



# Microcatheter tracking in thrombectomy procedures: A finite-element simulation study



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## ABSTRACT

**Background and objective:** Mechanical thrombectomy is a minimally invasive procedure that aims at removing the occluding thrombus from the vasculature of acute ischemic stroke patients. Thrombectomy success and failure can be studied using in-silico thrombectomy models. Such models require realistic modeling steps to be effective. We here present a new approach to model microcatheter tracking during thrombectomy.

**Methods:** For 3 patient-specific vessel geometries, we performed finite-element simulations of the microcatheter tracking (1) following the vessel centerline (centerline method) and (2) as a one-step insertion simulation, where the microcatheter tip was advanced along the vessel centerline while its body was free to interact with the vessel wall (tip-dragging method). Qualitative validation of the two tracking methods was performed with the patient's digital subtraction angiography (DSA) images. In addition, we compared simulated thrombectomy outcomes (successful vs unsuccessful thrombus retrieval) and maximum principal stresses on the thrombus between the centerline and tip-dragging method.

**Results:** Qualitative comparison with the DSA images showed that the tip-dragging method more realistically resembles the patient-specific microcatheter-tracking scenario, where the microcatheter approaches the vessel walls. Although the simulated thrombectomy outcomes were similar in terms of thrombus retrieval, the thrombus stress fields (and the associated fragmentation of the thrombus) were strongly different between the two methods, with local differences in the maximum principal stress curves up to 84%.

**Conclusions:** Microcatheter positioning with respect to the vessel affects the stress fields of the thrombus during retrieval, and therefore, may influence thrombus fragmentation and retrieval in-silico thrombectomy.

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## 1. Introduction

The treatment of diseases has been revolutionized by the introduction of minimally invasive procedures. Particularly, in interventional neuroradiology, the use of minimally invasive

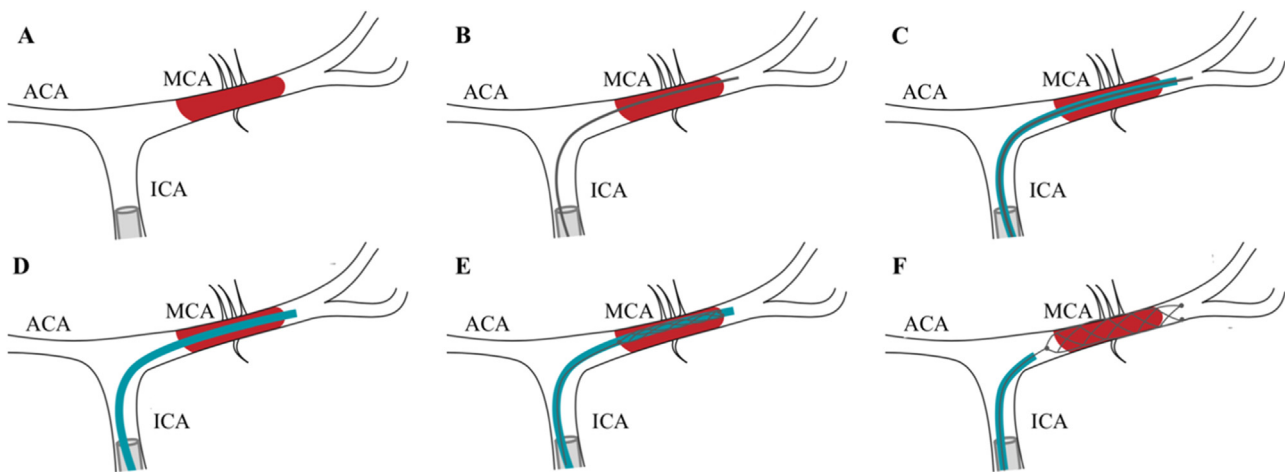
techniques in patients with stroke aids in the lack of patient improvement achieved by sole intravenous administration of pharmaceutical compounds [1].

In 2015, the first minimally invasive procedure to treat acute ischemic stroke, the leading cause of neurological death worldwide, was proven effective: mechanical thrombectomy [2]. Thrombectomy aims at mechanically removing the occluding thrombus from the vasculature, by using stent-retrievers and/or aspiration devices. In this study, we focus on stent-retriever thrombectomy.

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**Fig. 1. Thrombectomy steps.** (A) A guiding catheter is introduced in the ICA. (B) A micro-guidewire is introduced through the guiding catheter and the intracranial thrombus occluding the MCA. (C) A microcatheter is navigated over the micro-guidewire through the thrombus, ensuring that the tip of the microcatheter is placed beyond the thrombus. (D) The micro-guidewire is removed. (E) The stent-retriever is inserted through the microcatheter. (F) The stent retriever is deployed by retracting the microcatheter beyond the proximal part of the stent retriever. The stent-retriever with the entrapped thrombus is retrieved from the vasculature by pulling it to the guiding catheter. ACA, anterior cerebral artery; ICA, internal carotid artery; MCA, middle cerebral artery.

Stent-retriever thrombectomy consists of multiple steps (Fig. 1). First, a guiding catheter is introduced in the extracranial internal carotid artery (ICA) (Fig. 1A). Then, a micro-guidewire is introduced through the guiding catheter and past the intracranial thrombus (Fig. 1B). Next, a microcatheter is navigated over the micro-guidewire through the thrombus, ensuring that the tip of the microcatheter is placed beyond the thrombus (Fig. 1C). Consecutively, the micro-guidewire is removed to allow the introduction of the stent-retriever through the microcatheter and successive deployment in the thrombus by retracting the microcatheter beyond the proximal part of the stent (Fig. 1D–1F). Finally, the stent-retriever with the entrapped thrombus is retrieved from the vasculature by pulling it into the guiding catheter.

The success of thrombectomy is dependent on multiple factors including the (biomechanical) characteristics of the thrombus [3,4] and the size and positioning of the stent [5]. In-silico models can help in identifying reasons why the retrieval of the thrombus is not successful by studying aspects such as the optimal positioning of the stent, the interaction between the stent and the thrombus, or the optimal stent design for a particular thrombus type [6–9]. Such models allow to test for the same patient-specific characteristics all these different scenarios and find the optimal combinations that lead to the highest success rate. For this purpose, an accurate model resembling the real thrombectomy is required.

