permission from Goshima S, Kanematsu M, Kondo H, et al. Preoperative planning for endovascular aortic repair of abdominal aortic aneurysms: feasibility of nonenhanced MR angiography versus contrast-enhanced CT angiography. *Radiology* 2013;267(3):948–955.)

of anatomic constraints, the majority of which involve the proximal neck.^{13,14} Fenestrated stent grafting can provide an effective endovascular solution for some of these patients but there is currently no off-the-shelf availability, and the only U.S. Food and Drug Administration (FDA)–approved device (Zenith Fenestrated, Cook Medical, Bloomington, IN) can take 6 to 8 weeks to manufacture. In these patients, open

Table 1 Comparing favorable and unfavorable characteristics of aneurysms for endovascular repair

Favorable characteristics	Hostile characteristics	Corresponding measurement
Aortic neck diameter < 30 mm	Aortic neck diameter > 30 mm	a, b
Aortic neck length > 15 mm	Aortic neck length < 15 mm	c
Aortic angulation < 60 degrees	Aortic angulation > 60 degrees	‡
Aortic calcification < 50% total circumference	Aortic calcification > 50% total circumference	N/A
Absence of reverse taper morphology	Reverse taper morphology	N/A
<50% circumferential thrombus	>50% circumferential thrombus	N/A

Note: a, b, c and ‡ refer to the corresponding measurements outlined in Fig. 2. Please refer to Fig. 2 for corresponding measurement information.

AAA repair remains the gold standard but not all patients are suitable candidates for this type of surgery. To expand the pool of patients treated with traditional endovascular repair, methods for utilizing commercially available endografts have been developed.

This article is composed of two sections that together address these new endovascular approaches for treating aortic aneurysms with difficult proximal neck anatomy. The first section will explore advanced EVAR for difficult proximal necks using the traditional stent graft approach. The second section will discuss the snorkel technique for challenging aortic anatomy. Fenestrated stent grafting, both with the FDA-approved custom device and with operator-modified endografts, is beyond the scope of this chapter and will be discussed in more detail elsewhere in this issue of *Seminars in Interventional Radiology*. While the techniques presented in this manuscript may differ in terms of approach, they share the same goal of overcoming challenging proximal neck anatomy.

The Use of Traditional Stent Grafts in Patients with Unfavorable Aortic Neck Anatomy

Several recent studies have analyzed specific hostile aortic neck parameters that contribute to early and late complications following EVAR. Aburahma et al prospectively examined 258 patients who underwent EVAR using AneuRx (21%, Medtronic, Minneapolis, MN), Excluder (48%, W.L. Gore, Flagstaff, AZ), Zenith (19%, Cook Medical), and Talent (1%, Medtronic) grafts.¹³ Patients were stratified into two groups: favorable neck anatomy (FNA) and hostile neck anatomy (HNA). HNA was defined as having one or more of the following characteristics: neck angle greater than 60 degrees, neck length less than 10 mm, diameter greater than 29 mm, circumferential calcification greater than 50%, thrombus circumference greater than 50%, and reverse taper defined by gradual neck dilation more than 2 mm within the first 10 mm following the most caudal renal artery (►Fig. 2). Of the 258 patients, 63% were classified as having HNA. Overall, the perioperative complication rate was significantly higher in the HNA group when compared with FNA (16 vs. 3%, $p = 0.0027$). This included a higher rate of perioperative death (3 vs. 0%, $p = \text{NS}$), graft thrombosis or acute limb ischemia (7 vs. 0%, $p = 0.0148$), proximal type I early intra-

operative endoleak (23 vs. 9%, $p = 0.02$), and the need for early reintervention (28 vs. 9%, $p = 0.0006$). The rates for late reintervention, freedom from late type I endoleaks, graft patency, and overall survival at 1, 2, and 3 years, however, were similar between the two groups. This study highlighted that utilization of EVAR in patients with HNA results in an increased rate of early complications but does not seem to negatively impact long-term outcomes.

In 2013, Antoniou et al published a meta-analysis of EVAR outcomes in patients having hostile and favorable aortic neck anatomy.¹¹ This analysis included all the studies published to date that specifically stratified patient outcomes based on the morphologic characteristic of the aortic neck. In total, seven observational studies were identified comprising 1,559 patients. Among this patient group, 714 patients had HNA and 845 patients had favorable aortic neck anatomy. HNA was defined by aortic neck dimensions that were outside specific IFU as indicated by the stent graft manufacturers. Five different endografts were deployed in the majority of patients, including Endurant, Zenith, AneuRx, Excluder, and Talent. The majority of patients in all studies underwent graft surveillance with computed tomographic (CT) angiography. Multiple outcome parameters were assessed, addressing both early and late end points. Early outcome measures included technical success, perioperative morbidity and mortality, and incidence of type Ia endoleaks in the immediate operative and perioperative periods and perioperative morbidity and mortality as well as need for intervention within 30 days of repair. Late primary end points consisted of aneurysm-related mortality, need for follow-up intervention, and incidence of type Ia endoleaks during the follow-up period. After the data were pooled, four end points were found to have statistically significant differences between patients with hostile and favorable aortic neck anatomy (►Table 2). Patients with HNA required more adjunctive procedures (OR 3.1; 95% CI [1.9–4.9]) to achieve adequate proximal seal zones. Additionally, this patient population had a higher rate of 30-day morbidity (OR 2.3; 95% CI [1.0–5.1]). Overall, the presence of unfavorable neck morphology significantly increased the risk of both type Ia endoleaks (OR 4.6; 95% CI [1.4–14.6]) and aneurysm-related death within a 1-year follow-up (OR 9.4; 95% CI [1.6–55.1]). While this meta-analysis highlighted several unfavorable outcomes in patients with hostile aortic neck anatomy, it also revealed similar

Table 2 Summary of meta-analysis outcomes

Outcome measure	Meta-analysis model	OR (95% CI)	p-Value	p for publication bias
Adjunctive procedures	Fixed effects	3.1 (1.9–5.0)	<0.001	0.810
Technical success	Fixed effects	0.1 (0.0–1.3)	0.081	N/A
30-d mortality	Fixed effects	1.0 (0.4–2.5)	0.962	0.391
30-d morbidity	Fixed effects	2.3 (1.0–5.1)	0.043	N/A
Reintervention within 30 d	Fixed effects	1.1 (0.1–12.2)	0.949	N/A
Type I endoleak within 30 d	Fixed effects	2.5 (0.6–10.8)	0.232	0.574
Type I endoleak at 1 y	Fixed effects	4.6 (1.4–14.6)	0.01	N/A
Reinterventions at 1 y	Fixed effects	1.0 (0.5–1.8)	0.974	0.539
Aneurysm-related mortality at 1 y	Fixed effects	9.4 (1.6–55.1)	0.013	0.251

Abbreviations: CI, confidence interval; N/A, not applicable; OR, odds ratio.

Source: Reprinted with permission from Antoniou et al.¹¹

results with respect to technical success, 30-day mortality, and reintervention within 30 days and 1 year.

Some of the discrepancy between EVAR outcomes in patients with unfavorable neck anatomy is secondary to lack of consensus regarding the relative importance of various anatomical characteristics. Jordan et al recently published an outcome-based study that aimed at identifying criteria that most accurately predicted EVAR failure secondary to aortic neck anatomy.¹⁵ The study group consisted of 221 patients in the Aneurysm Treatment using the Heli-Fx Aortic Securement System Global Registry (ANCHOR), a population of aortic aneurysm patients with challenging neck anatomy and high incidence of EVAR failure defined by the occurrence of type Ia endoleak in the immediate postoperative period or during follow-up. This dataset provided an opportunity to conduct rigorous statistical analysis of specific aortic anatomic factors that are predictive of poor outcomes following EVAR. Of all the aortic characteristics, neck diameter, aneurysm sac diameter, and conical shape of the aortic neck were found to be predictive of endoleak in a statistically significant manner. Conversely, increased aortic neck length, funnel-shaped neck, and neck mural thrombus were found to be protective of type Ia endoleak. Of these, three variables were identified as independent predictors of type Ia endoleak: larger aortic neck diameter at the lowest renal artery (threshold = 26 mm, $p = 0.02$) and shorter aortic neck length (threshold = 17 mm, $p = 0.17$) were predictive of EVAR failure, while the presence of mural neck thrombus was found to be protective (threshold = 11 degrees of circumferential thrombus, $p = 0.001$). This study provides concrete anatomical characteristics that can be utilized in the risk stratification of patients with challenging aortic neck anatomy when EVAR is planned.

