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ANALYSIS OF ANEURYSMS IN MIDDLE CEREBRAL ARTERIES: A REVIEW OF CURRENT COMPUTATIONAL MODELLING

Ahmad Faiz Mat Zin[1]*, Ishkrizat Taib[2], Muhammad Riddha Abdul Rahman[3], Mohd Shahir Yahya[4], Muhammad Sufi Roslan[5]

[1]Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Malaysia
ahmadfaiz@uthm.edu.my https://orcid.org/0000-0001-7579-929X
[2]Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, Malaysia
iszat@uthm.edu.my https://orcid.org/0000-0002-4722-9211
[3]Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, Malaysia
ridhafiz@gmail.com https://orcid.org/0000-0002-0625-2597
[4]Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Malaysia
shahir@uthm.edu.my https://orcid.org/0000-0002-7149-0743
[5]Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, Malaysia
sufi@uthm.edu.my https://orcid.org/0000-0003-4838-1132
*Corresponding Author

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Abstract:

Cerebral aneurysms in the middle cerebral artery (MCA), particularly saccular aneurysms, present a significant clinical risk due to their potential for rupture and associated high morbidity and mortality. This review aims to analyse current computational modelling approaches used to investigate haemodynamics, rupture risk, and treatment strategies for MCA aneurysms. A systematic literature review was conducted using three major databases: PubMed, Scopus, and IEEE. Articles published between 2019 and 2024 were identified using predefined keywords related to saccular aneurysms, computational modelling, and MCA. Inclusion criteria focused on original studies involving human or patient-specific models, while non-computational studies, reviews, and non-MCA-related research were excluded. A total of 14 studies were selected following PRISMA guidelines. Data were extracted and synthesised based on modelling approaches, haemodynamic parameters, and clinical applications. Most studies employed computational fluid dynamics (CFD) to analyse haemodynamic factors, including wall shear stress (WSS), oscillatory shear index (OSI), and inflow jet dynamics. These parameters were consistently associated with aneurysm growth and rupture risk. Patient-specific modelling and integration with imaging techniques, such as computed tomography angiography (CTA) and magnetic resonance

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imaging (MRI), improved simulation accuracy. Alternative computational methods, including finite element analysis (FEA), statistical modelling, and image-based reconstruction, complement CFD in device evaluation and morphological assessment. Additionally, computational modelling has been widely applied in optimising treatment strategies, including flow-diverting devices and bypass surgeries. Computational modelling plays a crucial role in advancing the understanding and management of MCA aneurysms. While CFD remains the dominant approach for haemodynamic analysis, integrating multi-modal imaging, patient-specific data, and emerging techniques such as machine learning can further improve rupture risk prediction and personalised treatment planning. Future research should focus on enhancing model accuracy and clinical translation.

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Keyword:

Computational Fluid Dynamics, Haemodynamic, Middle Cerebral Artery, Patient-Specific Modelling, Rupture Risk, Saccular Aneurysm, Wall Shear Stress

Introduction

Cerebral aneurysms, particularly saccular aneurysms, pose significant clinical challenges due to their propensity for rupture, which can lead to severe neurological deficits and high mortality rates. Saccular cerebral aneurysms are the most prevalent type of intracranial aneurysm, characterised by a rounded shape. They typically form at arterial bifurcations, such as in the anterior circulation of the brain and at the origin of the middle cerebral artery. The risk of rupture is estimated to be 1% per year, but this can vary depending on factors such as the size and location of the aneurysm. Rupture in cerebral aneurysms commonly occurs at the weak apex or pole, yet some cases involve rupture at the aneurysm body or neck (Fukuzama et al., 2015). Once ruptured, the mortality rate from subarachnoid haemorrhage can be as high as 40–65%, with significant morbidity in survivors (Fennel et al., 2016).

Finding and treating aneurysms before their rupture is challenging, as the symptoms can be easily mistaken for other common brain diseases (Drapaca, 2018). Therefore, predicting aneurysm rupture is critical for effective patient management and intervention strategies. In recent years, computational modelling has emerged as a powerful tool for understanding the complex biomechanical behaviours of these vascular structures. Computational fluid dynamics (CFD) modelling has emerged as a promising tool for understanding thermal-fluid dynamics in biological tissues, further advancing understanding of the mechanisms underlying aneurysm initiation, growth, and rupture (Khairi Azhar et al., 2024). Specifically, CFD analysis can characterise the local haemodynamic features of rupture points in middle cerebral artery (MCA) aneurysms (Fukuzama et al.,2024). By leveraging patient-specific geometries and realistic pulsatile flow conditions, CFD can provide detailed, localised haemodynamic insights that are otherwise unattainable through experimental or clinical observation alone (Mat Zin et al., 2022).

This review explores computational approaches for predicting rupture of saccular aneurysms in the cerebral arteries, specifically the middle cerebral arteries. By integrating haemodynamic simulations, structural analyses, and patient-specific geometries, these models aim to enhance the accuracy of rupture risk assessments and improve clinical outcomes. Furthermore, we will discuss the current advancements, limitations, and future directions in this field, highlighting the potential of computational modelling to revolutionise aneurysm management.

