Simulation of the thrombectomy procedure in a realistic intracranial artery

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1. Introduction

An ischemic stroke is caused by a blood clot (thrombus) in an intracranial artery that prevents the blood to supply the downstream tissues. The thrombus may originate from the heart, from atherosclerotic plaques, or from vessel wall dissections. It is a mass of platelets, fibrin, and other blood components, activated by a hemostasis mechanism, which may present different composition. Red thrombi, red blood cell (RBC) dominant, are usually generated where the blood flow is slow and the fibrin network entraps the RBCs, while white thrombi, fibrin dominant, are generated under high shear flow and inflammatory conditions. The clot composition affects strongly its mechanical properties [1].

The main diagnostic techniques used during the stroke investigation are the Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). In any case, detection of the location of the intracranial occlusion must be done in a fast and accurate way to ensure speedy treatment. Treatment of acute ischemic stroke is aimed at restoring blood flow in the affected cerebral arteries as fast as possible after onset. *Time is crucial in stroke*, 2 million neurons are lost every second without reperfusion.

There are currently two main therapies: medical therapy using thrombolytic agents and interventional therapy using mechanical thrombectomy. Thrombolysis became available in recent times and involves the administration of tissue plasminogen activator within 4.5-6 hours after stroke onset. Innovative intra-arterial mechanical thrombectomy has been even more recently introduced in clinical application. Currently a combined approach of thrombolysis and mechanical thrombectomy are recommended for the treatment of acute ischemic stroke that involve large vessel occlusion, with both also being used in isolation depending on the patient circumstances. Two main classes of thrombectomy devices exist, (i) aspiration devices and (ii) stent retrievers. The recent MR CLEAN [2] and subsequently clinical trials confirmed the effectiveness and safety of stent-retrievers and their improved outcome compared to thrombolysis and to aspirations devices was demonstrated. The thrombectomy procedure consists of the mechanical removal of the thrombus by means of a Nickel-Titanium (NiTi) self-expandable stent at the end of a flexible wire, delivered in a crimped configuration in a microcatheter and positioned across the thrombus. Once there, the stent-retriever is deployed by withdrawing the microcatheter, even at this stage the expanded stent may restore the blood flow by pushing the clot against the arterial wall. Finally, the clot trapped in the stent struts is removed along with the stent, usually under flow arrest by aspirating on a balloon guide catheter with the balloon inflated.

The procedure is done during angiography (Fig. 1a). Revascularization of the affected vessels is strongly associated with improved clinical outcome for patients. But despite its increasing clinical application, the procedure may result in some adverse outcomes, such as distal thrombus embolization [3] and hemorrhagic events. In addition, some clots remain resistant to both thrombolysis and thrombectomy. Procedural success also greatly depends on vascular geometry (tortuosity) and thrombus characteristics. Consequently, there is still room for improvement in thrombectomy device technology. With the introduction of new stroke treatments, many new clinical trials are planned and expected. As such a great opportunity for thrombectomy numerical investigations exists to expediate, optimize or even replace these resource intensive trials. Even today, numerical modeling plays a decisive role in research and development of biomedical products. In combination with patient-specific models, *In silico* models can be used to build *in silico* clinical trials in which virtual patients are treated with virtual treatments.

In this context, the aim of this work is the development of an in-silico model of the thrombectomy procedure in a mock-patient-specific domain. To the best of our knowledge, this is the first modeling study of this clinical procedure with a stent retriever device. A sensitivity analysis on the thrombus material properties and on its friction coefficients with the arterial wall was also performed to identify the main parameters responsible for an efficient thrombus removal.