Advanced Endovascular Approaches to the Hostile Aortic Neck

While inadequate initial apposition of the endograft to the aortic neck may result in the presence of an immediate postdeployment endoleak, subsequent longitudinal migration of the graft can also lead to failure of aneurysm exclusion

and late device failure.¹⁶ Short aortic neck length has been shown to be an independent risk factor for stent migration, with every millimeter increase in neck length resulting in a 5.8% decrease in subsequent caudal movement at 2.5-year follow-up.¹⁷ Active fixation of the aortic stent graft (infrarenal or suprarenal) has been incorporated into many of these devices in an effort to reduce migration. A recent single-institution retrospective review of 1,379 EVARs identified 84 patients with straight short infrarenal necks (defined as < 15 mm).¹⁸ Of these, 60 patients (71.4%) were treated with a device providing active infrarenal fixation, while the other 24 (28.6%) were treated with a device providing active suprarenal fixation. There were no significant differences between the two groups with respect to the presence of proximal type I endoleaks at 30 days and 1 year. No migration of greater than 0.5 cm was identified in either group over the follow-up period, suggesting that the location of the active fixation relative to the renal arteries makes no difference in outcomes.

Devices are currently available to treat short infrarenal neck anatomy. The Endurant stent graft (Medtronic) is approved to treat an infrarenal aortic neck length of at least 10 mm. Recently, the Ovation stent graft (Trivascular Inc, Santa Rosa, CA) was approved by the U.S. FDA to treat a minimum aortic neck length of 7 mm. The Ovation stent graft applies a unique proximal sealing ring to the main body that is filled with polymer during deployment to achieve a conformable seal to the infrarenal aortic neck (► Fig. 3). This device also has active fixation with suprarenal anchors and comes in a low-profile delivery system. Early data for this device in a recently published trial showed promise, with no core laboratory-identified proximal type I endoleaks at 30 days or 1 year.¹⁹ It should be noted that only 24 patients in this cohort (15%) had infrarenal aortic neck lengths ≤ 10 mm. However, the authors did report in a post hoc analysis that patients with challenging anatomy had similar outcomes to patients with traditional anatomy with respect to major adverse events at 30 days and AAA-related secondary interventions. All patients with challenging anatomy achieved procedural success. Long-term data with this device in patients with short

Fig. 3 The ovation abdominal stent graft system. (a) Image of deployed device. (b) Schematic of deployed device with key design characteristics labeled. (c) Preoperative angiogram shows the aneurysm. (d) A postoperative angiogram demonstrates successful aneurysm exclusion with the Ovation Abdominal Stent Graft System. (Reprinted with permission from Mehta et al.¹⁹)

infrarenal aortic necks are necessary before drawing any solid conclusions.

Precise positioning of the stent graft in the infrarenal aorta when dealing with a short neck can be technically demanding. When attempting to create a seal in an aneurysm with a short infrarenal neck, taking advantage of every millimeter of aorta is crucial. Both the Zenith (Cook Medical) and the Endurant (Medtronic) stent grafts are similar in that they have the suprarenal stents housed in a top cap. This allows partial deployment of the main body with the ability to reposition slightly before completing the release of the top cap. The latest iteration of the Excluder device (W.L. Gore) has a mechanism in the delivery system (C3) that allows the main body to be reconstrained; this allows the operator to reposition the proximal main body, which can be very useful for difficult anatomy such as short necks or severe angulation.²⁰

Several advanced techniques with the Excluder device have also been described for challenging anatomy.²¹ The “endowedge” technique involves angioplasty balloons that are delivered via the brachial arteries and inflated in the renal arteries at the time of main body deployment. This allows the operator to be able to push the proximal edge of the aortic

stent graft as close as possible to the renal artery orifices without covering them. The “kilt” technique is useful for dumbbell-shaped aortic neck morphology and involves the initial deployment of an aortic cuff just below the proximal seal zone, with subsequent deployment of the main body inside the cuff and at level of the desired seal zone.²²

Deployment of large balloon-expandable stents such as the Palmaz XL (Cordis, Bridgewater Township, NJ) can be useful before or after deployment of the aortic stent graft. Similar to the kilt technique, initial deployment of a Palmaz stent in the infrarenal neck has been described to prevent migration of the aortic stent graft in patients with HNA.²¹ Adjunctive Palmaz stenting of the proximal neck is also well described both prophylactically in patients with HNA and to treat proximal type I endoleaks in similar patients.^{23,24}

Investigators have also developed adjunct endovascular devices that can be utilized in conjunction with traditional commercially available stent grafts. The Heli-Fx Aortic EndoAnchor is the first endovascular staple device to obtain FDA approval for clinical use (► Fig. 4).^{25–28} The EndoAnchor is “helical-like” metal alloy that is 4.5 mm in length, 3.0 mm in diameter, and 0.5 mm in width that is stapled through the

Fig. 4 The FDA-approved EndoAnchor for proximal fixation. (a) The Aptus HeliFix EndoAnchor, with its size relative to the U.S. dime. (b) The EndoAnchor system, which can be used for transmural fixation of an aortic stent graft to the aortic wall at its landing zones. (c) Fluoroscopic view of EndoAnchor delivery with applicator at aortic wall. The EndoAnchor is seen penetrating the aortic wall (open black arrow) and endoguide (radiopaque band on tip—arrowhead) providing angulation and “push” to keep applicator in proper apposition and tension for EndoAnchor delivery. (Reprinted with permission from Deaton²⁷ and Buck et al.²⁸)

deployed endograft, thereby augmenting the opposition with the aortic wall by mimicking a surgically sutured anastomosis.²⁷ Preliminary experiments in human cadavers using EndoAnchors in conjunction with six conventional endografts

lead to a dramatic increase in the displacement force required to dislocate the stent.²⁶ The safety and feasibility of the EndoAnchor has been investigated in two clinical trials, STAPLE-1 and STAPLE-2, with promising results.^{27,29} A recent prospective multicenter study by Jordan et al evaluated the therapeutic potential of EndoAnchors used in 319 patients who were undergoing EVAR for infrarenal AAA disease.³⁰ The primary treatment arm (242 patients, 75.9%) consisted of patients who had EndoAnchors implanted at the time of the original EVAR procedure at the discretion of the operator based on challenging aortic neck anatomy or the presence of an immediate postdeployment type Ia endoleak. The revision arm of this cohort included patients who had previous EVAR surgery that was complicated by late type Ia endoleak. The authors demonstrated high procedural success rates, defined as freedom from type Ia endoleak on completion angiography, in both the treatment (90%) and revision (80%) arms. Importantly, none of the patients developed a new type Ia endoleak or stent graft migration during a mean follow-up of 9.3 months.

Severe angulation of the aortic neck (> 60 degrees between the infrarenal aortic neck and the long axis of the AAA) has been shown to be associated with the development of both early and late type I endoleaks.⁷ Aortic neck angulation can be very difficult to overcome in terms of both device delivery and deployment. Techniques have been described to facilitate deployment of standard endografts in aneurysms with angulated necks, such as bending of the stiff access wire to allow for better alignment of the delivery system with the aneurysm.²¹ Advancing a large sheath via the contralateral iliac artery directly into the aortic neck with or without brachiofemoral wire access for the main body delivery can be used to straighten out neck angulation and allow for more precise deployment.³¹

The Aorfix device (Lombard Medical Technologies, Oxfordshire, UK) was recently approved by the FDA to treat aneurysms with aortic neck angulation of up to 90 degrees. The device utilizes circular nitinol stent technology that makes it highly conformable in aortas with angulated anatomy. This is the only currently available device that is FDA-approved to treat aneurysms with such significant angulation. In the PYTHAGORAS trial, 151 patients with neck angles ≥ 60 degrees (high angle), and 67 patients with neck angles <60 degrees (low angle), were treated with the Aorfix device. There was no significant difference between the low and high angle groups with respect to type I/III endoleaks at 1 year (0 vs. 1.9%, $p = 1.0$) and graft migration (0 vs. 1.9%, $p = 1.0$).³² A similar experience has been reported from Europe³³ in a small nonrandomized prospective trial. In 30 patients with highly angulated necks (median neck angulation 81.2 degrees) treated with the Aorfix device, there were no proximal type I endoleaks reported at 30 days and one proximal type I endoleak (3.3%) reported at 1 year. The small number of patients in this study limits the interpretation of the data, but when combined with the early results of the PYTHAGORAS trial the outcomes appear promising. Long-term follow-up is needed to validate the performance of the Aorfix device in highly angulated aortic neck anatomy.

