

Article

Not peer-reviewed version

Comparison of Hemodynamics After Fenestrated, Branched, and Chimney Endovascular Aneurysm Repair Employing Computational Fluid Dynamics

Stavros Malatos , [Spyridon Katsoudas](#) , [Anastasios Raptis](#) , [Laura Fazzini](#) , [Petroula Nana](#) , [George Kouvelos](#) , Athanasios Giannoukas , [Michails Xenos](#) , [Miltiadis Matsagkas](#) *

Posted Date: 22 January 2026

doi: 10.20944/preprints202601.1730.v1

Keywords: FEVAR; BEVAR; ChEVAR; computational fluid dynamics; hemodynamic performance; endograft-specific flow analysis



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Comparison of Hemodynamics After Fenestrated, Branched, and Chimney Endovascular Aneurysm Repair Employing Computational Fluid Dynamics

Stavros Malatos ¹, Spyridon Katsoudas ², Anastasios Raptis ³, Laura Fazzini ⁴, Petroula Nana ⁵, George Kouvelos ¹, Athanasios Giannoukas ¹, Michalis Xenos ² and Miltiadis Matsagkas ^{1,*}

¹ Department of Vascular Surgery, Faculty of Medicine, School of Health Sciences, University of Thessaly, 41334 Larissa, Greece

² Department of Mathematics, University of Ioannina, 45110 Ioannina, Greece

³ Laboratory of Biofluid Mechanics & Biomedical Technology, School of Mechanical Engineering, National Technical University of Athens, 15772 Zografou, Greece

⁴ Clinical Engineer Department, Asl Roma 6, 00041 Ariccia (Rome), Italy

⁵ German Aortic Center, Department of Vascular Medicine, University Hospital Eppendorf, Hamburg, 20251, Germany

* Correspondence: mimats@med.uth.gr, M.M.

Abstract

Background/Objectives: This study compared the hemodynamic performance of fenestrated (FEVAR), branched (BEVAR) and chimney endovascular aortic aneurysm repair (chEVAR) in patients with complex aortic aneurysms. **Methods:** The pre- (native) and post-endovascular repair (endograft-defined) blood lumen was reconstructed from computed tomography angiographies of nine (9) elective patients treated with FEVAR ($n=3$), BEVAR ($n=3$), and chEVAR ($n=3$). Computational Fluid Dynamics (CFD) simulations obtained blood flow properties. Velocity magnitude, wall shear stress (WSS), time-averaged wall shear stress (TAWSS), oscillatory shear index (OSI), relative residence time (RRT) and local normalized helicity (LNH) were computed at peak-systole and mid-diastole. The hemodynamic data were statistically analyzed to evaluate correlations between FEVAR, BEVAR and chEVAR, focusing on targeted visceral arteries. **Results:** Only slight differences were observed regarding RRT, OSI and TAWSS between FEVAR and BEVAR, whereas the chEVAR group demonstrated a marked deviation from both. In FEVAR, the postoperative helical flow structures appeared more compact, while in BEVAR, they were more developed and exhibited a more rotational configuration. The LNH of the visceral vessel patterns exhibited similar qualitative features across groups. Regarding TAWSS, higher values were found in BEVAR, whereas chEVAR showed the lowest. **Conclusions:** FEVAR, BEVAR, and chEVAR improved postoperative blood flow characteristics toward near-physiological conditions, reducing undesired flow patterns and recirculation zones. FEVAR showed more stable visceral flow, BEVAR demonstrated higher flow rates and fewer recirculation zones while chEVAR exhibited more streamlined visceral artery flow with reduced regurgitation at bridging stent entries. Despite variations, all approaches effectively preserved visceral artery perfusion.

Keywords: FEVAR; BEVAR; ChEVAR; computational fluid dynamics; hemodynamic performance; endograft-specific flow analysis

1. Introduction

Endovascular repair using fenestrated and branched endografts is the first line treatment for patients with juxtarenal and pararenal abdominal aortic aneurysms (AAAs) [1,2] while off-the-shelf solutions may be used in urgent setting or when the anatomy does not permit a custom-made

endograft application [3]. Endovascular treatment for complex aneurysms has emerged as a preferred approach in contemporary medical practice. The advancements in endovascular solutions, including the use of custom-made grafts that incorporate branches and fenestrations, alongside off-the-shelf devices, have greatly enhanced the feasibility and effectiveness of these interventions. Despite the high technical success, low early mortality and morbidity recorded in large retrospective cohorts of high-volume aortic centers, the durability of complex endovascular approaches is still questioned due to the higher reintervention rates [4–6]. Especially for complex endovascular aortic repair, target vessel adverse events are the leading cause for reintervention during the mid-term follow-up [5,6]. Previous analyses on fenestrated versus branched devices showed that fenestrations, when applicable, are superior to branches in terms of target vessel instability [7].

Recent studies show that postoperative hemodynamics in the visceral branches critically influence F / BEVAR and chEVAR success [8,9]. Abnormal flow patterns and shear-stress distributions have been linked to branch stenosis, impaired organ perfusion, and increase target vessel instability events. Given the variability in endograft and techniques, understanding the impact of configuration on target vessels blood flow remains an important unresolved issue [1,10–12]. Due to the lack of patient-specific hemodynamic data at the inlet and outlets of the 3D vascular models, advanced multiscale cardiovascular models, 3D–1D, can generate the required waveforms for the 3D simulations and assisted understanding of complex hemodynamic features [13].

This study aims to compare the blood-flow characteristics in target vessels after complex endovascular aortic aneurysm repair using different approaches (FEVAR, BEVAR and chEVAR) using patient-specific computational models.

2. Materials and Methods

Study design and patient selection. A retrospective analysis was conducted on blood flow features pre- and post- FEVAR, BEVAR and chEVAR, see Supplementary Figure 1, among patients that were managed for degenerative complex aortic aneurysms between 2018 and 2021 in a single-tertiary center. Computed tomography angiography (CTA) scans were used to define the pre- and post-repair blood flow lumens of patients with complex aortic aneurysms using computational fluid dynamics simulations, with special focus on the hemodynamic properties of the visceral vessels [8,13].

Patients with juxta-renal, para-renal and thoracoabdominal aortic aneurysms that were managed using FEVAR, BEVAR or chEVAR under elective setting and completed the one-month CTA (slice thickness <1mm and arterial phase) imaging follow-up were considered eligible. A revascularization and bridging of three (for chEVAR) or four target vessels was a criterion for inclusion. The decision for the treatment approach relied on patient-specific characteristics, anatomy of the aorta and target vessels and availability of devices and materials. Patients managed for aortic dissections (acute or chronic), pseudoaneurysms or had an anamnesis of previous endovascular or open aortic aneurysm repair were excluded. No surgeon-modified endografts were used during the study period.

