A detailed description of the local cerebrovasculature matters: insights from computational simulations of thrombectomy

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1. Introduction

Endovascular thrombectomy (EVT) is the main treatment to acute ischemic stroke (AIS) caused by large vessel occlusions (LVO), a pathology that occurs when a blood clot (thrombus) obstructs a cerebral artery preventing the perfusion of downstream tissues. The EVT is a minimally invasive procedure aiming at mechanically removing the thrombus by means of a stent-retriever. The procedure fails if the thrombus is not removed from the vessels or if it fragments causing an embolization. The cerebral arteries mostly affected by LVO are the internal carotid artery (ICA), the middle cerebral artery (MCA) and the anterior cerebral artery (ACA), which form the so-called T-junction (figure 1A). The ICA is characterized by a tortuous morphology, often referred to as carotid siphon, which can complicate the EVT procedure during the retrieval of the stent-thrombus complex. Few studies in the literature tried to correlate the clinical outcome of EVT with patient's anatomical features. In the clinical scenario, the considered geometric characteristics are usually the total length, the average diameter and the tortuosity (vessel length over head-tail distance) of the ICA, but these global parameters appear insufficient to describe the complex morphology of the artery. Moreover, the analyses are conducted retrospectively on clinical procedures where other variables influenced the outcome, hence the causality between vascular geometry and EVT success remains not clearly assessed [1]. This can be instead investigated with the use of computational simulations of the EVT procedure, where all the other parameters except for the vessel geometry can be maintained controlled and constant for different virtual patients. A finite-element (FEM) model of the stent-retriever EVT, useful to this purpose, was recently developed and validated [2]. The aim of this work is to set up a methodology for finding relations between patient-specific geometric parameters of cerebral arteries and the outcome of computational simulations of EVT. In particular, a set of 3 global geometric parameters usually used in the clinical setting and a set of 27 local geometric parameters are extracted from patient-specific vascular segmentations to verify the hypothesis that a more exhaustive geometric characterization allows a better understanding of the causes of success or failure of the simulated EVT procedure.