Methodology

Inclusion and Exclusion Criteria

For this review, the following inclusion criteria were set: (a) original articles on computational modelling of the aneurysm in the intracranial artery, especially saccular aneurysms in the middle cerebral artery; thus, the other arterial locations were excluded, and (b) studies on humans or human-simulated anatomy; thus, research on animals or animal simulations was excluded. In addition, this review excluded review papers and book chapters.

Sources and Search Criteria

Three central scientific databases were used for paper searching: PubMed, Scopus, and IEEE. The use of these databases was appropriate, as they index most publications in scientific, medical, and engineering research. We used the following keywords with Boolean operators as inclusion criteria: (saccular aneurysm) AND (computational modelling) AND (middle cerebral artery), and scanned all metadata, especially the title, keywords, and abstract. The search was also restricted to the literature spanning the past five years (2019-2024).

Study Selection

The identified papers were imported into an Excel file, including titles, authors' names, DOIs, and abstracts. The abstracts were used to screen eligible articles for full-text assessment, using the previously established inclusion and exclusion criteria. The study selection process is summarised in Figure 1.

Data Extraction and Synthesis

The following data were extracted from the papers that passed the abstract screening: the computational model, rupture risk prediction, treatment strategies and device evaluation, and imaging reconstruction. Subsequently, the thematic characteristics of the studies were formulated based on the reported findings of the papers

Results

Literature Search

The study used PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) study flow. Using the search strategy, 26 papers were identified from PubMed, 4

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from Scopus, and 1 from the IEEE database, as shown in Figure 1. After removing duplicates, 29 articles were identified. From there, we extracted the abstract to screen for eligibility for inclusion in this review. Based on the abstract screening, 18 papers were selected for full-text assessment. The rest of the papers were excluded because they were non-computational (VR simulation, robotics, and video angiography) or commentaries, and one paper was excluded for being written in Japanese. Of the 18 papers reviewed, 4 were excluded because they focused on arteries other than the MCA. Therefore, the final number of studies included in this review is 14.