The first commercially available fenestrated device (Zenith Fenestrated, Cook Medical) was approved by the FDA in 2012 for short infrarenal necks and juxtarenal AAAs (JAAs). One major drawback to the Zenith Fenestrated device is that the manufacturing time can take several weeks at least, making it not useful for urgent or emergent cases. To overcome this problem, physician-modified endografts have been described with good outcomes.³⁴ Simply put, this approach involves unsheathing of commercially available aortic stent grafts on a back-table, creation of fenestrations to suit the patients anatomy, re-sheathing of the graft, and subsequent implantation. Although the technique has been successful in treating patients with challenging anatomy in urgent/emergent situations, it should be remembered that this is an off-label use of devices, is technically challenging, and the long-term implications on the durability of the standard device once it has been altered are unknown. Other techniques have been described in an effort to use commercially available off-the-shelf devices for challenging aortic anatomy. These include open debranching,^{35,36} homemade fenestrations,³⁷ and alternative endovascular techniques. Furthermore, advances in technology have led to the generation of standard stent grafts that are more capable of successfully excluding complex aneurysmal morphology.

Snorkel-EVAR

One prominent endovascular strategy, termed Snorkel (Sn)-EVAR and “Chimney”-EVAR, provides solutions for aneurysms with anatomically inadequate proximal and distal landing zones, respectively. Based on the same concept, this technique involves the placement of single or multiple, uncovered or covered, stents parallel to the main aortic stent graft to extend the sealing zones while maintaining side branch patency. In the Sn-EVAR³⁸ technique, the conduit(s) travels in the cranial direction, with the proximal portion extending beyond the proximal edge of the main aortic stent graft³⁹ (► Fig. 5). This technique has been used to maintain flow in all of the supra-aortic vessels, the visceral and renal arteries, and the internal iliac arteries.⁴⁰

Technical Approach to Sn-EVAR

While numerous variations exist, in its simplest form, the main strategy for an elective snorkel procedure comprises six key stages.⁴¹ In order for these stages to proceed smoothly, significant preprocedural planning must occur. Key elements of the preprocedural planning phase and the basic procedural steps for the snorkel technique are reviewed here.

As an advanced endovascular procedure, a significant effort must be made prior to the execution of the procedure, estimated at 1 to 2 hours for experienced operators.⁴² These efforts are aimed at determining the optimal proximal landing zone that will provide a durable seal and exclude flow to the aneurysm sac; the size, placement, and three-dimensional alignment of snorkel endografts; and the appropriateness of upper extremity vessels to use for access. The length of the proximal landing zone will dictate which renal and/or visceral vessels require coverage, and thus the number of snorkel grafts (SGs) required. While controversial, most groups plan for a minimum length of 10- to 20-mm sealing zone.^{43,44} Once this is established, SG specifications can be determined from the measurements of (1) the distance from the proximal aspect of aortic stent graft to the origin of the branch vessel, (2) the length of the SG extending distal to the proximal edge of the aortic stent graft, (3) the length and diameter of the landing zone within the target vessel, and (4) the predicted curvature and orientation of the SG relative to the aortic graft.⁴¹ Lastly, the access vessels for the aortic stent graft and SGs require selection. A standard snorkel procedure for juxtarenal or pararenal AAAs involves bilateral femoral artery retrograde access for the aortic stent graft, and unilateral or bilateral upper extremity access for the SGs (depends on the number). Typically, the axillary or brachial arteries are selected to provide antegrade access for cannulation of the target snorkel vessels. Once these issues have been addressed, attention can be turned toward the procedure itself.

In the first stage of the procedure, access to the target snorkel vessels is obtained in an antegrade fashion from above (cranially). This involves initial cannulation with a flexible guidewire, which is then exchanged for a stiff 0.035" guidewire through an appropriate catheter (e.g., 5 French). Once

Fig. 5 The configuration of endografts in Sn-EVAR for pararenal AAAs. (a) Schematic representation of snorkel grafts in bilateral renal arteries. These are abutted by the main aortic stent graft, which excludes the aneurysm sac. (b) Aortic cross-section demonstrating the relationship between SGs and the main aortic stent graft, with the resultant creation of potential gutters. (Reprinted with permission from Wilson et al.⁶²)

the stiff wire is in place, a 6–8 French sheath is advanced into the target vessel. In the second stage, a bare stent or covered stent (either balloon mounted or self-expanding) is advanced through the sheath and within the target vessel to a position that leaves the proximal edge of the SG ~5 mm above the anticipated proximal landing position of the main aortic stent graft. The third stage involves delivering and deploying the aortic stent graft across the SG sheaths. Once the aortic graft is deployed, the fourth stage requires the adjustment and deployment of the SG once the desired position is achieved. Before moving on to the fifth stage, an angiogram is performed through the SG sheath to confirm patency of all components. In the fifth stage, the kissing balloon technique is utilized to simultaneously balloon the SG(s) and main aortic stent graft, to optimize the seal both between the endografts and with the aortic wall. In the last stage, the final angiogram is performed through the aortic stent graft; guide-wire access in the SGs is maintained until this angiogram is reviewed, thus allowing for re-ballooning or SG extension if necessary (►Fig. 6). The major deviation from this protocol involves the deployment of the SGs *before* the main aortic stent graft in stage 3; as opposed to the staged procedure just described, this allows for synchronous ballooning of the aortic stent graft and SG.^{45,46}

Unfortunately, no consensus exists for many of the technical details regarding this procedure. Much of the disagreement centers around how much to oversize the aortic stent graft, the combinations of different brands of aortic stent grafts and SGs, the use of covered versus uncovered stents as SGs, the use of balloon-expandable versus self-expanding stents, and the maximum number of SGs that can be placed without compromising the integrity of the procedure. The paucity of strong clinical data from comparative trials is likely due to the emergence of fenestrated endograft technology, which has secured many of the resources that would have supported such trials if it were the only approach available.

The Snorkel Technique: Review of the Clinical Data

While EVAR has largely replaced open surgical repair, ~20 to 30% of patients with AAAs are unsuitable for standard infrarenal repair, primarily due to challenging proximal neck morphology.^{13,14} It is thought that for 60 to 70% of patients

with challenging anatomy, the proximal neck is less than the optimal 10 to 15 mm or is an unsuitable landing zone.^{4,42,47} The importance of anatomical limitations around the proximal neck is reflected in the finding that proximal neck adequacy and endograft seal zone are long-term predictors of outcome and success post-EVAR.^{42,48} The snorkel strategy was developed to address this limitation in an endovascular manner.

First described by Greenberg et al in 2003, the snorkel technique consists of placing parallel stents, or stent grafts, adjacent to the aortic endograft main body to maintain perfusion to renal and/or visceral branches after aneurysm exclusion.^{38,49} In so doing, a proximal suprarenal sealing zone could be obtained using standard EVAR grafts.⁵⁰ While first developed as an adjunctive salvage procedure to treat unintentionally covered branch vessels,³⁸ it has slowly evolved into its current role as a primary treatment option for complex aortic diseases, including juxtarenal, suprarenal, and thoracoabdominal aneurysms.^{44,46,51}

Most of the clinical data on the snorkel technique for AAAs involve case reports,^{52–56} retrospective case series, and comparative trials (open surgical repair vs. snorkel, or more recently, snorkel vs. fenestrated grafts).^{40,43,46,49–51,57–60} Recently, as the published clinical experience has accumulated, higher quality evidence in the form of systematic reviews and meta-analyses^{61–63} has been published that attempts to draw overarching conclusions from the cumulative experience up to this point. The clinical data from all case series, comparative trials, and systematic reviews will be reviewed briefly below and are summarized in ►Tables 3 and 4.

The first case series for Sn-EVAR were published in 2008.^{40,59} Ohrlander's series consisted of six patients, five of whom were performed in the urgent setting. Eleven total SGs were implanted (renal arteries or superior mesenteric artery [SMA]); while there was one case of postoperative renal insufficiency requiring hemodialysis (HD) and one case of mesenteric ischemia requiring intervention, the 30-day mortality rate was 0% and no late complications were reported (e.g., endoleak, SG occlusion) over a mean follow-up of 2.4 months.⁴⁰ Larzon's series was slightly larger, reporting on 14 total implanted SGs (renal arteries only) in 13 patients, almost half of which were performed urgently (6 of 13). All

Fig. 6 Intraoperative angiogram depicting snorkel grafts into the superior mesenteric artery and both renal arteries. (a) Presnorkel aortogram showing juxtarenal aneurysm. (b) Kissing balloon technique (arrows) during snorkel EVAR. (c) Completion aortogram after snorkel EVAR.

