COMPUTATIONAL STUDY OF HEMODYNAMICS ANALYSIS BETWEEN MRI MEASUREMENT AND CFD SIMULATION ON SEGMENTED PATIENT-SPECIFIC CEREBRAL ANEURYSM MODEL

LIM SHEH HONG

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

____

(Supervisor's Signature)

Full Name : Ts. Dr. MOHD AZRUL HISHAM MOHD ADIB

Position : SENIOR LECTURER

Date : 28th November 2021

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

____

(Student's Signature)

Full Name : LIM SHEH HONG

ID Number : MMH19004

Date : 28th November 2021

COMPUTATIONAL STUDY OF HEMODYNAMICS ANALYSIS BETWEEN MRI MEASUREMENT AND CFD SIMULATION ON SEGMENTED PATIENT-SPECIFIC CEREBRAL ANEURYSM MODEL

LIM SHEH HONG

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

College of Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2021

ACKNOWLEDGEMENTS

First and foremost, I would like to present my deepest gratitude to Almighty God for His graces and blessings in securing bright path into my life and enabling me to complete my research study successfully.

I would like to express my deepest appreciation to my dearest supervisor, Ts. Dr. Mohd Azrul Hisham Mohd Adib for his guidance, encouragement, and motivation throughout this research study. It is my pleasure to experience an excellent research study under his supervision and lots of useful recommendations have been suggested by him for the sake of higher achievement in this research study despite of his busy schedule.

Furthermore, I would like to express my sincere gratitude to Assoc. Prof. Dr. Radhiana Hassan from International Islamic University Malaysia Medical Centre (IIUM-MC), Assoc. Prof. Dr. Mohd Shafie Abdullah as well as Dr. Nur Hartini Mohd Taib from Hospital Universiti Sains Malaysia (HUSM) for granting me special privilege in accessing all facilities in their institutions which expedites whole process of my research study.

I am extremely grateful to all the staffs from Institute of Postgraduate Studies (IPS) and College of Engineering (CoE), who have indirectly involved in my research study and offering me Master Research Scheme (MRS). I am proud to be one of the MRS recipients. Nevertheless, I would also like to express my sincere gratitude and special appreciation on the support from Ministry of Higher Education (MOHE) under FRGS grant FRGS/1/2018/TK03/UMP/02/23, Universiti Malaysia Pahang (UMP) under grant RDU190153 and PGRS2003201, Medical Engineering & Health Intervention Team (MedEHiT) as well as Human Engineering Group (HEG). Their support truly lightens my burdens in all ways during my research study.

Last but not least, I am highly indebted and thankful to my parents for their unconditional support, mentally or financially throughout my research study. This research study might not be done smoothly without their support. I am at a loss for words to show my appreciation for everyone’s devotion, support, and faith in my ability to achieve what I have today.

ABSTRAK

Pelaksanaan analisis dinamik bendalir berkomputeran (CFD) telah dilakukan secara meluas untuk menyiasat hemodinamik dengan menggunakan reka bentuk geometri aneurisma serebrum khususnya dari pesakit yang ditemberengkan dan dibina melalui imej perubatan dalam penyelidikan ini. Menurut kajian sebelum ini, imej perubatan pengimejan resonans magnetik (MRI) yang beresolusi rendah menghasilkan ralat pengukuran yang tinggi dan mengakibatkan pendekatan hemodinamik yang tidak tepat dengan perbezaan halaju besar sekitar 40 % antara pengukuran MRI dan simulasi CFD berdasarkan kajian sedia ada. Selain itu, penetapan syarat yang sempadan dengan pesakit adalah amat penting sebelum memulakan analisis CFD, tetapi tidak ada peraturan yang tetap terutamanya pada penetapan reka bentuk geometri dengan percabangan yang memerlukan pelbagai sempadan pada saluran keluar. Oleh itu, kajian ini bertujuan untuk mengkaji kesan reka bentuk geometri yang dihasilkan daripada nilai kitaran ambang, C_{thres}, yang berbeza melalui proses segmentasi gambar terhadap aneurisma serebrum khususnya dari pesakit dan menilai faktor hemodinamik untuk aneurisma serebrum dengan menggunakan imej perubatan angiografi penolakan digital (DSA) dan MRI melalui pendekatan tekanan tetap (P-fixed) dan pengukuran MRI yang amat penting untuk mencapai matlamat-matlamat kajian ini. Seterusnya, tren purata halaju, $\mathrm{V_{avg}}$, dan halaju maksimum, $\mathrm{V_{max}}$, antara pengukuran MRI dengan simulasi CFD turut dianalisis melalui purata ralat relatif, $\mathrm{E_{r,avg}}$, pada simulasi keadaan tunak. Kajian penyelidikan ini disimpulkan bahawa penghasilan reka bentuk geometri dengan nilai kitaran ambang yang berbeza telah membawa kesan yang mendalam pada unsur fizikal dan hemodinamik. Reka bentuk geometri aneurisma serebrum yang optima adalah didapati di antara nilai kitaran ambang, C_{thres}, 0.3 hingga 0.5. Selain itu, taburan tekanan ricih dinding (WSS), taburan tekanan dan medan aliran halaju yang tinggi adalah antara faktor hemodinamik menyumbang kepada pertumbuhan dan perpecahan aneurisma serebrum. Akhir sekali, penyelidikan ini mendapati bahawa terdapat perbezaan medan aliran halaju dengan purata ralat relatif, $\mathrm{E_{r,avg}}$, 11.6723 % dan 37.3647 % dari segi purata halaju, $\mathrm{V_{avg}}$, dan halaju maksimum, $\mathrm{V_{max}}$, masing-masing di antara pengukuran MRI dan simulasi CFD melalui pendekatan P-fixed.

ABSTRACT

The implementation of computational fluid dynamics (CFD) analysis was extensively performed to investigate the hemodynamics using segmented patient-specific cerebral aneurysm model geometry reconstructed from a medical image in this research. According to previous studies, the low-resolution magnetic resonance imaging (MRI) medical image produces a high measurement error and leads to inaccurate hemodynamics approximations with a large velocity difference of approximately 40 % between MRI measurement and CFD simulation. Besides, setting patient-specific boundary conditions before CFD analysis is critical, but there is no unified rule, especially for the setup of model geometry with bifurcation, which requires multiple outlet boundaries. Therefore, this study investigated the extracted model geometry with different threshold coefficients, C_{thres}, through image segmentation process on the patient-specific cerebral aneurysm and to evaluate the hemodynamics factors for cerebral aneurysms using digital subtraction angiography (DSA) and MRI medical images with the implementation of pressure fixed (P-fixed) approach as well as MRI measurement, which are the crucial elements in achieving the objectives. Moreover, the average relative error, $\mathrm{E_{r,avg}}$, upon steady-state simulation, was used to examine the trend of average velocity, $\mathrm{V_{avg}}$, and maximum velocity, $\mathrm{V_{max}}$, between MRI measurement and CFD simulation. This study concluded that the cerebral aneurysm model geometry extraction with different threshold values has profound effects on physical and hemodynamics parameters. The optimised cerebral aneurysm model geometry was found at threshold coefficients, C_{thres}, ranging from 0.3 to 0.5. Nevertheless, high wall shear stress (WSS) distribution, pressure distribution, and velocity flow field are among the hemodynamics factors contributing to the cerebral aneurysm growing and rupturing. This study also found a velocity flow field difference with average relative error, $\mathrm{E_{r,avg}}$, of 11.6723 % and 37.3647 %, in terms of average velocity, $\mathrm{V_{avg}}$, and maximum velocity, $\mathrm{V_{max}}$, respectively, between MRI measurement and CFD simulation through the P-fixed approach.