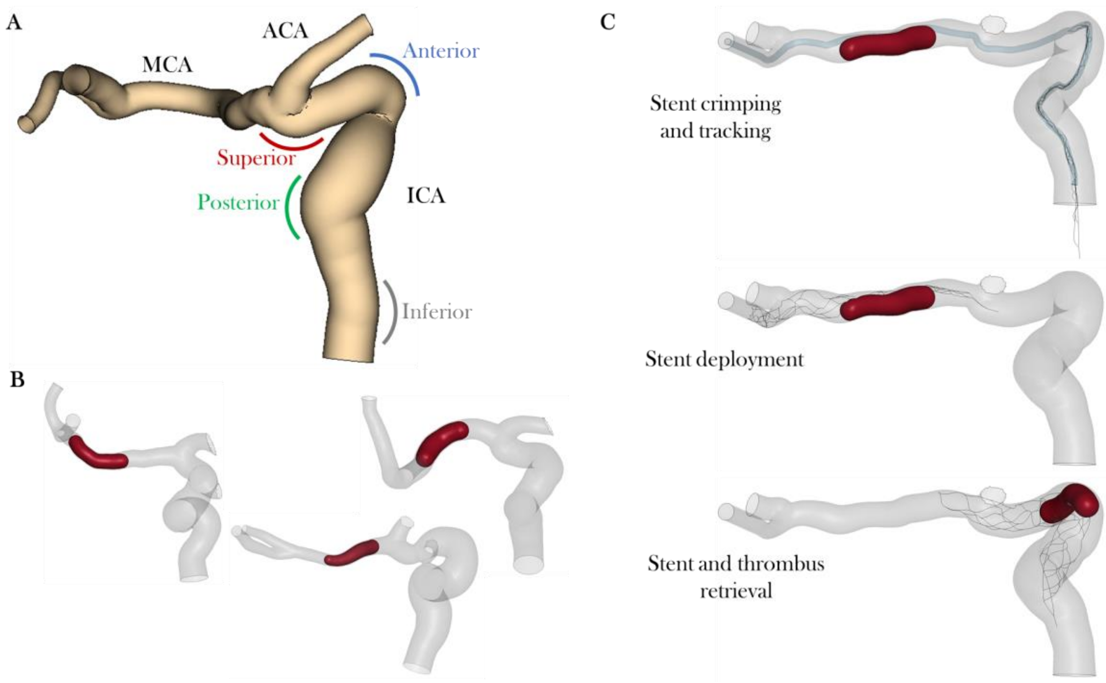

Figure 1 A) Cerebral arteries mostly affected by AIS and indication of the 4 ICA bends. B) Examples of models with patient-specific vasculature and same clot in the middle of MCA. C) Steps of the virtual simulation of the EVT procedure.

2. Methods

Cerebrovascular segmentations of 14 AIS patients with LVO were provided by the Amsterdam University Medical Center, location AMC. The segmentation was performed with Stroke Viewer (NICO.LAB, Amsterdam, The Netherlands) and vessel centerlines and local radii were extracted with iCAFE (© 2016-2018 University of Washington; used with permission). The centerlines of the arteries of interest, i.e. ICA, MCA and ACA, were isolated for the geometric characterization. First, the set of 3 global geometric parameters was collected for each patient-specific geometry. These parameters are the ones usually used in the clinical context, i.e. total length, average diameter and tortuosity (length over head-tail distance) of the ICA. Then, an automatic MATLAB (R2020a, The MathWorks, USA) script was developed to extract the set of 27 local geometric parameters. The first 3 parameters are the angles formed by ICA, MCA and ACA at the T-junction. Then, following the method proposed by Bogunović et al. [3], the ICA siphon is analysed. It is divided into 4 segments: superior, anterior, posterior and inferior bends (figure 1A). For each bend are measured: length, diameter in the point of maximum curvature, radius of curvature (the radius of the fitting circle) and tortuosity. The angles between planes containing consecutive bends and the distances between consecutive bends (distance between consecutive points of intersection between the centerline and the fitting circles) are collected. Finally, the average diameter of the MCA is computed. To investigate the impact of the collected geometric parameters on the outcome of virtual EVT procedures, a FEM model was built for each of the 14 patient-specific vascular geometries, placing a thrombus of the same length and composition in the middle of the MCA (the most frequent thrombus location [4]) (figure 1B). The thrombus parameters were chosen as average values from the literature: 14 mm length [4] and 35% red blood cells – 65% fibrin composition [5], which influences the mechanical properties of the thrombus. The thrombus diameter was set as 90% of the MCA diameter. The same model of TREVO ProVue stent-retriever (Stryker, USA) was used in all the virtual EVT procedures, which followed the same steps: crimping of the stent inside the catheter and positioning at the thrombus location, deployment of the stent to entrap the thrombus and retrieval of the thrombus-stent complex (figure 1C). Details about the meshing parameters and the simulations settings can be found in [2]. The simulations were run with the FEM solver LS-DYNA (ANSYS, USA). The outcome of a simulation is successful if the thrombus is retrieved out of the ICA, while it is unsuccessful if the thrombus is lost inside the vessels. The outcomes of the 14 simulations were correlated with the patient-specific sets of global and local geometric parameters and their combinations, to find a geometric description able to discriminate between positive and negative outcomes of EVT simulations.