Table 3 Baseline characteristics from studies on snorkel grafts for AAA repair

Reference	Year	No. of patients	Mean AAA size (mm)	No. of snorkels	Mean follow-up (mo) ^a	Immediate patency ^b	Elective:urgent repair
Donas et al ⁴⁶	2010	72	63.9	127	14.1 (1–29)	127 (100)	72:0
Lee et al ⁴⁹	2012	28	64.8	56	9.6 (3–25)	55 (98)	28:0
Bruen et al ⁴⁴	2011	21	66.8	37	12	36 (97)	21:0
Coscas et al ⁴³	2011	16	62	26	10.7 (3–25)	25 (96)	16:0
Larzon et al ⁵⁹	2008	13	65	14	17 (1–40) ^c	14 (100)	7:6
Hiramoto et al ⁵⁸	2009	8	60	8	N/A	8 (100)	8:0
Ohrlander et al ⁴⁰	2008	6	N/A	11	3.3 (N/A) ^c	11 (100)	1:5
Moulakakis et al ⁶¹	2012	3	N/A	4	8.6 (N/A)	4 (100)	2:1
Pecoraro et al ⁶⁰	2011	3	89.3	8	10 (3–24) ^c	7 (88)	0:3
Ducasse et al ⁵⁰	2013	22	58.5	22	18 (7–35)	22 (100)	18:4
Scali et al ⁵¹	2014	41	65	76	18.2 (1.4–41.5) ^c	74 (97)	30:11
Banno et al ⁶⁵	2014	38	66	60	12 (0–48)	59 (98)	32:6

Abbreviation: N/A, data not available.

Source: Reprinted, with minor adaptations, with permission from Wilson et al.⁶²

^aValues in parentheses are ranges.

^bValues in parentheses are percentages.

^cData provided for combined cohort of abdominal aortic aneurysm (AA) and thoracic or thoracoabdominal aortic aneurysms as authors did not distinguish between repairs.

SGs remained patent throughout the immediate and late follow-up periods (mean 17 months). Two patients (15.3%) died after 6 months from causes not related to aneurysm. Two (15.3%) distal type I endoleaks, one intraoperatively and one on follow-up, were intervened upon with success; two (15.3%) type II endoleaks were noted in follow-up and left untreated. Other pertinent complications included femoral artery thrombosis requiring graft interposition, retroperitoneal hematoma from renal artery injury, and new-onset renal insufficiency (none requiring HD).⁵⁹

In 2009, Hiramoto et al published a series of eight patients with electively treated AAAs who received unilateral renal SGs.⁵⁸ One intraoperative (12.5%) and two postoperative (25%) (at 1 month) type I endoleaks were reported; all were successfully resolved with either intervention (former) or watchful waiting (latter). Two (25%) type 2 endoleaks, but no stent graft migration or type I endoleak, occurred after 1 month of follow-up. One patient (12.5%) required a renal stent to treat a procedure-related renal artery dissection. SG patency was 100% and mortality 0% throughout the study period (mean follow-up 12.5 months) for this patient sample.

In 2011, Coscas et al described their 10-year experience with elective Sn-EVAR in 16 high-risk patients (4 emergent, 12 elective) with JAAs.⁴³ Twenty-six SGs were placed (SMA and renal arteries) with an average follow-up of 10.5 months. Four patients (25%) had intraoperative type I endoleaks, three of which resolved with angioplasty. Thirty-day mortality was 12.5%, attributable to one case of hemorrhagic shock of unknown etiology and another case after multiorgan failure secondary to mesenteric stent thrombosis. Other major postoperative complications included one stroke (6.3%), two retroperitoneal hematomas requiring intervention (12.5%),

two iliac dissections (12.5%), and two segmental renal infarctions (12.5%). Two patients (12.5%) had minor early type Ia endoleaks, one (6.3%) had a persistent late type Ia endoleak, and another (6.3%) had a late type V endoleak. Three patients (18.8%) developed chronic renal insufficiency, two of whom required HD. SG patency during follow-up was 96%.

In the same year, Pecoraro et al reported on a series of nine patients who underwent a combination of Sn-EVAR and Pe-EVAR for ruptured thoracoabdominal aortic aneurysms (TAAAs), pararenal AAAs, or infrarenal AAAs. A total of 24 vessels (11 renals and 13 visceral arteries) were reperfused using 17 periscope (or reverse-chimney grafts) and 7 SGs. The 30-day mortality rate was 11%, attributable to one patient death from multiorgan failure. Intraoperatively, one patient's (11.1%) right kidney was sacrificed after a stent graft became dislocated and access could not be re-obtained. Two patients (22.2%) had early type I endoleaks requiring treatment prior to discharge. Through a mean follow-up period of 10 months, three additional patients (33.3%) had died from unrelated causes and all SG grafts remained patent. One low-flow type III endoleak (11.1%) and one persistent type Ib endoleak (11.1%) were noted on follow-up imaging and did not require reintervention.⁶⁰

Lee et al published their extensive Sn-EVAR experience for JAAs at Stanford in 2012, which included 56 SGs (renal arteries, celiac artery, and SMA) in 28 patients with a follow-up of 10.7 months.⁴⁹ All patients were treated on an elective basis. The 30-day mortality rate was 7%, attributable to one death from sepsis related to pneumonia and another from a right hemispheric stroke. Other major complications included perinephric hematomas (7.1%), chronic renal failure requiring HD (3.6%), iliac artery injury requiring endoconduit

Table 4 Complications and outcomes after snorkel grafts for AAA repair

Reference	30-d mortality	Early (<30-d) type I endoleak	SG patency at 6 mo	Renal dysfunction ^a	30-d complications	Further deaths	Late complications
Donas et al ⁴⁶	0 (0)	6 (8)	126 of 127 (99.2)	0	1 MI, 1 perinephric hematoma (n)	0	6 type II/III endoleaks (u), 1 type I endoleak (t)
Lee et al ⁴⁹	2 (7)	2 (7)	54 of 56 (96)	2 (1)	2 perinephric hematomas (n), 1 MI, 1 plexus injury	1	4 type II/III endoleaks (u), 1 type III endoleak (t)
Bruen et al ⁴⁴	1 (5)	1 (5)	35 of 37 (95)	5 (0)	3 false aneurysms (u), 2 strokes, 1 MI	2	3 type II endoleaks (u), 1 PTA of stent
Coscas et al ⁴³	2 (13)	2 (13)	25 of 26 (96)	3 (2)	2 hematomas (1t, 1u), 2 dissections (1t, 1u), 1 stroke	2	1 type V endoleak (u)
Larzon et al ^{59, b}	0 (0)	1 (8)	14 (100)	3 (0)	1 MI, 1 hematoma (t), 1 femoral thrombosis (t)	2	2 type II endoleaks (u), 1 type I endoleak (t)
Hiramoto et al ⁵⁸	0 (0)	1 (13)	8 (100)	0	2 type II leaks (u), 1 renal artery dissection (t)	0	0
Ohrlander et al ⁴⁰	0 (0)	1 (17)	11 (100)	1 (1)	1 mesenteric ischemia (t)	1	0
Moulakakis et al ⁶¹	0 (0)	1 (33)	4 (100)	0	0	0	0
Pecoraro et al ⁶⁰	1 (33)	1 (33)	7 of 8 (88)	0	0	0	1 type I endoleak (t)
Ducasse et al ⁵⁰	1 (4.5)	1 (4.5)	22 (100)	2 (0)	1 death from decompensated CHF, 1 hemispheric stroke, 1 iliac leg occlusion (t)	0	3 type II endoleaks (u)
Scali et al ^{51, b}	2 (5)	1 (2.5)	66 of 76 (88)	8 (2)	1 type I endoleak (t), 2 strokes, 3 MIs/arrhythmia, 3 gastrointestinal, 1 spinal cord ischemia, 5 access vessel injuries (t)	5	3 type Ia endoleaks (1t, 2 awaiting t), 4 type II endoleaks, 3 indeterminate type endoleaks, 1 SG thrombosis (t)
Banno et al ⁶⁵	3 (7.9)	2 (5.3)	57 of 60 (95)	7 (1)	1 stroke, 1 ARDS, 1 SG stenosis (t), 2 bowel ischemia (u), 3 access vessel complications (2t, 1u), 3 retroperitoneal/intra-abdominal hematomas (2t, 1u), 1 limb stenosis (t)	4	2 type II (1t, 1u) and 2 type I endoleaks (1t, 1u), 1 access complication (t), 1 SG stenosis (t)

Abbreviations: MI, myocardial infarction; PTA, percutaneous transluminal angioplasty; t, treated; u, untreated.