TABLE OF CONTENT

REFERENCES

Acar, T., Karakas, A. B., Ozer, M. A., Koc, A. M., & Govsa, F. (2019). Building Three-Dimensional Intracranial Aneurysm Models from 3D-TOF MRA: A Validation Study. *Journal of Digital Imaging*, *32*(6), 963–970. https://doi.org/10.1007/s10278-019-00256-6

Adib, M. A. H. M., & Hasni, N. H. M. (2015). Effect on the reconstruction of blood vessel geometry to the thresholds image intensity level for patient aneurysm. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, *22*, 89–95. https://doi.org/10.4028/www.scientific.net/JBBBE.22.89

Adib, M. A. H. M., Hong, L. S., Abdullah, M. S., Hassan, R., & Wada, S. (2020). A perspective review: Technical study of combining phase contrast magnetic resonance imaging and computational fluid dynamics for blood flow on carotid bifurcation artery. *Journal of Mechanical Engineering and Sciences*, *14*(4 SE-Article). https://doi.org/10.15282/jmes.14.4.2020.25.0599

Ailani, A. G., Saiful Azli, M. N., Regunath, K., Abdul Rahman Izani, G., & Azmin Kass, R. (2017). Assessment of pre-and post-operative cerebral perfusion in anterior circulation intracranial aneurysm clipping patients at Hospital Sungai Buloh using CT perfusion scan and correlations to Fisher, Navarro and WFNS scores. *Malaysian Journal of Medical Sciences*, *24*(1), 47–58. https://doi.org/10.21315/mjms2017.24.1.6

Akshaya, B., Atchaya, G., A, B. N., Hemalatha, K., Tamilarasan, T., & Shanmugavalli, M. (2020). Blood Flow Analysis in Thoracic Aorta During Aneurysm. *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering*, *8*(3), 40–44. https://doi.org/10.17148/IJIREEICE.2020.8307

American Stroke Association. (2019). *What You Should Know About Cerebral Aneurysms | American Stroke Association*. American Stroke Association. https://www.stroke.org/en/about-stroke/types-of-stroke/hemorrhagic-strokes-bleeds/what-you-should-know-about-cerebral-aneurysms

Amili, O., Schiavazzi, D., Moen, S., Jagadeesan, B., Van de Moortele, P.-F., & Coletti, F. (2018). Hemodynamics in a giant intracranial aneurysm characterized by in vitro 4D flow MRI. *PloS One*, *13*(1), e0188323–e0188323. https://doi.org/10.1371/journal.pone.0188323

Aranda, A., & Valencia, A. (2018). Study on Cerebral Aneurysms: Rupture Risk Prediction Using Geometrical Parameters and Wall Shear Stress With Cfd and Machine Learning Tools. *Machine Learning and Applications: An International Journal*, *5*(4), 01–13. https://doi.org/10.5121/mlaij.2018.5401

Augst, A. D., Barratt, D. C., Hughes, A. D., Glor, F. P., Thom, S. A. M., & Xu, X. Y. (2003). Accuracy and Reproducibility of CFD Predicted Wall Shear Stress Using

3D Ultrasound Images . *Journal of Biomechanical Engineering*, *125*(2), 218–222. https://doi.org/10.1115/1.1553973

Azrul, M., Mohd, H., Satoshi, A., & Yoshiyuki, I. (2017). Minimizing the blood velocity differences between phase - contrast magnetic resonance imaging and computational fluid dynamics simulation in cerebral arteries and aneurysms. *Medical & Biological Engineering & Computing*, *55*(9), 1605–1619. https://doi.org/10.1007/s11517-017-1617-y

Baek, H., Jayaraman, M. V., & Karniadakis, G. E. (2009). Wall shear stress and pressure distribution on aneurysms and infundibulae in the posterior communicating artery bifurcation. *Annals of Biomedical Engineering*, *37*(12), 2469–2487. https://doi.org/10.1007/s10439-009-9794-y

Bawin, A., Henrotte, F., & Remacle, J.-F. (2021). Automatic feature-preserving size field for 3D mesh generation. *International Journal for Numerical Methods in Engineering*. https://doi.org/10.1002/nme.6747

Błaszczyk, M., Jabbar, R., Szmyd, B., & Radek, M. (2021). 3D Printing of Rapid, Low-Cost and Patient-Specific Models of Brain Vasculature for Use in Preoperative Planning in Clipping of Intracranial Aneurysms. *Journal of Clinical Medicine*, *10*(6), 1201. https://doi.org/10.3390/jcm10061201

Blazek, D., Stastny, P., Maszczyk, A., Krawczyk, M., Matykiewicz, P., & Petr, M. (2019). Systematic review of intra-abdominal and intrathoracic pressures initiated by the Valsalva manoeuvre during high-intensity resistance exercises. *Biology of Sport*, *36*(4), 373–386. https://doi.org/10.5114/biolsport.2019.88759

Bordones, A. D., Leroux, M., Kheyfets, V. O., Wu, Y.-A., Chen, C.-Y., & Finol, E. A. (2018). Computational Fluid Dynamics Modeling of the Human Pulmonary Arteries with Experimental Validation. *Annals of Biomedical Engineering*, *46*(9), 1309–1324. https://doi.org/10.1007/s10439-018-2047-1

Botnar, R, Scheidegger, M. B., & Boesiger, P. (1996). Quantification of blood flow patterns in human vessels by magnetic resonance imaging. *Technology and Health Care : Official Journal of the European Society for Engineering and Medicine*, *4*(1), 97–112. https://doi.org/10.3233/THC-1996-4111

Botnar, René, Rappitsch, G., Beat Scheidegger, M., Liepsch, D., Perktold, K., & Boesiger, P. (2000). Hemodynamics in the carotid artery bifurcation: A comparison between numerical simulations and in vitro MRI measurements. *Journal of Biomechanics*, *33*(2), 137–144. https://doi.org/10.1016/S0021-9290(99)00164-5

Boussel, L., Rayz, V., Martin, A., Acevedo-bolton, G., Lawton, M. T., Higashida, R., Smith, W. S., Young, W. L., & Saloner, D. (2009). Phase-Contrast Magnetic Resonance Imaging Measurements in Intracranial Aneurysms In Vivo of Flow Patterns, Velocity Fields, and Wall Shear Stress : Comparison with Computational Fluid Dynamics. *Magnetic Resonance in Medicine*, *417*, 409–417.

https://doi.org/10.1002/mrm.21861

Brain Aneurysm Foundation. (2018). *Brain Aneurysm Basics – Brain Aneurysm Foundation*. Brain Aneurysm Foundation. https://bafound.org/about-brain-aneurysms/brain-aneurysm-basics/

Bryant, D. J., Payne, J. A., Firmin, D. N., & Longmore, D. B. (1984). Measurement of Flow with NMR Imaging Using a Gradient Pulse and Phase Difference Technique. *Journal of Computer Assisted Tomography*, *8*(4). https://journals.lww.com/jcat/Fulltext/1984/08000/Measurement_of_Flow_with_NMR_Imaging_Using_a.2.aspx