Pseudonymized pre- and post-operative computed tomography angiographies (CTA) of 3 cases for each technique (FEVAR, BEVAR and chEVAR) were collected and analyzed. This study complied with the declaration of Helsinki. No Ethics Committee approval was required due to its retrospective nature and pseudonymized information.

Endovascular approaches. FEVAR was used for the treatment of juxta- and para-renal aortic aneurysms, if the apposition of the device on the aortic wall and especially the level of the target vessels was expected. All FEVAR cases were managed with company-manufactured custom-made devices relying on the Zenith Platform (Cook Medical, Bloomington, IN, USA) [14]. BEVAR was chosen for patients with more extensive aortic pathologies, including thoracoabdominal aneurysms, when a device apposition on the aortic wall was not expected. Patients managed with BEVAR were treated using off-the-shelf branched devices (T-Branch device, William Cook Europe, Bjaeverskov, Denmark); all relying on the Zenith platform. ChEVAR was used in urgent cases (symptomatic or ruptured juxta- or pararenal aortic aneurysms) or aneurysms with a diameter over 70mm, when a

custom-made was not available due to the long-time interval for device design and manufacture. For patients managed with chEVAR, the Endurant IIs (Medtronic, Santa Rosa, CA, USA) device was used as aortic component. All aortic devices were oversized by 20%, except for chEVAR, where the aortic device was oversized by 30%, respecting that three target vessels were revascularized [15].

All target vessels were bridged using the same bridging stents (BeGraft Peripheral, Bentley, Hechingen, Germany). The bridging stent diameter and length was decided upon the technical features of the main device and the distal landing zone and anatomy of the target vessels. Details on anatomic parameters and devices are presented in Table 1.

Table 1. Main body and bridging stent details of each patient.

Cases	Main body	Max aortic diameter at proximal landing zone	Max visceral aortic diameter	Infrarenal aortic angulation	Neck calcification/thrombus in >25% of the circumference of landing zone	Bridging stent	Diameter of TVs at landing zone	Angles of TVs*
FEVAR								
1	COOK FENESTRATED GRAFT: 36x22x162 mm	30.2mm	33.0mm	20.0°	No	RRA: BeGraft 6x28mm - LRA: BeGraft 6x28mm - SMA: BeGraft 8x37mm - CA: BeGraft 9x37mm	RRA: 6.1mm LRA: 6.1mm SMA: 7.5mm	RRA: 25° LRA: 3° SMA: 27°
2	COOK FENESTRATED GRAFT: 30x22x114 mm	26.0mm	29.6mm	8.0°	No	RRA: BeGraft 6x28mm - LRA: BeGraft 6x28mm - SMA: BeGraft 8x37mm	RRA: 6.0mm LRA: 5.7mm SMA: 7.6mm	RRA: 23° LRA: 18° SMA: 10°
3	COOK FENESTR	31.5mm	30.7mm	17.0°	No	RRA: BeGraft	RRA: 5.7mm	RRA: 27° LRA: 17°

	ATED GRAFT: 38x35x162 mm					6x28mm - LRA: Begraft 6x28mm - SMA: Begraft 8x37mm - CA: Begraft 9x37mm	LRA: 6.0mm SMA: 7.7mm	SMA: 23°
ChEVAR								
1	ENDURA NT IIs GRAFT: 36x14x103 mm	27.6mm	32.0mm	15.8°	No	RRA: BeGraft 6x58mm - LRA: BeGraft 6x58mm - SMA: BeGraft 8x57mm	RRA: 5.3mm LRA: 6.0mm SMA: 7.9mm	RRA: 32° LRA: 12° SMA: 31°
2	ENDURA NT IIs GRAFT: 36x14x103 mm	27.1mm	27.6mm	31.0°	No	RRA: Begraft 6x58mm - LRA: BeGraft 6x58mm - SMA: BeGraft 8x57mm	RRA: 5.1mm LRA: 5.6mm SMA: 7.9mm	RRA: 37° LRA: 8° SMA: 26°
3	ENDURA NT IIs GRAFT: 36x14x103 mm	27.0mm	29.0mm	28.0°	No	RRA: BeGraft 6x58mm - LRA: BeGraft 6x58mm - SMA: BeGraft 8x57mm	RRA: 5.5mm LRA: 5.9mm SMA: 7.7mm	RRA: 24° LRA: 28° SMA: 43°
BEVAR								
1	COOK T- BRANCH DEVICE:	30.5mm	36.8mm	15°	No	RRA: BeGraft 6x57mm -	RRA: 5.6MM	RRA:21° LRA:20° SMA: 17°

	34x19x202 mm					LRA: BeGraft 6x57 – CA: BeGraft 8*57 – SMA: BeGraft 8x57	LRA:5.2M M CA: 8.1MM SMA: 7.8MM	
2	COOK THORAC IC 49x36x217 mm+ COOK T- BRANCH DEVICE: 34x19x202 mm	26mm	32.4mm	14°	No	RRA: BeGraft 7x57mm – LRA: BeGraft 7x57 – CA: BeGraft 9x59mm – SMA: BeGraft 8x57mm	RRA: 6.7mm LRA:7mm CA: 8.6mm SMA: 8.1mm	RRA:6° LRA:16° SMA: 6°
3	COOK T- BRANCH DEVICE: 34x19x202 mm	31mm	33mm	15°	No	RRA: BeGraft 6x57mm – LRA: BeGraft 7x57 – CA: BeGraft 8x59mm – SMA: BeGraft 9x57mm	RRA: 6.5mm LRA:7.1m m CA: 8mm SMA: 8.6mm	RRA:10° LRA:14° SMA: 101°

Modeling. The 3D model of the FEVAR, chEVAR, BEVAR system, including the Celiac Artery (CA), Superior mesenteric Artery (SMA), Left Renal Artery (LRA), Right Renal Artery (RRA), was constructed using the CTA scan for each patient Supplementary Figure 1A. The reconstruction of the DICOM images into a 3D lumen model was performed using the methodology mentioned in previous studies [8,9,13].

