Resolving the Issue of Resolution

This Journal, as well as practically all publications that deal, directly or indirectly, with hemodynamics and vascular pathophysiology (from a clinical or biomechanical perspective, if there is a difference) have seen an explosion of articles using computational methodologies— often tagged with the CFD acronym, Computational Fluid Dynamics. This research addresses conditions like atherosclerosis, stenosis, and, of interest to this article, aneurysms. In light of this undeniable surge of interest, an article like the one published in this volume entitled, "Mind the Gap: Impact of Computational Fluid Dynamics Solution Strategy on Prediction of Intracranial Aneurysm Hemodynamics and Rupture Status Indicators,"[1] by Valen-Sendstad and Steinman, which documents in very robust, quantifiable, and indisputable terms "how to do it right" is most welcome and will certainly become indispensable guidance in the computational hemodynamics for aneurysms community.

If I were to summarize the article in 2 sentences, I would say that thorough literature inspection and reproduction of published cases shows that often under-resolved simulations (ie, simulations involving meshes that are coarser than necessary) are used to generate hemodynamic data for aneurysm cases. The consequence of this process is that quantitative deductions may be less accurate and specific than necessary. The authors demonstrated their case excellently, and there is little ground for argument. From a certain perspective, this article contributes to a very lively discussion involving CFD that started with the article of Kallmes[2] and attracted many subsequent commentaries and editorials. The discussion that emanated from Kallmes[2] focused more on the "why" of CFD, whereas the article of Valen-Sendstad and Steinman[1] emphasized the "how."

Nevertheless, I think that the "Mind the Gap" part of the title of the article implies "Re-mind the Gap." As the authors clearly show, often simulations are conducted and presented with computational effort that does not do justice to the complexity of the fluid dynamics involved in aneurysm flows. Actually, only recently, very-high-accuracy modeling showed that blood flow features that can be of great fundamental and diagnostic interest may be present in aneurysms and may be missed if not computed at the level of detail necessary.[3] Nevertheless, the computational fluid mechanics community knows how to confirm adequate mesh resolution and has established techniques and protocols that can be followed to ensure that the resolution used for every flow problem covers the fluid physics adequately. One can mention, for example, the National Aeronautics and Space Administration–led initiative: the National Project for Application-Oriented Research in CFD Alliance and its CFD Verification and the Validation Website (http://www.grc.nasa.gov/WWW/wind/valid), where a formal procedure to ensure grid independence in CFD has been established. Similarly, journals involving flow computations, published by the American Society of Mechanical Engineers, like the *Journal of Fluids Engineering – Transactions of the American Society of Mechanical Engineers* compel authors to abide by their "Statement on the Control of Numerical Accuracy," a formal editorial policy for these journals (http://journaltool.asme.org/templates/JFENumAccuracy.pdf). Maybe, given the explosion of computational modeling in the field of neuroradiology, a similar set of guidelines can be inspired by the article of Valen-Sendstad and Steinman[1] for the *American Journal of Neuroradiology*.

There is another side to consider when one argues necessary resolution (and the price modelers and users are willing to pay, in terms of computational cost): what is the clinical question the simulation is aspiring to answer and, consequently, what is the required level of accuracy for responding to that particular question effectively? Although many different aspects of aneurysm health care management have been examined computationally, I can categorize the clinically relevant studies into 3 broad themes:

1) Computation of hemodynamics is used to extract indicators that are then directly correlated to inception, growth, or rupture.[4,5] Usually, statistically meaningful numbers of cases are examined in such studies. In effect, such approaches strive to bypass the biologic complexity of vascular wall biomechanics and link hemodynamics with system-level responses and clinical outcomes directly.

2) At the next level, hemodynamics is combined with arterial wall biology modeling, attempting an almost first-principles coupling of mechanical stimuli (flow-induced wall shear stress, for example) with outcomes (inception, growth, or rupture) by ac-

counting explicitly for the vascular growth and remodeling processes at play.[6]

The first strand of studies mentioned above is more mature and is already used to extract interesting conclusions regarding the effect of hemodynamics in aneurysmal evolution. In contrast, the second thrust is still at a relatively early stage of development, with qualitative and, especially, quantitative know-how regarding the biologic signaling, mechanotransduction, and inflammatory processes often missing. I will come back to that.