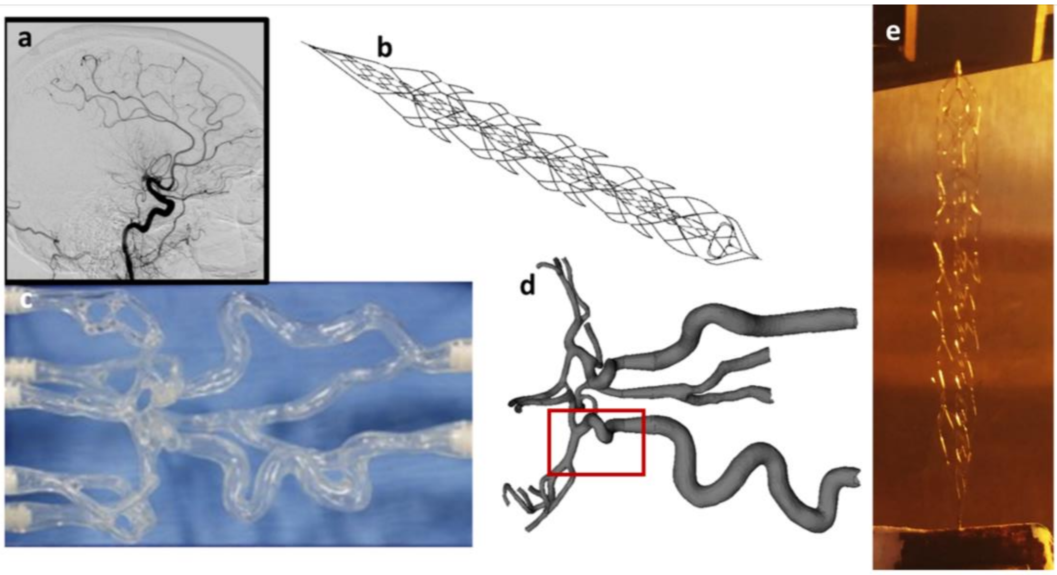

Figure 1 *(a) Angiography to guide the procedure, (b) CAD model of the EmboTrap II stent-retriever, patient-specific (c) bench-top and (d) CAD model, (e) uniaxial tensile test.*

2. Method

2.1 Stent-Retriever model

The CAD model of the EmboTrap II (CERENOVUS, Galway, Ireland) was analyzed to extract the center-lines of the frame (Fig. 1b). It was discretized with 4,353 beam elements with 0.15 mm of length, after a proper mesh size sensitivity analysis. The Hughes-Liu beam formulation was adopted with rectangular equivalent section. The NiTi material parameters were identified through a numerical-experimental coupling: the stent underwent a uniaxial tensile test at 0.05 mm/min up to 4.5 mm, in a temperature-controlled chamber 37.0±0.1°C (EnduraTEC ELF 3200, BOSE). The experiment was then truthfully computationally reproduced.

2.2 Patient-Specific model

The CAD model of the bench-top silicone model (Fig. 1c) was discretized with triangular elements (Fig. 1d) and its material was considered rigid due to its high stiffness. An idealized thrombus was drawn with reasonable dimensions, 8 mm of length and 3 mm of diameter. It was discretized with 12,982 tetrahedron elements with one-point integration and modelled with a linear elastic law. A sensitivity analysis was performed on thrombus Young's modulus which varied from 400 to 1500 Pa [4].

2.3 Thrombectomy analysis

The finite element simulations were performed on 40 CPUs of an Intel-MPI Xeon64 with 240 GB of RAM memory using the commercial finite element solver LS-DYNA 971 Release 11.0 (LSTC, Livermore, CA, USA). A mass proportional damping coefficient was used for both the thrombus and the stent parts, after a proper sensitivity analysis. A quasi-static condition in each step was achieved, with a ratio between the kinetic and the internal energy less than 2 %. A selective mass-scaling was adapted in order to have a time-step between 10^{-6} and 10^{-7} s.

The simulation of the thrombectomy procedure consisted of four steps:

(i) the stent retriever was crimped in a 1 mm diameter rigid catheter. A penalty contact was defined between the beam elements of the stent and the shell elements of the catheter;

(ii) the crimped stent was positioned in the location of the clot. A penalty contact was defined between the thrombus and the microcatheter and between the thrombus and the arterial wall; a sensitivity analysis on the friction coefficient of this latter contact was conducted [5];

(iii) the stent was released by unsheathing the microcatheter and it went in contact with the thrombus. A soft penalty contact was defined between the beam elements of the stent and the thrombus;

(iv) the thrombus, trapped inside the stent, was finally retrieved along the vessel.