The reconstruction of geometry under consideration started just above the CA and ended just below the iliac bifurcation, while the region of interest was the visceral aorta and specifically the CA, SMA, RRA and LRA. For the FEVAR and BEVAR cases, the segmentation was performed as a combined structure. Regarding chEVAR cases, the lumen of the covered abdominal aorta and stented visceral arteries (SMA, RRA, LRA) were segmented separately using the same software, Supplementary Figure 1. The optimal smoothing factor value (SFV) was determined to be 0.05, based on a smoothing parameter study performed on renal and mesenteric diameters using the Vascular Modeling Toolkit (VMTK) [8].

The following hemodynamic parameters: Time Average Wall Shear Stress (TAWSS), Oscillatory Shear Index (OSI), Relative residence time (RRT) and Local Normalized Helicity (LNH) were calculated. The postoperative results presented correspond to a representative patient from each group, as no significant differences between patients were observed.

Numerical simulations were performed with the software package Ansys Fluent (Ansys Inc., Canonsburg, Pennsylvania, United States). Blood was considered a Newtonian fluid with a density of $\rho = 1050 \text{ kg/m}^3$ and a kinematic viscosity of $\nu = 3.2 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$. The zero-velocity condition was applied on the surface of the endograft, following the rigid wall assumption. Over two million tetrahedral elements were discretized from the fluid domain, with an additional three-layer boundary the inner element size was approximately 1 mm. The boundary conditions at the inlet and outlets were defined using the flow and pressure waveforms obtained from the multiscale model (0D-3D) developed in our previous studies [9,13]. Specifically, a flow waveform representing physiological (healthy) conditions, obtained from the literature, was applied to the input [9,13]. At the outlets, resistance-based boundary conditions (pressure waveforms) derived from the 1D mathematical model were imposed for each respective artery. The velocity profile at the outputs was almost parabolic during the systolic phase [8,13,16–20]. Convergence to the solution at each step was considered achieved when the computational error fell below 10^{-4} . We used exclusively the results of the last cardiac cycle, avoiding any dynamic behavior of the first pulses [10]. Grid independence tests were performed in regions of predicted disturbed flow to determine the optimal mesh size. The simulation was considered grid-independent when the hemodynamic parameters (velocity and pressure) varied by less than 2% between successive mesh refinements [21]. In all 3D cases, a parabolic velocity waveform is imposed at the inlet, no-slip condition at the wall (i.e. on the stent-graft surface) and pressure waveforms at all outlets (Supplementary Figure 2). The latter (pressure waveforms) were derived from a 1D hemodynamic model of the entire arterial network [13,16,18–20,22–25]. Paraview (Kitware Inc.) software was used for the visualization of hemodynamic parameters.

Statistical analysis. Differences in hemodynamic parameters (RRT, OSI, TAWSS) among the three endograft groups were assessed in the target vessels (SMA, LRA, RRA) using one-way ANOVA, with $p < 0.05$ considered statistically significant.

3. Results

Wall Shear Stress (WSS). Postoperatively, during the peak systole, WSS values showed the maximum value of 3Pa for all designs (Figure 1). Higher WSS values across the whole structure and especially in the visceral arteries were observed for BEVAR cases, followed by intermediate values for FEVAR and the lowest values for chEVAR as shown in Table 2.

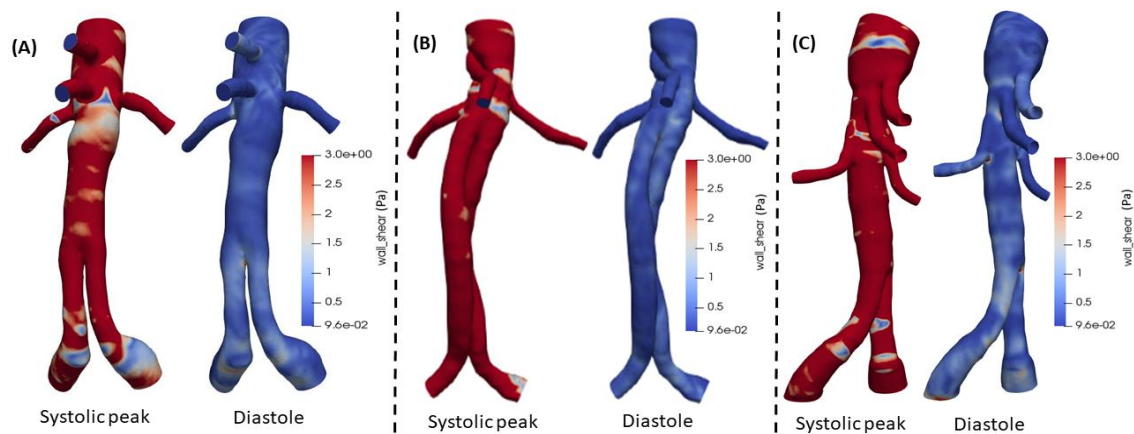


Figure 1. WSS in (A) FEVAR, (B) ChEVAR and (C) BEVAR cases, for systolic peak and diastole.

Local Normalized Helicity (LNH). The helical structures in all three endograft groups are distributed evenly throughout the device (Figure 2). In FEVAR cases (Figure 2A), the helical patterns appear more compact and smoother compared to those observed in BEVAR (Figure 2C). Postoperatively, the helical structures in BEVAR were more pronounced and exhibited a clearer rotational configuration ($|LNH| < 0.3$). According to the literature, a threshold value of 0.3 is typically considered indicative of rotational flow structures [26–28]. In contrast, in FEVAR cases (Figure 2A), the local normalized helicity (LNH) shows less rotational behavior compared to chEVAR (Figure 2B). Additionally, in the visceral arteries of all groups, a relatively uniform distribution of helical structures was observed postoperatively.

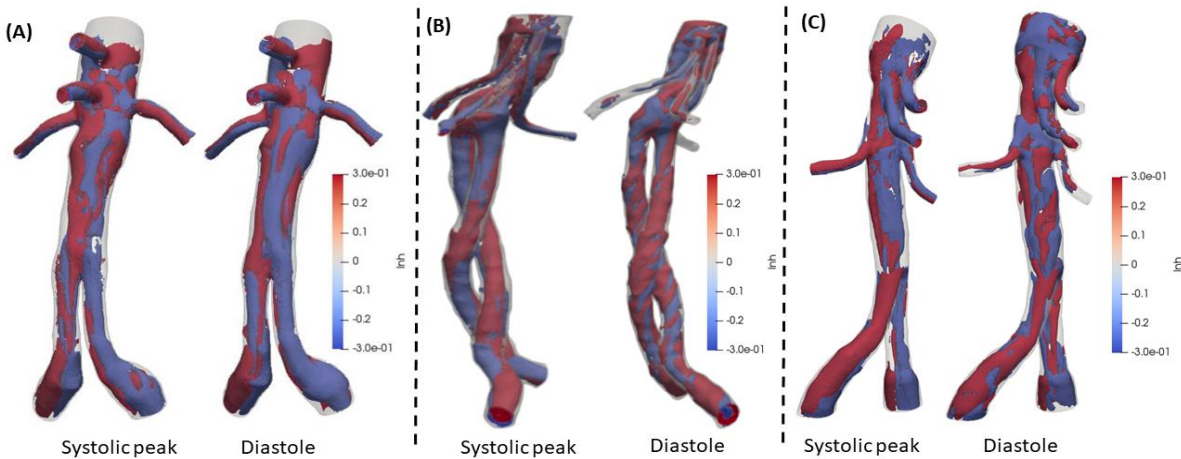


Figure 2. LNH in (A) FEVAR, (B) ChEVAR and (C) BEVAR cases in different cardiac phases.