The 2 themes above aspire to address the same clinical question—that is, the risk of rupture for a detected aneurysm. Contrary to that, a similarly important question involves the design, application, and performance assessment of interventional devices:

3) Computation of aneurysmal hemodynamics in the presence of interventional devices,[7-10] in which the desired outcome is to evaluate whether a particular device will introduce adequate blood flow stagnation and thus lead to stable thrombus formation.

An interesting point can be made here if articles pertaining to these 3 themes are inspected: There is a stronger motivation for very high accuracy when the first and third classes of studies are involved than when the second theme is examined. I believe that the reason behind this correlation, which is indicated by the article of Valen-Sendstad and Steinman,[1] is that the reward for the higher computational cost involved in better resolved simulations is directly redeemable for device-evaluation modeling: A clear-cut answer that indicates which device performs better is acquired, and this effectively responds directly and in a predictive manner to a clinical question. On the other hand, the causality connected with the second theme above involves several unknowns from the biologic side, but also uncertainty regarding relatively fundamental quantities involved in growth and remodeling studies. Consider, for example, that imaging cannot give us, yet, a good estimate of aneurysm dome wall thickness—a parameter of undisputed importance if a reliable rupture-risk model is to be established. In such a framework, a 10% or 20% uncertainty in the estimation of, say, wall shear stress is less important because it is to be fed through a biologic pathway that presents us with at least similar uncertainties. A similar point can be made regarding the fibrous composition of the wall, endothelial coverage, proteomic activity, and so forth. It is extremely promising that improvements in imaging modalities, in image processing, and in molecular imaging are all making important steps in closing the gap: The information available is becoming more complete and more comprehensive; therefore, the need for accuracy and consistency has become more pressing and more persistent, as Valen-Sendstad and Steinman[1] correctly assert.

The overall message is very positive and should be iterated here, as is expressed in the "Mind the Gap"[1] article: CFD can provide useful and valuable answers if the right questions are asked and if it is done properly. The neuroradiology-CFD community needs to be reminded that the ease and availability of computational simulations currently do not relax the requirements for rigor, adequate resolution and consistency; instead, they further emphasize these requirements. The general fluid mechanics community has introduced formal "re-minders" of these requirements, as mentioned above, and it is extremely important that medically geared modelers are similarly "re-minded"—the article by Valen-Sendstad and Steinman[1] does that in a most convincing manner.

REFERENCES

1. Valen-Sendstad K, Steinman DA. **Mind the gap: impact of Computational Fluid Dynamics solution strategy on prediction of intracranial aneurysm hemodynamics and rupture status indicators.** *AJNR Am J Neuroradiol* 2014;35:536–43
2. Kallmes DF. **Point: CFD-computational fluid dynamics or confounding factor dissemination.** *AJNR Am J Neuroradiol* 2012;33:395–96
3. Baek H, Jayaraman MV, Richardson PD, et al. **Flow instability and wall shear stress variation in intracranial aneurysms.** *J R Soc Interface* 2010;7:967–88
4. Cebral JR, Mut F, Weir J, et al. **Association of hemodynamic characteristics and cerebral aneurysm rupture.** *AJNR Am J Neuroradiol* 2011;32:264–70
5. Chen HY, Selimovic A, Thompson H, et al. **Investigating the influence of haemodynamic stimuli on intracranial aneurysm inception.** *Ann Biomed Eng* 2013;41:1492–504
6. Watton PN, Selimovic A, Raberger NB, et al. **Modelling evolution and the evolving mechanical environment of saccular cerebral aneurysms.** *Biomech Model Mechanobiol* 2011;10:109–32
7. Cebral JR, Mut F, Raschi M, et al. **Aneurysm rupture following treatment with flow-diverting stents: computational hemodynamics analysis of treatment.** *AJNR Am J Neuroradiol* 2011;32:27–33
8. Larrabide I, Aguilar ML, Morales HG, et al. **Intra-aneurysmal pressure and flow changes induced by flow diverters: relation to aneurysm size and shape.** *AJNR Am J Neuroradiol* 2013;34:816–22
9. Mitsos AP, Kakalis NMP, Ventikos YP, et al. **Haemodynamic simulation of aneurysm coiling in an anatomically accurate computational fluid dynamics model: technical note.** *Neuroradiology* 2008;50:341–47
10. Stuhne GR, Steinman DA. **Finite-element modeling of the hemodynamics of stented aneurysms.** *J Biomech Eng* 2004;126:382–87

Y. Ventikos
Department of Mechanical Engineering
University College London
London, United Kingdom

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