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Graphical abstract

Case-based simulation to support complex active catheterization: preliminary results

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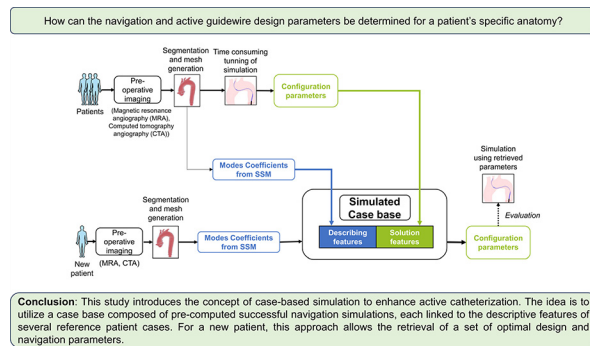
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IRBM ●●●●, ●●●, ●●●



Highlights

- Support for complex catheterization with active guidewire and configuration software.
- Case-based simulation (CBS) merges case-based reasoning and finite element method.
- Adaptation of active guidewire design and navigation parameters to patient anatomy.
- CBS enables real-time preoperative planning for complex endovascular navigation.

1 I. Introduction

2 Endovascular therapies are more and more popular mini-invasive techniques to treat vascular
3 pathologies [1]. About 20% of the endovascular procedures involve *complex* targets (e.g. supra aortic-
4 trunks or renal arteries), which are difficult to reach with conventional tools as they present large
5 tortuosities [2]. A study suggests that vessel tortuosity significantly impacts procedural success,
6 particularly in internal carotid artery access, where increased angulation reduces the likelihood of
7 effective recanalization [3]. Additionally, prolonged intervention times due to complex navigation lead
8 to greater radiation exposure, posing risks to patient safety [4]. These factors underscore the need for
9 advanced navigation strategies to enhance procedural efficiency, reduce radiation exposure, and
10 improve intervention outcomes. To overcome endovascular navigation difficulties, active
11 catheterization devices for NeuroInterventional Radiology (NIR) have been proposed [5], [6]. They
12 mostly focus on the development of catheters or active guidewires based on on-board actuators. In this
13 domain, Shape-Memory-Alloy-based (SMA-based) actuators are the most extensively studied approach
14 [7]. Szewczyk et al. [8] developed a new electrically controlled SMA-based micro-actuator using the
15 shape memory effect of NiTi. This active device is now developed by Basecamp Vascular (BCV) (Paris,
16 France). It includes a distal portion with two independent controllable SMA-based actuators. The two
17 controllable flexions are in the same plane but in opposite directions, resulting in an active "S" shape
18 facilitating the navigation. The use of this device relies on specific gestures that differ from traditional
19 passive tools. For a given patient, the geometry of the active tool (design parameters) and the associated
20 gestures (navigation parameters) should be identified in advance to maximize the chances to access the
21 specific complex target. However, appropriate use of the active device for a specific patient can be
22 challenging [9]. The issue we address in this study is how to obtain, among a set of predefined
23 configurations, the most suitable set of design and navigation parameters for a given patient anatomy,
24 using numerical simulation of active catheterization.

25 Numerical simulation is indeed an effective approach for evaluating multiple configurations by varying
26 tool design and manipulation within a patient specific anatomy [10]. For a given patient, it can help