Microcatheter placement may influence the positioning of the stent with respect to the vessel and the thrombus, and therefore, affect the retrieval phase and its outcome. Notably, in previous in-silico modeling of thrombectomy efforts, the microcatheter tracking either followed the vessel centerline (which is an oversimplification of the real scenario) [6,10] or was manually defined [11,12]. There is no comparison between the modeled microcatheter positioning and clinical images in current literature. Certainly, the imaging obtained during thrombectomy procedures shows that the microcatheter (and stent) bends and approximates certain parts of the vessel curvature, not following the vessel centerline. Moreover, in other minimally invasive surgery models, more realistic finite element simulations have been proposed to model the correct tracking of catheters [13–20]. The guidewire tracking is currently neglected in the simulation steps of thrombectomy since it is not required to model the retrieval phase – only the final microcatheter positioning is needed. The microcatheter positioning might be a crucial step in the simulation of thrombectomy since

the stent placement follows the path dictated by the microcatheter (Fig. 1D–1F), which ultimately impacts the interaction between the stent and the thrombus. Studying the effect of the microcatheter (and stent) positioning can be relevant in clinical scenarios where the thrombus is in challenging configurations such as in bifurcated vessels, where the interventionalist has to make a conscious decision on the branch where the stent will be deployed.

This work aims at improving the microcatheter-tracking step of in-silico thrombectomy procedures by developing a more realistic method to virtually position the microcatheter (Fig. 1D). The virtual microcatheter positioning is qualitatively evaluated with images from patient-specific cases acquired during the thrombectomy procedure. Finally, the importance of properly modeling the microcatheter tracking as the first step for in-silico thrombectomy procedures is studied by running the same procedure with different microcatheter tracking methodologies for patient-specific cases.

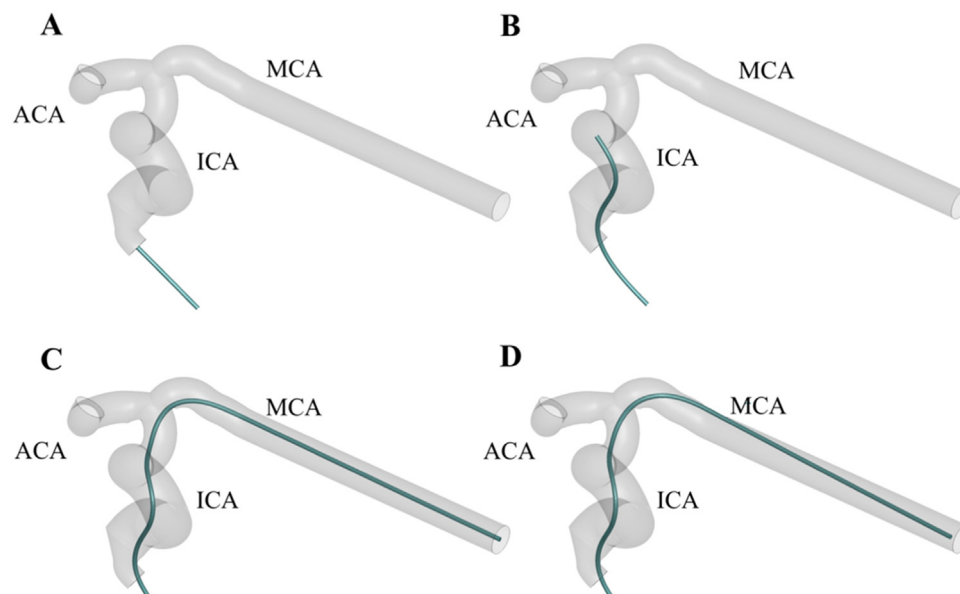
## 2. Methods

### 2.1. Patient data

Imaging data were acquired from the MR CLEAN Registry, an ongoing, prospective, observational, multicenter study, including data from acute ischemic stroke patients treated with endovascular treatment in the Netherlands [21]. We used imaging data of three patients (patients I, II, and III) with a middle cerebral artery (MCA)-M1 segment occlusion, who had available thin-slice computed tomography angiography (CTA) and non-contrast computed tomography (NCCT) scans prior to any treatment, and good quality digital subtraction angiography (DSA) images acquired during thrombectomy, where the position of the microcatheter (or stent) is visible.

### 2.2. Microcatheter tracking simulation: the tip-dragging method

The patient-specific vessel geometries were acquired from computed tomography angiography (CTA) scans as described in Luraghi et al. 2021 [6]. Briefly, the intracranial region of interest was selected on the NCCT scan and was subsequently registered to the CTA using Elastix's rigid registration [22]. Afterward, all intracranial vessels (arteries and veins) were segmented using StrokeViewer (NICOLAB, The Netherlands), a convolutional-neural-network-based



**Fig. 2. Steps of the tip-dragging method.** (A) The microcatheter is aligned with the ICA entrance. (B) The tip is dragged along the vessel centerline. (C) The tip of the microcatheter reaches the end position in the MCA-M1 segment. (D) In the absence of external forces or constraints, the microcatheter accommodates in the vessel governed by its elastic properties until it reaches an equilibrium position. ACA, anterior cerebral artery; ICA, internal carotid artery; MCA, middle cerebral artery.

software. Subsequently, a trained observer amended the segmentation by selecting the arteries and excluding the veins using ITK-snap software [23]. Finally, centerlines and local radii were extracted using iCAFE (©2016–2018 University of Washington. Used with permission.). With these data, the vessel surfaces were subsequently reconstructed in SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France), a computer-aided design (CAD) modeling software. The MCA-M1 vessel segment surface was extended since the reconstructed geometries terminate at the original occlusion location (where contrast cannot flow), i.e., the M1 segment.

For the tracking simulation, the vessels were modeled as a rigid material with quadrilateral elements (mean element size of 0.3 mm). The microcatheter was modeled as a linear elastic material ( $E = 3.6$  GPa [13]) consisting of linear beam elements with tubular cross-sections (mean element length of 0.2 mm and cross-section diameter of 0.5 mm). A soft penalty contact interaction without friction was defined between the vessel and the microcatheter. More details on the finite element simulations can be found in Luraghi et al. 2021 [6].

