Computational Modelling and Haemodynamic Investigation of Intracranial Aneurysm Before and After Flow-Diversion Treatment

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論文内容要約

Intracranial aneurysm (IA), also referred to as a brain aneurysm or cerebral aneurysm, is an intracranial vascular disorder that appears as a balloon-like bulge dilates out from the localised weakness in the brain artery wall. A severe consequence of IA development, the rupture of the aneurysm, may result in bleeding into the brain, known as subarachnoid haemorrhage (SAH). Patients with SAH have high risk of brain damaging with paralysis or coma, even death. It is reported that the SAH threatens patients' health and life with high morbidity and mortality rate. According to clinical experiences, larger aneurysms have higher tendency to rupture than smaller aneurysm; and also saccular aneurysms have higher risk of SAH than fusiform aneurysms.

The treatment of an aneurysm is determined according to the patient's need and the condition of the aneurysm; the size and location, and whether or not the aneurysm has ruptured help medical doctors make different decision on the treatment. Flow-diverting (FD) stent, which is one of those commonly adopted endovascular devices, is regarded as the breakthrough treatment for complex aneurysms, for example the wide-neck aneurysm, the fusiform aneurysm, and the bifurcation aneurysm. It offers these patients an alternative to the previous treatment strategies with high successful rate. FD stent is a tubular metal mesh to be deployed in the parent artery across the aneurysm neck, to divert blood flow away from entering the aneurysm sac. Currently, FD stents on the markets are available with different brands, while each of them has individual structures, varying in wire number, wire thickness, layer of wire, braiding angle, and porosity (metal-free to metal-covered area). The diversity of stent structure can result in different flow-diversion effects and treatment outcomes.

Haemodynamic information is believed as one of the most crucial factors affecting the initiation, development, growth, and rupture of IAs. Therefore, the simulation of local aneurysmal haemodynamics should be carried out with adequate accuracy, as it helps to imply the aneurysm statues. Moreover, the post-treatment aneurysmal haemodynamic can also be useful information in the evaluation of aneurysm healing progress, as well as in the assessment of treatment effects.

Many studies of haemodynamic simulation contribute to the understanding of aneurysmal flow dynamics; however,

inconclusive still remains for aneurysms with abnormal parent artery geometries, and furthermore, many of the published studies were in lack of clarification and justification as to the validity of simulation results. First, clinical reports indicate a noticeable prevalence rate of the co-existence of aneurysm and parent-artery stenosis, especially for the stenosed ICA. When such complex vascular disorders exist, along with other morphological complexities (e.g. aneurysms located at the apex of a highly-curved parent artery), the local blood flow patterns would become extremely unpredictable, resulting in a big difficulty in estimating the FD treatment outcomes. Moreover, the accuracy of simulation results would be drastically compromised, when the simulation was not performed following a rigorous protocol or in lack of discussion of validity (e.g. the precision of model geometry reconstruction, the reasonable of parameter settings, the consistency in the recurrence of circulation environment, etc.). Despite that hundreds of IA simulation studies with/without FD stents have been published, few of them have sought to clarify their results' validity, via comparison with the real fluid environment *in vivo* or *in vitro*. Those accuracy-related discussions become particularly crucial, and cannot be avoided in the haemodynamic studies of any 'patient-specific' cases. In addition, for most simulations in which a model FD stent is needed, the model FD stent's properties failed to be calibrated to match that was represented, due to the neglect of the diversity in FD stent structure. Among different types of model FD stents, PM model is one of those most popularly adopted models, as it can save computational time, as well as relieve the burden of performing a virtual stent deployment simulation. However, many simulations using PM model failed to consider the drastic consequences resulting from different stent wire configurations. Instead, the only parameter setting used in their studies to define the PM model stent was a set of parameter with unaltered values. As these model FD stents ignored the importance of parameter setting to be calibrated to the match the representing FD stents, the simulation of flow-diversion effect could not be accurately predicted.

Thus, this study aims to discover the factors that contribute to a more accurate and comprehensive simulation of aneurysmal haemodynamics and its flow-diversion treatment. We took specific interests in the impact of parameter variation on aneurysmal haemodynamic and flow-diversion effects in the following three aspects: 1) the effects of morphologic parameters on aneurysm haemodynamics with consideration of the existence of stenosis, the parent artery curvature, etc.; 2) the accuracy evaluation of computational fluid dynamics (CFD) predictions of aneurysmal haemodynamics before and after FD stent treatment, by comparing to other experimental fluid mechanics methods; 3) the calibration of model FD stent parameters to represent the commercially available FD stents, by derivation of parameters like permeability (k) that account for the flow resistance induced by the model stent.

To meet these interests, using computational models of idealised aneurysms, reconstructed patient-specific aneurysms, and model FD stents, haemodynamic investigation of IAs and their flow-diversion treatments have been carried out. With these studies, we expect to discover the simulation parameters and morphologic characteristics that may affect the credibility of aneurysm haemodynamic simulations, thereby contributing to a more comprehensive and valid understanding of the aneurysmal haemodynamics. Furthermore, we seek to provide future model FD studies a set of parameters after calibration to a variety of treatment modes.

