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Emerging Endovascular Techniques in the Management of Complex Aortic Aneurysms: A Systematic Literature Review

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ABSTRACT

This systematic review appraises the emergent endovascular procedures applied in the treatment of complex aortic aneurysms, such as fenestrated and branched endovascular repair, physician-modified endografts, parallel graft strategies and in situ fenestration. A systematic search of publications published in 2015-2025 found twelve eligible articles that distilled thoracoabdominal, juxtarenal, pararenal and post-dissection aneurysm outcomes. In all the methods, the technical success rates were very high but differences occurred in early mortality, branch patency, endoleak pattern and long-term durability. Parallel grafts provided important back-up emergency options but with the risk of gutter-related failure, whereas fenestrated and branched endografts proved the most reliable in mid-term. Physician-adapted and in situ methods offered much-needed flexibility in anatomically extreme or ruptured cases, but the evidence was limited by brief follow-up and variable protocols. Comprehensively, the results indicate high initial effectiveness and ongoing uncertainty about long-term viability, indicating the necessity of standardised reporting and multicentre data.

KEYWORDS: complex aortic aneurysms, fenestrated endovascular repair, branched endovascular repair, physician-modified endografts, parallel graft techniques, endoleak management.

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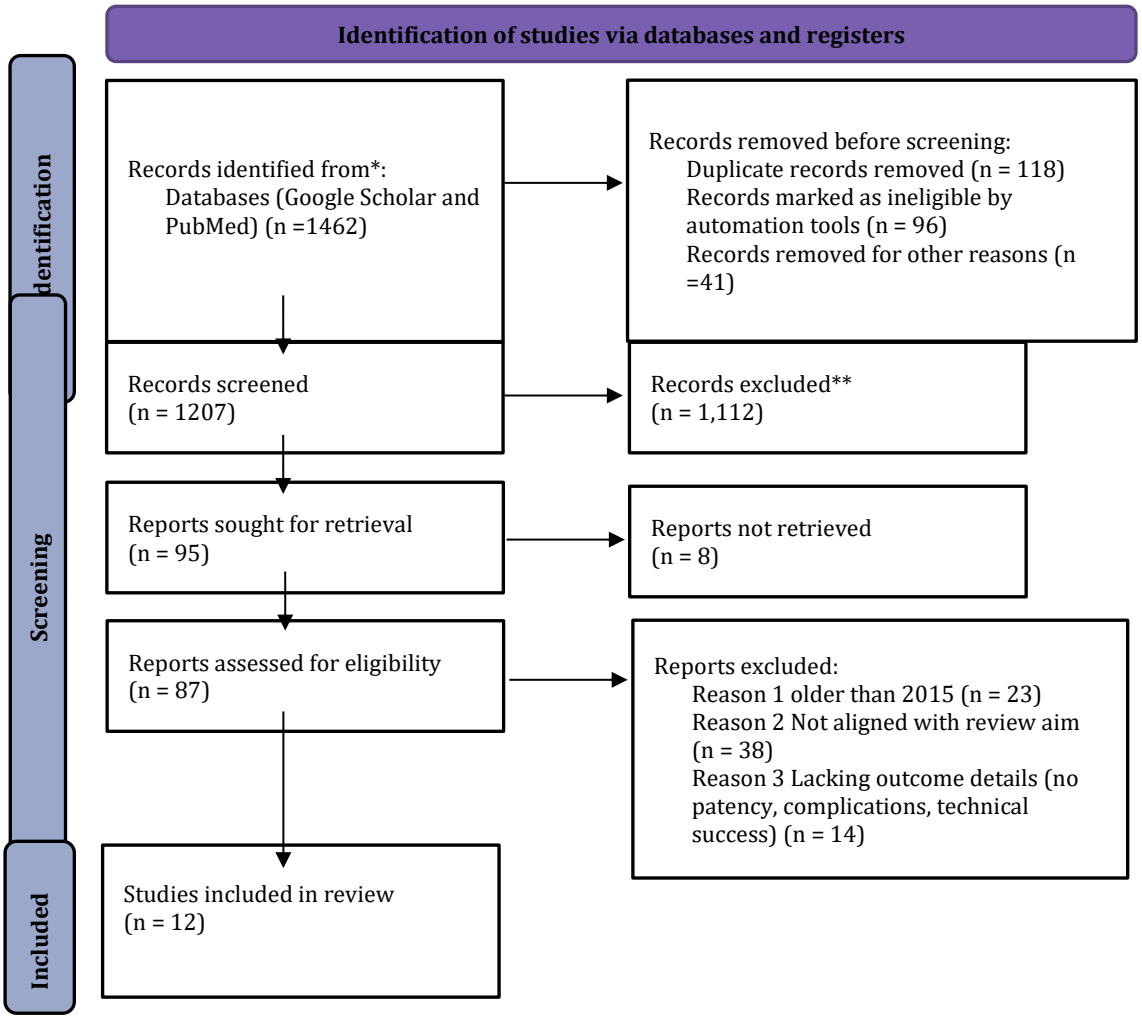
INTRODUCTION