The microcatheter tip-dragging technique consisted of a one-step simulation in which the microcatheter tip was pulled along the vessel centerline while the body was free to move and adjust inside the vessel (Fig. 2). Specifically, the microcatheter was aligned with the most proximal part of the ICA centerline (Fig. 2A). In order for the microcatheter to advance, the microcatheter node closest to the ICA entrance was constrained to move following the vessel centerline (Fig. 2B). The remaining nodes of the microcatheter beam were not constrained or subjected to this boundary condition and were, therefore, free to move during the insertion. Once the microcatheter was completely inserted into the vessel, it was left free to adjust to the vessel configuration (governed by its elastic properties) and to reach an equilibrium condition (Fig. 2D).

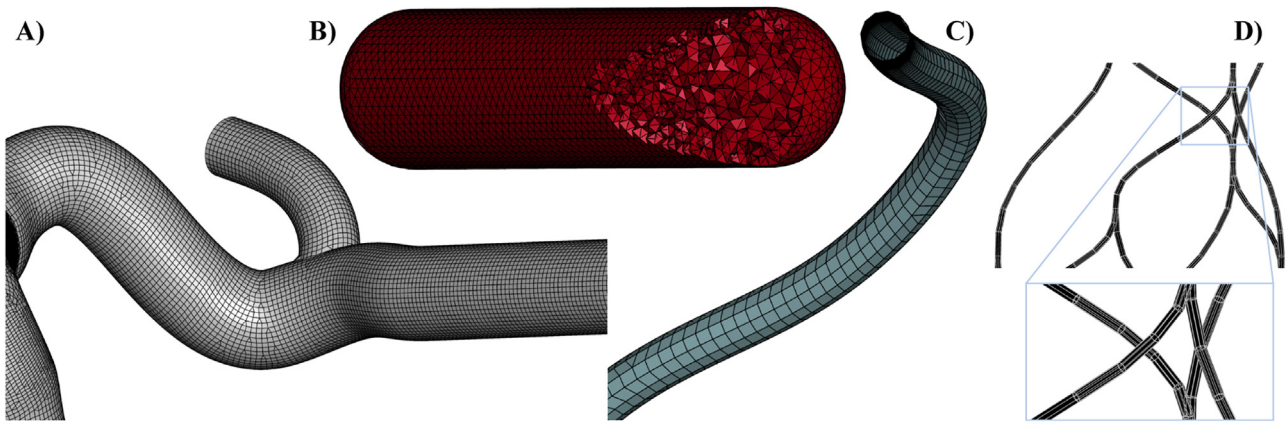
The microcatheter positioning was visually and qualitatively evaluated by comparing the final simulated microcatheter configuration with the patient-specific DSA image. For each patient, two microcatheter configurations were studied: (1) the vessel centerline method [6] and (2) the here described tip-dragging technique.

### 2.3. Thrombectomy simulation

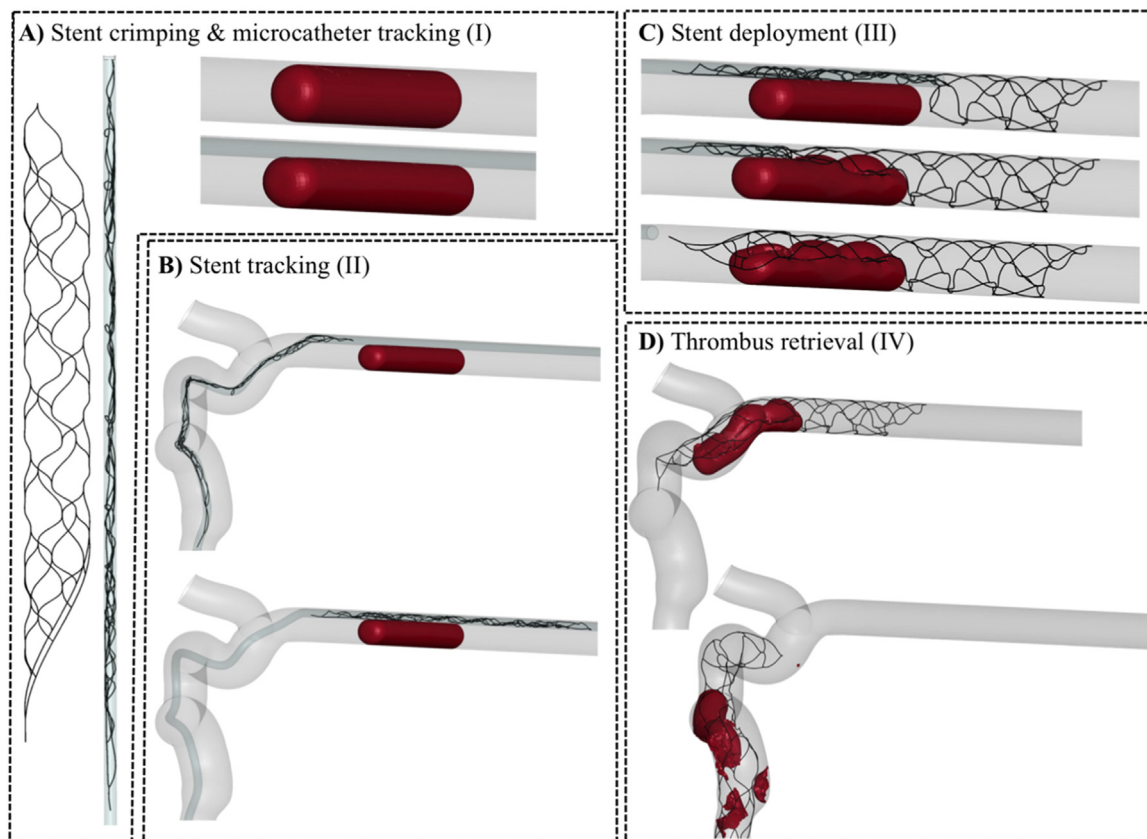
For each patient, two simulations of the same thrombectomy procedure were implemented for both microcatheter configurations.