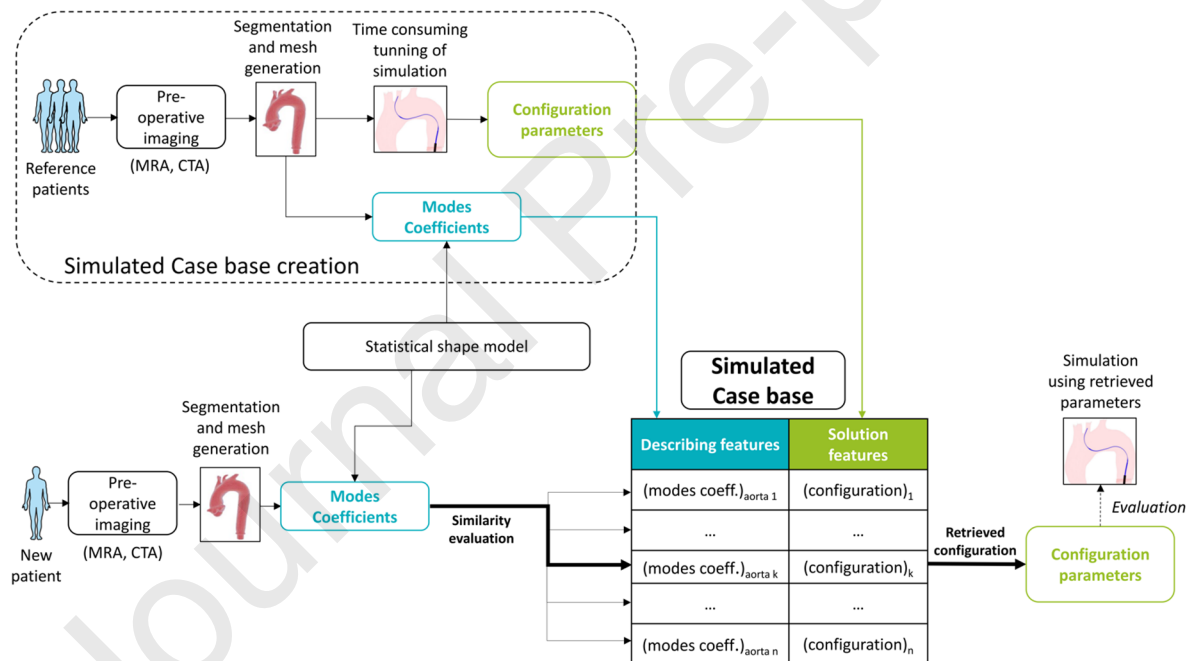
27 identify a successful configuration during the preoperative phase, maximizing the chances to reach the
28 target. By exploring different tool setups and navigation strategies, simulation improves procedural
29 planning, reducing reliance on intraoperative trial and error and ultimately minimizing procedural time.
30 Recently, Badrou et al. [11] developed a finite element (FE) model to simulate the endovascular
31 navigation with the mentioned active guidewire and associated commercially available catheters,
32 aiming to reach neurovascular targets through the left carotid artery. However, its high computational
33 cost does not allow, even pre-operatively, to run a large amount of simulations within the clinical
34 workflow. We hypothesize that an approach inspired by case-based reasoning (CBR) [12] can overcome
35 the issue of prohibitive computation time. CBR entails solving new problems by reusing solutions
36 adopted for similar problems in the past. A case base is utilized to identify cases that are analogous to
37 the new case. The solutions of these cases are then employed to formulate a solution to the new case.
38 Combining CBR and FE simulation approaches, we introduce and investigate the new paradigm of
39 case-based simulation (CBS). The case base consists of a limited number of reference cases simulated
40 from patient data. In this work, it is made up of three typical aortic arches associated with the
41 configuration that allowed a successful simulated navigation. The configuration suitable for the
42 catheterization of a new aortic anatomy is then obtained from that of the nearest simulated case, using
43 an appropriate distance metric based on the aortic centerline geometry. In this paper, after introducing
44 the global process of the CBS, we present the FE model and the distance metric. We then present the
45 results obtained on three aortic arches considered as test cases.

46 **II. Method**

47 **A. Overview of the method**

48 Case-based simulation consists in finding a successful set of catheterization parameters (design and
49 navigation) based on the similarity of a new patient with patient cases in which successful simulated
50 navigation has been precomputed. For this study, the catheterization of the left carotid is considered.
51 The global approach is given in Figure 1. The idea is to find the adequate catheterization parameters
52 (described by design and navigation parameters) for the new patient aorta from selected reference

53 aortas. The key hypothesis is that aortas with similar geometries will share similar catheterization
 54 parameters. The objective is to identify the so-called *retrieved* aorta in the database, which is defined
 55 as the aorta which geometry most closely matches the new aorta. Each case is characterized by
 56 *describing features* that are used to compare the new case with the cases contained in the simulated
 57 cases base. For a new patient, the retrieved anatomy is identified using a distance metric between the
 58 *describing features* of the new case with those of each case of the case base [13]. The parameters that
 59 enable successful navigation for a given case are called *solution features* of the case. The *solution*
 60 *features* of the retrieved aorta are expected to yield successful navigation in the new aorta. So these
 61 retrieved parameters are directly proposed to catheterize the new anatomy. This would give, almost
 62 instantaneously, support for catheterization by getting close to the result of a time-consuming tuned
 63 simulation.



64
65 Figure 1: Case-based simulation support workflow.