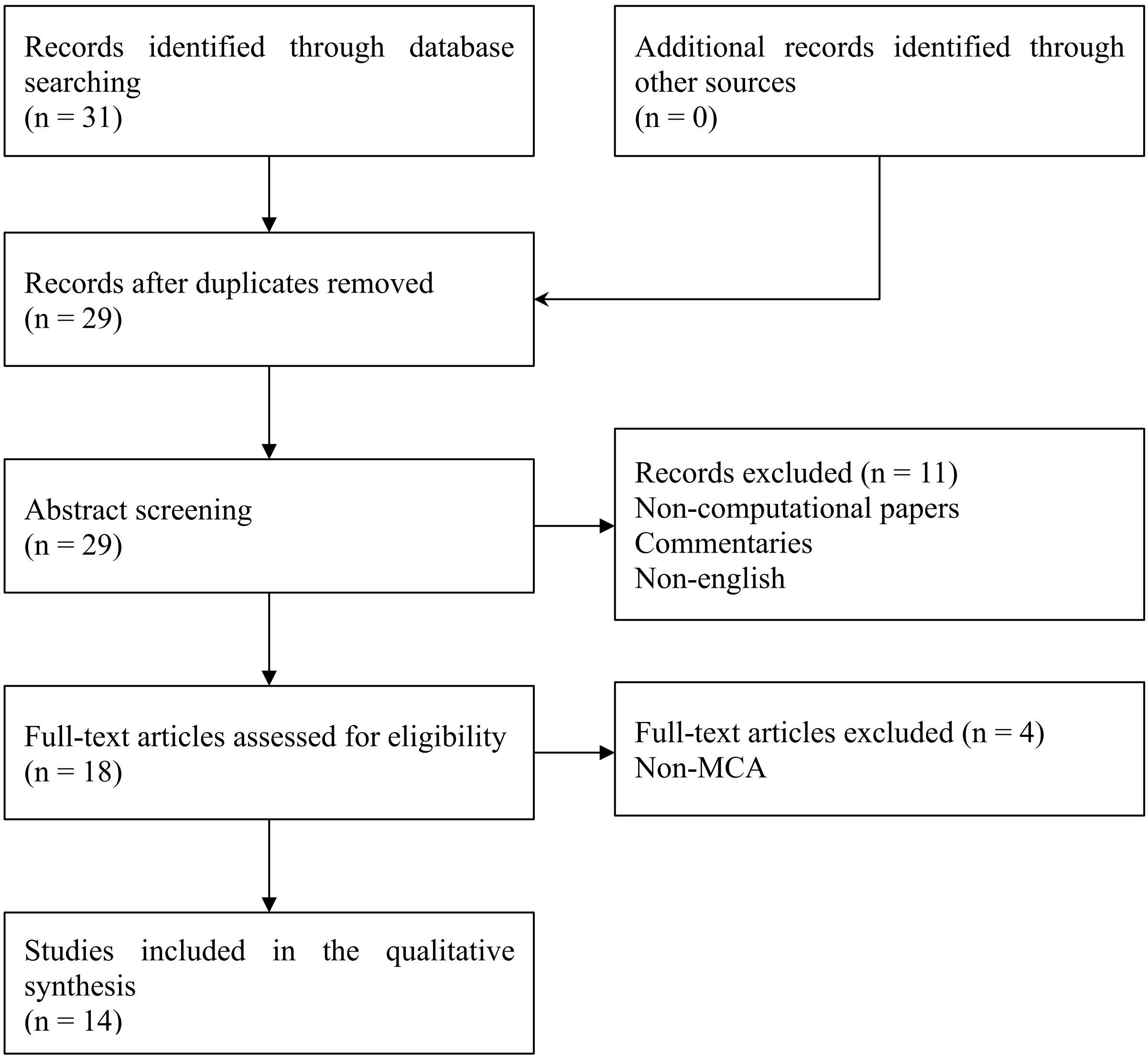

Figure 1: PRISMA Study Flow.

Study Characteristics

From the previous selection, 14 papers that studied the computational model of the saccular aneurysm in the MCA have been identified and reviewed. For this review, the middle cerebral artery was selected as the primary location for the prediction. Table 1 summarises the study characteristics of the reviewed paper.

Aside from the previous characteristics, the studies were also grouped by their use of computational modelling analysis. Most of the studies leverage CFD to explore the relationship between haemodynamic parameters and aneurysm behaviour. In total, ten studies utilised CFD modelling. These investigations applied CFD to simulate blood flow, predict treatment outcomes, and analyse haemodynamic changes. Notably, four studies evaluated haemodynamic parameters, including wall shear stress (WSS) and oscillatory shear index (OSI) (Hu et al., 2022; Larsen et al., 2020; Li et al., 2024; Wiśniewski et al., 2024a, 2024b; Rajabzadeh-Oghaz et al., 2020; Zimny et al., 2021; Sindeev et al., 2019). In comparison, two studies examined the influence of inflow patterns and pressure changes on these parameters (Wiśniewski et al., 2024b; Misaki et al., 2021). Additionally, CFD modelling was enhanced by three-dimensional (3D) aneurysm model reconstructions derived from medical imaging, enabling patient-specific geometric analyses (Wiśniewski et al., 2024a, 2024b; Sindeev et al., 2019). Treatment optimisation and outcome predictions were explored in four studies (Wiśniewski et al., 2024a, 2024b; Lyu et al., 2024; Boite et al., 2023), and aneurysm instability or rupture risk assessments were conducted in four others (Hu et al., 2022; Zimny et al., 2021; Sindeev et al., 2019; Saqr K.M, 2020).

Table 1: Study Characteristics of The Papers Included in The Review

Study Type	n	Demography
Retrospective clinical studies		
Hu et al., 2022	40	Patients with MCA aneurysms
Larsen et al., 2020	22	Patients with focal wall enhancement on magnetic resonance imaging (MRI)
Li et al., 2024	9	Patients treated with extracranial-to-intracranial (EC-IC) bypass surgery
Patient-Specific Computational Studies		
Wiśniewski et al., 2024a	3	Patients with giant intracerebral aneurysms (GIA)
Rajabzadeh-Oghaz et al., 2020	8	Patients with MCA aneurysms
Wiśniewski et al., 2024b	3	Patients with GIA
Zimny et al., 2021	38	Patients with MCA aneurysms
Sindeev et al., 2019	1	Patients with MCA aneurysms
Comparative Computational Studies		
Saqr, 2020	4	Patients with ruptured aneurysm
Lyu et al., 2024	2	Patients with MCA bifurcation aneurysms
Boite et al., 2023	1	Patients with MCA bifurcation aneurysm
Imaging and Biomarker Studies		

Larsen et al., 2020	22	Patients with focal wall enhancement on MR imaging
Munarriz et al., 2021	40	Patients with aneurysmal subarachnoid haemorrhage
Misaki et al., 2021	23	Patients with unruptured aneurysms
Device Design and Testing Studies		
Randhawa et al., 2020	N/A (theoretical study and modelling)	

Other computational models have also been utilised to study aneurysm behaviour and rupture risk. In contrast, four papers employed alternative computational approaches tailored to their specific research objectives. Among the methods used were statistical/clinical analysis (Larsen et al., 2020; Li et al., 2024), structural/mechanical analysis (Li et al., 2024), computer-aided design (CAD), finite element analysis (FEA), basic fluid modelling (Randhawa et al., 2020), and image processing/morphometrics (Munarriz et al., 2021). These studies prioritise imaging biomarkers, device design, 3D reconstruction accuracy, and surgical risk analysis over detailed haemodynamic simulations. Table 2 outlines the CFD and non-CFD studies.

Table 2: Grouping of Studies Using CFD and Non-CFD Modelling Strategies

Modelling strategies	**Count**
CFD modelling (Hu et al., 2022; Wiśniewski et al., 2024a, 2024b; Rajabzadeh-Oghaz et al., 2020; Zimny et al., 2021; Sindeev et al., 2019; Saqr K.M., 2020; Lyu et al., 2024; Boite et al., 2023; Misaki et al., 2021)	10
Non-CFD modelling	
Statistical biomarker analysis (Larsen et al., 2020)	1
CAD, FEA, basic fluid modelling (Randhawa et al., 2020)	1
Image segmentation and morphometrics (Huo et al., 2024)	1
Clinical/biomechanical statistical analysis (Li et al., 2024)	1

Afterwards, four key thematic characteristic groups were identified and extracted from the papers: haemodynamic analysis and rupture risk prediction; treatment strategies and device evaluation; imaging and 3D reconstruction; and novel devices and technologies. Regarding aneurysms, these papers discussed saccular and GIA aneurysms involving the MCA. Table 3 and Table 4 summarise the thematic groups of the studies and the type of aneurysm at the MCA, respectively.