The same vessel models were adopted in all the simulations (Fig. 3A). The microcatheter positioning was extracted from the previous step: 1) following the vessel centerline and 2) based on the final configuration obtained with the tip-dragging technique. These microcatheters were modeled as cylindrical tubes with 0.5 mm of diameter, discretized with rigid quadrilateral elements (mean element size of 0.2 mm) (Fig. 3C). The thrombus was always placed in the central part of the MCA-M1 segment with the following characteristics: length of 14 mm and a composition of 35% red blood cells and 65% fibrin [7]. The thrombus diameter was set to occlude 90% of the patient-specific MCA diameter. Thrombi were discretized with linear tetrahedral elements (mean element size of 0.2 mm) and modeled as a compressible hyperelastic material with a stress-threshold failure (Fig. 3B) [6]. The TREVO ProVue 4–20 mm stent (Stryker, USA) was chosen for the virtual procedure. It was discretized with linear beam elements with cross-section integration (mean element length of 0.2 mm) and modeled as a shape memory alloy material (Fig. 3D). More details on the stent mesh discretization can be found in Luraghi et al. 2022 [24]. For the reader's convenience, after comparing various element formulations, discretizations and integrations, we concluded that the chosen beam elements were sufficiently accurate for our simulations. Mesh sizes for the thrombus and vessel were chosen to be similar to that of the stent, so that the contact between them can be optimally simulated. Details about the nickel-titanium material parameter definitions can be found in Luraghi et al. 2021 [6].

The thrombectomy simulation consists of four consecutive steps: (I) the thrombus is pushed against the vessel wall in order to create space for the microcatheter, by rigidly displacing the microcatheter itself until it reaches its final inserted configuration; subsequently, the stent is crimped to a diameter of 0.5 mm, by dragging the stent tip inside the microcatheter (Fig. 4A); (II) the crimped stent is placed across the thrombus location through



**Fig. 3. Mesh discretization.** (A) Vessel discretized with quadrilateral elements with mean size of 0.3 mm. (B) Thrombus discretized with linear tetrahedral elements with mean size of 0.2 mm. (C) Microcatheter discretized with quadrilateral elements with mean size of 0.2 mm. (D) Stent discretized with linear beam elements with mean length of 0.2 mm and cross-section integration.



**Fig. 4. Thrombectomy steps.** (A) the stent is crimped down to 0.5 mm in diameter while the microcatheter is positioned at the occlusion location; (B) the stent is tracked along the microcatheter; (C) the stent is gradually deployed and is left free to interact with the thrombus; (D) the stent-thrombus complex is retrieved from the vasculature following the microcatheter position. The figures displayed here correspond to the simulation with the centerline method.

the microcatheter, imposing the movement of the stent tail along the microcatheter centerline (Fig. 4B); (III) the crimped stent is deployed by gradually removing the microcatheter (Fig. 4C); (IV) finally, the stent together with the entrapped thrombus are retrieved by imposing the displacement of the stent tip along the microcatheter centerline until the most proximal part of the ICA (Fig. 4D).

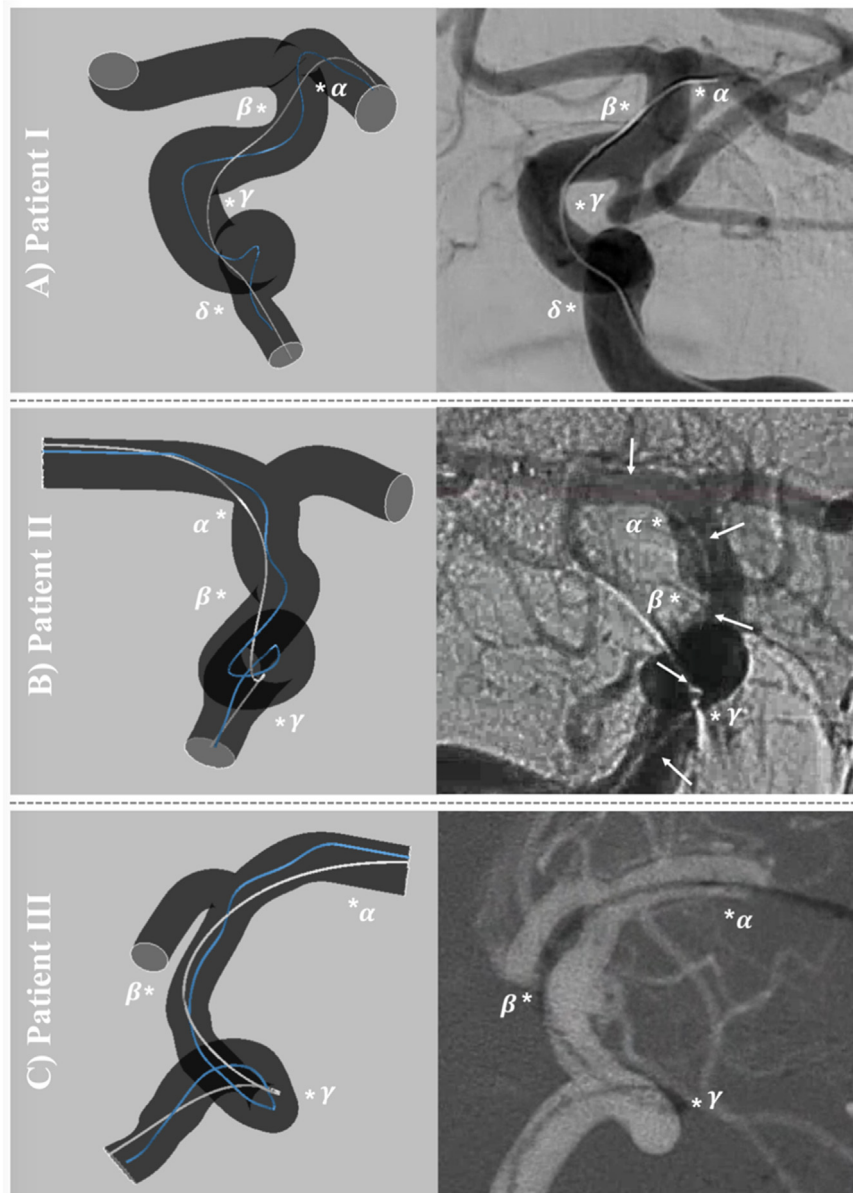
During the microcatheter tracking, a frictionless soft-penalty contact was defined between the thrombus and the microcatheter and a rough soft-penalty contact between the thrombus and the vessel wall. During stent tracking and deployment, a hard-penalty

contact was set between the stent and microcatheter, a soft-penalty contact between the stent and the thrombus, and a hard-penalty contact between the stent and the vessel wall. For a more detailed description of the contact algorithms, time step, damping system, and other technical details refer to Luraghi et al. [6,12].