Time Averaged Wall Shear Stress (TAWSS). The results were evaluated assuming a maximum TAWSS value of 3Pa. As shown in Table 2, BEVAR exhibited the highest TAWSS values, compared to the other two techniques. BEVAR and FEVAR demonstrated relatively high TAWSS, with only minor deviations between them, whereas chEVAR cases showed significantly lower TAWSS (Figure 3). In BEVAR cases, increased TAWSS was distributed across nearly the entire surface of the structure, while in FEVAR cases, moderate TAWSS values were observed primarily in the region below the renal arteries and above the iliac bifurcation (Figure 3A).

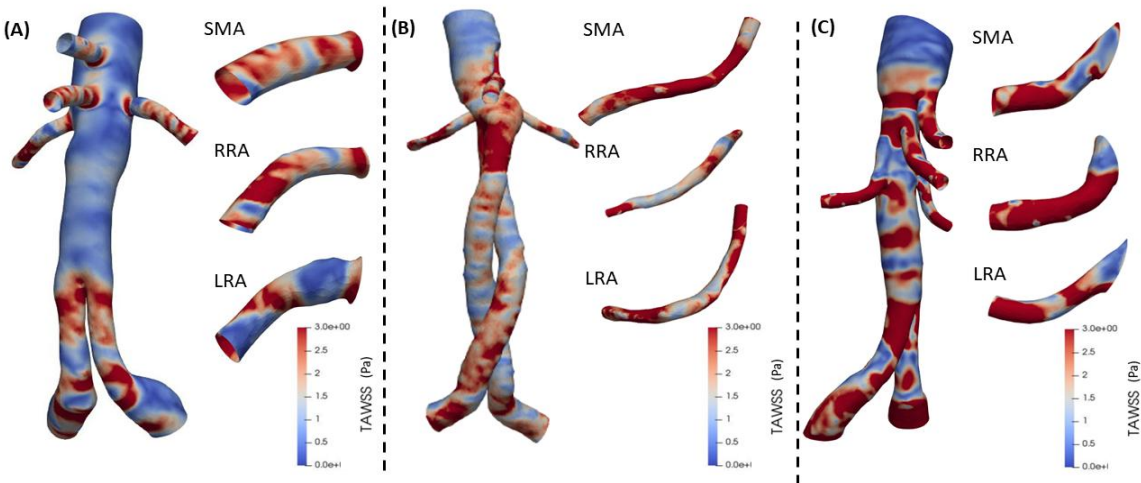


Figure 3. Time averaged Wall Shear Stress (TAWSS) in (A) FEVAR, (B) chEVAR and (C) BEVAR cases.

Table 2. Mean values for the hemodynamic parameters, between FEVAR, chEVAR and BEVAR cohorts.

	FEVAR	ChEVAR	BEVAR	FEVAR	ChEVAR	BEVAR	FEVAR	ChEVAR	BEVAR
RRT-Mean (1/Pa)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	1,0069	0,5225	0,5350	1,0478	1,0941	0,5196	1,4802	0,9316	0,8077
P2	0,6430	1,7459	0,9139	0,6088	2,0717	0,7050	0,5181	0,8775	0,6557
P3	0,5212	0,8302	0,6503	0,8630	1,0577	0,4820	0,7628	0,9322	0,9160
Average	0,7237	1,0328	0,6997	0,8399	1,4078	0,5689	0,9204	0,9138	0,7931
OSI-Mean (Dimensionless)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	0,0070	0,0084	0,0062	0,0061	0,0175	0,0067	0,0107	0,0073	0,0091
P2	0,0038	0,0118	0,0095	0,0052	0,0129	0,0064	0,0050	0,0210	0,0045
P3	0,0040	0,0073	0,0075	0,0033	0,0053	0,0098	0,0038	0,0057	0,0111
Average	0,0049	0,0092	0,0077	0,0048	0,0119	0,0076	0,0065	0,0114	0,0083
TAWSS-Mean (Pa)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	2,0107	1,6635	3,3955	1,8828	0,9943	4,5400	1,7417	1,4609	2,8088
P2	2,4245	1,1021	2,5005	2,7818	1,3462	3,0023	2,8822	2,1734	2,1953
P3	2,6638	1,9726	3,0866	2,2412	2,7191	4,3557	2,4512	2,1275	2,1453
Average	2,3663	1,5794	2,9942	2,3019	1,6865	3,9660	2,3584	1,9206	2,3831
Mean Flow Rate of the cardiac cycle (l / s)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	1,20E-05	7,05E-06	1,25E-05	7,77E-06	3,22E-06	8,78E-06	7,99E-06	4,79E-06	8,78E-06
P2	4,53E-06	4,39E-06	8,67E-06	5,77E-06	1,59E-06	6,88E-06	4,78E-06	4,14E-06	4,14E-06
P3	8,29E-06	3,92E-06	1,13E-05	5,04E-06	1,62E-06	6,65E-06	5,90E-06	2,51E-06	5,90E-06
Average	8,28E-06	5,12E-06	1,08E-05	6,20E-06	2,15E-06	7,44E-06	6,22E-06	3,81E-06	6,27E-06

Pressure -MAP (Mean Arterial Pressure) (Pa)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	12448,0	12595,4	13042,2	12423,6	12607,7	12881,4	12436,0	12523,1	12937,9
P2	12449,0	12528,7	12794,0	12425,3	12515,9	12691,8	12436,3	12573,5	12652,1
P3	12447,6	12447,3	12903,6	12423,6	12423,3	12889,4	12436,0	12437,0	12986,0
Average	12448,2	12523,8	12913,2	12424,2	12515,6	12820,9	12436,1	12511,2	12858,7
WSS- Mean at peak systole (Pa)	SMA	SMA	SMA	RRA	RRA	RRA	LRA	LRA	LRA
P1	15,75	11,40	23,92	12,61	7,96	31,86	13,09	9,94	26,29
P2	21,32	14,95	22,98	20,66	12,23	21,89	22,79	15,52	19,16
P3	20,58	27,57	26,27	18,05	19,52	33,24	19,60	18,70	26,67
Average	19,22	17,98	24,39	17,11	13,24	28,99	18,50	14,72	24,04