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Table 3: Thematic Groups Identified from The Papers Included in The Review

Thematic group	**Count**
Haemodynamics Analysis and Rupture Risk Prediction (Hu et al., 2022; Larsen et al., 2020; Zimny et al., 2021; Sindeev et al., 2019; Saqr K.M, 2020; Misaki et al., 2021)	6
Treatment Strategies and Device Evaluation (Li et al., 2024; Wiśniewski et al., 2024a, 2024b; Lyu et al., 2024; Boite et al., 2023; Randhawa et al., 2020)	6
Imaging And 3D Reconstruction (Larsen et al., 2020; Munarriz et al., 2021; Misaki et al., 2021)	3

Table 4: Types of Aneurysms Found in the MCA

Aneurysm type	Count
Saccular Aneurysms (Hu et al., 2022; Rajabzadeh-Oghaz et al., 2020; Zimny et al., 2021; Sindeev et al., 2019; Lyu et al., 2024; Boite et al., 2023)	6
Giant Intracranial Aneurysms (Li et al., 2024; Wiśniewski et al., 2024a, 2024b)	3

Among the reviewed studies, six papers focused on predicting rupture risk and analysing haemodynamic factors. For instance, elevated WSS, positive WSS gradients, and low WSS zones were associated with heightened rupture risk in MCA aneurysms (Hu et al., 2022; Zimny et al., 2021; Sindeev et al., 2019). However, Hu et al. (2022) and Zimny et al. (2021) prioritised morphological factors, such as aneurysm size and neck diameter, alongside WSS (Hu et al., 2022; Zimny et al., 2021), whereas Sindeev et al. (2019) emphasised flow impingement zones (Sindeev et al., 2019). Saqr (2020) distinguishes itself by comparing Newtonian and non-Newtonian blood flow models, advocating for the modified Krieger model to better capture rupture-prone haemodynamics (Saqr K.M, 2020), while Misaki et al. (2021) validate CFD-predicted inflow patterns, such as jet dynamics, against four-dimensional (4D) flow MRI (Misaki et al., 2021). Collectively, these studies underscore the centrality of CFD in rupture risk assessment while highlighting the need for context-specific analysis, whether through advanced imaging integration (Misaki et al., 2021), non-Newtonian modelling (Saqr K.M, 2020), or artery-specific haemodynamic profiling (Hu et al., 2022; Zimny et al., 2021; Sindeev et al., 2019).

Treatment strategies and device evaluation were also discussed in some of the papers reviewed. In particular, the evaluation of flow diverters, bypass surgery, and novel devices, such as contour devices, for treating aneurysms was explored, with papers focused on optimising treatment outcomes and reducing complications. Wiśniewski et al. (2024) employed CFD to simulate EC-IC bypass combined with proximal artery occlusion for GIAs (Wiśniewski et al., 2024a, 2024b) , while Boite et al. (2023) and Lyu et al. (2024) evaluated flow-diverting devices, such as the Contour device, for MCA bifurcation aneurysms (Lyu et al., 2024; Boite et al., 2023). These approaches aim to minimise aneurysm inflow while preserving flow to adjacent branches. Notably, Randhawa et al. (2020) diverge by proposing a novel device for treating

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haemorrhagic stroke caused by ruptured saccular aneurysms, shifting the focus from prevention to post-rupture intervention (Randhawa et al., 2020). Methodologically, these studies rely on CFD for haemodynamic analysis, though Li et al. (2024) incorporate retrospective clinical data and biomechanical models to assess bypass risks (Li et al., 2024), and Randhawa et al. (2020) combine CAD with CFD for device development (Randhawa et al., 2020).

Lastly, three papers discussed model reconstruction from imaging data. These studies focus on advanced imaging techniques, such as magnetic resonance angiography (MRA) and computed tomography angiography (CTA), as well as 3D reconstruction methods for aneurysm analysis and treatment planning. Specifically, Larsen et al. (2020) examined focal wall enhancement on MR imaging as a potential biomarker for aneurysm instability (Larsen et al., 2020). Munarriz et al. (2021) evaluated the reliability and accuracy of reconstruction software (VMTKlab) for generating 3D aneurysm models from CTA images (Munarriz et al., 2021). Moreover, Misaki et al. (2021) investigated inflow haemodynamics using a combination of CFD and 4D flow MRI (Misaki et al., 2021).