The discretization process was done in ANSA Pre Processor (BETA CAE System, Switzerland) while all the simulations were performed in LS-DYNA R13 (ANSYS, USA).

For each patient, we compared the in-silico thrombectomy outcome (thrombus retrieved successfully vs. unsuccessfully), the kinematics of the thrombus with respect to the stent, and the





**Fig. 5. Simulated and real microcatheter tracking.** Left) Vessel model showing the arterial geometry and tracked microcatheter following the centerline (blue) and by dragging the tip (white). The white stars indicate the bending points of interest ( $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ ). Right) Patient-specific DSA image displaying the arteries and the devices. The white arrows indicate the positioning of the device. Patient I and III have a left MCA M1-segment occlusion; Patient II has a right MCA M1-segment occlusion. DSA, digital subtraction angiography; MCA, middle cerebral artery. (Fig. 5C-DSA is an overlay image automatically generated by the consecutive imaging of the stent and the vessel).

stress field of the thrombus during the procedure. In particular, the maximum principal stress value (PSMAX, averaged value over 10 elements with the highest values) was computed.

### 3. Results

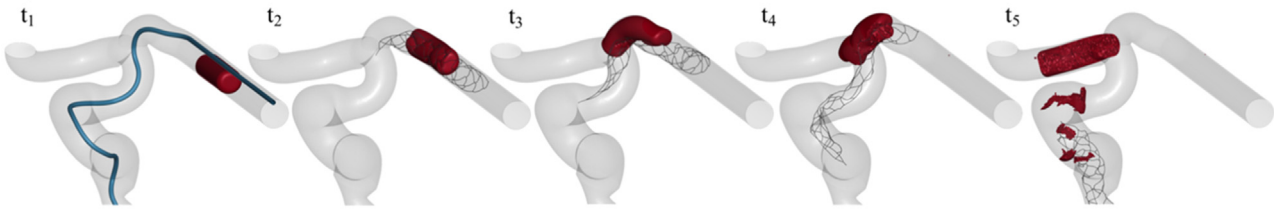
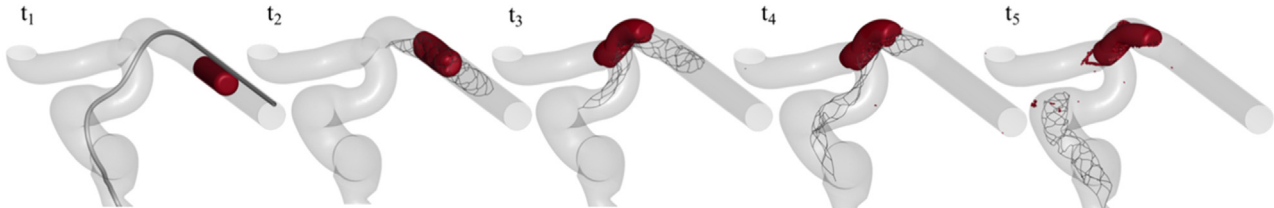
#### 3.1. Virtual and real-life microcatheter tracking

Fig. 5 displays the simulated microcatheter tracking for both centerline and tip-dragging methods, as well as the DSA images acquired during the thrombectomy procedure. In **Patient I**, the visual comparison showed that the tip-dragging method better resembles the microcatheter positioning in the bends compared to the centerline method, as indicated by points  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  (Fig. 5A). As for **Patient II**, the tip-dragging method also seemed to better reproduce the microcatheter behavior within the vessel, especially clear

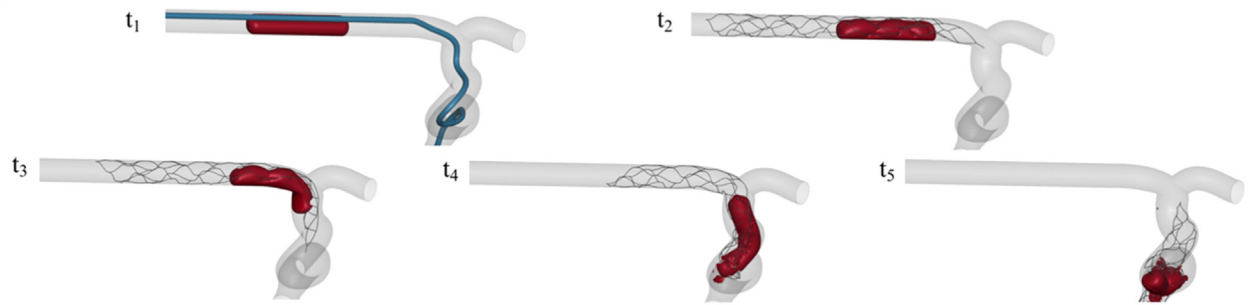
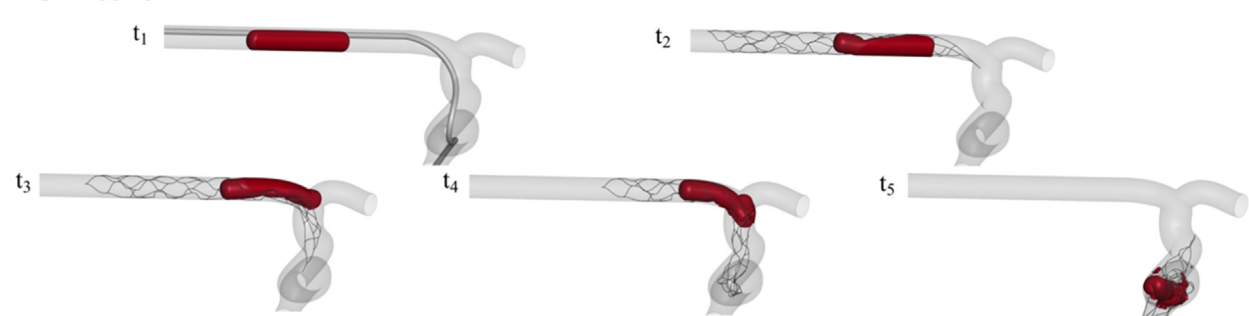
at points  $\alpha$ ,  $\beta$ , and  $\gamma$ , where the stent approaches the vessel wall (Fig. 5B). For **Patient III**, points  $\alpha$  and  $\beta$  show that the tip-dragging method better resembled the real curvature of the microcatheter. For point  $\gamma$ , the centerline method seems to better catch the shape of the loop, but the tip-dragging method better captures the microcatheter position close to the vessel wall, as observed from the DSA image (Fig. 5C).