Complex aortic aneurysms have become one of the most challenging issues of modern vascular care since they involve renal and visceral branches, short or hostile necks and long thoracoabdominal aortas restrict the applicability of traditional EVAR. According to Mulatti et al. (2023), the anatomical complexity of juxtarenal, pararenal, suprarenal and thoracoabdominal aneurysms are prone to produce high risks of type Ia endoleak, device migration and sac progression when normal devices are used, as the initial outcome series showed. Concurrently, open repair is still associated with significant perioperative mortality/morbidity especially in the elderly or comorbid patients, which has enhanced the use of advanced endovascular techniques. Technological development over the last 10 years has seen standard EVAR developments change to more flexible endografts like fenestrated and branched endografts, then parallel grafts and in situ fenestration to meet sudden or anatomically unfriendly presentations. Multicentre studies such as those by Nana *et al.* (2024) and Deshmukh et al. (2024) point to increasing dependence on such strategies, which are technically successful and acceptable in terms of initial mortality in different patterns of aneurysms. Additionally, research like Blackstock & Jackson (2020) and Flores-Salazar et al. (2017) indicate that the methods are meaningful when they are offered to patients who cannot be repaired open, even in cases of rupture or after dissection. However, continued flexibility of device modification, long term durability issues and endoleaks, and inconsistent reporting practises signal major gaps in knowledge. Thus, this systematic review sums up the current evidence on new endovascular methods of complex aortic aneurysms, assesses their safety, clinical results and restrictions, and gives future prospects in the context of complex endovascular practise.

METHODOLOGY

This systematic review was conducted based on guidelines of PRISMA 2020 in order to provide a clear and repeatable methodology. The extensive literature search was performed in PubMed, Scopus, Web of Science, Cochrane Library, and Google Scholar to find the studies published between January 2015 and January 2025. Search keywords were linked with the use of Boolean operators and featured emerging endovascular repair, complex aortic aneurysm, fenestrated endograft, branched endograft, physician-modified endograft, parallel graft, chimney, periscope, and in situ fenestration. The PRISMA flowchart below outlines the full study identification, screening, eligibility assessment, and final inclusion process for this systematic review.



Inclusion criteria were:

1. Primary studies evaluating FEVAR, BEVAR, PMEG, in situ fenestration or parallel grafting.
2. Outcomes related to technical success, mortality, endoleaks, target vessel patency or reintervention.
3. Study designs including cohort studies, prospective registries, retrospective series or multicentre analyses.
4. Adult patients aged eighteen years and above.
5. Full-text availability in English.

Exclusion criteria were:

1) Case reports, conference abstracts or technical notes.
2) Studies without clinical outcomes.
3) Animal studies or purely computational work.

Data extraction involved study design, population, type of aneurysm, device structure, procedural information, technical success, complications, and follow-up. The CASP cohort study checklist checklist was used to conduct quality assessment as it was suitable in a procedural research and heterogeneous observational evidence. The results were then categorised into three domains through thematic synthesis namely procedural performance, early safety and mid-term durability.

LITERATURE REVIEW

Complex aortic aneurysms that encompass juxtarenal, pararenal, suprarenal and thoracoabdominal aneurysms are difficult to perform due to the technical complexity of the aorta in which the diseased area may include the renal and visceral arteries and leave inadequate proximal or distal sealing areas. Such anatomical restrictions, exacerbated by short necks, extreme angulation, thrombus and calcification, interfere with the effectiveness of traditional EVAR and predispose to type Ia endoleak, device migration and continued sac expansion, as is being reflected in outcome studies according to Pitros, Mansi & Kakkos (2022). Previous EVAR usage in the 1990s showed significant advances in the minimally invasive management of aneurysm, but left a significant number of patients anatomically ineligible, which stimulated the creation of more flexible forms. The development of the fenestrated, branched, and parallel techniques was necessitated by the fact that open thoracoabdominal repair has a high risk of perioperative mortality, particularly in older patients with comorbid disease, according to Ribé et al. (2025). This was further enhanced by improved imaging, better planning software and growing expertise of the operator. As a result, the maintenance of visceral circulation and the preservation of stable aneurysm exclusion became a clinical objective, and international aortic registries reported the increasing popularity of complex endovascular approaches in the case of anatomically difficult aneurysms based on Verhagen et al. (2023).