Discussion

The studies reviewed collectively demonstrate the transformative role of computational modelling, advanced imaging, and clinical data analysis in understanding, diagnosing, and treating intracranial aneurysms. These investigations can be broadly categorised into two groups: those employing CFD to analyse haemodynamics and rupture risk and those utilising alternative computational methods, such as statistical analysis, image processing, and structural mechanics, to address distinct clinical challenges. Below, we discuss these studies in the context of their key thematic groups: haemodynamic analysis and rupture risk, treatment strategies and device evaluation, and imaging and biomarker studies.

Haemodynamic Analysis and Rupture Risk

Haemodynamic factors play a crucial role in the development, progression, and rupture risk of intracranial aneurysms (Huo & Chang, 2024; Can & Du, 2016). Recent studies employing CFD, 4D flow MRI, and patient-specific modelling have provided valuable insights into the biomechanical forces influencing aneurysm stability (Hu et al., 2022; Larsen et al., 2020; Rajabzadeh-Oghaz et al, 2020; Zimny et al., 2021; Sindeev et al., 2019; Saqr K.M., 2020; Misaki et al., 2021). Across multiple studies, several key haemodynamic parameters have emerged as strong predictors of rupture, including WSS, OSI, wall shear stress gradient (WSSG), and inflow jet velocity.

Low WSS has been consistently associated with aneurysm wall degeneration and an increased likelihood of rupture. Studies by Sindeev et al. (2019), Saqr (2020), Larsen et al. (2020), and Misaki et al. (2021) confirm that regions of low WSS, particularly in the aneurysm dome, are prone to endothelial dysfunction and thinning of the arterial wall (Larsen et al., 2020; Sindeev et al., 2019; Saqr K.M., 2020; Misaki et al., 2021). Furthermore, Sindeev et al. (2019) highlight swirling flow patterns and high-velocity impingement zones, which can contribute to progressive wall weakening (Sindeev et al., 2019). Conversely, Larsen et al. (2020) and Hu et al. (2022) identify high OSI as a significant marker of aneurysm instability, as it indicates disturbed, bidirectional blood flow that exacerbates endothelial stress (Hu et al., 2022; Larsen et al., 2020). These findings suggest that the interaction between low WSS and high OSI creates a haemodynamic environment conducive to aneurysm growth and rupture.

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In addition to WSS and OSI, recent research by Zimny et al. (2021) introduces WSSG as an independent predictor of aneurysm formation and rupture risk. This study demonstrates that aneurysms are more likely to develop in regions of high WSS combined with a positive WSSG, underscoring the importance of shear stress fluctuations in aneurysm pathology (Zimny et al., 2021). This novel parameter provides a more nuanced understanding of the mechanical forces influencing aneurysm evolution. Similarly, Rajabzadeh-Oghaz et al. (2020) emphasise the necessity of patient-specific blood flow conditions in CFD-based rupture risk assessments, demonstrating that variations in inflow rate can lead to significant discrepancies in WSS and OSI calculations. The findings suggest that generalised CFD models, which do not account for inter-patient variability, may lead to inaccurate risk stratification (Rajabzadeh-Oghaz et al., 2020).

A key area of investigation is the comparative efficacy of CFD and 4D flow MRI in haemodynamic analysis. Misaki et al. (2021) reveal that CFD provides superior spatial and temporal resolution in detecting inflow jet dynamics, particularly in bifurcation aneurysms. While 4D flow MRI remains a valuable non-invasive diagnostic tool, it has been shown to underestimate WSS by 22–76% compared to CFD (Misaki et al., 2021). These findings highlight the continued need for CFD in aneurysm research and clinical decision-making, particularly when precise haemodynamic measurements are required. Furthermore, Saqr (2020) demonstrates that non-Newtonian blood models, such as the Modified Krieger Model (MKM), provide more realistic haemodynamic predictions than traditional Newtonian assumptions. This is particularly relevant for aneurysm rupture risk assessment, as Newtonian models tend to overestimate WSS and may misclassify at-risk aneurysms (Saqr K.M., 2020). Accordingly, these studies highlight the importance of a multi-parametric approach to assessing aneurysm rupture risk.

Treatment Strategies and Device Evaluation

Advancements in endovascular devices and surgical techniques have significantly expanded treatment options for intracranial aneurysms. Recent studies have explored the efficacy of flow-diverting stents, novel endovascular implants, and bypass procedures, demonstrating the importance of haemodynamic optimisation in treatment planning (Li et al., 2024; Wiśniewski et al., 2024a, 2024b; Boite et al., 203; Randhawa et al., 2020). The integration of CFD and FEA has further refined these strategies, enabling clinicians to assess device performance and predict post-treatment haemodynamic changes.

A key area of innovation is the development of novel flow-diversion devices. Lyu et al. (2024) compare the Contour device, a novel flow disruptor, with conventional flow diverters, highlighting its superior aneurysm inflow reduction (~91.25%) while preserving side branch patency. In contrast, traditional flow-diverters demonstrated a higher risk of branch occlusion (~8.60%), which can compromise cerebral perfusion (Lyu et al., 2024). This finding aligns with Boite et al. (2023), who investigated flow-diverting stents in bifurcation aneurysms and found that stent placement significantly reduces WSS within the aneurysm sac. However, the study emphasises that stent positioning can affect blood flow in adjacent branches, necessitating precise preoperative planning to avoid ischaemic complications (Boite et al., 2023).