Oscillatory Shear Index (OSI) and Relative Residence Time (RRT). There were areas of low OSI values, in the main aortic endograft for all groups. More regions of low value of localized OSI, mainly occurred in the FEVAR and BEVAR cases. OSI showed intense oscillations in individual locations of the visceral arteries in the chEVAR group. In postoperative BEVAR cases, the OSI showing increased values among the mesenteric and renal arteries Supplementary Figure 3C. In BEVAR target vessels, low levels of OSI in proximal end and moderate values in the distal end were recorded, in contrary to chEVARs, where high value localized OSI prevails [Supplementary Figures 3C and B]. In all cases, the RRT values were mainly driven by the OSI patterns following the opposite behavior (Supplementary Figures 3 and 4).

Flow comparison in FEVAR, chEVAR and BEVAR. The flow at peak systole in FEVAR, chEVAR and BEVAR groups is depicted in Figure 4. The maximum flow velocity in the visceral arteries was recorded in BEVAR ~2.5 m/s versus ~2.2 m/s in chEVAR and ~1.7m/s in FEVAR cases (Table 2). No statistically significant differences in visceral vessel flow were observed between FEVAR and chEVAR. The endograft segment between the CA and renal arteries showed increased flow in BEVAR, while the flow was smoother in the main body of the other two techniques (Figure 4) than in chEVAR [Supplementary Figure 5B], during the systolic phase.

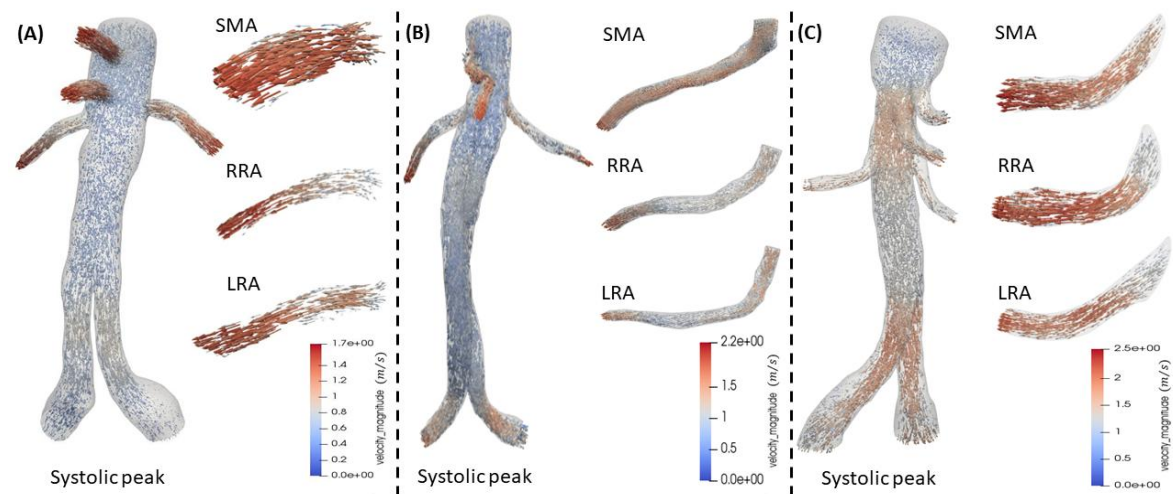


Figure 4. Flow comparison (velocity magnitude) of the secondary arteries at systolic peak, mesenteric (SMA) and renal arteries (LRA, RRA), between (A) FEVAR, (B) chEVAR and (C) BEVAR cases.

Mean visceral hemodynamics. No statistically significant differences were found in RRT and OSI of the target vessels among the techniques. Comparing the mean values of hemodynamic parameters (RRT, OSI and TAWSS), only slight differences were observed between FEVAR and BEVAR. In contrast, chEVAR showed deviation from the other two groups Figure 5.

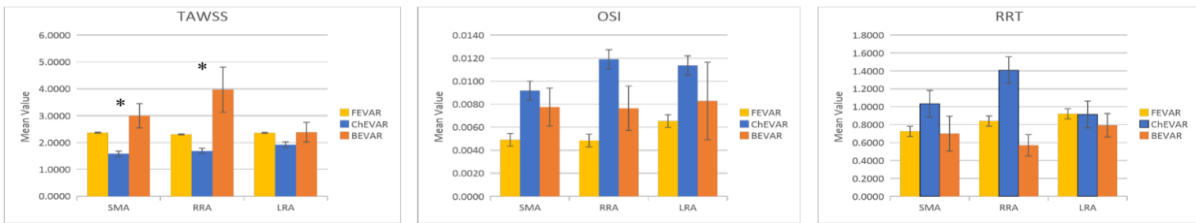


Figure 5. Mean values for the hemodynamic parameters (RRT, OSI and TAWSS) between FEVAR, chEVAR and BEVAR endograft groups.

Statistically significant differences ($p < 0.05$) were observed for TAWSS, for the SMA ($p = 0.0162$) and RRA ($p = 0.0255$) in the post-operative setting. Regurgitant flow in the visceral arteries was computed and compared across FEVAR, chEVAR, and BEVAR cases. chEVAR exhibited the highest mean value, FEVAR intermediate, and BEVAR the lowest, Table 3 [8,17].

Table 3. Percentage of flow reversal in visceral arteries of FEVAR, chEVAR and BEVAR cases.

FEVAR cases				
Target vessel	Patient 1 (%)	Patient 2 (%)	Patient 3 (%)	Mean Value
SMA	11.1834	24.7713	14.3677	16.7741
LRA	5.4558	19.0680	6.2420	10.2552
RRA	1.6034	10.3179	6.0401	5.9871
ChEVAR cases				
Target vessel	Patient 1 (%)	Patient 2 (%)	Patient 3 (%)	Mean Value
SMA	14.3160	29.9458	20.5075	21.5897

LRA	11.9259	21.2901	29.2485	20.8215
RRA	10.0024	36.8587	26.1691	24.3434
BEVAR cases				
Target vessel	Patient 1 (%)	Patient 2 (%)	Patient 3 (%)	Mean Value
SMA	3.6570	13.2076	12.8335	9.8994
LRA	2.2868	23.7582	60.3961	28.0514
RRA	2.2868	2.4989	10.3019	5.0292

Footnotes: SMA: superior mesenteric artery; LRA: left renal artery; RRA: right renal artery.