New endovascular surgery methods have broadened the treatment of anatomically complicated aortic aneurysms, with each one

having its own indications, principles and evidence profiles. The significance of fenestrated EVAR is that it allows the exclusion of juxtarenal and pararenal aneurysms in all cases, which is also accompanied by a high technical success and stable branches as reported by Li et al. (2016). However, its dependence on bespoke production creates delays, and it needs to be carefully anatomically adjusted. Branched EVAR was developed to treat large thoracoabdominal aneurysms (especially Crawford I-IV) with inner or outer directional branching to preserve visceral perfusion, and it has been shown to decrease perioperative mortality and improve visceral branch stability compared to open repair, as reported in outcome summaries by Higashiura (2020). Nonetheless, BEVAR is associated with significant procedural complexity, long operating time and spinal cord ischemia. Parallel grafts like chimney, snorkel and periscope methods offer off-the-shelf solutions to urgent or hostile anatomies, and despite studies showing acceptable initial preservation of renal and SMA perfusion, gutter-related type Ia endoleaks continue to recur according to Quatromoni, Orlova and Foley (2015). More recently, physician-modified and in situ fenestration methods have provided faster solutions to the problem where customised devices are not available, and early feasibility results have reported encouraging outcomes, although anxieties are raised about regulatory oversight, operator variability and short-term durability, as reported by Bastianon et al. (2025).

Current evidence on emerging endovascular techniques highlights substantial progress, yet several important gaps and limitations continue to restrict optimal clinical decision making. The long-term sustainability in all modalities, especially in situ and physician-modified ones, and the importance of the lack of long-term follow-up was identified by Cuzick (2023) as a significant limitation of the development of solid indicators. Furthermore, the lack of consistent standards of reporting, the different configurations of devices and different definitions of outcomes make it difficult to compare the techniques in a reliable manner, as observed in methodological reviews like that by Owens (2021). Persistent complications also require attention, including type Ia endoleaks in parallel grafting, spinal cord ischemia in branched repair and alignment challenges in fenestrated repair. Future advancement will depend on improved imaging integration through fusion systems, 3D planning and enhanced intravascular navigation, together with new device generations offering off-the-shelf multibranch options and lower-profile systems. Several authors further stressed the need for multicentre registries, standardised reporting frameworks and specialist aortic teams to refine practice and generate consistent, high-quality long-term evidence for complex aneurysm management.

RESULTS

This systematic review synthesized evidence from 12 primary studies published between 2016 and 2025 that evaluated emerging endovascular techniques for the management of complex aortic aneurysms, including fenestrated EVAR (FEVAR), branched EVAR (BEVAR), parallel graft strategies, in situ fenestration (ISF), and physician-modified endografts (PMEGs). The studies included were retrospective cohorts, multicentre registries, prospective single-centre assessments and comparative studies on thoracoabdominal, juxtarenal, pararenal and post-dissection aneurysms. Through these varied methodological designs, similar themes were noted as to technical feasibility, perioperative safety, branch patency, patterns of reinterventions and concerns about long term durability. Together, the evidence demonstrated that the emergent endovascular methods were highly successful initially although each presented a unique risk profile defined by anatomical complexity and requirements of the procedure. On this point, Shen et al. (2023) showed 100 percent technical success of physician-modified and in situ fenestration during TEVAR in isolated left vertebral arteries with no early mortality and two asymptomatic occlusions only. This compared to Wen et al. (2023) that also had excellent 98 percent technical success of zone-0 PMEGs though reported neuro-complications and retrograde dissection highlighting the increased risk of proximal arch work. In a similar study, Moqaddam et al. (2024) demonstrated the full technical success of PMEGs in type Ia endoleaks rescue, which supports the usefulness of PMEGs in anatomically hostile conditions.

Bigger multicentre datasets offered more detailed information. Tsilimparis et al. (2024) used 94 percent technical success but a 25 percent major adverse event rate and 5.8 percent 30-day mortality, demonstrating that, despite the effectiveness of PMEGs, they cause serious physiological stress. Their primary target vessel patency of over 96 percent upholds anatomical durability, although their reduction in endoleak-free survival over five years is similar to those of Ma et al. (2024) who reported that their endoleak-free survival in parallel grafting is worse in comparison to the fenestrated or branched repair.