In addition to endovascular devices, surgical bypass procedures remain a viable option for complex aneurysms. Wiśniewski et al. (2024) employed CFD simulations to evaluate intracranial bypass surgery, demonstrating that bypass revascularisation combined with parent artery occlusion effectively reduces intra-aneurysmal pressure and promotes thrombosis formation (Wiśniewski et al., 2024a, 2024b). The study also finds that bypass placement significantly alters global cerebral haemodynamics, reinforcing the need for individualised surgical planning based on patient-specific vascular anatomy (Wiśniewski et al., 2024b). Similarly, Li et al. (2024) investigated the use of proximal artery clipping combined with a distal high-flow bypass for GIAs and identified the "stump phenomenon" as a potential postoperative complication. The study highlights that patients lacking adequate collateral circulation may experience increased haemodynamic stress, which could elevate the risk of rupture following surgery (Li et al., 2024).

Beyond clinical application, device engineering and computational modelling play a crucial role in refining treatment strategies. Randhawa et al. (2020) introduced a novel self-expanding Nitinol stent with an expanded polytetrafluoroethylene (ePTFE) graft, designed to prevent blood leakage in ruptured aneurysms. Through a combination of FEA for structural analysis and CFD for haemodynamic assessment, the study demonstrates that a closed-cell stent with an "S" connector provides optimal stability and flow regulation (Randhawa et al., 2020). Similarly, a computational study by Wiśniewski et al. (2024) supports integrating preoperative CFD-based virtual surgery to determine the most effective bypass configurations for reducing haemodynamic stress on aneurysm walls (Wiśniewski et al., 2024a).

Collectively, these studies highlight the need for a patient-specific, haemodynamically optimised approach to aneurysm treatment. Endovascular flow-diversion devices, bypass techniques, and novel stent design each offer distinct advantages, yet their success depends on precise preoperative modelling and personalised treatment selection. As computational methods continue to advance, they will play an increasingly pivotal role in optimising device design, predicting treatment outcomes, and improving long-term patient safety.

Imaging and Biomarker Studies

Advancements in medical imaging and 3D reconstruction techniques have significantly improved the assessment of aneurysm morphology, haemodynamics, and rupture risk. Recent studies have explored the reliability of imaging-based aneurysm measurements, biomarker identification through vessel wall imaging, and the validation of computational haemodynamic models against in vivo imaging (Larsen et al., 2020; Munarriz et al., 2021; Misaki et al., 2021). These approaches enhance both diagnostic accuracy and treatment planning, particularly when combined with CFD and patient-specific imaging data.

A key area of investigation is the accuracy of 3D reconstruction software in assessing aneurysm morphology. Munarriz et al. (2021) evaluated VMTKLab, a 3D reconstruction tool, by comparing its aneurysm measurements with digital subtraction angiography (DSA), the clinical gold standard. The study finds that VMTKLab provides reliable measurements of aneurysm size and shape but tends to underestimate neck diameter, a critical parameter in rupture risk and treatment decisions (Munarriz et al., 2021). This discrepancy suggests that while 3D reconstruction software is valuable for aneurysm assessment, caution is warranted when interpreting neck dimensions, particularly for surgical or endovascular planning.

Beyond morphology, imaging-based biomarkers have emerged as a promising tool for predicting aneurysm rupture risk. Larsen et al. (2020) explored the role of vessel wall enhancement on MRI, finding that regions of wall enhancement correlate strongly with low

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WSS and high OSI, both haemodynamic indicators of aneurysm instability. Additionally, the histological analysis of enhanced regions reveals signs of inflammation and endothelial degeneration, suggesting that MRI-based wall enhancement may serve as a non-invasive biomarker of aneurysm instability (Larsen et al., 2020). These findings highlight the potential of advanced MRI techniques in complementing CFD-based haemodynamic analysis, particularly for identifying aneurysms that may be at higher risk of rupture despite appearing stable based on morphology alone.

Another critical development in imaging-based aneurysm assessment is the comparison of 4D flow MRI with CFD simulations. Misaki et al. (2021) validated CFD-based haemodynamic analysis against in vivo 4D flow MRI, demonstrating a strong correlation in aneurysm inflow rate, velocity patterns, and inflow jet dynamics. However, the study notes that 4D flow MRI underestimates WSS by 22–76% compared with CFD, likely due to lower spatial resolution and partial-volume effects (Misaki et al., 2021). While CFD remains the preferred method for detailed haemodynamic analysis, 4D flow MRI provides a valuable, non-invasive alternative for clinical settings, particularly for monitoring aneurysms over time without requiring computational modelling.

Taken together, these studies emphasise the importance of integrating imaging-based aneurysm assessment with computational modelling. 3D reconstruction tools enhance morphological evaluation, MRI-based biomarkers provide insights into aneurysm wall pathology, and 4D flow MRI offers a non-invasive means of validating haemodynamic models.