Source: Reprinted, with minor adaptations, with permission from Wilson et al.⁶²

Note: Values are percentages unless otherwise indicated.

^aValues in parentheses indicate number of patients on hemodialysis.^bData provided for combined cohort of abdominal aortic aneurysm (AA) and thoracic or thoracoabdominal aortic aneurysms as authors did not distinguish between repairs.

placement (3.6%), and brachial nerve injury (3.6%). At 1-month follow-up, one SG was found to be occluded and 25% of patients demonstrated an endoleak (two type I, three type II, and two type III endoleaks); only the type III endoleak (3.6%) was intervened upon. All type I and type III endoleaks resolved without intervention by 6 months. As a follow-up study, this same group subsequently compared, in a prospective manner, the early learning curves (patient characteristics, imaging, and operative techniques for the first 15 patients treated by each operator) of Sn-EVAR and fenestrated EVAR (Fe-EVAR) at their institution.⁴² In a population of similar demographics and AAA morphology, total operative times were similar (3–4 hours), but more time was allocated to fluoroscopy in Fe-EVAR because of differing strategies of renal premarking; this did, however, lead to a lower volume of contrast used in these cases. The only other major difference was a higher rate of iliac conduits needed in Fe-EVAR cases because of the larger delivery systems involved. Otherwise, perioperative complications, short-term renal patency rates, and evidence of acute kidney injury (AKI) were similar between both groups. The authors concluded that the overall early experiences were similar, with a significant portion of the learning curve involving the planning of branch vessel cannulation.⁴²

Donas's group in Germany has been particularly active in reporting their experience with Sn-EVAR. In 2010, they published their initial experience in 15 patients with pararenal AAAs who received a total of 15 balloon-expandable SGs (renal arteries only).⁴⁶ Their initial technical success was 100%. No type I endoleaks and only one (6.7%) early type II endoleak occurred (which was not intervened upon). No type I endoleaks were discovered during follow-up (mean 6.8 months); however, one left renal SG (6.7%) was found to be occluded on postoperative day 45, which required thrombectomy and iliorenal bypass without long-term renal insufficiency or HD. Subsequently, these authors compared balloon-expandable stent grafts (46 SGs in 37 patients; renal arteries and SMA) to self-expanding stent grafts (81 SGs in 35 patients; renal arteries, SMA, and celiac artery) used in snorkel procedures.⁴⁵ In addition to the previously noted occluded left renal balloon-expandable SG in their 2010 study, one other SG from the same arm required angioplasty for high grade in-stent stenosis at 12 months. No such occlusions occurred in the self-expandable group (97.8 vs. 100% patency rates, respectively). While five type Ia perioperative endoleaks were noted in the self-expandable group compared with one in the balloon-expandable group (14.2 vs. 2.1%, $p > 0.05$), only two of these six persisted (both from the self-expandable arm) with only one requiring intervention at 1 year for aneurysm sac enlargement. The rates of type II endoleaks were not significantly different between the balloon- and self-expandable stent groups (4.3 vs. 11.4%, respectively). No patients developed persistent renal insufficiency, and the perioperative and long-term mortality rates were 0% for both arms.

In another study, Donas et al evaluated 40 patients (73 SGs) from multiple centers out to 2 years postoperatively. Of three patients (7.5%) with perioperative type Ia endoleaks, two

required intervention. Seven patients (17.5%) developed type II endoleaks. Two of the 73 SGs (2.7%) occluded over this time span, both of which required intervention. Ten percent of patients demonstrated sac progression, the causes of which were one type Ia endoleak, two type II endoleaks, and one type V endoleak.⁶⁴

Ducasse et al recently reported promising results using Sn-EVAR for 22 patients (22 SGs; renal arteries only) with JAAs. The technical success rate was 100% and only one type Ia endoleak was noted, which resolved by 3 months postoperatively. The 30-day mortality rate was 4.5%, attributable to one patient with preoperative congestive heart failure who died from acute decompensated heart failure postoperatively. The other major postoperative complication was a hemispheric stroke. Two patients (9.2%) developed AKI postoperatively, which eventually resolved without requiring HD. All SGs remained patent on follow-up (median 18 months) without evidence of aneurysm sac enlargement.⁵⁰

Another recent series, from Scali et al, has suggested that perioperative complications and major adverse events (SG occlusion and endoleak) may occur at a higher rate than previously reported.⁵¹ This study included 41 patients with complex AAAs treated with 76 SGs (renal arteries, SMA, celiac artery) for a variety of indications. Technical success rate was 93%: one patient had a type Ia endoleak at case conclusion, while another had a target vessel that was unable to be cannulated. Seven patients (17%) had intraoperative complications, consisting of graft maldeployment ($n = 2$) and access vessel injury requiring repair ($n = 5$). Eight patients (20%) had major postoperative complications, including two strokes, two cases of renal failure requiring HD, and one case of spinal cord ischemia. Thirty-day mortality and in-hospital mortality rates were 5 and 7%, respectively. Median follow-up was 18 months, during which 15% of the aneurysms progressed in size and 32% of patients were noted to have an endoleak. One patient (2.4%) underwent open surgical revision. Patency of all SGs was 83 and 85% at 1 and 3 years, respectively. Most importantly, the estimated survival rates for all patients at 1 and 5 years were 85 and 65%, respectively. Given these results, the authors concluded that while Sn-EVAR can be completed with a high degree of success, the high prevalence of postoperative complications necessitates a cautious approach to elective Sn-EVAR, with continued comparison of long-term outcomes to Fe-EVAR and open repair to determine the best approach.⁵¹

Two groups have compared outcomes from Sn-EVAR to those of other treatment modalities (fenestrated or open), with surprisingly similar results.^{44,65} Bruen et al compared 21 patients undergoing Sn-EVAR for juxtarenal or suprarenal AAAs to an anatomically matched cohort undergoing open surgical repair.⁴⁴ Despite a significantly higher number of patients with chronic renal insufficiency and oxygen dependence, there was no difference in 30-day mortality rate (4.8% for each arm) or net decline in glomerular filtration rate (GFR) at 12 months (11.1 vs. 10.4 for Sn-EVAR vs. open, respectively). In addition, blood loss was less, length of stay shorter, and percentage of patients requiring HD lower (0 vs. 2) in the Sn-EVAR group. Other Sn-EVAR-specific complications were a

type Ia endoleak that was seen at 30 days but that resolved by 6 months, one asymptomatic SMA SG occlusion, and one SMA SG partial compression. Only one patient's aneurysm sac (6%) enlarged in size due to a type II endoleak that spontaneously resolved; only one other type II endoleak was noted during follow-up. The other comparative trial investigated Sn-EVAR and Fe-EVARs at the same institution for pararenal and JAAs. The arms of the study were not matched, as 6 of the 30 (20%) Sn-EVARs were emergent, while all 80 Fe-EVARs were elective. Nevertheless, the fenestrated and snorkel groups compared favorably, without any statistically significant differences in 30-day mortality rates (6.3 vs. 7.9%, respectively), moderate-severe complication rates (27 vs. 39%), estimated survival rate at 2 years (77 vs. 71%), reintervention-free rates (71 vs. 72%), primary patency rate of reconstructed vessels (91 vs. 87%), or sac shrinkage greater than 5 mm (43 vs. 30%).⁶⁵ Thus, the authors concluded that Sn-EVAR may represent an attractive option for patients not suitable for Fe-EVAR.

Multiple systematic reviews have been published in an attempt to summarize the clinical Sn-EVAR experience thus far. Moulakakis et al included all Sn-EVAR series up through 2011, which included 93 patients with 134 SGs (renal arteries, SMA, celiac artery) for juxtarenal, pararenal, and thoracoabdominal aneurysms.⁶¹ Twenty-four percent of cases were urgent. Thirty-day mortality rate was 4.3%. Most patients received one or two SGs (67 and 34%), but a small subset of patients received three or four SGs. Fourteen percent of patients developed a type I endoleak, three of which were detected and treated intraoperatively. In the postoperative period, 10 type I endoleaks were detected, 4 of which were intervened upon. During a mean follow-up of 9 months, 97.8% of SGs remained patent; two renal and one SMA SG occluded. The rate of other postoperative complications were 11.8% renal function impairment, 2.1% myocardial infarction, and 3.2% stroke.