4. Discussion

FEVAR / BEVAR expanded their targeted patient population and currently represents the recommended approach in patients with adequate anatomy and complex aortic aneurysms while chimney technique received a lot of criticism regarding the risk for failure of the proximal landing zone and higher endoleak rates and represents mainly a bailout approach [29–31]. FEVAR and chEVAR endovascular aortic repair have been applied in anatomically suitable complex aortic aneurysms. Regardless of the technique, endovascular management seems to provide a higher benefit in terms of mortality and morbidity perioperatively while the need for reintervention still represents a major issue, with most of them though being minor and endovascularly performed, without impact on survival [29–31]. Except for the main device, target-vessels’ fate plays a significant role in FBEVAR and chEVAR clinical success, with endoleaks, occlusions and instability affecting the durability of the procedure and being related mainly to branches [32]. In this study a multiscale computational approach composed of simple holistic mathematical models combined with advanced 3D CFD simulations could provide clinicians with important information about patients’ hemodynamics. Further clinicians can evaluate the applications of the 3 methods, follow the appropriate treatment strategy for each patient in the treatment of complex aneurysms and predict any postoperative complications. In this analysis evaluating the hemodynamic performance of fenestrated, branched devices and chimney approaches, it was shown that all techniques lead to a reconstruction of the aortic and visceral vessel geometry and hemodynamic results close to normal levels [8,10–13]. Higher-pressure values during the systolic phase were obtained proximally in the main device regarding target-EVAR cases followed by chEVAR while the lowest values were recorded in FEVAR cases. Overall, FEVAR and BEVAR seem to provide similar smoother flow with less regurgitation than the chimney technique.

FEVAR and chEVAR are usually applied in anatomically similar complex abdominal aortic aneurysms, but their application may lead to distinct local hemodynamic changes. An overall improvement in hemodynamics was detected after repair with either technique, with improved hemodynamics towards normal values and reduced recirculation zones in the main graft and target vessels. Preoperatively, a disturbed pro-thrombotic WSS profile was recorded in several zones of the sac in both FEVAR and chEVAR cases. The LNH results showed a better organization of the helical structures at post-operative setting, decreasing thrombus formation, with either modality. Similarly, TAWSS increased and OSI decreased post-operatively, signaling non-disturbed blood flow. The RRT was locally reduced. The flow in target vessels tended to be more streamlined in chEVAR, compared to evident recirculation regions at renal and superior mesenteric artery fenestrations ($p = 0.06$); a finding probably related to the configuration of the bridging stent, with chimney grafts running vertically while the fenestration bridging stents run transversely. However, FEVAR showed less intense flow regurgitation in bridging stents.

Regarding the comparative findings on BEVAR and FEVAR, the hemodynamic characteristics after the repair were clearly improved regardless of the approach. The WSS profiles of BEVARs show slightly higher values, compared to FEVARs. LNH in both cases improved by suppressing the

disturbed blood flow but providing a more balanced distribution in FEVARs cases. The distribution of TAWSS in BEVAR was prominently increased in the entire structure, which leads to low values of OSI and RRT. The flow in target vessels seems to be more streamlined in FEVAR but presents an instant increase, compared to BEVAR where the flow develops gradually, with BEVAR showing slightly less recirculation zones in the branches, in contrast to FEVAR where the flow is more stable. These findings justify the fact that in FEVAR, we have less occlusion and more stable technical outcomes in target vessels as also reported in the literature [33,34].

Limitations. The elastic properties of the graft material were not considered, and the surface of the lumen was modeled as rigid. Blood could be modeled as non-Newtonian fluid, separating red blood cells from plasma, which were considered in the current study as a single continuum medium. The geometric and structural parameters employed in the 1D arterial model were based on bibliographic data. A future arterial model could be constructed with a geometry and elasticity database derived from patient-based measurements, and the model predictions would be compared with non-invasive measurements. The selection of the patients utilized in the present study was made after anatomical control, so that our sample is morphologically comparable. In the comparative results of FEVAR, chEVAR and BEVAR, the different preoperative anatomical characteristics should be considered. To validate the hemodynamic predictions, we could impose patient-specific boundary conditions on each individual patient. An extended study on a larger cohort of patients could shed light on the hemodynamics of patients undergoing complex endovascular repair. In addition, patient-specific boundary conditions could be imposed on each individual patient for obtaining more accurate hemodynamic predictions.

5. Conclusions

In this study, a multiscale modeling framework was employed, coupling low-order computational models with three-dimensional CFD simulations to investigate postoperative aortic hemodynamics. Key flow-related quantities, including velocity, local normalized helicity (LNH), wall shear stress (WSS), and time-averaged wall shear stress (TAWSS), were analyzed in patient-specific aortic geometries following implantation of advanced endovascular devices, namely BEVAR, chEVAR, and FEVAR.

All three endovascular designs led to an overall improvement in postoperative blood flow characteristics toward near-physiological conditions, with a reduction in adverse flow patterns and recirculation zones. FEVAR demonstrated more stable visceral artery perfusion, BEVAR exhibited higher flow rates with fewer recirculation regions, while chEVAR showed more streamlined visceral artery flow accompanied by reduced regurgitation at the bridging stent entries. Despite these differences, all configurations effectively preserved visceral artery perfusion.