Campos, J. K., Ball, B. Z., Cheaney Ii, B., Sweidan, A. J., Hasjim, B. J., Hsu, F. P. K., Wang, A. S., & Lin, L.-M. (2020). Multimodal management of giant cerebral aneurysms: Review of literature and case presentation. *Stroke and Vascular Neurology*, *5*(1), 22–28. https://doi.org/10.1136/svn-2019-000304

Canstein, C., Cachot, P., Faust, A., Stalder, A. F., Bock, J., Frydrychowicz, A., Küffer, J., Hennig, J., & Markl, M. (2008). 3D MR flow analysis in realistic rapid-prototyping model systems of the thoracic aorta: Comparison with in vivo data and computational fluid dynamics in identical vessel geometries. *Magnetic Resonance in Medicine*, *59*(3), 535–546. https://doi.org/10.1002/mrm.21331

Cebral, J R, Castro, M. A., Appanaboyina, S., Putman, C. M., Millan, D., & Frangi, A. F. (2005). Efficient pipeline for image-based patient-specific analysis of cerebral aneurysm hemodynamics: technique and sensitivity. *IEEE Transactions on Medical Imaging*, *24*(4), 457–467. https://doi.org/https://doi.org/10.1109/TMI.2005.844159

Cebral, Juan R, Putman, C. M., Alley, M. T., Hope, T., Bammer, R., & Calamante, F. (2009). Hemodynamics in normal cerebral arteries : Qualitative comparison of 4D phase-contrast magnetic resonance and image-based computational fluid dynamics. *Journal of Engineering Mathematics*, 367–378. https://doi.org/10.1007/s10665-009-9266-2

Cebral, Juan R, Yim, P. J., Löhner, R., Soto, O., & Choyke, P. L. (2002). Blood Flow Modeling in Carotid Arteries with Computational Fluid Dynamics and MR Imaging. *Academic Radiology*, *9*(11), 1286–1299. https://doi.org/https://doi.org/10.1016/S1076-6332(03)80562-7

Cebral, Juan Raul, & Löhner, R. (2001). From medical images to anatomically accurate finite element grids. *International Journal for Numerical Methods in Engineering*, *51*(8), 985–1008. https://doi.org/10.1002/nme.205

Chang, H. H., Duckwiler, G. R., Valentino, D. J., & Chu, W. C. (2009). Computer-assisted extraction of intracranial aneurysms on 3D rotational angiograms for computational fluid dynamics modeling. *Medical Physics*, *36*(12), 5612–5621. https://doi.org/10.1118/1.3260841

Chen, J. L., Ding, G. H., Yang, X. J., & Li, H. Y. (2011). Effects of parent artery segmentation and aneurismal-wall elasticity on patient-specific hemodynamic simulations. *Journal of Hydrodynamics*, *23*(5), 660–668. https://doi.org/10.1016/S1001-6058(10)60162-X

Chen, S., Yang, D., Liu, B., Wang, L., Chen, Y., Ye, W., Liu, C., Ni, L., Zhang, X., & Zheng, Y. (2020). Identification and validation of key genes mediating intracranial aneurysm rupture by weighted correlation network analysis. *Annals of Translational Medicine*, *8*(21), 1407. https://doi.org/10.21037/atm-20-4083

Chen, T. F., Chen, K. W., Chien, Y., Lai, Y. H., Hsieh, S. T., Ma, H. Y., Wang, K. C., & Shiau, C. Y. (2019). Dental pulp stem cell-derived factors alleviate subarachnoid hemorrhage-induced neuroinflammation and ischemic neurological deficits. *International Journal of Molecular Sciences*, *20*(15), 1–15. https://doi.org/10.3390/ijms20153747

Chivukula, V. K., Marsh, L., Chassagne, F., Barbour, M. C., Kelly, C. M., Levy, S., Geindreau, C., Roscoat, S. R. du, Kim, L. J., Levitt, M. R., & Aliseda, A. (2021). Lagrangian Trajectory Simulation of Platelets and Synchrotron Microtomography Augment Hemodynamic Analysis of Intracranial Aneurysms Treated With Embolic Coils. *Journal of Biomechanical Engineering*, *143*(7). https://doi.org/10.1115/1.4050375

Cibis, M., Potters, W. V, Selwaness, M., Gijsen, F. J., Franco, O. H., Arias, A. M., Bruijne, M. De, Hofman, A., Lugt, A. Van Der, Nederveen, A. J., & Wentzel, J. J. (2016). Relation between wall shear stress and carotid artery wall thickening MRI versus CFD. *Journal of Biomechanics*, *49*(5), 735–741. https://doi.org/10.1016/j.jbiomech.2016.02.004

Columbia University Department of Neurology. (2019). *Cerebral Aneurysm | Neurology*. Columbia University Department of Neurology. http://www.columbianeurology.org/neurology/staywell/document.php?id=35871

Compagne, K. C. J., Dilba, K., Postema, E. J., van Es, A. C. G. M., Emmer, B. J., Majoie, C. B. L. M., van Zwam, W. H., Dippel, D. W. J., Wentzel, J. J., van der Lugt, A., & Gijsen, F. J. H. (2019). Flow Patterns in Carotid Webs : A Patient-Based Computational. *American Journal of Neuroradiology*, 703–708. https://doi.org/10.3174%2Fajnr.A6012

D’Elia, M., Perego, M., & Veneziani, A. (2012). A variational data assimilation procedure for the incompressible navier-stokes equations in hemodynamics. *Journal of Scientific Computing*, *52*(2), 340–359. https://doi.org/10.1007/s10915-011-9547-6

Darvish, H., Fatouraee, N., & Nabaei, M. (2021). Numerical investigation of perfusion rates in the circle of Willis in different anatomical variations and ischemic stroke. *Physics of Fluids*, *33*, 41901. https://doi.org/10.1063/5.0040348

Department of Statistics Malaysia. (2020). *Department of Statistics Malaysia Official*

Portal. Department of Statistics Malaysia. https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=401&bul_id=QTU5T0dKQ1g4MHYxd3ZpMzhEMzdRdz09&menu_id=L0pheU43NWJwRWVSZklWdzQ4TlhUUT09

Dominguez, M. (2019). *Subarachnoid Hemorrhage - Neurology - Medbullets Step 2/3*. https://step2.medbullets.com/neurology/120301/subarachnoid-hemorrhage

Ernemann, U. U., Grönewäller, E., Duffner, F. B., Guervit, O., Claassen, J., & Skalej, M. D. (2003). Influence of geometric and hemodynamic parameters on aneurysm visualization during three-dimensional rotational angiography: An in vitro study. *American Journal of Neuroradiology*, *24*(4), 597–603.

