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Change in aneurysmal flow pulsatility after flow diverter treatment

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ABSTRACT

Motivation: Treatment of intracranial aneurysms with flow diverters (FDs) has recently become an attractive alternative. Although considerable effort has been devoted to understand their effects on the time-averaged or peak systolic flow field, no previous study has analyzed the variability of FD-induced flow reduction along the cardiac cycle.

Methods: Fourteen saccular aneurysms, candidates for FD treatment because of their morphology, located on the internal carotid artery were virtually treated with FDs and pre- and post-treatment blood flow was simulated with CFD techniques. Common hemodynamic variables were recorded at each time step of the cardiac cycle and differences between the untreated and treated models were assessed.

Results: Flow pulsatility, expressed by the pulsatility index (PI) of the velocity, significantly increased (36.0%; range: 14.6–88.3%) after FD treatment. Peak systole velocity reduction was significantly smaller (30.5%; range: 19.6–51.0%) than time-averaged velocity reduction (43.0%; range: 29.1–69.8%). No changes were observed in the aneurysmal pressure.

Conclusions: FD-induced flow reduction varies considerably during the cardiac cycle. FD treatment significantly increased the flow pulsatility in the aneurysm.

1. Introduction

Flow diverters (FDs) have in recent years become an attractive alternative to treat cerebral aneurysms [1,2]. These endovascular devices are low-porosity stents, placed in the parent artery to divert blood flow away from the aneurysm. The flow reduction is aimed at promoting thrombosis inside the aneurysm and effectively excluding it from blood circulation. In particular, wide-necked, fusiform and giant aneurysms are well-suited for this treatment option [3].

Hemodynamic changes after FD treatment have been extensively studied using computational fluid dynamics (CFD), both for idealized [4–6] and anatomically realistic vascular geometries [7–10,1,12–14]. Many studies have focused on quantifying flow reduction as a measure of treatment performance and evaluating its dependency on stent design and configuration [4,5,8], aneurysm morphology [5,10,6] and inflow rate boundary conditions [14]. Others have replicated specific treatments to investigate associations between treatment outcome and hemodynamics [7,9,1,12,13]. Primarily, the performance of FDs has been evaluated by considering the time-averaged or peak systolic flow field, but as the performance may vary during the cardiac cycle [15], analyzing changes in the aneurysmal flow dynamics could provide relevant additional information.

Although animal experiments, CFD studies and clinical series have already shown impressive effectiveness of this technology, the effects on local hemodynamics are yet not fully understood [16,17,7]. Besides complete aneurysm occlusions in the majority of the cases, longer term persisting patency and delayed aneurysm ruptures have also been reported after FD treatment. Since the advent of the technology, different studies have been developed to model these devices and to provide a better understanding of their effect on hemodynamics. The aim of this study was to determine the effect of FDs on the flow pulsatility inside the aneurysm during the cardiac cycle, by considering that the hydraulic resistance of the flow diverter depends on the Reynolds number, which is defined as the ratio of inertial forces to viscous forces.

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Fig. 1. Surface models for the 14 cases analyzed in this study.

2. Materials and methods

2.1. Materials

Fourteen vascular models of the internal carotid artery (ICA) harboring saccular aneurysms were included in this study (Fig. 1). All images were acquired at the Hôpitaux Universitaires de Genéve, Switzerland. All patients consented their pseudonymised data to be shared with the scientific community for the purpose of cerebrovascular research according to the @neurIST protocol, information sheets and consent forms [18]. All aneurysm were located at the internal carotid artery to reduce the hemodynamic variability due to different vascular morphology [19]. Anatomical models, represented by triangular surface meshes, were constructed by segmenting three-dimensional rotational angiography (3DRA) images using a geodesic active regions approach [20] and manually performing mesh cleaning, hole filling and smoothing operations [21]. Images were acquired with an Integris^{TM} Allura System (Philips Healthcare, Best, The Netherlands). Voxel sizes in the reconstructed 3D images were 0.208 × 0.208 × 0.208 mm.

The 14 cases used in this study were selected by three clinicians as being most appropriate for endovascular FD treatment. Their criteria for selecting the treatment was (1) the aneurysm was suboptimal for treatment with coils because of its morphology and/or neck width and (2) the absence of branching arteries (typically ophtalmic artery or the anterior choroidal artery) nearby the aneurysm that could be occluded by the device.

2.2. Flow diverter models

The Fast Virtual Stenting (FVS) method was used [22] for the virtual placement of FDs in the vascular models. The stent struts and their connectivity were defined over a subset of points of a 2-simplex mesh with a size of 4 × 4, which was repeated 24 times circumferentially (resulting in 48 wires, 24 rotating right and 24 rotating left). The number of longitudinal repetitions varied between models depending on the used FD length, ensuring full coverage of the aneurysm neck and one extra diameter on each side of the aneurysm. For more details on the FVS method we refer the reader to [22]. The diameter of the stent wires was 60 microns. Portions of the stent laying on the vessel wall were removed to reduce computational time, following previous studies [23]. The FD models used were generic and did not mimic the device of any particular manufacturer intentionally, as there is variability between their designs (wire thickness, brading angulation, etc.) and the aim of this study is to remain generic. The mean±SD porosity of the FD across the neck among all cases was 75.20±2.66, ranging from 70.40% and 80.85%. In Fig. 2 are presented the resulting FD geometries used for the CFD models for 6 selected cases.

2.3. Computational fluid dynamics analysis

Volumetric meshes were generated using ICEM CFD software package, Version 11.0 (ANSYS, Canonsburg, Pennsylvania). Meshes were composed of unstructured tetrahedral in the lumen and 6-node prism elements near the vessel wall. Smaller tetrahedral elements were used to resolve the stent struts. To ensure CFD simulations independent from mesh element size, in particular around the FDs, a mesh independency analysis was carried out. The convergence criterion of mesh independence was that wall shear stress (WSS) and intra-aneurysmal velocity had to be within 2.5% from the finest tested mesh. Convergence was reached with an element size around the stent strut of 0.016 mm, 3 prism layers with a total size of 0.3 mm defined everywhere but in the region of the FDs

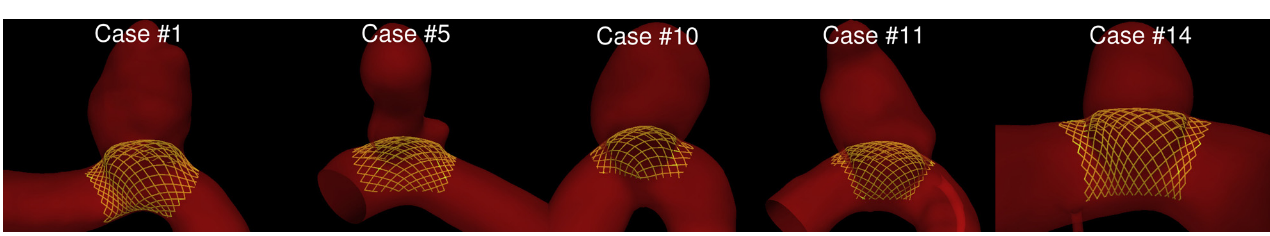

Fig. 2. Vascular models with deployed FDs. Only the portion of the FD covering the aneurysm neck was kept for the CFD simulation. Some vessels were truncated to prevent them from blocking the view. The complete vasculatures are shown in Fig. 1.