Another group extended this analysis to include all snorkel studies through 2012 with similar results. A total of 176 patients with JAAs were included, with a total of 302 SGs placed (90% were urgent). Thirteen patients (7.4%) had a type I endoleak on completion angiography, which increased to 18 (10.2%) at the first postoperative CT. Five of these type I endoleaks required further intervention, while two had persistent endoleaks at the end of follow-up. Thirty-day mortality rate was similar at 3.4%. Eleven patients (6.3%) developed AKI postoperatively, four (2.3%) of which required HD; six additional patients (3.5%) developed perinephric hematomas (3.4%). During the average follow-up of 12 months, three SGs occluded; the 6-month visceral branch patency rate was 97.7%. Seventeen late endoleaks occurred: 13 were type II or III, 3 were type I, and 1 was type V; all type I endoleaks and one type III endoleak required reintervention.⁶² Other groups have attempted to compare all data in the literature from Sn-EVAR and Fe-EVAR.⁶³ Sn-EVAR was associated with statistically higher rates of stroke and early proximal type I endoleak compared with Fe-EVAR, with similar rates of 30-day mortality and target vessel patency on follow-up.

The snorkel technique was originally adopted for use in the emergent setting. Since then, as experience with it has grown, it has been applied in the elective setting for the treatment of aneurysms in patients that would otherwise not have been candidates for open surgical repair due to challenging aortic anatomy. However, as the indications for this technique has grown, so too have technical questions regarding its implementation. Currently, the decision to pursue one alternative over another remains largely operator-dependent, resulting from previous experience and personal preference rather than well-founded data. Specifically, questions that remain unanswered include: (1) the use of uncovered versus covered stents to perfuse branch vessels; (2) the use of balloon-expandable as opposed to self-expanding stent grafts; (3) the maximum number of SGs that can be safely deployed adjacent to an aortic stent graft; (4) the sequence of snorkel and main aortic stent graft deployment; (5) the optimal amount of oversizing required of the main aortic stent graft to minimize gutter formation while maximizing seal; and (6) the optimal types and combination of snorkel and aortic stent grafts.

No agreement currently exists regarding the use of covered as opposed to uncovered stents as SGs. Furthermore, no studies have been conducted that compare the performance of either option, thus making data scant; multiple investigators have rationalized the use of one over another based on the clinical context.^{44,49,58} Early in the overall snorkel experience, Hiramoto et al successfully used uncovered stents to extend the proximal landing zone because they had good "trackability, deploy precisely, and provide excellent radial force," as opposed to covered stents, which tended to be "bulkier, stiffer, and more difficult to insert." Furthermore, these authors did not believe there was any advantage in terms of renal artery patency or protection against type I endoleak from covered stents. As Lee et al postulate, this may have been because their selected patient population had a small length of "suitable" neck, that is, a minimum "sealing ring," below the region of overlap of a bare snorkel stent and the main aortic stent graft.⁴⁹ Bruen et al postulated that the presence of this "sealing ring," such as in a funnel-shaped aortic neck, would allow for the use of an uncovered stent.⁴⁴ They further noted that in the absence of such a seal zone, a covered stent would perform better from a seal standpoint. Lee further argued that covered stents extend the allowable seal zone more proximally, right up to the SMA, thus making more challenging JAAs amenable to Sn-EVAR.⁴⁹

Another area of debate revolves around the use of balloon-expandable stents as opposed to self-expanding stents. Balloon-expandable stents are characterized by high radial force and excellent fluoroscopic visibility, both of which contribute to precise placement in target vessels. These devices are also advantageous because of their efficiency: both the deployment and molding occur in one step, negating the additional wire and catheter exchanges associated with a self-expandable snorkel stent.⁴⁹ Self-expandable devices, on the other hand, demonstrate excellent flexibility and kink resistance. These devices can also be placed within balloon-expandable stents to increase their flexibility; however, the drawback to this

technique is that additional metal in target vessel narrows the lumen and predisposes to occlusion.⁴⁶ Similarly, after placing self-expandable stents, some investigators choose to place a balloon-expandable stent within the self-expanding stent in regions that overlap the aortic endograft to ensure a tight seal. It is thought that the flexibility of self-expanding stents may limit gutter leaks due to increased conformity to the aortic wall and main aortic stent graft, as well as prove advantageous in angulated anatomies. As opposed to other topics of debate regarding these techniques, there are actual data to rely on for guidance. A recent comparison between the two demonstrated an increased frequency of type I endoleaks in the self-expanding group, but no other significant differences in terms of technical success or patency during follow-up.⁴⁵ Given all the variables that affect the decision to use one type of stent or another (variations in anatomy, adjacent aortic atherosclerosis, etc.), it is likely that a single approach will not be applicable in all patients.

Surprisingly, the maximum number of vessels that can be safely targeted for the snorkel technique has not been systematically studied.⁶¹ In general, it is presumed that more SGs would compromise the proximal seal and lead to a higher rate of type I endoleaks and aneurysmal sac enlargement. For this reason, many investigators limit the targeted number of vessels to two per patient.⁴⁴ However, this is not a concrete rule, as case reports exist of patients who had all four major visceral and renal branches snorkeled (four total vessels).⁶⁶ Some data do support this notion, as Moulakakis observed a type I endoleak rate of 7.0% in patients with one SG, 15.6% in patients with two SGs, and 100% of patients with four SGs.⁶¹

Other technical details, such as the sequence of snorkel and main aortic stent graft deployment and the optimal amount of oversizing required of the main aortic stent graft component, remain open for debate. While most surgeons prefer to first deploy the main aortic stent graft followed by the SG, this is by no means universal as the other approach has certain advantages (see technical section). Similarly, oversizing the main aortic stent graft is an approach adopted by some,^{42,58,61} but not all.^{44,50} The theoretical benefit of oversizing is that the size of peripheral gutters is minimized because the aortic stent graft better conforms to the SGs, creating strong wall apposition; the converse is that infolding leads to decreased lumen diameter and less radial force.⁶⁷ Operators who do oversize tend to aim for a 20 to 30% oversize. Mathematical models, taking into account the number of SGs, have been created to aid in the determination of the optimal aortic stent graft diameter.⁶²

While one of the advantages of Sn-EVAR is the ability to use most off-the-shelf devices, this may also be considered its "Achilles heel." As described by a systematic review of the literature, a wide variety of main aortic stent grafts (Zenith Flex, Endurant, Excluder, among others) and SGs (Viabahn, Advanta, and iCAST) have been reported with success; the number of possible combinations only increases exponentially when these endografts are mixed and matched. In vitro data have suggested differences among these devices in terms of the associated gutters that form around them and the compression forces they exert.⁶⁷ The device-to-device and

device-to-aortic interactions have been difficult to predict because they depend on multiple factors, from the device (intrinsic qualities and oversizing) to the native vessels (aortic and target branch vessel wall quality, angulation, calcification).⁵¹ Indeed, Scali et al even argue that the interaction between the SG and the aortic device is difficult to predict given the various combination of devices and dynamic physiologic nature of cardiovascular structures.⁵¹ Such variability within the Sn-EVAR literature will make standardized comparisons difficult.

Conclusion

The utilization of available aortic stent grafts to treat aneurysms with challenging anatomy is attractive as it offers previously option-limited patients an opportunity to undergo endovascular repair and the benefits of such an approach. Although the clinical experience with the snorkel technique continues to increase, the overall sample size is still small and the presence of prospective, randomized trials is lacking. Furthermore, the data that are available still do not answer the question about long-term outcomes in this population. While some studies are starting to report on patients 2 years out from these procedures,⁶⁴ the long-term durability and effectiveness of these interventions is still unknown as compared with the wealth of data surrounding standard open surgical repair.² Similarly, the long-term results with traditional infrarenal devices used to treat challenging anatomy are unclear.

Nevertheless, the cumulative available data suggest that this technique leads to high rates of technical success. Impressively, these results were obtained in patients often unsuitable for open repair or standard EVAR based on comorbidities or anatomic factors. Akin to standard EVAR, however, this approach remains encumbered by high rates of postoperative complications such as endoleaks, renal injury, and strokes, among others, which necessitate frequent follow-up and reinterventions.^{41,62} With the impending widespread adoption of fenestrated technology, and the impending arrival of off-the-shelf fenestrated devices, the question of whether or not there will be a role for these techniques is a valid one.