Futami, K., Uno, T., Misaki, K., Tamai, S., Nambu, I., Uchiyama, N., & Nakada, M. (2019). Identification of Vortex Cores in Cerebral Aneurysms on 4D Flow MRI. *American Journal of Neuroradiology*, *40*(12), 2111–2116. https://doi.org/10.3174/ajnr.A6322

Gao, H., Zhu, X., & Wang, J.-X. (2020). A bi-fidelity surrogate modeling approach for uncertainty propagation in three-dimensional hemodynamic simulations. *Computer Methods in Applied Mechanics and Engineering*, *366*, 113047. https://doi.org/https://doi.org/10.1016/j.cma.2020.113047

Gholampour, S., & Mehrjoo, S. (2021). Effect of bifurcation in the hemodynamic changes and rupture risk of small intracranial aneurysm. *Neurosurgical Review*, *44*(3), 1703–1712. https://doi.org/10.1007/s10143-020-01367-3

Harloff, A., Albrecht, F., Spreer, J., Stalder, A. F., Bock, J., Frydrychowicz, A., Schollhorn, J., Hetzel, A., Schumacher, M., Hennig, J., & Markl, M. (2009). 3D blood flow characteristics in the carotid artery bifurcation assessed by flow-sensitive 4D MRI at 3T. *Magnetic Resonance in Medicine*, *61*(1), 65–74. https://doi.org/10.1002/mrm.21774

Harloff, Andreas, Nußbaumer, A., Bauer, S., Stalder, A. F., Frydrychowicz, A., Weiller, C., Hennig, J., & Markl, M. (2010). In vivo assessment of wall shear stress in the atherosclerotic aorta using flow-sensitive 4D MRI. *Magnetic Resonance in Medicine*, *63*(6), 1529–1536. https://doi.org/10.1002/mrm.22383

Heitmann, K. A., Dalen, H., Holmen Gundersen, G., Ingvaldsen, R. P., & Welde, B. (2019). Intra-arterial blood pressure traits during and after heavy resistance exercise in healthy males. *Translational Sports Medicine*, *2*(6), 325–333. https://doi.org/10.1002/tsm2.102

Hoi, Y., Meng, H., Woodward, S. H., Bendok, B. R., Hanel, R. A., Guterman, L. R., & Hopkins, L. N. (2004). Effects of arterial geometry on aneurysm growth: Three-dimensional computational fluid dynamics study. *Journal of Neurosurgery*, *101*(4), 676–681. https://doi.org/10.3171/jns.2004.101.4.0676

Hong, L. S., Adib, M. A. H. M., Abdullah, M. S., Taib, N. H. M., Hassan, R., & Aziz,

A. A. (2021). Investigation into Physical and Pathophysiological Changes of Hemodynamics on Segmented Patient-Specific Cerebral Aneurysm Models through Computational Analysis. *2020 IEEE-EMBS Conference on Biomedical Engineering and Sciences (IECBES)*, 136–141. https://doi.org/10.1109/IECBES48179.2021.9398747

Howarth, C. B., De Marco, J. J., & Shanebrook, J. R. (1998). Vortex Blood Pump. In T. Akutsu & H. Koyanagi (Eds.), *Heart Replacement* (pp. 74–78). Springer Japan. https://doi.org/10.1007/978-4-431-65921-1_11

Ishikawa, T., Guimaraes, L. F. R., Oshima, S., & Yamane, R. (1998). Effect of non-Newtonian property of blood on flow through a stenosed tube. *Fluid Dynamics Research*, *22*(5), 251–264. https://doi.org/10.1016/s0169-5983(97)00041-5

Isoda, H., Ohkura, Y., Kosugi, T., Hirano, M., Alley, M. T., Bammer, R., Pelc, N. J., Namba, H., & Sakahara, H. (2010). Comparison of hemodynamics of intracranial aneurysms between MR fluid dynamics using 3D cine phase-contrast MRI and MR-based computational fluid dynamics. *Neuroradiology*, *52*(10), 913–920. https://doi.org/10.1007/s00234-009-0634-4

Izumo, T., Matsuo, T., Morofuji, Y., Hiu, T., Horie, N., Hayashi, K., & Nagata, I. (2015). Microsurgical clipping for recurrent aneurysms after initial endovascular coil embolization. *World Neurosurgery*, *83*(2), 211–218. https://doi.org/10.1016/j.wneu.2014.08.013

Joo, S.-P., & Kim, T.-S. (2017). The Clinical Importance of Perforator Preservation in Intracranial Aneurysm Surgery: An Overview with a Review of the Literature. *Chonnam Medical Journal*, *53*(1), 47. https://doi.org/10.4068/cmj.2017.53.1.47

Jou, L. Der, Quick, C. M., Young, W. L., Lawton, M. T., Higashida, R., Martin, A., & Saloner, D. (2003). Computational Approach to Quantifying Hemodynamic Forces in Giant Cerebral Aneurysms. *American Journal of Neuroradiology*, *24*(9), 1804–1810. http://www.ajnr.org/content/24/9/1804

Kerl, H. U., Boll, H., Fiebig, T., Figueiredo, G., Förster, A., Nölte, I. S., Nonn, A., Groden, C., & Brockmann, M. A. (2014). Implantation of pipeline flow-diverting stents reduces aneurysm inflow without relevantly affecting static intra-aneurysmal pressure. *Neurosurgery*, *74*(3), 321–334. https://doi.org/10.1227/NEU.0000000000000253

Kilner, P. J., Yang, G. Z., Mohiaddin, R. H., Firmin, D. N., & Longmore, D. B. (1993). Helical and retrograde secondary flow patterns in the aortic arch studied by three-directional magnetic resonance velocity mapping. *Circulation*, *88*(5 I), 2235–2247. https://doi.org/10.1161/01.CIR.88.5.2235

Kimura, Y., Mashiko, T., Watanabe, E., & Kawai, K. (2021). Preoperative simulation of a middle cerebral artery aneurysm clipping using a rotational three-dimensional digital subtraction angiography. *Surgical Neurology International*, *12*(70), 1–7. https://doi.org/10.25259/SNI_934_2020

Kroon, M. (2011). Simulation of cerebral aneurysm growth and prediction of evolving rupture risk. *Modelling and Simulation in Engineering*, *2011*, 1–10. https://doi.org/10.1155/2011/289523

Ku, D. N., Giddens, D. P., Phillips, D. J., & Strandness Jr., D. E. (1985). Hemodynamics of the normal human carotid bifurcation: In vitro and in vivo studies. *Ultrasound in Medicine and Biology*, *11*(1), 13–26. https://doi.org/10.1016/0301-5629(85)90003-1

Kulcsár, Z., Ugron, Á., Marosfoi, M., Berentei, Z., Paál, G., & Szikora, I. (2011). Hemodynamics of cerebral aneurysm initiation: The role of wall shear stress and spatial wall shear stress gradient. *American Journal of Neuroradiology*, *32*(3), 587–594. https://doi.org/10.3174/ajnr.A2339

Kuwahara, S., Uga, S., & Mori, K. (2001). Successful treatment of a ruptured enlarged infundibular widening of the posterior communicating artery: Case report. *Neurologia Medico-Chirurgica*, *41*(1), 25–28. https://doi.org/10.2176/nmc.41.25

Larrabide, I., Aguilar, M., Morales, H., Geers, A., Kulcsár, Z., Rüfenacht, D., & Frangi, A. (2012). Intra-Aneurysmal Pressure and Flow Changes Induced by Flow Diverters: Relation to Aneurysm Size and Shape. *AJNR. American Journal of Neuroradiology*, *34*. https://doi.org/10.3174/ajnr.A3288

Lee, J., Cho, W.-S., Yoo, R. E., Yoo, D. H., Cho, Y. D., Kang, H.-S., & Kim, J. E. (2021). The Fate of Partially Thrombosed Intracranial Aneurysms Treated with Endovascular Intervention. *Journal of Korean Neurosurgical Society*, *64*(3), 427–436. https://doi.org/10.3340/jkns.2020.0195

Levitt, M. R., Chivukula, V. K., Clark, A., Barbour, M. C., Johnson, L., Kelly, C. M., Geindreau, C., Rolland, S., Kim, L. J., & Aliseda, A. (2020). Reconstructing Patient-Specific Cerebral Aneurysm Vasculature for In Vitro Investigations and Treatment Efficacy Assessments. *Journal of Clinical Neuroscience : Official Journal of the Neurosurgical Society of Australasia*, *61*, 153–159. https://doi.org/10.1016/j.jocn.2018.10.103