66 Pre-operative imaging from eight patients is used to segment vascular structures from which meshes
 67 are generated. First, centerlines are extracted from the meshes description of the vascular structure. A
 68 statistical shape model (SSM) is computed from the centerlines of these eight patients, capturing the
 69 main modes of variation in aorta geometry. Among these eight patients, three are selected as reference

70 cases for which navigation simulations are manually tuned to find a successful set of configuration
71 parameters (design and navigation parameters). These parameters are stored as the *solution features*.
72 Then, for each reference case, the centerline is projected onto the SSM to obtain its modes coefficients,
73 which serve as *describing features* for case comparison. Separately, three additional patients (not
74 included in the set of eight patients used for SSM construction) are selected for evaluation. For these
75 test cases, segmentation and mesh generation are performed from preoperative imaging in the same
76 manner as for the other patients. Their centerlines are also projected onto the SSM to compute their
77 modes coefficients. When the modes coefficients of one centerline are close to those of another, it
78 indicates a great similarity between the anatomies (and corresponding endovascular paths) they
79 represent. To identify the most relevant reference case for a new patient, an Euclidian distance is used
80 to compare the describing features (SSM modes coefficients) of the new case with those of the reference
81 cases in the case base. A small distance indicates that the anatomies represented by the centerlines are
82 similar. Once the closest patient is retrieved, its *solution features*, i.e., the configuration parameters, are
83 proposed for the new patient. For the sake of evaluation, the new patient catheterization is simulated
84 within our FE framework with these configuration parameters. The navigation is deemed successful if
85 the simulation results in the hooking of the left carotid artery.

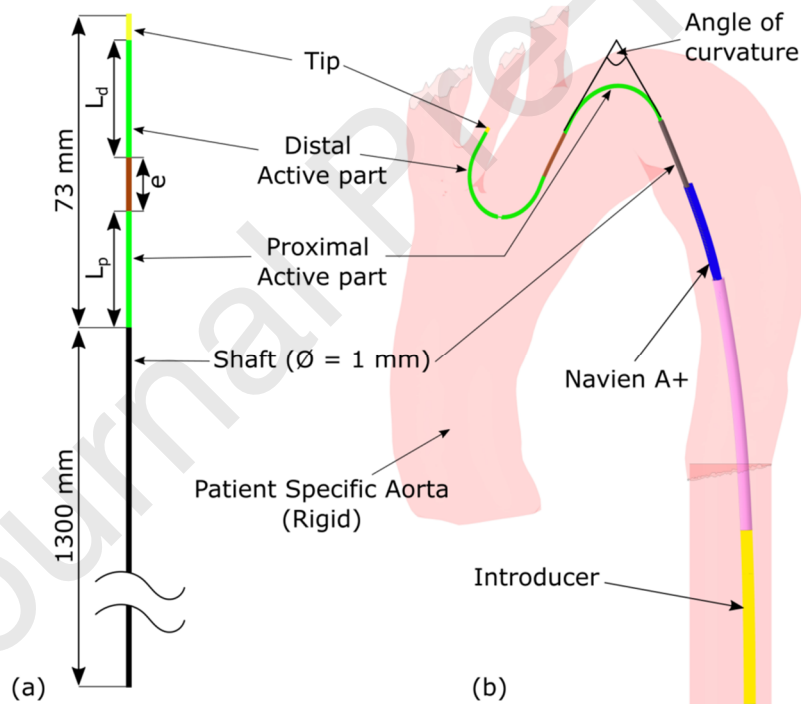
86 **B. Data**

87 Pre-operative magnetic resonance angiography (MRA) of the aortic arch was collected retrospectively
88 on 11 patients from the Hopital Fondation Adolphe de Rothschild (FOR) (Paris, France). For each
89 patient, the 3D vascular structure was segmented [14] and converted into meshes. Two criteria were
90 used to characterize the aorta geometries in terms of path complexity towards the left carotid artery,
91 considering the iso-centerlines as weighted shortest paths. The first one corresponds to the angle
92 formed by the first stretch of the left carotid and the tangent of the aortic arch at the left carotid
93 ostium; the second is the angle between the aortic arch apex and the left carotid ostium (see Appendix
94 A). Based on these criteria, three reference aortas denoted R_1 , R_2 and R_3 were selected for simulation.
95 These three aortas were chosen to represent distinguishable anatomies. Three other aortas represented

96 by T_1 , T_2 and T_3 were selected for evaluation. The SSM was computed on the eight aortas that were
 97 not considered for the evaluation.

98 C. Simulated cases

99 Active endovascular navigation involves maneuvering an active guidewire made of two active SMA
 100 modules that can be curved under an electric impulse (Figure 2). The guidewire is co-manipulated with
 101 a catheter (Navien intracranial A+), which slides on the guidewire upon reaching the left carotid artery.
 102 An introducer (Neuron MAX catheter) is utilized to stabilize the endovascular tools. In the FE model,
 103 the material properties of the tools were established in a prior study [15]. The device is activated using
 104 a displacement command that curves the active parts. Further details on the FE model, including mesh
 105 characteristics and boundary conditions, are provided in Appendix B, with additional information
 106 available in [11].