In Chapter III, aneurysmal haemodynamics such as flow pattern, velocity vector field, and pressure change were observed when a stenosis exists at the upstream of the aneurysm, by performing numerical simulation of idealised geometries. Different combinations of geometric characteristics were considered, including different degrees of pre-aneurysmal stenosis located at various distance to the aneurysm, when the aneurysm occurs in straight vessels, as well as at the apex of the convex side of highly curved vessels in two curvatures. Eventually, 7 straight models and 14 curved models were studied. From the morphological effects of such complex artery geometries, significant variations in both aneurysmal haemodynamics and parent artery flows are clarified. The existence of stenosis in the artery, as a sudden narrow, induces the recirculation at the boundary closely after the stenosis. With increasing degree of stenosis, the reattachment length is further promoted. However, the recirculation after stenosis in curved vessels can be compromised, due to the inertia-driven flow, resulting in smaller reattachment length compared to that of the straight vessels. The distance between stenosis and aneurysm, together with the reattachment length, will produce a complicated flow pattern, from their interaction, in the parent artery and aneurysm sac. Conclude from the results, the aneurysmal flow can be disturbed as long as the direction of flow at the aneurysm orifice is affected by the recirculation, or any other factors. Special attentions should be to paid to vascular with severe pre-aneurysmal stenosis that locates close to the aneurysm in clinical cases.

In Chapter IV, the accuracy and validity of CFD predictions of aneurysmal haemodynamics before or after flow-diversion treatment was discussed respectively in Part I and II, by comparing the resolved velocity vector field in two patient-specific aneurysms to different experimental fluid mechanics methods, such as particle imaging velocimetry (PIV) and phase-contrast magnetic resonance imaging (PCMRI). The simulation and experiments were carried out under same flow regime and boundary condition. The *in vitro* experimental aneurysm models were silicone phantoms, manufactured based on the clinical imaging data. In Part I, the three-dimensional (3D) virtual aneurysm model was reconstructed using the scanned image of the silicone phantom. Comparison between PIV and CFD showed good similarities both in flow pattern and two-dimensional (2D) velocity vector field, while similar 3D streamlines in the centre of aneurysm—the vortexes—were observed by comparison between PCMRI and CFD. However, boundary flow pattern of 2D velocity vector field analysed by PCMRI showed discrepancies, compared to that of PIV and CFD, which is considered as a consequence of the low spatial resolution used in PCMRI measurement, as it can obviously increase the difficulties in the measurement and detection of model boundary. In Part II, the FD stent was modelled using porous medium (PM), the properties of which was simply defined following the k and inertial resistance factor (C_2) derived from a Silk stent introduced in the reference. Comparison results of untreated case between PIV and CFD showed very good similarities in the velocity vector field. For the treated cases, PIV results reflected different flow-diversion effects respectively with two FD stents. CFD result, when the PM model stent was defined under the unaltered value, was able to accurately predict the flow pattern, while discrepancies in velocity magnitude were observed, which is believed to be reasonable, for the reason that the definition of PM model FD stent has ignored the parameters to be calibrated to match each FD stents used in PIV experiments. Results have further suggested that the defining the PM model FD stent with calibrated *k* for each FD stent can provide improved concordance between PIV and CFD. Conclude from such results, CFD can be a reliable and convenient tool to accurately predict the aneurysm haemodynamics, provided that the materials and parameters used in simulation are reasonably controlled and determined, for example, the precision of model reconstruction, the adoption of simulation parameters, the reproduction of a consistent flow environment, *etc*.

In Chapter V, impacts on aneurysmal haemodynamics was investigated when the PM model stent is designed with various thickness within a certain range, as well as the adjustment of *k*. As a result, the thickness of PM model (within the range of 50 to 200 μm studied in this thesis) has been found to have negligible influence to the aneurysmal haemodynamics while the k and C_2 are compensated for retaining the pressure drop. This assures the benefit of using PM model stent in the procedure of mesh generation, for the reduced difficulties and improved mesh quality; furthermore, the computational time can be apparently decreased.

In Chapter VI, PM model FD stents were respectively calibrated to reflect the flow resistance created by several treatment modes using commercially available FD stents. Flow-diversion effects of such calibrated PM model FD stents were further compared between different treatment modes in two patient-specific aneurysms. From the results, flow-diversion effects reveal significant variations with respect to different PM model stents, which suggests the importance of model FD stent to be calibrated to match with the representing FD stents. With such specific settings of PM stent properties, this study demonstrates the advantages of FD stent simulation using PM models, by providing medical doctors and other researchers with an individualised method that is more efficient than fully-resolved CFD simulations while also achieving better simulation accuracy than with uncalibrated PM models.

Overall, aneurysmal haemodynamics is found to be sensitive to the morphologies of itself and its parent artery, as w~ll as to the properties of the FD stents. The CFD prediction is also proved to be able to accurately resolve the aneurysm flow dynamics. These studies certainly contributes to an improved validity aneurysmal haemodynamic simulatic thereby enhancing the clinical relevance of such aneurysmal haemodynamic studies in the future.