Lewandowska, N., & Cialkowski, M. (2019). A new concept of surgical patch used in vascular surgery. *E3S Web of Conferences*, *02004*, 1–5. https://doi.org/10.1051/e3sconf/201912802004

Lieber, B. B., Livescu, V., Hopkins, L. N., & Wakhloo, A. K. (2002). Particle image velocimetry assessment of stent design influence on intra-aneurysmal flow. *Annals of Biomedical Engineering*, *30*(6), 768–777. https://doi.org/10.1114/1.1495867

Lim, S. H., Mohd Adib, M. A. H., Abdullah, M., & Hassan, R. (2020). Qualitative and Quantitative Comparison of Hemodynamics Between MRI Measurement and CFD Simulation on Patient-specific Cerebral Aneurysm – A Review. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *68*, 112–123. https://doi.org/10.37934/arfmts.68.2.112123

Lim, S. H., Mohd Adib, M. A. H., Abdullah, M. S., Mohd Taib, N. H., Hassan, R., & Abd Aziz, A. (2020). Study of Extracted Geometry Effect on Patient-Specific Cerebral Aneurysm Model with Different Threshold Coefficient (Cthres). *CFD Letters*, *12*(10 SE-), 1–14. https://doi.org/10.37934/cfdl.12.10.114

Lim, S. H., Mohd Adib, M. A. H., Abdullah, M. S., Mohd Taib, N. H., Hassan, R., & Abd Aziz, A. (2021). Reconstruction of Patient-Specific Cerebral Aneurysm Model Through Image Segmentation. *BT - Intelligent Manufacturing and Mechatronics In M. S. Bahari, A. Harun, Z. Zainal Abidin, R. Hamidon, & S. Zakaria (Eds.)*, 207–214. https://doi.org/10.1007/978-981-16-0866-7_16

Liou, T. M., & Liou, S. N. (1999). A review on in vitro studies of hemodynamic characteristics in terminal and lateral aneurysm models. *Proceedings of the National Science Council, Republic of China. Part B, Life Sciences*, *23*(4), 133–148. http://europepmc.org/abstract/MED/10518314

Lugt, H. J. (1983). Vortex flow in nature and technology. *Wiley-Interscience New York*. https://doi.org/10.1119/1.14177

MacDonald, M., & Frayne, R. (2015). Cerebrovascular MRI: A review of state-of-the-art approaches, methods and techniques. *NMR in Biomedicine*, *28*. https://doi.org/10.1002/nbm.3322

Mahrous, S. A., Sidik, N. A. C., & Saqr, K. M. (2020). Newtonian and non-newtonian CFD models of intracranial aneurysm: A review. *CFD Letters*, *12*(1), 62–86. https://www.akademiabaru.com/doc/CFDLV12_N1_P62_86.pdf

Mahrous, S. A., Sidik, N. A. C., & Saqr, K. M. (2021). Numerical study on the energy cascade of pulsatile Newtonian and power-law flow models in an ICA bifurcation. *PloS One*, *16*(1), e0245775. https://doi.org/10.1371/journal.pone.0245775

Marciuc, E. A., Dobrovat, B. I., Popescu, R. M., Dobrin, N., Chiriac, A., Marciuc, D., Eva, L., & Haba, D. (2021). 3D Printed Models—A Useful Tool in Endovascular Treatment of Intracranial Aneurysms. *Brain Sciences*, *11*(5). https://doi.org/10.3390/brainsci11050598

Mario, Z., & Andrew, R. (2016). Unruptured Brain Aneurysm. *Mayfield Brain and Spine*, 1–7. http://www.mayfieldclinic.com/PE-AneurUn.htm

Markl, M., Chan, F. P., Alley, M. T., Wedding, K. L., Draney, M. T., Elkins, C. J., Parker, D. W., Wicker, R., Taylor, C. A., Herfkens, R. J., & Pelc, N. J. (2003). Time-resolved three-dimensional phase-contrast MRI. *Journal of Magnetic Resonance Imaging*, *17*(4), 499–506. https://doi.org/10.1002/jmri.10272

Marshall, I., Robertson, M. B., Long, Q., Xu, X. Y., & Hoskins, P. R. (2001). MRI Measurement of Wall Shear Stress Vectors in Bifurcation Models and Comparison With CFD Predictions. *Journal of Magnetic Resonance Imaging : JMRI*, *14*(5), 563–573. https://doi.org/10.1002/jmri.1220

Marshall, I., Zhao, S., Papathanasopoulou, P., Hoskins, P., & Xu, X. Y. (2004). MRI and CFD studies of pulsatile flow in healthy and stenosed carotid bifurcation models. *Journal of Biomechanics*, *37*, 679–687. https://doi.org/10.1016/j.jbiomech.2003.09.032

Meckel, S., Markl, M., & Wetzel, S. (2020). Identification of Vortex Cores in Cerebral Aneurysms on 4D Flow MRI. *American Journal of Neuroradiology*, *41*(5), E26. https://doi.org/10.3174/ajnr.A6480

Miller, G. M. (2003). The Promise of Computational Fluid Dynamics as a Tool for Delineating Therapeutic Options in the Treatment of Aneurysms. *American Journal of Neuroradiology*, *24*(4), 556. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8148693/

Miura, Y., Ishida, F., Umeda, Y., & Tanemura, H. (2013). Low Wall Shear Stress Is Independently Associated With the Rupture Status of Middle Cerebral Artery Aneurysms. *Stroke*, *44*(2), 519–521. https://doi.org/10.1161/STROKEAHA.112.675306

Mo, X., Meng, Q., Yang, X., & Li, H. (2020). The Impact of Inflow Angle on Aneurysm Hemodynamics: A Simulation Study Based on Patient-Specific Intracranial Aneurysm Models. *Frontiers in Neurology*, *11*, 534096. https://doi.org/10.3389/fneur.2020.534096

Mohd Adib, M. A. H. (2016). Measurement of Threshold Image Intensities on Difference of Vascular Model: Effect on Computational Fluid Dynamics for Patient-Specific Cerebral Aneurysm. *Journal of Biomimetics, Biomaterials and Biomedical Engineering*, *27*, 55–59. https://doi.org/10.4028/www.scientific.net/JBBBE.27.55

Mohd Adib, M. A. H., Ii, S., Watanabe, Y., & Wada, S. (2017). Minimizing the blood velocity differences between phase-contrast magnetic resonance imaging and computational fluid dynamics simulation in cerebral arteries and aneurysms. *Medical and Biological Engineering and Computing*, *55*(9), 1605–1619. https://doi.org/10.1007/s11517-017-1617-y

Molla, M. M., & Paul, M. C. (2012). LES of non-Newtonian physiological blood flow in a model of arterial stenosis. *Medical Engineering and Physics*, *34*(8), 1079–1087. https://doi.org/10.1016/j.medengphy.2011.11.013

Moore, J. A., Steinman, D. A., & Ross Ethier, C. (1997). Computational blood flow modelling: Errors associated with reconstructing finite element models from magnetic resonance images. *Journal of Biomechanics*, *31*(2), 179–184. https://doi.org/https://doi.org/10.1016/S0021-9290(97)00125-5

