Computational design of artificial organs

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Computer- based numerical flow and mass transport simulation tools, such as Computational Fluid Dynamics (CFD), can provide detailed, three-dimensional predictions of transport in complex geometries. CFD has begun to alter the development process of any blood contacting medical device with demanding performance and reliability requirements. Used at appropriate stages of the design cycle, ideally integrated with other computational tools such as finite-element analysis (FEA) , CFD offers a detailed understanding of fluid mechanics which complements the clinical, technical and experimental experience of the design team. A major benefit offered is the ability to evaluate at early stage designs quickly, before committing to the expense of prototype manufacture and testing. When applied with sound engineering judgement, CFD and FEA can therefore reduce the costs, timescales and risks associated with development of a new design. At the detailed design stage, CFD can quickly investigate the effects of design changes on blood flow, to reduce the risk of unexpected knock-on effects which otherwise would only become apparent at a later stage. When a final design has been reached, CFD analysis can be used to confirm that design goals have been achieved. The detailed CFD picture of the flow field can often be used to support and explain experimental results, potentially strengthening regulatory submissions and providing a scientific base for clinical use.
Computational assessment, when validated, decreases the effort and cost of design and has the potential to improve interventional techniques as clearly will be shown for (the design of) stents. In essence, (bio)mechanical modelling of stents can be categorized in three distinct domains. A first domain consists of numerical studies regarding the solid mechanical aspects of stenting (e.g. stent deployment) based on the Finite Element Method. A second field studies the impact of the stent design (e.g. strut shape, interstrut distance) on the blood flow patterns using Computational Fluid Dynamics. Finally the kinetics of the drug release – in the case of Drug-Eluting Stents (DES) – can also be examined numerically.

From the review presented by De Beule [1], it is obvious that the finite element method offers numerous possibilities in the optimization of revascularization procedures. The application of this numerical approach in this specific biomechanical research domain is quite recent (1997) and has known an enormous evolution the last few years. Undoubtedly all reviewed papers have contributed to the current level of understanding the mechanics of both stent design and angioplasty procedures and the quality of the studies should be evaluated taking into account the available prescience and computational facilities (at the moment of publication). However, an astonishing observed fact in numerous studies is the lack of experimental evidence for the obtained numerical results, creating a missing-link with reality and provoking an (understandable) scepticism with respect to numerical models and to the conclusions drawn from them. The little validation that is performed is often merely qualitative, and thus not always applicable to interpret and verify the numerical results. The only consistent quantitative validation regarding the stent free expansion is from Migliavacca et al. [2], showing the considerable discrepancy between the numerical results and reality when discarding the presence of the balloon in the model and from De Beule et al. [3], demonstrating a very close correlation between experimental and numerical expansion data when taking the folded balloon into account in the model. Regarding the vascular reaction to stent deployment, it should be nuanced that measuring the – by the stent (expansion) induced – deformations and stresses in the vessel wall in an experimental setup is a huge challenge.

Recently Connolley et al. [4] succeeded in creating a 3D representation of stent deployment in a mock artery using synchrotron facilities and Auer and colleagues [5] were able to capture the arterial wall deformations during balloon angioplasty of in vitro samples with MRI. Combining these recently developed tools will certainly allow to investigate the mechanics of different interventional techniques (e.g. to treat bifurcation lesions) and stent designs.

As already stated by Verdonck [6] in 2002, an important question to address during the use of numerical transport simulations is the validation of the predicted results since the results of numerical simulations are only as valid as the physical models incorporated in the governing equations. Therefore *in vitro* (and if possible *in vivo)* validation should be an essential part when studying flow patterns and/or drug kinetics in stented vessels. A possible two step design strategy could be defined as follows:
Step 1: Stents can be deployed *in vitro* within anatomically realistic models and high temporal and spatial resolution Particle Image Velocimetry (PIV) can be acquired. Subsequently these models (with stents deployed) can be imaged on a micro-CT system, followed by a volume reconstruction and CFD simulation. Comparison between CFD results and PIV velocity fields will allow for an assessment of CFD endovascular modelling accuracy, under ideal, in vitro, conditions.
Step 2: In vivo validation can involve controlled in vivo animal experiments. First the target vessel will be imaged using multi-slice CT, followed by stent implantation and a subsequent high resolution Digital Subtraction Angiogram (DSA). Next the vasculature of the target vessel will be reconstructed from the CT-scan and the virtual deployment of the stent within the reconstructed vessel will be modelled. A careful CFD analysis of the target vessel with the implanted stent will be carried out followed by the application of virtual angiography allowing for validation of the CFD predicted flow dynamics against the in vivo DSA data.
Coupling CFD simulations with mass transfer models has the potential to predict the drug deposition in the case of DES. However, again one should keep in mind the strong dependency of the numerical results of the diffusivity properties of the arterial wall, necessitating innovative and complex bench mark tests to (try to) obtain these parameters.

To conclude, given the recent developments, the idea of a surgeon implanting a patient specific stent, selected by means of a numerical presurgical planning tool, no longer seems science fiction. However, the reach this goal, one should proceed (validated) step by (validated) step.

References

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