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ON UNCERTAINTY, VERIFICATION AND VALIDATION OF CARDIOVASCULAR CFD MODELS

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CFD has become a staple tool in the study of blood flow dynamics and their role in the pathogenesis, diagnosis and treatment of cardiovascular diseases. An essential ingredient has been the development of "image-based" or "patient-specific" CFD, whereby medical imaging provides the boundary conditions for the CFD simulations. For well-studied engineering flows, the geometric and flow boundary conditions, and the fluid and wall properties, are usually known with some certainty, and it is often sufficient to perform mesh refinement studies (verification) and compare against benchmark experiments (validation). In the cardiovascular realm, however, issues around uncertainty, verification and validation are much more complex and subtle:

- Imaging resolution and noise, physiological and operator variability, and modelling assumptions all conspire to introduce error bars into a CFD simulation. Nevertheless, these error bars are rarely known, and even if they are/were, most CFD results are visualized or quantified as being precise.
- Robust mesh and temporal refinement studies – verification – are often not performed or reported, and when they are they are poorly documented. Furthermore, I would argue that studies claiming to *validate* "patient-specific" CFD against in vitro measurements are, in effect, merely verifying an "image-based" CFD model.
- Determining if a "patient-specific" CFD model is a faithful representation of that patient – validation – is hampered by the fact that ground truth imaging data is rarely available. (If it were, we wouldn't need CFD in the first place.) The next best option, then, is for CFD to meet imaging halfway, to allow for necessary "sanity checks".

In my presentation I will review some of my group's past and recent efforts to uncover or clarify the impact of uncertainties and assumptions throughout the image-based CFD pipeline. My intention is not to focus on the usual suspects (e.g., image segmentation, Newtonian fluid, rigid walls) but rather the often hidden assumptions underlying the imaging acquisition and CFD solution processes, and their non-negligible impact on image-based CFD and its verification/validation.