#### 3.2. Impact of the microcatheter tracking on thrombectomy

The full thrombectomy simulation with the centerline method lasted approximately 24 h on a system featuring 40 CPUs (Intel Xeon64) with a RAM memory of 256 GB. The mean CPU time for the additional simulations of the tip-dragging method was of approximately 1 h.

**PATIENT I****A) Centerline method****B) Tip-dragging method**

**Fig. 6. Thrombectomy outcomes for Patient I.** Results of the thrombectomy simulations at the end of the microcatheter tracking ( $t_1$ ), at the end of the stent deployment ( $t_2$ ), and during the retrieval phase ( $t_3$  to  $t_5$ ) for (A) the centerline method and (B) the tip-dragging method.

**PATIENT II****A) Centerline method****B) Tip-dragging method**

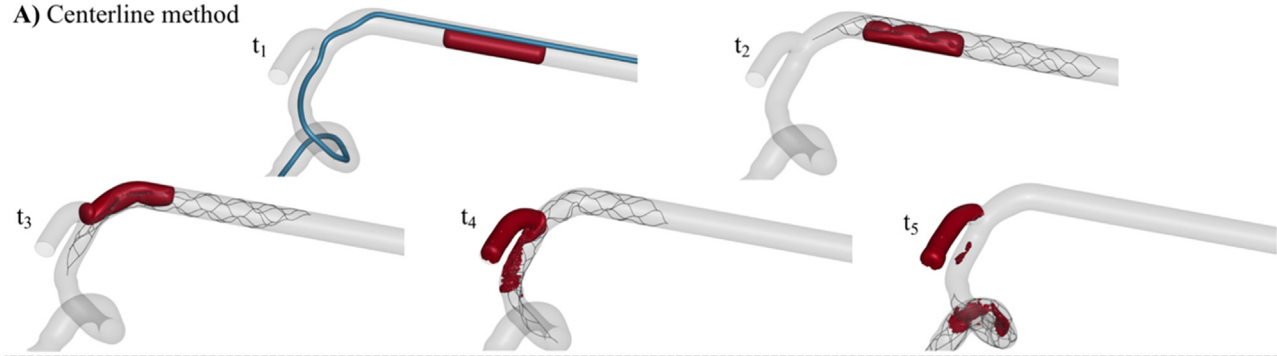
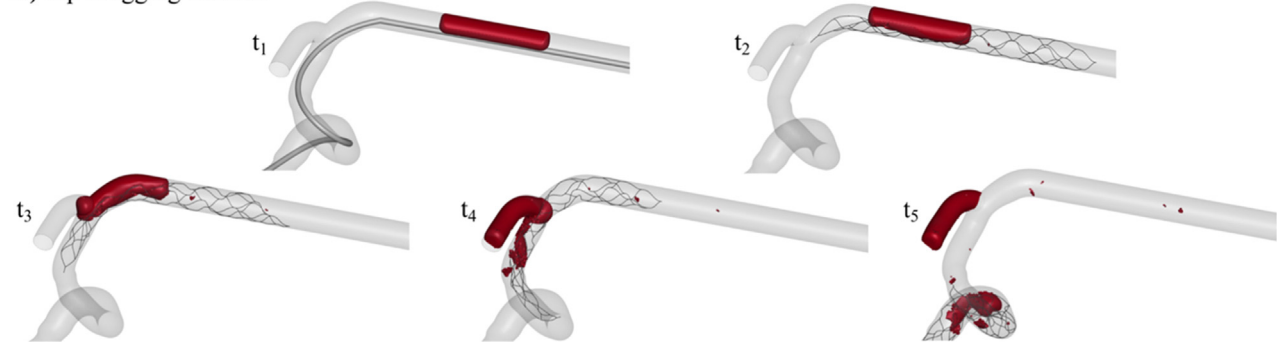
**Fig. 7. Thrombectomy outcomes for Patient II.** Results of the thrombectomy simulations at the end of the microcatheter tracking ( $t_1$ ), at the end of the stent deployment ( $t_2$ ), and during the retrieval ( $t_3$  to  $t_5$ ) for (A) the centerline method and (B) the tip-dragging method.

The in-silico thrombectomy procedures are displayed in Figs. 6–8 (Panel A: centerline method; Panel B: tip-dragging method), which include  $t_1$  the microcatheter tracking;  $t_2$  the stent deployment;  $t_3$ ,  $t_4$ , and  $t_5$  the retrieval phase.