Limitation and Future Directions

Despite these advancements, challenges remain. Many CFD studies rely on simplified assumptions, such as Newtonian blood flow or rigid vessel walls, which may not fully capture the complexity of in vivo conditions. While low WSS, high OSI, and high WSSG remain the most reliable haemodynamic predictors, incorporating patient-specific inflow conditions, non-Newtonian blood viscosity models, and advanced imaging techniques such as 4D flow MRI can further enhance predictive accuracy. Future research should focus on integrating these methodologies into a comprehensive clinical framework to improve early detection and personalised treatment strategies for patients with intracranial aneurysms. Moreover, focus should also be given to refining imaging techniques for more precise haemodynamic assessments, improving 3D reconstruction accuracy, and integrating multimodal imaging with CFD for a more comprehensive aneurysm risk-stratification framework.

Additionally, the clinical translation of computational findings requires further validation through prospective studies and multicentre collaborations. Future research should also explore integrating machine learning and deep learning techniques to enhance the predictive power of computational models and develop real-time simulation tools for intraoperative decision support.

Conclusion

The integration of computational methods, imaging techniques, and novel treatment devices has significantly advanced the understanding and management of intracranial aneurysms. CFD has proven invaluable for haemodynamic analysis, providing precise assessments of WSS, OSI, and inflow dynamics, all of which are critical for predicting rupture risk. However, the accuracy of CFD models is highly dependent on patient-specific boundary conditions, as highlighted by studies demonstrating the limitations of generalised assumptions in flow modelling. Furthermore, alternative computational techniques, including FEA for structural integrity assessment, FSI for arterial wall behaviour analysis, and machine learning for predictive modelling, have complemented CFD, enhancing both diagnostic accuracy and treatment planning. Advances in medical imaging, such as 4D flow MRI and MRI vessel wall enhancement, have provided valuable non-invasive biomarkers of aneurysm instability, though these techniques still require refinement to match the spatial and temporal precision of CFD. The development of novel endovascular devices, such as the Contour flow disruptor and optimised flow-diverting stents, has further improved treatment efficacy and patient outcomes, demonstrating the importance of computational modelling in device design and placement optimisation. As research progresses, the integration of multi-modal imaging, patient-specific computational simulations, and artificial intelligence-driven diagnostics will be essential in refining rupture risk assessment, enhancing personalised treatment strategies, and ultimately improving clinical decision-making in aneurysm management.

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References

Boite, Y., Klein, T. S., De Andrade Medronho, R., & Wajnberg, E. (2023). Numerical simulation of flow-diverting stent: comparison between branches in bifurcation brain aneurysm. Biomechanics and Modeling in Mechanobiology, 22(6), 1801–1814. https://doi.org/10.1007/s10237-023-01733-2.

Can, A., & Du, R. (2016). Association of Hemodynamic Factors With Intracranial Aneurysm Formation and Rupture: Systematic Review and Meta-analysis. Neurosurgery, 78(4), 510–520. https://doi.org/10.1227/NEU.0000000000001083.

Drapaca, C. S. (2018). Poiseuille Flow of a Non-Local Non-Newtonian Fluid with Wall Slip: A First Step in Modeling Cerebral Microaneurysms. *Fractal and Fractional*, *2*(1), 9. https://doi.org/10.3390/fractalfract2010009.

Fukazawa, K., Ishida, F., Umeda, Y., Miura, Y., Shimosaka, S., Matsushima, S., Taki, W., & Suzuki, H. (2015). Using computational fluid dynamics analysis to characterize local hemodynamic features of middle cerebral artery aneurysm rupture points. *World neurosurgery*, *83*(1), 80–86. https://doi.org/10.1016/j.wneu.2013.02.012.

Fennell, V. S., Kalani, M. Y., Atwal, G., Martirosyan, N. L., & Spetzler, R. F. (2016). Biology of Saccular Cerebral Aneurysms: A Review of Current Understanding and Future Directions. *Frontiers in surgery*, *3*, 43. https://doi.org/10.3389/fsurg.2016.00043.

Hu, S. Q., Chen, R. D., Xu, W. D., & Yu, J. S. (2022). Risk factors for the rupture of mirror middle cerebral artery aneurysm using computer-assisted semiautomated measurement and hemodynamic analysis. *Journal of stroke and cerebrovascular diseases : the official journal of National Stroke Association*, *31*(12), 106841. https://doi.org/10.1016/j.jstrokecerebrovasdis.2022.106841.

Huo, H., & Chang, Y. (2024). Hemodynamic study of the ICA aneurysm evolution to attain the cerebral aneurysm rupture risk. *Scientific Reports*, *14*(1), 8984. https://doi.org/10.1038/s41598-024-59242-w.

Khairi Azhar, N. M. H., Ishkrizat Taib, Martin, A. ., Tajul Arifin, A. M. ., Kamarudin, M. S. ., & Roseman, A. H. (2024). Heat Propagation in Multiple Malignant Tumours using the Hyperthermia Therapy. *Journal of Advanced Research in Numerical Heat Transfer*, *26*(1), 1–21. https://doi.org/10.37934/arnht.26.1.121.

Larsen, N., Flüh, C., Saalfeld, S., Voß, S., Hille, G., Trick, D., Wodarg, F., Synowitz, M., Jansen, O., & Berg, P. (2020). Multimodal validation of focal enhancement in intracranial aneurysms as a surrogate marker for aneurysm instability. *Neuroradiology*, *62*(12), 1627–1635. https://doi.org/10.1007/s00234-020-02498-6.