References

- 1 De Bruin JL, Baas AF, Buth J, et al; DREAM Study Group. Long-term outcome of open or endovascular repair of abdominal aortic aneurysm. *N Engl J Med* 2010;362(20):1881-1889
- 2 Greenhalgh RM, Brown LC, Powell JT, Thompson SG, Epstein D, Sculpher MJ; United Kingdom EVAR Trial Investigators. Endovascular versus open repair of abdominal aortic aneurysm. *N Engl J Med* 2010;362(20):1863-1871
- 3 Mohan IV, Laheij RJ, Harris PL; EUROSTAR COLLABORATORS. Risk factors for endoleak and the evidence for stent-graft oversizing in patients undergoing endovascular aneurysm repair. *Eur J Vasc Endovasc Surg* 2001;21(4):344-349
- 4 Carpenter JP, Baum RA, Barker CF, et al. Impact of exclusion criteria on patient selection for endovascular abdominal aortic aneurysm repair. *J Vasc Surg* 2001;34(6):1050-1054

- 5 Sternbergh WC III, Carter G, York JW, Yoselevitz M, Money SR. Aortic neck angulation predicts adverse outcome with endovascular abdominal aortic aneurysm repair. *J Vasc Surg* 2002;35(3):482–486
- 6 Albertini JN, Macierewicz JA, Yusuf SW, Wenham PW, Hopkinson BR. Pathophysiology of proximal perigraft endoleak following endovascular repair of abdominal aortic aneurysms: a study using a flow model. *Eur J Vasc Endovasc Surg* 2001;22(1):53–56
- 7 Hobo R, Kievit J, Leurs LJ, Buth J; EUROSTAR Collaborators. Influence of severe infrarenal aortic neck angulation on complications at the proximal neck following endovascular AAA repair: a EUROSTAR study. *J Endovasc Ther* 2007;14(1):1–11
- 8 Hovsepian DM, Hein AN, Pilgram TK, et al. Endovascular abdominal aortic aneurysm repair in 144 patients: correlation of aneurysm size, proximal aortic neck length, and procedure-related complications. *J Vasc Interv Radiol* 2001;12(12):1373–1382
- 9 Schanzer A, Greenberg RK, Hevelone N, et al. Predictors of abdominal aortic aneurysm sac enlargement after endovascular repair. *Circulation* 2011;123(24):2848–2855
- 10 Sampaio SM, Panneton JM, Mozes G, et al. Aortic neck dilation after endovascular abdominal aortic aneurysm repair: should oversizing be blamed? *Ann Vasc Surg* 2006;20(3):338–345
- 11 Antoniou GA, Georgiadis GS, Antoniou SA, Kuhan G, Murray D. A meta-analysis of outcomes of endovascular abdominal aortic aneurysm repair in patients with hostile and friendly neck anatomy. *J Vasc Surg* 2013;57(2):527–538
- 12 Dillavou ED, Muluk SC, Rhee RY, et al. Does hostile neck anatomy preclude successful endovascular aortic aneurysm repair? *J Vasc Surg* 2003;38(4):657–663
- 13 Aburahma AF, Campbell JE, Mousa AY, et al. Clinical outcomes for hostile versus favorable aortic neck anatomy in endovascular aortic aneurysm repair using modular devices. *J Vasc Surg* 2011;54(1):13–21
- 14 Leurs LJ, Kievit J, Dagnelie PC, Nelemans PJ, Buth J; EUROSTAR Collaborators. Influence of infrarenal neck length on outcome of endovascular abdominal aortic aneurysm repair. *J Endovasc Ther* 2006;13(5):640–648
- 15 Jordan WD Jr, Ouriel K, Mehta M, et al; Aneurysm Treatment using the Heli-FX Aortic Securement System Global Registry (ANCHOR); Aneurysm Treatment using the Heli-FX Aortic Securement System Global Registry ANCHOR. Outcome-based anatomic criteria for defining the hostile aortic neck. *J Vasc Surg* 2015;61(6):1383–1390.e1
- 16 Tonnessen BH, Sternbergh WC III, Money SR. Mid- and long-term device migration after endovascular abdominal aortic aneurysm repair: a comparison of AneuRx and Zenith endografts. *J Vasc Surg* 2005;42(3):392–400, discussion 400–401
- 17 Zarins CK, Bloch DA, Crabtree T, Matsumoto AH, White RA, Fogarty TJ. Stent graft migration after endovascular aneurysm repair: importance of proximal fixation. *J Vasc Surg* 2003;38(6):1264–1272, discussion 1272
- 18 Hager ES, Cho JS, Makaroun MS, et al. Endografts with suprarenal fixation do not perform better than those with infrarenal fixation in the treatment of patients with short straight proximal aortic necks. *J Vasc Surg* 2012;55(5):1242–1246
- 19 Mehta M, Valdés FE, Nolte T, et al; A Pivotal Clinical Study to Evaluate the Safety and Effectiveness of the Ovation Abdominal Stent Graft System Investigators. One-year outcomes from an international study of the Ovation Abdominal Stent Graft System for endovascular aneurysm repair. *J Vasc Surg* 2014;59(1):65–73. e1–e3
- 20 Smeds MR, Jacobs DL, Peterson GJ, Peterson BG. Short-term outcomes of the C3 excluder for patients with abdominal aortic aneurysms and unfavorable proximal aortic seal zones. *Ann Vasc Surg* 2013;27(1):8–15
- 21 Ghouri MA, Dougherty KG, Krajcer Z. Technical tips for endovascular treatment of abdominal aortic aneurysms with challenging infrarenal neck anatomy using the Excluder endoprosthesis. *J Endovasc Ther* 2010;17(6):705–711
- 22 Minion DJ, Yancey A, Patterson DE, Saha S, Endean ED. The endowedge and kilt techniques to achieve additional juxtarenal seal during deployment of the Gore Excluder endoprosthesis. *Ann Vasc Surg* 2006;20(4):472–477
- 23 Cox DE, Jacobs DL, Motaganahalli RL, Wittgen CM, Peterson GJ. Outcomes of endovascular AAA repair in patients with hostile neck anatomy using adjunctive balloon-expandable stents. *Vasc Endovascular Surg* 2006;40(1):35–40
- 24 Farley SM, Rigberg D, Jimenez JC, Moore W, Quinones-Baldrich W. A retrospective review of Palmaz stenting of the aortic neck for endovascular aneurysm repair. *Ann Vasc Surg* 2011;25(6):735–739
- 25 de Vries JP, Schrijver AM, Van den Heuvel DA, Vos JA. Use of endostaples to secure migrated endografts and proximal cuffs after failed endovascular abdominal aortic aneurysm repair. *J Vasc Surg* 2011;54(6):1792–1794
- 26 Melas N, Perdikides T, Saratzis A, Saratzis N, Kiskinis D, Deaton DH. Helical EndoStaples enhance endograft fixation in an experimental model using human cadaveric aortas. *J Vasc Surg* 2012;55(6):1726–1733
- 27 Deaton DH. Improving proximal fixation and seal with the HeliFX Aortic EndoAnchor. *Semin Vasc Surg* 2012;25(4):187–192
- 28 Buck DB, van Herwaarden JA, Schermerhorn ML, Moll FL. Endovascular treatment of abdominal aortic aneurysms. *Nat Rev Cardiol* 2014;11(2):112–123
- 29 Deaton DH, Mehta M, Kasirajan K, et al. The phase I multicenter trial (STAPLE-1) of the Aptus endovascular repair system: results at 6 months and 1 year. *J Vasc Surg* 2009;49(4):851–857, discussion 857–858
- 30 Jordan WD Jr, Mehta M, Varnagy D, et al; Aneurysm Treatment using the Heli-FX Aortic Securement System Global Registry (ANCHOR) Workgroup Members. Results of the ANCHOR prospective, multicenter registry of EndoAnchors for type Ia endoleaks and endograft migration in patients with challenging anatomy. *J Vasc Surg* 2014;60(4):885–92.e2
- 31 Lee JT, Ullery BW, Zarins CK, Olcott C IV, Harris EJ Jr, Dalman RL. EVAR deployment in anatomically challenging necks outside the IFU. *Eur J Vasc Endovasc Surg* 2013;46(1):65–73
- 32 Malas MB, Qazi U, Beck AW, et al. The aorfix AAA endograft in highly angulated aortic necks: performance in the Pythagoras U.S. Clinical Trial. *J Vasc Surg* 2014;60(6):1717–1718
- 33 Weale AR, Balasubramaniam K, Macierewicz J, Hardman J, Horrocks M. Outcome and safety of Aorfix™ stent graft in highly angulated necks - a prospective observational study (arbitrator 2). *Eur J Vasc Endovasc Surg* 2011;41(3):337–343
- 34 Starnes BW. Physician-modified endovascular grafts for the treatment of elective, symptomatic, or ruptured juxtarenal aortic aneurysms. *J Vasc Surg* 2012;56(3):601–607
- 35 Lee WA, Brown MP, Martin TD, Seeger JM, Huber TS. Early results after staged hybrid repair of thoracoabdominal aortic aneurysms. *J Am Coll Surg* 2007;205(3):420–431
- 36 Quinones-Baldrich W, Jimenez JC, DeRubertis B, Moore WS. Combined endovascular and surgical approach (CESA) to thoracoabdominal aortic pathology: A 10-year experience. *J Vasc Surg* 2009;49(5):1125–1134
- 37 Oderich GS, Ricotta JJ II. Modified fenestrated stent grafts: device design, modifications, implantation, and current applications. *Perspect Vasc Surg Endovasc Ther* 2009;21(3):157–167
- 38 Greenberg RK, Clair D, Srivastava S, et al. Should patients with challenging anatomy be offered endovascular aneurysm repair? *J Vasc Surg* 2003;38(5):990–996
- 39 Dias NV, Resch T, Sonesson B, Malina M. Single superior mesenteric artery periscope grafts to facilitate urgent endovascular repair of acute thoracoabdominal aortic pathology. *J Endovasc Ther* 2011;18(5):656–660