Moran, P. R. (1982). A flow velocity zeugmatographic interlace for NMR imaging in humans. *Magnetic Resonance Imaging*, *1*(4), 197–203. https://doi.org/10.1016/0730-725X(82)90170-9

Morbiducci, U., Mazzi, V., Domanin, M., De Nisco, G., Vergara, C., Steinman, D. A., & Gallo, D. (2020). Wall Shear Stress Topological Skeleton Independently Predicts Long-Term Restenosis After Carotid Bifurcation Endarterectomy. *Annals of Biomedical Engineering*, *48*(12), 2936–2949. https://doi.org/10.1007/s10439-020-02607-9

Naito, T., Miyachi, S., & Matsubara, N. (2012). Magnetic resonance fluid dynamics for intracranial aneurysms — comparison with computed fluid dynamics. *Acta Neurochir*, *154*, 993–1001. https://doi.org/10.1007/s00701-012-1305-5

Narloch, J. A., & Brandstater, M. E. (1995). Influence of breathing technique on arterial blood pressure during heavy weight lifting. *Archives of Physical Medicine and Rehabilitation*, *76*(5), 457–462. https://doi.org/10.1016/S0003-9993(95)80578-8

National Institute of Neurological Disorders and Stroke. (2020). *Cerebral Aneurysms Fact Sheet | National Institute of Neurological Disorders and Stroke*. National Institute of Neurological Disorders and Stroke. https://www.ninds.nih.gov/Disorders/Patient-Caregiver-Education/Fact-Sheets/Cerebral-Aneurysms-Fact-Sheet

Nayler, G. L., Firmin, D. N., & Longmore, D. B. (1986). Blood Flow Imaging by Cine Magnetic Resonance. *Journal of Computer Assisted Tomography*, *10*(5). https://journals.lww.com/jcat/Fulltext/1986/09000/Blood_Flow_Imaging_by_Cine_Magnetic_Resonance.1.aspx

Nguyen, K. L., Hu, P., & Finn, J. P. (2021). Cardiac Magnetic Resonance Quantification of Structure-Function Relationships in Heart Failure. *Heart Failure Clinics*, *17*(1), 9–24. https://doi.org/10.1016/j.hfc.2020.08.001

Ohhara, Y., Oshima, M., Iwai, T., Kitajima, H., Yajima, Y., Mitsudo, K., Krdy, A., & Tohnai, I. (2016). Investigation of blood flow in the external carotid artery and its branches with a new 0D peripheral model. *Biomedical Engineering Online*, *15*, 16. https://doi.org/10.1186/s12938-016-0133-x

Omodaka, S., Endo, H., Niizuma, K., Fujimura, M., Endo, T., Sato, K., Sugiyama, S., Inoue, T., & Tominaga, T. (2018). Circumferential Wall Enhancement on Magnetic Resonance Imaging is Useful to Identify Rupture Site in Patients with Multiple Cerebral Aneurysms. *Neurosurgery*, *82*(5), 638–644. https://doi.org/10.1093/neuros/nyx267

Omodaka, S., Inoue, T., Funamoto, K., Sugiyama, S. I., Shimizu, H., Hayase, T., Takahashi, A., & Tominaga, T. (2012). Influence of surface model extraction parameter on computational fluid dynamics modeling of cerebral aneurysms. *Journal of Biomechanics*, *45*(14), 2355–2361. https://doi.org/10.1016/j.jbiomech.2012.07.006

Ooij, P. Van, Potters, W. V, Gu, A., Schneiders, J. J., Marquering, H. A., Majoie, C. B., & Nederveen, A. J. (2013). Wall Shear Stress Estimated With Phase Contrast MRI in an In Vitro and In Vivo Intracranial Aneurysm. *Journal of Magnetic Resonance*

Imaging : JMRI, *38*(4), 876–884. https://doi.org/10.1002/jmri.24051

Oore, J. A. M., Teinman, D. A. S., Oldsworth, D. W. H., & Thier, C. R. E. (1999). Accuracy of Computational Hemodynamics in Complex Arterial Geometries Reconstructed from Magnetic Resonance Imaging. *Annals of Biomedical Engineering*, *27*, 32–41. https://doi.org/10.1114/1.163

Oshima, M., Sakai, H., & Torii, R. (2005). Modelling of inflow boundary conditions for image-based simulation of cerebrovascular flow. *International Journal for Numerical Methods in Fluids*, *47*, 603–617. https://doi.org/10.1002/fld.834

Ou, C., Qian, Y., Zhang, X., Liu, J., Liu, W., Su, H., Zhang, N., Zhang, J., He, X., & Duan, C. Z. (2020). Elevated Lipid Infiltration Is Associated With Cerebral Aneurysm Rupture. *Frontiers in Neurology*, *11*(April), 1–8. https://doi.org/10.3389/fneur.2020.00154

Owen, D. G., Schenkel, T., Shepherd, D. E. T., & Espino, D. M. (2020). Assessment of surface roughness and blood rheology on local coronary haemodynamics: A multi-scale computational fluid dynamics study. *Journal of the Royal Society, Interface*, *17*(169), 20200327. https://doi.org/10.1098/rsif.2020.0327

Papathanasopoulou, P., Zhao, S., Ko, U., Robertson, M. B., Long, Q., Hoskins, P., Xu, X. Y., & Marshall, I. (2003). MRI Measurement of Time-Resolved Wall Shear Stress Vectors in a Carotid Bifurcation Model, and Comparison With CFD Predictions. *Journal of Magnetic Resonance Imaging*, *17*(2), 153–162. https://doi.org/10.1002/jmri.10243

Pelc, N. J., Herfkens, R. J., Shimakawa, A., & Enzmann, D. R. (1991). Phase contrast cine magnetic resonance imaging. *Magnetic Resonance Quarterly*, *7*(4), 229–254. https://europepmc.org/article/med/1790111

Perktold, K., & Rappitsch, G. (1995). Mathematical modeling of arterial blood flow and correlation to atherosclerosis. *Technology and Health Care*, *3*, 139–151. https://doi.org/10.3233/THC-1995-3301

Polanczyk, A., Piechota-Polanczyk, A., Stefańczyk, L., & Strzelecki, M. (2020a). Shape and Enhancement Analysis as a Useful Tool for the Presentation of Blood Hemodynamic Properties in the Area of Aortic Dissection. *Journal of Clinical Medicine*, *9*, 1330. https://doi.org/10.3390/jcm9051330

Polanczyk, A., Piechota-Polanczyk, A., Stefańczyk, L., & Strzelecki, M. (2020b). Spatial Configuration of Abdominal Aortic Aneurysm Analysis as a Useful Tool for the Estimation of Stent-Graft Migration. *Diagnostics (Basel, Switzerland)*, *10*(10). https://doi.org/10.3390/diagnostics10100737

Pozniak, M. A., & Allan, P. L. (2013). *Clinical Doppler Ultrasound E-Book: Expert Consult: Online*. Elsevier Health Sciences. https://books.google.com.my/books?id=SYCzAQAAQBAJ

Printz, M. P., & Jaworski, R. L. (2018). *Hypertension; Overview*. Academic Press. https://doi.org/10.1016/B978-0-12-801238-3.03801-0

Puiseux, T., Sewonu, A., Moreno, R., Mendez, S., & Nicoud, F. (2021). Numerical simulation of time-resolved 3D phase-contrast magnetic resonance imaging. *PloS One*, *16*(3), e0248816. https://doi.org/10.1371/journal.pone.0248816