Overall, all EVAR designs produced comparable hemodynamic outcomes across most parameters and consistently improved flow conditions relative to the pathological state. FEVAR was associated with lower velocity magnitudes and more uniform, smoother helicity distributions compared to BEVAR and chEVAR. In contrast, the multiscale model predicted higher visceral artery flow values in the BEVAR configuration relative to FEVAR. The use of three-dimensional, patient-specific aortic models enhances the clinical relevance of the present findings and supports their potential application in personalized treatment planning. These results may further contribute to the future technological refinement of branch endografts tailored for use in F/BEVAR and chEVAR procedures.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Conceptualization, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; methodology, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; software, S.M, S.K, A.R, L.F., and M.X.; validation, S.M, S.K, A.R, L.F., P.N., M.X. and M.M.; formal analysis, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; investigation, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; resources, A.G., M.X. and M.M.; data curation,

S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; writing—original draft preparation, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; writing—review and editing, S.M, S.K, A.R, L.F., P.N., G.K., A.G., M.X. and M.M.; visualization, S.M, S.K, A.R and L.F.; supervision, P.N., G.K., A.G., M.X. and M.M.; project administration, A.G., M.X. and M.M.; funding acquisition, G.K., A.G., M.X. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially carried out within the framework of the Action “Flagship actions in interdisciplinary scientific fields with a special focus on the productive fabric”, which is implemented through the National Recovery and Resilience Plan Greece 2.0, funded by the European Union—NextGenerationEU (Project ID: TAEDR-0535983).”.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FEVAR	Fenestrated endovascular repair
BEVAR	Branched endovascular repair
chEVAR	Chimney endovascular repair
CFD	Computational fluid dynamics
WSS	Wall shear stress
AAA	Abdominal aortic aneurysm
RRA	Right renal artery
LRA	Left renal artery
SMA	Superior mesenteric Artery
CA	Celiac artery
RRT	Relative residence time
OSI	Oscillatory Shear Index
TAWSS	Time-averaged wall shear stress
LNH	Local normalized helicity

References

1. Tran K, Deslarzes-Dubuis C, DeGlise S, Kaladji A, Yang W, Marsden AL, et al. Patient-specific computational flow simulation reveals significant differences in paravisceral aortic hemodynamics between fenestrated and branched endovascular aneurysm repair. *JVS-Vascular Science* 2024;5. <https://doi.org/10.1016/j.jvssci.2023.100183>,284.
2. Greenberg R, Eagleton M, Mastracci T. Branched endografts for thoracoabdominal aneurysms. *The Journal of Thoracic and Cardiovascular Surgery* 2010; 140:S171–8. <https://doi.org/10.1016/j.jtcvs.2010.07.061>
3. Wanhainen A, Van Herzelee I, Bastos Goncalves F, Bellmunt Montoya S, Berard X, Boyle JR, D'Oria M, Prendes CF, Karkos CD, Kazimierczak A, Koelemay MJW, Kölbel T, Mani K, Melissano G, Powell JT, Trimarchi S, Tsilimparis N; ESVS Guidelines Committee; Antoniou GA, Björck M, Coscas R, Dias NV, Kolh P, Lepidi S, Mees BME, Resch TA, Ricco JB, Tulamo R, Twine CP; Document Reviewers; Branzan D, Cheng SWK, Dalman RL, Dick F, Golledge J, Haulon S, van Herwaarden JA, Ilic NS, Jawien A, Mastracci TM, Oderich GS, Verzini F, Yeung KK. Editor's Choice -- European Society for Vascular Surgery (ESVS) 2024 Clinical Practice Guidelines on the Management of Abdominal Aorto-Iliac Artery Aneurysms. *Eur J Vasc Endovasc Surg.* 2024 Feb;67(2):192-331.

4. Finnesgard EJ, Jones DW, Beck AW, Eagleton MJ, Farber MA, Gasper WJ, Lee WA, Oderich GS, Schneider DB, Sweet MP, Timaran CH, Schanzer A; United States Aortic Research Consortium. Trends and outcomes over time with fenestrated and branched endovascular aortic repair in the United States Aortic Research Consortium. *J Vasc Surg*. 2025 Jun;81(6):1235-1243.
5. Fargion AT, Esposito D, Speziali S, Pulli R, Gallitto E, Faggioli G, Gargiulo M, Bertoglio L, Melissano G, Chiesa R, Simonte G, Isernia G, Lenti M, Pratesi C; Italian Multicentre Fenestrated and Branched (IMF&B) Study Group. Fate of target visceral vessels in fenestrated and branched complex endovascular aortic repair. *J Vasc Surg*. 2023 Sep;78(3):584-592.e2.
6. Dossabhoy SS, Simons JP, Diamond KR, Flahive JM, Aiello FA, Arous EJ, Messina LM, Schanzer A. Reinterventions after fenestrated or branched endovascular aortic aneurysm repair. *J Vasc Surg*. 2018 Sep;68(3):669-681.
7. Gorgatti F, Nana P, Panuccio G, Rohlfes F, Torrealba JL, Kölbel T. Post-dissection Thoraco-abdominal Aortic Aneurysm Managed by Fenestrated or Branched Endovascular Aortic Repair. *Eur J Vasc Endovasc Surg*. 2024 Sep;68(3):325-334.
8. Malatos S, Fazzini L, Raptis A, Nana P, Kouvelos G, Tasso P, et al. Evaluation of Hemodynamic Properties After Chimney and Fenestrated Endovascular Aneurysm Repair. *Annals of Vascular Surgery* 2024; 104:237–47. <https://doi.org/10.1016/j.avsg.2023.12.084>.
9. Katsoudas S, Malatos S, Raptis A, Matsagkas M, Giannoukas A, Xenos M. Blood Flow Simulation in Bifurcating Arteries: A Multiscale Approach After Fenestrated and Branched Endovascular Aneurysm Repair. *Mathematics*. 2025; 13(9):1362. <https://doi.org/10.3390/math13091362>.
10. Raptis A, Xenos M, Georgakarakos E, Kouvelos G, Giannoukas A, Labropoulos N, et al. Comparison of physiological and post-endovascular aneurysm repair infrarenal blood flow. *Comput Methods Biomech Biomed Engin* 2017; 20:242–9. <https://doi.org/10.1080/10255842.2016.1215437>.
11. Suess T, Anderson J, Danielson L, Pohlson K, Remund T, Blears E, et al. Examination of near-wall hemodynamic parameters in the renal bridging stent of various stent graft configurations for repairing visceral branched aortic aneurysms. *Journal of Vascular Surgery* 2016; 64:788–96. <https://doi.org/10.1016/j.jvs.2015.04.421>.
12. Tran K, Deslarzes-Dubuis C, DeGlise S, Kaladji A, Yang W, Marsden AL, et al. Patient-specific computational flow simulation reveals significant differences in paravisceral aortic hemodynamics between fenestrated and branched endovascular aneurysm repair. *JVS-Vascular Science* 2024;5. <https://doi.org/10.1016/j.jvssci.2023.100183>.
13. Malatos S, Raptis A, Xenos MA, Kouvelos G, Katsargyris A, Giannoukas A, et al. A multiscale model for hemodynamic properties' prediction after fenestrated endovascular aneurysm repair. *A pilot study* 2019;1.
14. Chait J, Tenorio ER, Mendes BC, Barbosa Lima GB, Marcondes GB, Wong J, Macedo TA, De Martino RR, Oderich GS. Impact of gap distance between fenestration and aortic wall on target artery instability following fenestrated-branched endovascular aortic repair. *J Vasc Surg*. 2022 Jul;76(1):79-87.e4.
15. Fazzini S, Martinelli O, Torsello G, Austermann M, Pipitone MD, Torsello GF, Irace L, Donas KP. The PROTAGORAS 2.0 Study to Identify Sizing and Planning Predictors for Optimal Outcomes in Abdominal Chimney Endovascular Procedures. *Eur J Vasc Endovasc Surg*. 2021 Apr;61(4):591-602.
16. Olufsen MS, Peskin CS, Kim WY, Pedersen EM, Nadim A, Larsen J. Numerical simulation and experimental validation of blood flow in arteries with structured-tree outflow conditions. *Ann Biomed Eng* 2000; 28:1281–99. <https://doi.org/10.1114/1.1326031>.