3. Results

The simulations of EVT procedure resulted in 9 successful and 5 unsuccessful procedures, in which the thrombus was lost in the anterior bend of the ICA. The outcomes were correlated with the corresponding global and local geometric parameters, singularly and pair-wise, to find an index able to discriminate between different results. Among the global parameters, the best classification index was the ratio between the clot diameter and the average ICA diameter (D^{clot}/D^{ICA}). However, this index does not allow to define a robust separating threshold and one case is misclassified (figure 2A). Using the set of local parameters, a better index is found: considering the combination of radius of curvature of the ICA anterior bend (r^{ant}) and the ratio between the clot diameter and the diameter of the anterior bend in the point of maximum curvature (D^{clot}/D^{ant}) it is possible to identify thresholds which correctly separate the cases with successful and unsuccessful outcome (figure 2B).

4. Discussion

In this work, a methodology to build in silico patient-specific cerebral vasculature and to run virtual EVT procedures is developed. In particular, the proposed numerical method aims at investigating the influence of the complex cerebral vasculature on the outcome of computational simulations of the EVT procedure. The results are limited by the number of patients considered. Nonetheless, the importance of analyzing local geometric parameters rather than global ones was highlighted. For example, figure 2C shows the cases of patients 8 and 9, which share similar values of the global parameters, while a significant difference is observed in the radius of curvature of the anterior bend, which determined the failure of the EVT procedure in patient 8. These results refer to the specific choice of thrombus characteristics and stent-retriever. A similar analysis should be repeated with different thrombi and with other devices used in the clinical practice. Once ready, this analysis may provide a tool for pre-operative planning of the EVT procedure in a selected patient and may improve the procedure outcome and patient recovery.

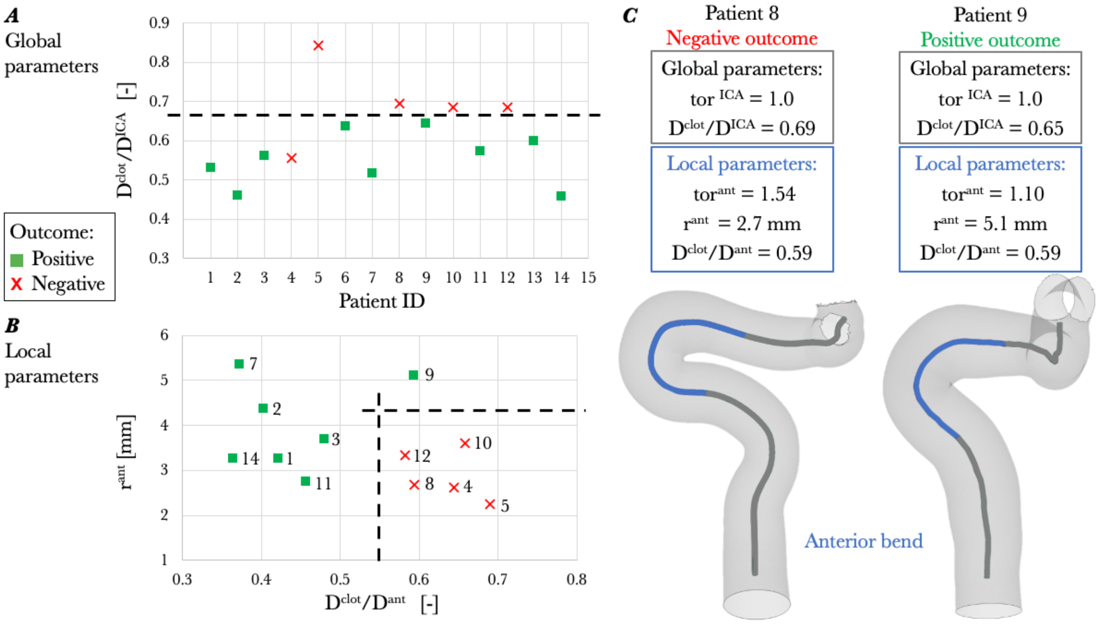

Figure 2 *Best classification indices with global* ***(A)*** *and local* ***(B)*** *geometric parameters (the segmentation for patients 6 and 13 included only the superior bend).* ***C)*** *Example of two patients with similar global parameters but different local parameters, which resulted in a different virtual EVT outcome.*

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