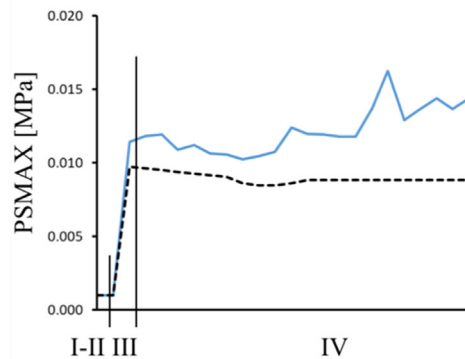
Fig. 6 shows the thrombectomy results for **Patient I** in different instants of the virtual procedure. The microcatheter tracking (Fig. 6A and 6B,  $t_1$ ), stent deployment (Fig. 6A and 6B,  $t_2$ ), and the first part of the retrieval phase (Fig. 6A and 6B,  $t_3$ ) are similar for the two methods. This is also reflected in the PS MAX curves (Fig. 9A), with higher PS MAX values for the centerline method (17% higher at the end of the stent deployment). At the T-junction (i.e., ACA-MCA bifurcation location), the thrombus got stuck at the ACA,

leading to an unsuccessful retrieval in both cases (Fig. 6A and 6B,  $t_4$  and  $t_5$ ). With the centerline method, some small fragments are dislodged (Fig. 6A and 6B,  $t_5$ ). The corresponding PS MAX curve (Fig. 9A) presents some oscillations in the second part of the retrieval phase with a maximum PS MAX value 84% larger for the centerline method.

In contrast, for **Patient II**, the thrombus was successfully retrieved in both scenarios (Fig. 7A and 7B). However, the interaction between the thrombus and stent was different and, consequently, the thrombus kinematics. After the stent deployment, the thrombus took a different orientation in the vessel (Fig. 7A and 7B,  $t_2$ ). At the T-junction, for the centerline method, the thrombus

**PATIENT III****A) Centerline method****B) Tip-dragging method**

**Fig. 8. Thrombectomy outcomes for Patient III.** Results of the thrombectomy simulations at the end of the microcatheter tracking ( $t_1$ ), at the end of the stent deployment ( $t_2$ ), and during the retrieval ( $t_3$  to  $t_5$ ) for (A) the centerline method and (B) the tip-dragging method.

**A)PATIENT I**

Curves:

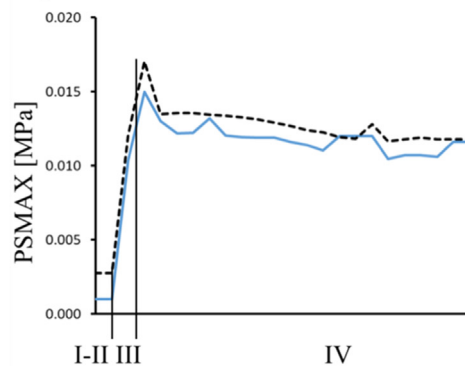
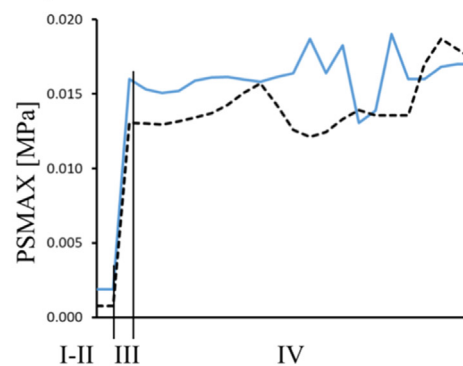
— Centerline method

--- Tip-dragging method

I-II: Microcatheter tracking

III: Stent deployment

IV: Retriever

**B) PATIENT II****C) PATIENT III**

**Fig. 9. Stress fields on the thrombi.** Maximum principal stress (PSMAX) values (averaged over the 10 elements with the highest values) of the thrombus during the thrombectomy steps: (I) stent-crimping; (II) stent tracking; (III) stent deployment; (IV) thrombus retrieval. The centerline method is displayed by the blue line and the tip-dragging technique with the dashed line. (A) Patient I; (B) Patient II; (C) Patient III.

was located at the intrados (Fig. 7A  $t_3$ ) and remained in contact with the stent during the whole retrieval (Fig. 7A  $t_4$ ); while, for the tip-dragging method, the thrombus was located at the extrados (Fig. 7B  $t_3$ ), and remained stuck at the T-junction by sliding along the stent prior to the final retrieval (Fig. 7B  $t_4$ ). The comparison between the PSMAx curves shows slightly lower PSMAx values for the centerline method during the whole simulation, with a maximum difference of 10% compared to the tip-dragging method (Fig. 9B).

For **Patient III**, both in-silico thrombectomies were unsuccessful: the thrombi remained in the ACA (Fig. 8A and 8B). The different positionings of the microcatheters led to different deployment configurations (Fig. 8A and 8B,  $t_2$ ). This difference is highlighted at the first part of the PSMAx curves, with up to 22% higher values for the centerline method (Fig. 9C). At the T-junction, the thrombus got stuck at the ACA, which led to a loss of contact between the stent and the thrombus in both cases (Fig. 8A and 8B,  $t_3$ ). Some small fragments were retrieved in both simulations (Fig. 8A and 8B,  $t_4$ ). In the second half of the PSMAx curves, the PSMAx values are higher for the centerline method, with a maximum difference of 54% with respect to the tip-dragging technique (Fig. 9C).

#### 4. Discussion

In our study, we presented a new method to simulate the tracking of the microcatheter, which influences the position of the stent, during in-silico thrombectomy. We showed that our method better resembles clinical scenarios compared to the previously used method. In addition, we demonstrated that the positioning of the microcatheter with respect to the vessel impacts the stress fields in the thrombus and the retrieval dynamics.

The scope of this article is to optimize the computational modeling of thrombectomy, and not to advise the interventionists on how to position the microcatheter. The standard computational approach was to use the vessel centerline. This study further elaborates on how computational modeling is influenced when using a more realistic position based on real images from interventions.

Previous studies have developed alternative computational methods to simulate the guidewire/catheter tracking in the context of other cardiovascular applications. The validation methods presented in those studies are similar to the ones proposed in our work. Some studies have (visually) compared their results to *in-vitro* experiments of guiding catheters/guidewires in transfemoral and intracranial vessels [13,16–18]. Other studies have qualitatively and quantitatively compared their simulated and real wire positions by characterizing the local distances [14,19,20] and quantifying the curvature angles [25] of both the simulated and patient-specific guidewires through the abdominal aorta. To our knowledge, our study is the first one on microcatheter tracking for the in-silico thrombectomy procedure with stent-retrievers.