- 40 Ohrlander T, Sonesson B, Ivancev K, Resch T, Dias N, Malina M. The chimney graft: a technique for preserving or rescuing aortic branch vessels in stent-graft sealing zones. *J Endovasc Ther* 2008;15(4):427–432
- 41 Patel RP, Katsargyris A, Verhoeven ELG, Adam DJ, Hardman JA. Endovascular aortic aneurysm repair with chimney and snorkel grafts: indications, techniques and results. *Cardiovasc Intervent Radiol* 2013;36(6):1443–1451
- 42 Lee JT, Lee GK, Chandra V, Dalman RL. Comparison of fenestrated endografts and the snorkel/chimney technique. *J Vasc Surg* 2014;60(4):849–856, discussion 856–857
- 43 Coscas R, Kobeiter H, Desgranges P, Becquemin JP. Technical aspects, current indications, and results of chimney grafts for juxtarenal aortic aneurysms. *J Vasc Surg* 2011;53(6):1520–1527
- 44 Bruen KJ, Feezor RJ, Daniels MJ, Beck AW, Lee WA. Endovascular chimney technique versus open repair of juxtarenal and suprarenal aneurysms. *J Vasc Surg* 2011;53(4):895–904, discussion 904–905
- 45 Donas KP, Pecoraro F, Torsello G, et al. Use of covered chimney stents for pararenal aortic pathologies is safe and feasible with excellent patency and low incidence of endoleaks. *J Vasc Surg* 2012;55(3):659–665
- 46 Donas KP, Torsello G, Austermann M, Schwindt A, Troisi N, Pitoulas GA. Use of abdominal chimney grafts is feasible and safe: short-term results. *J Endovasc Ther* 2010;17(5):589–593
- 47 Green RM. Patient selection for endovascular abdominal aortic aneurysm repair. *J Am Coll Surg* 2002;194(1, Suppl):S67–S73
- 48 Chaikof EL, Fillinger MF, Matsumura JS, et al. Identifying and grading factors that modify the outcome of endovascular aortic aneurysm repair. *J Vasc Surg* 2002;35(5):1061–1066
- 49 Lee JT, Greenberg JJ, Dalman RL. Early experience with the snorkel technique for juxtarenal aneurysms. *J Vasc Surg* 2012;55(4):935–946, discussion 945–946
- 50 Ducasse E, Lepidi S, Brochier C, et al. The “open” chimney graft technique for juxtarenal aortic aneurysms with discrepant renal arteries. *Eur J Vasc Endovasc Surg* 2014;47(2):124–130
- 51 Scali ST, Feezor RJ, Chang CK, et al. Critical analysis of results after chimney endovascular aortic aneurysm repair raises cause for concern. *J Vasc Surg* 2014;60(4):865–873, discussion 873–875
- 52 Allaqaband S, Jan MF, Bajwa T. “The chimney graft”—a simple technique for endovascular repair of complex juxtarenal abdominal aortic aneurysms in no-option patients. *Catheter Cardiovasc Interv* 2010;75(7):1111–1115
- 53 Brechtel K, Ketelsen D, Endisch A, et al. Endovascular repair of acute symptomatic pararenal aortic aneurysm with three chimney and one periscope graft for complete visceral artery revascularization. *Cardiovasc Intervent Radiol* 2012;35(2):413–417
- 54 d’Utra G, O’Brien N, Maioli F, et al. Challenging treatment of a secondary endoleak in a fenestrated endograft. *J Endovasc Ther* 2010;17(4):458–461
- 55 Ricci C, Ceccherini C, Leonini S, et al. Double renal chimney graft using only femoral approach. *J Cardiovasc Surg (Torino)* 2011;52(1):93–97
- 56 Tan GW, Wong D, Punamiya S, et al. Aortoenteric fistula treated with endovascular aortic stent-graft and bilateral chimney stent-grafts to renal arteries. *Ann Vasc Surg* 2012;26(3):422.e13–422.e16
- 57 Brossier J, Coscas R, Capdevila C, Kitzis M, Coggia M, Goeau-Brissonniere O. Anatomic feasibility of endovascular treatment of abdominal aortic aneurysms in emergency in the era of the chimney technique: impact on an emergency endovascular kit. *Ann Vasc Surg* 2013;27(7):844–850
- 58 Hiramoto JS, Chang CK, Reilly LM, Schneider DB, Rapp JH, Chuter TAM. Outcome of renal stenting for renal artery coverage during endovascular aortic aneurysm repair. *J Vasc Surg* 2009;49(5):1100–1106
- 59 Larzon T, Eliasson K, Gruber G. Top-fenestrating technique in stent grafting of aortic diseases with mid-term follow-up. *J Cardiovasc Surg (Torino)* 2008;49(3):317–322
- 60 Pecoraro F, Pfammatter T, Mayer D, et al. Multiple periscope and chimney grafts to treat ruptured thoracoabdominal and pararenal aortic aneurysms. *J Endovasc Ther* 2011;18(5):642–649
- 61 Moulakakis KG, Mylonas SN, Avgerinos E, et al. The chimney graft technique for preserving visceral vessels during endovascular treatment of aortic pathologies. *J Vasc Surg* 2012;55(5):1497–1503
- 62 Wilson A, Zhou S, Bachoo P, Tambyraja AL. Systematic review of chimney and periscope grafts for endovascular aneurysm repair. *Br J Surg* 2013;100(12):1557–1564
- 63 Katsargyris A, Oikonomou K, Klonaris C, Töpel I, Verhoeven EL. Comparison of outcomes with open, fenestrated, and chimney graft repair of juxtarenal aneurysms: are we ready for a paradigm shift? *J Endovasc Ther* 2013;20(2):159–169
- 64 Donas KP, Pecoraro F, Bisdas T, et al. CT angiography at 24 months demonstrates durability of EVAR with the use of chimney grafts for pararenal aortic pathologies. *J Endovasc Ther* 2013;20(1):1–6
- 65 Banno H, Cochenec F, Marzelle J, Becquemin JP. Comparison of fenestrated endovascular aneurysm repair and chimney graft techniques for pararenal aortic aneurysm. *J Vasc Surg* 2014;60(1):31–39
- 66 Lachat M, Frauenfelder T, Mayer D, et al. Complete endovascular renal and visceral artery revascularization and exclusion of a ruptured type IV thoracoabdominal aortic aneurysm. *J Endovasc Ther* 2010;17(2):216–220
- 67 Mestres G, Uribe JP, García-Madrid C, et al. The best conditions for parallel stenting during EVAR: an in vitro study. *Eur J Vasc Endovasc Surg* 2012;44(5):468–473