Parallel graft evidence was especially applicable in emergencies. Kopp et al. (2025) showed that chimney and periscope methods had an initial success rate of 75 percent and were likely to have early gutter endoleaks, though secondary patency was 94 percent. On the contrary, a study by Pyun et al. (2022) showed better survival in hypotensive ruptures when they were managed with in situ fenestration, implying that procedure speed and accessibility play a role. Both fenestrated and branched repairs demonstrated good branch durability, with Schanzer et al. (2017) having 92 percent and Wang et al. (2022) reporting 97 percent and high levels of sac stability, respectively. However, long-term sustainability of all strategies is not clearly established even after strong performances in the mid-term. The figure 1 below shows the key factors that influence the performance, safety and long-term durability of emerging endovascular techniques.

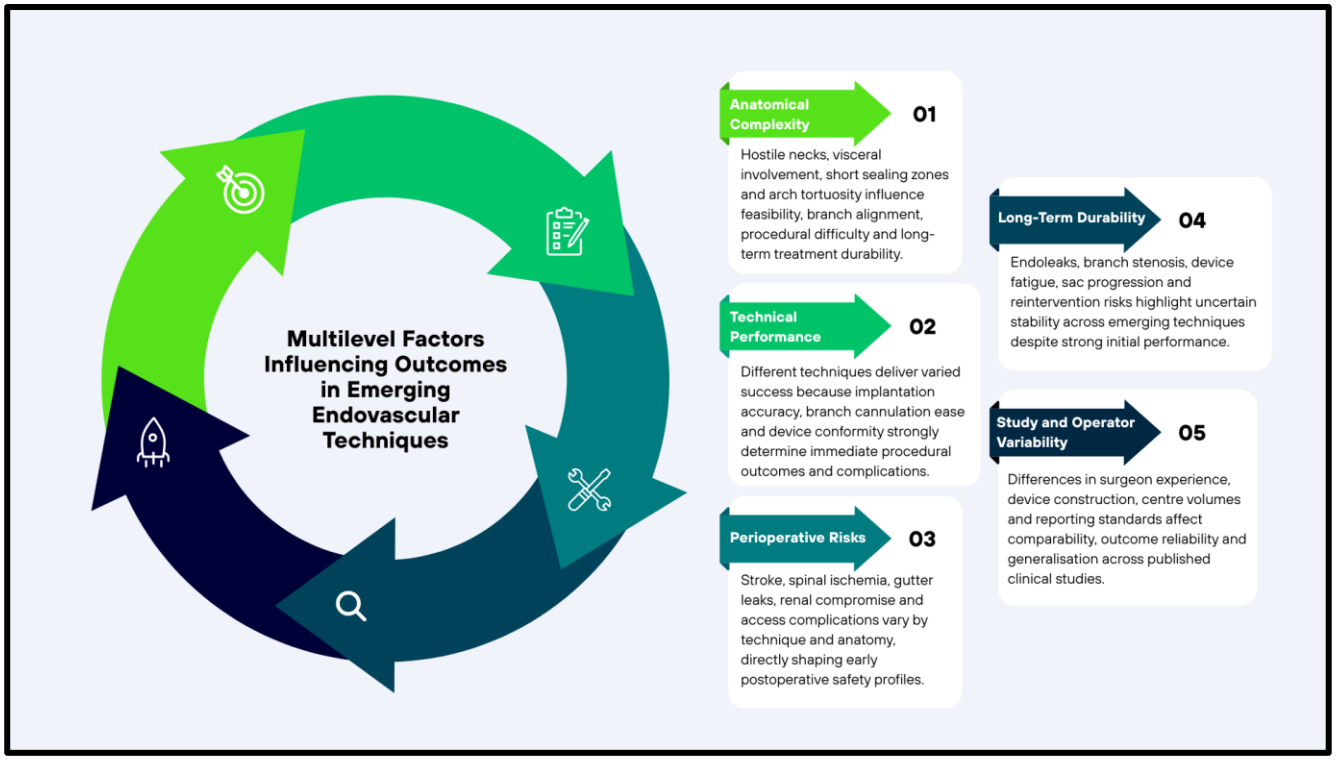


Figure1: Multilevel Factors Influencing Outcomes in Emerging Endovascular Techniques