Rabbi, M. F., Laboni, F. S., & Arafat, M. T. (2020). Computational analysis of the coronary artery hemodynamics with different anatomical variations. *Informatics in Medicine Unlocked*, *19*, 100314. https://doi.org/10.1016/j.imu.2020.100314

Rayz, V. L., Boussel, L., Lawton, M. T., Acevedo-Bolton, G., Ge, L., Young, W. L., Higashida, R. T., & Saloner, D. (2008). Numerical modeling of the flow in intracranial aneurysms: Prediction of regions prone to thrombus formation. *Annals of Biomedical Engineering*, *36*(11), 1793–1804. https://doi.org/10.1007/s10439-008-9561-5

Rayz, V L, Abla, A., Boussel, L., Leach, J. R., Acevedo-Bolton, G., Saloner, D., & Lawton, M. T. (2015). Computational modeling of flow-altering surgeries in basilar aneurysms. *Annals of Biomedical Engineering*, *43*(5), 1210–1222. https://doi.org/10.1007/s10439-014-1170-x

Rayz, Vitaliy L, Boussel, L., Acevedo-Bolton, G., Martin, A. J., Young, W. L., Lawton, M. T., Higashida, R., & Saloner, D. (2008). Numerical Simulations of Flow in Cerebral Aneurysms: Comparison of CFD Results and In Vivo MRI Measurements. *Journal of Biomechanical Engineering*, *130*(5). https://doi.org/10.1115/1.2970056

Rispoli, V. C., Nielsen, J. F., Nayak, K. S., & Carvalho, J. L. A. (2015). Computational fluid dynamics simulations of blood flow regularized by 3D phase contrast MRI. *BioMedical Engineering OnLine*, 1–23. https://doi.org/10.1186/s12938-015-0104-7

Sadasivan, C., Fiorella, D. J., Woo, H. H., & Lieber, B. B. (2013). Physical factors effecting cerebral aneurysm pathophysiology. *Annals of Biomedical Engineering*, *41*(7), 1347–1365. https://doi.org/10.1007/s10439-013-0800-z

Sankar, D. S., & Hemalatha, K. (2007). A non-Newtonian fluid flow model for blood flow through a catheterized artery-Steady flow. *Applied Mathematical Modelling*, *31*(9), 1847–1864. https://doi.org/10.1016/j.apm.2006.06.009

Santini, F., Pansini, M., Hrabak-Paar, M., Yates, D., Langenickel, T. H., Bremerich, J., Bieri, O., & Schubert, T. (2020). On the optimal temporal resolution for phase contrast cardiovascular magnetic resonance imaging: establishment of baseline values. *Journal of Cardiovascular Magnetic Resonance : Official Journal of the Society for Cardiovascular Magnetic Resonance*, *22*(1), 72. https://doi.org/10.1186/s12968-020-00669-1

Sawchuk, A. P., Unthank, J. L., Davis, T. E., & Dalsing, M. C. (1994). A prospective, in vivo study of the relationship between blood flow hemodynamics and atherosclerosis in a hyperlipidemic swine model. *Journal of Vascular Surgery*, *19*(1), 54–58. https://doi.org/10.1016/s0741-5214(94)70120-2

Schievink, W. I. (1997). Intracranial Aneurysms. *New England Journal of Medicine*, *336*(1), 28–40. https://doi.org/10.1056/NEJM199701023360106

Schubiger, O., Valavanis, A., & Wichmann, W. (1987). Growth-mechanism of giant intracranial aneurysms; demonstration by CT and MR imaging. *Neuroradiology*, *29*, 266–271. https://doi.org/10.1007/bf00451765

Secomb, T. W. (2016). Hemodynamics. *Comprehensive Physiology*, *6*(2), 975–1003. https://doi.org/10.1002/cphy.c150038

Sforza, D. M., Putman, C. M., & Cebral, J. R. (2009). Hemodynamics of cerebral aneurysms. *Annual Review of Fluid Mechanics*, *41*, 91–107. https://doi.org/10.1146/annurev.fluid.40.111406.102126

Sharma, R. K., Yamada, Y., Tanaka, R., Sharma, S., Miyatani, K., Higashiguchi, S., Kawase, T., Talluri, S., & Kato, Y. (2020). Unusually Located Proximal Middle Cerebral Artery Saccular Aneurysm. *Asian Journal of Neurosurgery*, *15*(3), 769–772. https://doi.org/10.4103/ajns.AJNS_264_19

Sheh Hong, L., Azrul Hisham Mohd Adib, M., Uzair Matalif, M., Shafie Abdullah, M., Hartini Mohd Taib, N., & Hassan, R. (2020). Modeling and Simulation of Blood Flow Analysis on Simplified Aneurysm Models. *IOP Conference Series: Materials Science and Engineering*, *917*, 012067. https://doi.org/10.1088/1757-899x/917/1/012067

Shibata, E., Takao, H., Amemiya, S., & Ohtomo, K. (2017). 3D-printed visceral aneurysm models based on ct data for simulations of endovascular embolization: Evaluation of size and shape accuracy. *American Journal of Roentgenology*, *209*(2), 243–247. https://doi.org/10.2214/AJR.16.17694

Shojima, M. (2004). Magnitude and Role of Wall Shear Stress on Cerebral Aneurysm. Computational Fluid Dynamic Study of 20 Middle Cerebral Artery Aneurysms. *Stroke*, 2500–2505. https://doi.org/10.1161/01.str.0000144648.89172.of

Smith, M., & Citerio, G. (2015). What's new in subarachnoid hemorrhage. *Intensive Care Medicine*, *41*(1), 123–126. https://doi.org/10.1007/s00134-014-3548-5

Sorteberg, A., & Farhoudi, D. (2006). The Influence of Aneurysm Configuration on Intra-Aneurysmal Pressure and Flow. *Interventional Neuroradiology : Journal of Peritherapeutic Neuroradiology, Surgical Procedures and Related Neurosciences*, *12*(3), 203–214. https://doi.org/10.1177/159101990601200302

Stalder, F., Bley, T. A., Bock, J., Frydrychowicz, A., Burkhardt, H., & Markl, M. (2010). 4D Phase Contrast MRI at 3 T : Effect of Standard and Blood-Pool Contrast Agents on SNR , PC-MRA , and Blood Flow Visualization. *Magnetic*

Resonance in Medicine, *63*(2), 330–338. https://doi.org/10.1002/mrm.22199

Stoll, V. M., Loudon, M., Eriksson, J., Bissell, M. M., Dyverfeldt, P., Ebbers, T., Myerson, S. G., Neubauer, S., Carlhäll, C.-J., & Hess, A. T. (2018). Test-retest variability of left ventricular 4D flow cardiovascular magnetic resonance measurements in healthy subjects. *Journal of Cardiovascular Magnetic Resonance : Official Journal of the Society for Cardiovascular Magnetic Resonance*, *20*(1), 15. https://doi.org/10.1186/s12968-018-0432-4

Sugiyama, S. ichiro, Endo, H., Omodaka, S., Endo, T., Niizuma, K., Rashad, S., Nakayama, T., Funamoto, K., Ohta, M., & Tominaga, T. (2016). Daughter Sac Formation Related to Blood Inflow Jet in an Intracranial Aneurysm. *World Neurosurgery*, *96*, 396–402. https://doi.org/10.1016/j.wneu.2016.09.040