In our study, the qualitative comparison between the modeled microcatheters and corresponding DSA images showed that the tip-dragging microcatheter tracking better approximates real-life scenarios compared to the centerline tracking. In **Patients I** and **II**, the microcatheter model was able to reproduce the bends observed in the real device (Fig. 5A and 5B). Regarding **Patient III**, the differences between the simulated and real positioning were more evident at the ICA loop and at the occlusion location: the simulated microcatheter moves on the upper side of the vessel while the real microcatheter/stent bends downwards (Fig. 5C). This difference can be explained by the insertion of the micro-guidewire through the lower part of the thrombus: when the catheter encounters the thrombus while navigating the vasculature, it will slip in either underneath or over the thrombus. Our models do not consider any interaction with the thrombus

during the insertion step, and therefore, may lead to a different positioning in the vicinity of the occlusion.

Regarding the impact of the microcatheter position on the thrombectomy procedure, we showed that the newly implemented tip-dragging method does not change the retrieval outcome with respect to the previous centerline method in 3 patients: both outcomes were unsuccessful for Patient I and Patient III, and successful for Patient II.

The size and positioning of the stent with respect to the thrombus and their association with thrombectomy outcomes have previously been researched in clinical practice. Some studies claimed that the optimal stent size and positioning with respect to the thrombus may lead to first-pass reperfusion and reduce the risk of fragmentation [5,26]. In current clinical practice, once the microcatheter is tracked up to the occluded vessel, its positioning is not adjusted (unless it does not properly capture the thrombus). Our study suggests that the positioning of the microcatheter within the vessel, and therefore of the stent, does have an impact on the thrombus kinematics and on the stresses that the thrombus is subjected to during the retrieval phase. These stresses influence thrombus fragmentation - one of the main complications during thrombectomy.

The effect of the microcatheter (and stent) positioning on thrombus fragmentation should be further investigated, especially in more complex cases such as bifurcated thrombi. Currently, in these bifurcated cases, clinicians aim at one branch expecting that the thrombus in the other occluded branch will come along. The choice of the occluded branch for stent placement has been associated with the chances of successful reperfusion [27]. Few individual studies have suggested the use of double stents targeting both branches in bifurcated thrombi refractory to retrieval [28–31], a technique under debate since it might be more prompt to damage or even rupture the vessel wall. Given the observed importance of in-silico stent tracking in the stresses affecting the thrombus, our method could be used to select the optimal branch to be targeted in a bifurcation occlusion, which could potentially lead to a lower risk of thrombus fragmentation and higher chances of a successful outcome. Moreover, our method could be similarly applied for other minimally invasive procedures.

##### 4.1. Limitations

Since the thrombectomy simulations are focused on the simulation of the retrieval phase to study thrombus retrieval and fragmentation, the virtual thrombectomy does not reproduce all the clinical procedural steps. For example, the insertion of the micro guidewire, and the introduction of the guiding microcatheter through this guidewire are not simulated.

Blood flow might affect the thrombectomy procedure. In current clinical practice, a balloon guiding catheter is commonly used to stop blood flow during the retrieval phase, since its use has been associated with improved technical and clinical outcomes and reduced patient complications [32]. We assumed this flow-arrest scenario for all simulated thrombectomies.

The mechanical properties of the microcatheter were extracted from the literature, and not from the specific device used during the procedure, mainly because of the lack of this information in the literature. We assumed our microcatheters to be isotropic, which is an oversimplification of real microcatheters. The latter are commonly anisotropic with a double-coiled wired at the most internal diameter, and a braided coil at the most external diameter, to give more stability to the microcatheter.

There are several microcatheter and stent-retriever models (with different design and sizes) available. These different devices can be modelled without changing the methodology described in



this study but only a specific characteristic of the procedure. Our goal was not to make a comparison in this regard.

Given the data scarcity on vessel compliance, especially during thrombectomy, the vessels were modeled as a rigid material as already discussed in our previous papers [6–8,12]. Despite this rigid-wall assumption that will be removed in the future, the results are valid and suggest how the methodology we are proposing is a step forward in a more realistic simulation of the mechanical thrombectomy.

In addition, the vessel anatomies used in this study only capture the intracranial configuration as seen in CTA, and therefore, although less critical, do not capture the extracranial anatomy as seen in DSA (nor the whole retrieval phase down to the (groin) puncture site).

The DSA images used for the visual comparison were two-dimensional and only included a single frontal view, which hindered the visual comparison and prevented us from any attempt to perform a more quantitative comparison as seen in previous literature [19,20].

The number of patients included for validation was limited – current clinical practice does not include the DSA imaging at the moment when the micro-guidewire/microcatheter/stent are *in situ* during the thrombectomy procedure, and it is only performed at the discretion of the treating interventionalist. Given the available data, we aim to qualitatively validate the tracking of the microcatheter and not the whole thrombectomy procedure; the virtual thrombectomy procedure was selected independently from the real procedure to which the patients were subjected.

## 5. Conclusion

Microcatheter positioning within the vessel has an impact on the stress fields of the thrombus and the dynamics of the retrieval during in-silico thrombectomy. Correct positioning of the microcatheter, and therefore of the stent, should be considered when studying (in-silico) thrombus fragmentation.

## Ethics approval

These patients are part of the MR CLEAN Registry, a multicenter prospective observational registry of all patients undergoing EVT for AIS in the Netherlands. This registry was approved by the central medical ethics committee of the Erasmus Medical Center Rotterdam, which served as the review board of all participating centers (MEC-2014-235). The requirement for written informed consent was waived, but all patients or legal representatives were provided with oral and written information on the registry and had the opportunity to withdraw consent to use their data via an opt-out form, conforming to the European Union General Data Protection Regulation.

## Declaration of Competing Interest

HAM reports co-founder and shareholder of Nicolab, a company that focuses on the use of artificial intelligence for medical image analysis. CBLMM reports grants from the European Commission during the conduct of the study; grants from CVON/ Dutch Heart Foundation, TWIN Foundation, Healthcare Evaluation Netherlands, and Stryker, outside the submitted work; and shareholder of Nicolab. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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