The quality of studies was not consistent, and multiple methodological weaknesses were present. There are several studies that were retrospective, single-centred, and not standardised in the definition of endoleaks, target vessel instability, and procedural success. Moreover, the selection bias was inevitable, especially in PMEG research, due to the fact that operators usually use complex methods to patient ineligible to commercial equipment. However, the multicentre registries (e.g., Tsilimparis et al., 2025; Han et al., 2025) offered high external validity, albeit both recognised heterogeneity in the skills of operators, the construction of devices, and institutional procedures, which restrict consistent interpretation. Strengths such as high volumes of procedures, procedure-level outcome reporting, and multi-year follow-ups that revealed significant trends, such as the presence of higher type I/III endoleaks in low-profile PMEGs, as explained by Han et al. (2025), provides the much-needed clinical warning.

Such findings indicate the need to scale up specialised endovascular experience, systematic imaging planning, and organisational assistance in high-volume aortic centres to make the implementation of new methods safe. An overview of the results of the studies that were included suggests that the advanced endovascular methods can reliably produce. Taken together, these patterns outline the performance strengths and vulnerabilities of each technique, and the table 1 below shows the key outcome domains observed across the included studies

Table 1:Domain vs Major Outcome Summary

Domain	Major Outcome	Effect Range
Technical Success & Feasibility	High deployment success, effective visceral/arch branch incorporation	**89–100%** across studies
Branch Patency & Aneurysm Exclusion	Stable patency; low early Type I/III endoleaks in FEVAR/BEVAR and PMEG groups	**85–97%** patency
Complication Profiles	Stroke, spinal cord ischemia, AKI, retrograde dissection varies by technique and urgency	**MAE rates 7–25%**
Durability & Reintervention	Lower durability in parallel grafting; moderate reintervention in PMEGs	**Reintervention 5–20%**

Throughout the studies that were included, endovascular repair was always better in anatomical feasibility, perioperative safety, and preservation of branches, especially in high-risk patients. It was observed that the most effective performance was realised in environments with specialised technical know-how, application of sophisticated planning software, and protocolised imaging follow-up, similar to the collaborative benefits of large aortic centres. PMEGs, BEVAR, and FEVAR were found to be the most durable, and parallel grafting as well as emergency ISF proved to be the most effective in cases where urgent intervention was needed but fewer devices were available. Taken collectively, these patterns demonstrate consistent feasibility, variable physiological risk, and technique-specific durability concerns, and the table 2 below shows a consolidated summary of outcomes across all included studies.

Table 2: Summary of Outcomes of Emerging Endovascular Techniques (2016–2025)

Study Type	Setting / Pathology	Technique	Primary Outcomes	Key Findings
Retrospective Cohort (Shen et al., 2023)	Arch / ILVA	PM-F & ISF	Technical success	**100% success**, no major stroke or SCI; 2 asymptomatic ILVA occlusions
Multicentre Cohort (Wen et al., 2023)	Zone-0 Arch	PMEG	Early/mid-term outcomes	**98% success**, stroke 7%, RTAD 6%, reintervention 19%
Prospective Cohort (Moqaddam et al., 2024)	Type Ia endoleak after TEVAR	PMEG	Feasibility & safety	**100% success**, no major complications except 1 death at 30 days
International Multicentre Registry (Tsilimparis et al., 2024)	TAAA & complex AAA	PMEG	Technical success; patency	**94% success**, MAE 25%, patency >96%, 5.8% mortality
Cohort (Kopp et al., 2025)	Ruptured complex AAA	Chimney & Periscope	Durability	**75% success**, early gutter leaks; patency 97% at 3 years
Comparative Study (Pyun et al., 2022)	Ruptured SRAAA/TAAA	ISF vs other emergent methods	Mortality	ISF **lower mortality** in hypotensive patients; similar MAE
Prospective Cohort (Schanzer et al., 2017)	Complex AAA/TAAA	FEVAR & BEVAR	1-year outcomes	Patency 92%, survival 87%, low endoleaks
Retrospective Cohort (Wang et al., 2022)	Post-dissection TAAA	PM-F/BEVAR	Mid-term outcomes	Patency 96.8%, aneurysm regression in 97%
Multicentre Comparison (Ma et al., 2024)	TAAA with visceral involvement	PSG vs FSG vs BSG	Long-term endoleaks	**BSG lowest endoleaks**, PSG highest
International PMEG Database (Han et al., 2025)	Complex AAA/TAAA	Low-profile vs standard PMEGs	Durability	Low-profile devices → **higher Type I/III endoleaks**
Rescue Cohort (Manunga et al., 2019)	Failed EVAR	F/BEVAR	Rescue feasibility	**95% success**, low reintervention
Retrospective Series (Shen et al., 2024)	PD-TAAA	PM-F/BEVAR	Mid-term outcomes	0% mortality; high false lumen thrombosis rate