The meshing procedure and the post-processing analysis were performed with ANSA and META 19.0 (BETA CAE System, Swi

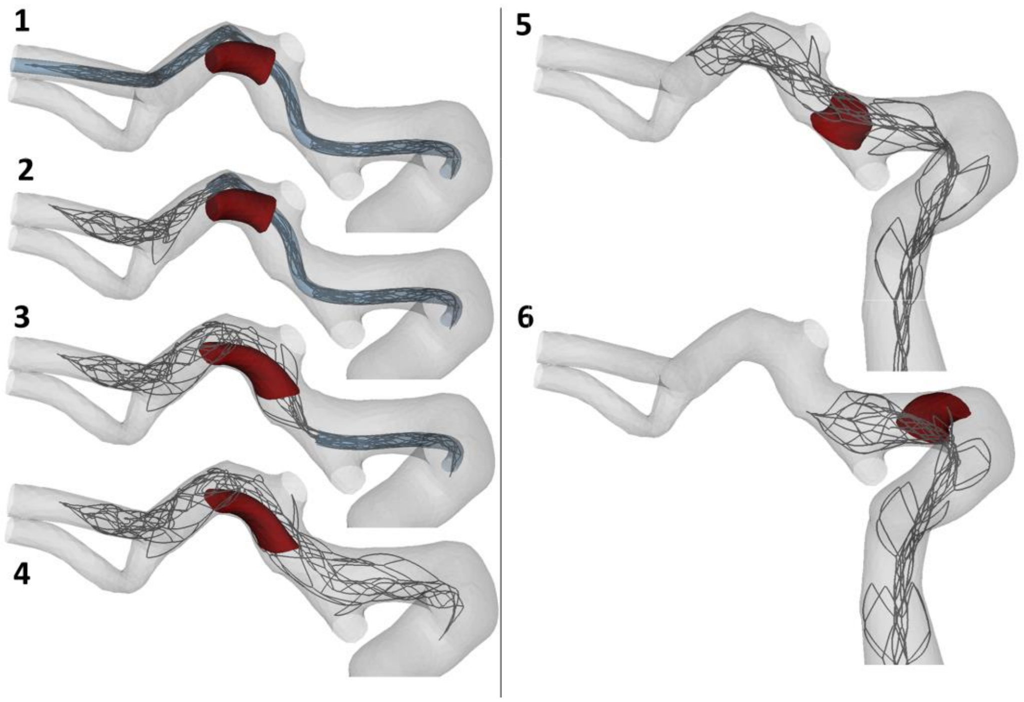

__Figure 2__ Thrombectomy simulation: release (1-4) of the stent after its positioning within the microcatheter; retrieval (5-6) of the stent and the trapped thrombus along the vessel.

3. Results

The results of the simulations were confirmed by evaluating the efficacy of the methodology to replicate all the steps of the thrombectomy clinical procedure. Both of the analyzed parameters (thrombus material properties and its friction coefficients with the arterial wall) were significant influencers that affected the procedure outcomes.

4. Conclusion

In the *in silico* trial arena, numerical models of clinical procedures on patient-specific domains are becoming an important tool. The novel methodology developed showed the potential of our finite element analysis to model all the steps of a thrombectomy procedure in an accurate way. In particular, the patient-specific analysis can be used to predict potential revascularization outcomes, help to interpret adverse effects and to improve the understanding of the influence of individual patient anatomies.

There is possibility for further improvement of the thrombectomy technique, which is generally considered the most important issue in improving stroke treatment today. Another interesting subject is to use numerical modeling to better understand the complications of the treatment despite successful recanalization. There are still open questions about the treatments, such as the effect of combination of thrombolysis and stent-retriever thrombectomy and the design of new, more effective devices.

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