Li, S., Huang, Z., Chen, H., & Chen, F. (2024). Proximal Clipping and Distal High-Flow Bypass in the Treatment of Giant/Complex Intracranial Aneurysm: An Opportunity or a Risk from a Fluid-Structural Interaction Analysis. *Cardiovascular engineering and technology*, *15*(2), 159–170. https://doi.org/10.1007/s13239-023-00704-z.

Lyu, M., Torii, R., Liang, C., Peach, T. W., Bhogal, P., Makalanda, L., Li, Q., Ventikos, Y., & Chen, D. (2024). Treatment for middle cerebral artery bifurcation aneurysms: in silico comparison of the novel Contour device and conventional flow-diverters. *Biomechanics and modeling in mechanobiology*, *23*(4), 1149–1160. https://doi.org/10.1007/s10237-024-01829-3.

Mat Zin, A. F., Ishkrizat Taib, Asril Rajo Mantari, M. H., Bukhari Manshoor, Tajul Arifin, A. M., Mohamad, M. A. H., … Azman, M. R. (2022). Temperature Variation with Hemodynamic Effect Simulation on Wall Shear Stress in Fusiform Cerebral

Aneurysm. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *95*(2), 40–54. https://doi.org/10.37934/arfmts.95.2.4054.

Misaki, K., Futami, K., Uno, T., Nambu, I., Yoshikawa, A., Kamide, T., & Nakada, M. (2021). Inflow Hemodynamics of Intracranial Aneurysms: A Comparison of Computational Fluid Dynamics and 4D Flow Magnetic Resonance Imaging. *Journal of stroke and cerebrovascular diseases : the official journal of National Stroke Association*, *30*(5), 105685. https://doi.org/10.1016/j.jstrokecerebrovasdis.2021.105685.

Munarriz, P. M., Bárcena, E., Alén, J. F., Castaño-Leon, A. M., Paredes, I., Moreno-Gómez, L. M., García-Pérez, D., Jiménez-Roldán, L., Gómez, P. A., & Lagares, A. (2021). Reliability and accuracy assessment of morphometric measurements obtained with software for three-dimensional reconstruction of brain aneurysms relative to cerebral angiography measures. *Interventional neuroradiology : journal of peritherapeutic neuroradiology, surgical procedures and related neurosciences*, *27*(2), 191–199. https://doi.org/10.1177/1591019920961588.

Rajabzadeh-Oghaz, H., van Ooij, P., Veeturi, S. S., Tutino, V. M., Zwanenburg, J. J., & Meng, H. (2020). Inter-patient variations in flow boundary conditions at middle cerebral artery from 7T PC-MRI and influence on Computational Fluid Dynamics of intracranial aneurysms. *Computers in biology and medicine*, *120*, 103759. https://doi.org/10.1016/j.compbiomed.2020.103759.

Randhawa, H. S., Pearce, G., Hepton, R., Wong, J., Zidane, I. F., & Ma, X. (2020). An investigation into the design of a device to treat haemorrhagic stroke. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *234*(4), 323-336. https://doi.org/10.1177/0954411919890698.

Saqr K. M. (2020). Computational fluid dynamics simulations of cerebral aneurysm using Newtonian, power-law and quasi-mechanistic blood viscosity models. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine*, *234*(7), 711–719. https://doi.org/10.1177/0954411920917531.

Sindeev, S., Frolov, S., & Potlov, A. (2019). Mathematical Modeling of Blood Flow in a Patientspecific Model of the Middle Cerebral Artery Taking into Account Non-Newtonian Blood Behavior. *2019 International Science and Technology Conference “EastConf,” 9*, 1–5. https://doi.org/10.1109/eastconf.2019.8725318.

Wiśniewski, K., Reorowicz, P., Tyfa, Z., Price, B., Jian, A., Fahlström, A., Obidowski, D., Jaskólski, D. J., Jóźwik, K., Drummond, K., Wessels, L., Vajkoczy, P., & Adamides, A. A. (2024). Computational fluid dynamics; a new diagnostic tool in giant intracerebral aneurysm treatment. *Computers in Biology and Medicine*, *181*, 109053. https://doi.org/10.1016/j.compbiomed.2024.109053.

Wiśniewski, K., Reorowicz, P., Tyfa, Z., Price, B., Jian, A., Fahlström, A., Obidowski, D., Jaskólski, D. J., Jóźwik, K., Drummond, K., Wessels, L., Vajkoczy, P., & Adamides, A. A. (2024b). Intracranial bypass for giant aneurysms treatment assessed by computational fluid dynamics (CFD) analysis. *Scientific Reports*, *14*(1), 21548. https://doi.org/10.1038/s41598-024-72591-w.

Zimny, M., Kawlewska, E., Hebda, A., Wolański, W., Ładziński, P., & Kaspera, W. (2021). Wall shear stress gradient is independently associated with middle cerebral artery aneurysm development: a case-control CFD patient-specific study based on 77 patients. *BMC neurology*, *21*(1), 281. https://doi.org/10.1186/s12883-021-02251-3