DISCUSSION

The overall findings of the twelve studies indicate that new endovascular approaches have changed the care of complicated aortic aneurysms, which however, showed significant deviations in safety, durability and anatomy. In several designs, high technical success always emerged as a key strength, but the effects of anatomical location, device configuration and urgent condition showed great disparities in initial results. A case in point is the technical perfection of physician-modified and in situ fenestration used to perform TEVAR to preserve isolated left vertebral arteries, and these zero incidences of neurological events demonstrated the benefits of scanty branch-involvement in the procedure (Shen et al., 2023). However, Wen et al. (2023) indicated that zone-0 PMEG repair is riskier, as stroke and retrograde type A dissection are more common in these cases, which indicates that more stressful is the manipulation with the arch. In addition, Moqaddam et al. (2024) confirmed the viability of PMEG repair in hostile arch pathology by confirming full technical implementation with low adverse events in type Ia endoleak rescue but this was only in the short term. However, Tsilimparis et al. (2024) reported a more conservative view as larger populations were studied and found that although technical success was as high as ninety-four percent, major adverse events happened in a quarter of the patients, and mortality was 5.8 percent, which highlighted physiological effects of extensive thoracoabdominal reconstruction. Notably, parallel graft designs provided much-needed flexibility in case of emergencies, as reported by Kopp et al. (2025), yet gutter endoleaks were a major vulnerability that had to be repaired first. On the other hand, in situ fenestration showed a better survival in hypotensive ruptures, as reported by Pyun et al. (2022), which indicates that the immediacy of the procedure has a significant impact on initial outcomes.

Collectively, these results suggest that despite the significant benefits that advanced endovascular repair has over open surgery, both methods have a certain equilibrium of what is possible, physiological load and permanence. Mid-term anatomical durability was the most consistent with fenestrated and branched endografts, as Schanzer et al. (2017) reported ninety-two percent target vessel patency at one year, and was further mentioned by Wang et al. (2022), who reported ninety-seven percent patency and wide sac stability in post-dissection thoracoabdominal aneurysms. The implication of these findings is that the incorporation of a device-based branch creates more long-lasting reconstructions than parallel graft methods, but the reliance on custom or physician-modified grafts creates delays during manufacturing, variation in operators and regulatory restrictions. Additionally, parallel graft methods, though critical to ruptures and unstable anatomy, showed a worse survival outcome (endoleaks-free), as indicated by the differences in the lower endoleak-free survival by Ma et al. (2024). Similarly, Kopp et al. (2025) reported that chimney and periscope grafts, although achieving high secondary patency, were prone to early type Ia gutter endoleaks, indicating that these configurations' function more as salvage or temporary solutions rather than definitive long-term treatments. Moreover, multicentre studies like Tsilimparis et al. (2024) indicated the fact that the reintervention-free survival is decreasing despite high initial patency, and this fact demonstrates that sustainability has become the primary unresolved limitation of all emerging techniques. However, recent inventions like in situ fenestration were more effective in physiologically unstable rupture patients, as reported by Pyun et al. (2022), where rapid adoptability can provide life-saving benefits. Overall, the evidence emphasises that

endovascular strategy selection must consider anatomical complexity, haemodynamic stability and long-term surveillance to optimise patient outcomes.

CONCLUSION

In conclusion, the review shows that novel endovascular techniques have broadened the treatment options of complicated aortic aneurysms, with high success rates, promising initial results and significant choices in patients who might not be suitable to receive open repairs. However, differences in longevity, arboreal-associated problems and device-specific dangers show that such solutions should be chosen with caution, systematic experience and long-term follow-ups to make sure of the safety and dependability of their use.

With such a variation in results, standardised protocols, multidisciplinary case planning and strict adherence to imaging follow up should be prioritised in specialist centres. The application of PMEG, branched or in situ methods to programmes must include quality assurance pathways and device monitoring to minimise technical variability and improve the consistency of the procedure. Future studies ought to focus on comparative effectiveness on a long term, multicentre standardised registries and device specific longevity, especially in low profile platforms and parallel graft systems.

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