17. Reymond P, Merenda F, Perren F, Rüfenacht D, Stergiopoulos N. Validation of a one-dimensional model of the systemic arterial tree. *American Journal of Physiology-Heart and Circulatory Physiology* 2009; 297:H208–22. <https://doi.org/10.1152/ajpheart.00037.2009>.
18. Malatos S. *Advances in Low-Dimensional Mathematical Modeling of the Human Cardiovascular System* n.d.
19. Morbiducci U, Ponzini R, Gallo D, Bignardi C, Rizzo G. Inflow boundary conditions for image-based computational hemodynamics: impact of idealized versus measured velocity profiles in the human aorta. *J Biomech* 2013; 46:102–9. <https://doi.org/10.1016/j.jbiomech.2012.10.012>.
20. van de Vosse F, Stergiopoulos N. Pulse Wave Propagation in the Arterial Tree. *Annu Rev Fluid Mech* 2011; 43:467–99. <https://doi.org/10.1146/annurev-fluid-122109-160730>.
21. Raptis A, Xenos M, Georgakarakos E, Kouvelos G, Giannoukas A, Matsagkas M. Hemodynamic Profile of Two Aortic Endografts Accounting for Their Postimplantation Position. *Journal of Medical Devices* 2017;11. <https://doi.org/10.1115/1.4035687>.
22. Reymond P, Bohraus Y, Perren F, Lazeyras F, Stergiopoulos N. Validation of a patient-specific one-dimensional model of the systemic arterial tree. *Am J Physiol Heart Circ Physiol* 2011;301:H1173–1182. <https://doi.org/10.1152/ajpheart.00821.2010>.
23. Alastruey J, Parker K, Peiro J, Sherwin S. Lumped parameter outflow models for 1-D blood flow simulations: Effect on pulse waves and parameter estimation. *Communications in Computational Physics* 2008; 4:317–36.
24. Sherwin SJ, Franke V, Peiró J, Parker K. One-dimensional modelling of a vascular network in space-time variables. *Journal of Engineering Mathematics* 2003; 47:217–50. <https://doi.org/10.1023/B:ENGL.0000007979.32871.e2>.
25. Xiao N, Humphrey JD, Figueroa CA. Multi-scale computational model of three-dimensional hemodynamics within a deformable full-body arterial network. *Journal of Computational Physics* 2013; 244:22–40. <https://doi.org/10.1016/j.jcp.2012.09.016>.
26. Tasso P, Raptis A, Matsagkas M, Rizzini ML, Gallo D, Xenos M, et al. Abdominal Aortic Aneurysm Endovascular Repair: Profiling Postimplantation Morphometry and Hemodynamics With Image-Based Computational Fluid Dynamics. *J Biomech Eng* 2018; 140:111003. <https://doi.org/10.1115/1.4040337>.
27. Pan W, Kulisa P, Bou-Saïd B, Hajem ME, Simoëns S, Sigovan M. A proposal of risk indicators for pathological development from hemodynamic simulation: application to aortic dissection. *Journal of Cardiology and Cardiovascular Medicine* 2023; 8:029–38. <https://doi.org/10.29328/journal.jccm.1001150>.
28. Gallo D, Bijari PB, Morbiducci U, Qiao Y, Xie YJ, Etesami M, et al. Segment-specific associations between local haemodynamic and imaging markers of early atherosclerosis at the carotid artery: an in vivo human study. *J R Soc Interface* 2018; 15:20180352. <https://doi.org/10.1098/rsif.2018.0352>.
29. Raulli SJ, Gomes VC, Parodi FE, Vasan P, Sun D, Marston WA, Pascarella L, McGinagle KL, Wood JC, Farber MA. Five-year outcomes of fenestrated and branched endovascular repair of complex aortic aneurysms based on aneurysm extent. *J Vasc Surg*. 2024 Aug;80(2):302–310.
30. Dossabhoy SS, Sorondo SM, Tran K, Stern JR, Dalman RL, Lee JT. Reintervention does not affect long-term survival after fenestrated endovascular aneurysm repair. *J Vasc Surg*. 2022 Nov;76(5):1180–1188.e8.
31. Bannazadeh M, Beckerman WE, Korayem AH, McKinsey JF. Two-year evaluation of fenestrated and parallel branch endografts for the treatment of juxtarenal, suprarenal, and thoracoabdominal aneurysms at a single institution. *J Vasc Surg*. 2020 Jan;71(1):15–22.
32. Tenorio ER, Schanzer A, Timaran CH, Schneider DB, Mendes BC, Eagleton MJ, Farber MA, Parodi FE, Gasper WJ, Beck AW, Sweet MP, Huang Y, Oderich GS; U.S. Fenestrated and Branched Aortic Research

- Consortium. Mid-term Renal and Mesenteric Artery Outcomes During Fenestrated and Branched Endovascular Aortic Repair for Complex Abdominal and Thoracoabdominal Aortic Aneurysms in the United States Aortic Research Consortium. *Ann Surg*. 2023 Oct 1;278(4): e893-e902.
33. T Pini R, Faggioli G, Gallitto E, Mascoli C, Fenelli C, Ancetti S, Vacirca A, Gargiulo M. The different effect of branches and fenestrations on early and long-term visceral vessel patency in complex aortic endovascular repair. *J Vasc Surg*. 2020 Apr;71(4):1128-1134.
34. T Martin-Gonzalez T, Mastracci T, Carrell T, Constantinou J, Dias N, Katsargyris A, Modarai B, Resch T, Verhoeven E, Haulon S. Mid-term Outcomes of Renal Branches Versus Renal Fenestrations for Thoracoabdominal Aneurysm Repair. *Eur J Vasc Endovasc Surg*. 2016 Aug;52(2):141-8.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.