Szajer, J., & Ho-shon, K. (2018). A comparison of 4D fl ow MRI-derived wall shear stress with computational fl uid dynamics methods for intracranial aneurysms and carotid bifurcations — A review. *Magnetic Resonance Imaging*, *48*(April 2017), 62–69. https://doi.org/10.1016/j.mri.2017.12.005

Tadjfar, M. (2006). Flow into an arterial branch model. *Journal of Engineering Mathematics*, *54*(4), 359–374. https://doi.org/10.1007/s10665-006-9031-8

Tateshima, S., Murayama, Y., Villablanca, J. P., Morino, T., Nomura, K., Tanishita, K., & Viñuela, F. (2003). In vitro measurement of fluid-induced wall shear stress in unruptured cerebral aneurysms harboring blebs. *Stroke*, *34*(1), 187–192. https://doi.org/10.1161/01.STR.0000046456.26587.8B

Tateshima, S., Viñuela, F., Villablanca, J. P., Murayama, Y., Morino, T., Nomura, K., & Tanishita, K. (2003). Three-dimensional blood flow analysis in a wide-necked internal carotid artery-ophthalmic artery aneurysm. *Journal of Neurosurgery*, *99*(3), 526–533. https://doi.org/10.3171/jns.2003.99.3.0526

Taylor, C. A., & Steinman, D. A. (2010). Image-based modeling of blood flow and vessel wall dynamics: Applications, methods and future directions: Sixth international bio-fluid mechanics symposium and workshop, March 28-30, 2008 Pasadena, California. *Annals of Biomedical Engineering*, *38*(3), 1188–1203. https://doi.org/10.1007/s10439-010-9901-0

Teimouri, K., Tavakoli, M. R., Ghafari, A., & Kim, K. C. (2021). Investigation of the plaque morphology effect on changes of pulsatile blood flow in a stenosed curved artery induced by an external magnetic field. *Computers in Biology and Medicine*, *135*, 104600. https://doi.org/https://doi.org/10.1016/j.compbiomed.2021.104600

Thamm, A., Freitag, N., Figueiredo, P., Doma, K., Rottensteiner, C., Bloch, W., & Schumann, M. (2019). Can Heart Rate Variability Determine Recovery Following Distinct Strength Loadings? A Randomized Cross-Over Trial. *International Journal of Environmental Research and Public Health*, *16*(22). https://doi.org/10.3390/ijerph16224353

Thomas, J. B., Milner, J. S., Rutt, B. K., & Steinman, D. A. (2003). Reproducibility of image-based computational fluid dynamics models of the human carotid bifurcation. *Annals of Biomedical Engineering*, *31*(2), 132–141. https://doi.org/10.1114/1.1540102

Torii, R., Oshima, M., Kobayashi, T., Takagi, K., & Tezduyar, T. E. (2007). Numerical investigation of the effect of hypertensive blood pressure on cerebral aneurysm - Dependence of the effect on the aneurysm shape. *International Journal for Numerical Methods in Fluids*, *54*(6–8), 995–1009. https://doi.org/10.1002/fld.1497

Ujihara, Y., Nakamura, M., Miyazaki, H., & Wada, S. (2010). Proposed spring network cell model based on a minimum energy concept. *Annals of Biomedical Engineering*, *38*(4), 1530–1538. https://doi.org/10.1007/s10439-010-9930-8

Valencia, A., Campos, F., Munizaga, J., Perez, J., Rivera, R., & Bravo, E. (2011). Hemodynamics in cerebral aneurysms models and the effects of a simple stent models. *Advances and Applications in Fluid Mechanics*, *9*(2), 105–128. https://www.researchgate.net/publication/267989504_Hemodynamics_in_cerebral_aneurysms_models_and_the_effects_of_a_simple_stent_models

Wang, J. L., Yuan, Z. G., Qian, G. L., Bao, W. Q., & Jin, G. L. (2018). 3D printing of intracranial aneurysm based on intracranial digital subtraction angiography and its clinical application. *Medicine (United States)*, *97*(24), 1–6. https://doi.org/10.1097/MD.0000000000011103

Weir, B. (2002). Unruptured Intracranial Aneurysms: A Review. *Journal of Neurosurgery*, *96*(1), 3–42. https://doi.org/10.3171/jns.2002.96.1.0003

Whitlock, M. C., & Hundley, W. G. (2015). Noninvasive Imaging of Flow and Vascular Function in Disease of the Aorta. *JACC. Cardiovascular Imaging*, *8*(9), 1094–1106. https://doi.org/10.1016/j.jcmg.2015.08.001

Wigström, L., Ebbers, T., Fyrenius, A., Karlsson, M., Engvall, J., Wranne, B., & Bolger, A. F. (1999). Particle trace visualization of intracardiac flow using time-resolved 3D phase contrast MRI. *Magnetic Resonance in Medicine*, *41*(4), 793–799. https://doi.org/10.1002/(SICI)1522-2594(199904)41:4<793::AID-MRM19>3.0.CO;2-2

Woodward, S. H., & Taulbee, D. B. (2007). Validation of CFD Simulations of Cerebral Aneurysms With Implication of Geometric. *Journal of Biomechanical Engineering*, *128*(6), 844–851. https://doi.org/10.1115/1.2354209

World Health Organization (WHO). (2020). *Cardiovascular diseases (CVDs)*. World Health Organization (WHO). https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)

Zarins, C. K., Giddens, D. P., Bharadvaj, B. K., Sottiurai, V. S., Mabon, R. F., & Glagov, S. (1983). Carotid bifurcation atherosclerosis. Quantitative correlation of plaque localization with flow velocity profiles and wall shear stress. *Circulation*

Research, *53*(4), 502–514. https://doi.org/10.1161/01.RES.53.4.502

Zhang, C., Chau, N., & Ho, H. (2020). Patient-Specific Blood Flow Analysis for Cerebral Arteriovenous Malformation Based on Digital Subtraction Angiography Images. *Frontiers in Bioengineering and Biotechnology*, *8*(July), 1–11. https://doi.org/10.3389/fbioe.2020.00775

Zhang, Y., Wang, W., Liang, X., Bazilevs, Y., Hsu, M. C., Kvamsdal, T., Brekken, R., & Isaksen, Jø. (2009). High-fidelity tetrahedral mesh generation from medical imaging data for fluid-structure interaction analysis of cerebral aneurysms. *CMES - Computer Modeling in Engineering and Sciences*, *42*(2), 131–148. https://doi.org/10.3970/cmes.2009.042.131

Zhou, X., Papadopoulou, V., Leow, C. H., Vincent, P., & Tang, M.-X. (2019). 3-D Flow Reconstruction Using Divergence-Free Interpolation of Multiple 2-D Contrast-Enhanced Ultrasound Particle Imaging Velocimetry Measurements. *Ultrasound in Medicine & Biology*, *45*(3), 795–810. https://doi.org/10.1016/j.ultrasmedbio.2018.10.031

Zimmerman, B., Rypma, B., Gratton, G., & Fabiani, M. (2021). Age-related changes in cerebrovascular health and their effects on neural function and cognition: A comprehensive review. *Psychophysiology*, *58*(7), e13796. https://doi.org/10.1111/psyp.13796

Zimmermann, J., Loecher, M., Kolawole, F. O., Bäumler, K., Gifford, K., Dual, S. A., Levenston, M., Marsden, A. L., & Ennis, D. B. (2021). On the impact of vessel wall stiffness on quantitative flow dynamics in a synthetic model of the thoracic aorta. *Scientific Reports*, *11*(1), 6703. https://doi.org/10.1038/s41598-021-86174-6