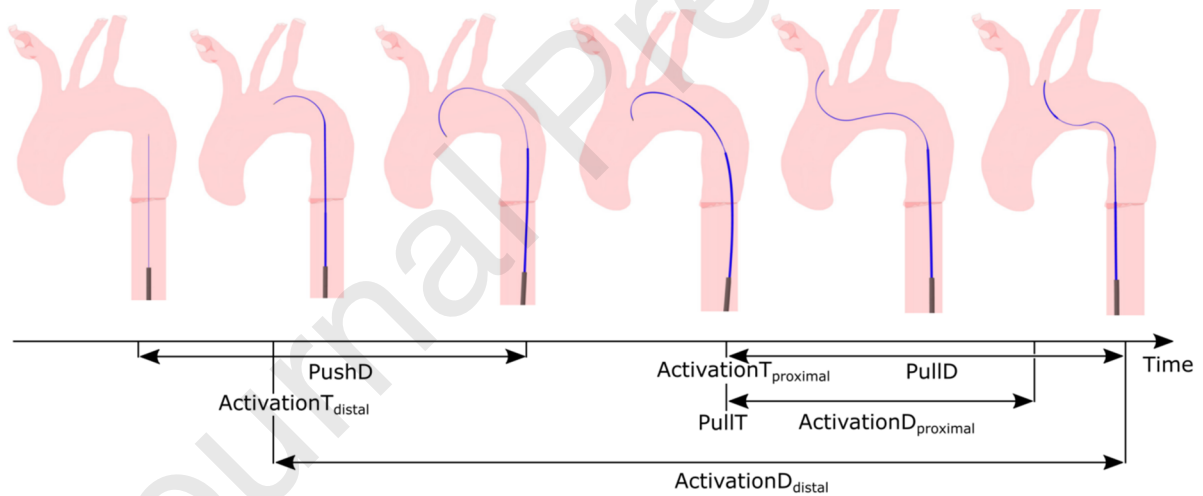
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108 Figure 2: (a) Schematic representation of the active guidewire with two active parts. When the tool is activated,
 109 it takes an S-shape, facilitating navigation. It is manipulated using the end of the shaft in translation or rotation.

110 (b) Hooking onto a specific aorta is achieved through a combination of various catheters and bending of the
 111 active guidewire, whose performance is assessed based on the angle of curvature. Each color denotes a segment
 112 with specific mechanical properties.

113 The navigation simulation is driven by the active guidewire design parameters (L_p , L_d , and e from
 114 Figure 2) and several *navigation* parameters that describe a single gesture sequence: at the beginning of
 115 the simulation, the active guidewire is always pushed (with a duration of $PushD$), then it can be pulled
 116 to limit buckling (at a time $PullT$ and during $PullD$), then the two active parts are activated at times
 117 ($ActivationT_{proximal}$, $ActivationT_{Distal}$) respectively during ($ActivationD_{proximal}$,
 118 $ActivationD_{Distal}$) respectively. The navigation parameters are illustrated in Figure 3. As the catheter
 119 only slides on the guidewire once the hooking is achieved, parameters related to the catheter are not
 120 taken into account. Each simulation configuration is described by a specific set of three design
 121 parameters and seven navigation parameters. Through a trial-and-error approach, we fine-tuned both
 122 the design and navigation parameters until successfully hooking the left carotid for the three reference
 123 aortas that represent the case base.

124



125

126 Figure 3: Illustration of the navigation parameters during the hooking of the left carotid artery in a patient-
 127 specific aorta.

128 D. Distance metric

129 We assume that endovascular navigation configuration is mostly related to the vascular structure
 130 geometry, so the similarity between two cases was evaluated based on their respective geometry. A
 131 Statistical Shape Model (SSM) was first constructed from the centerlines of the set of 8 aortas obtained

132 from MRA (including the 3 reference aortas) to obtain a compact representation of the geometry, before
 133 a distance metric was built.

134 In practice, centerlines were resampled such that the number of points from the beginning of the left
 135 common carotid artery to the end of the left middle cerebral artery was equal to 100. Then only a subset
 136 of 40 points around the bifurcation from the aortic arch to the left common carotid artery was kept: 10
 137 points on the left common carotid artery and 30 points on the aortic arch. These centerlines were then
 138 translated and rotated to describe iso-centerlines. Using these centerlines, the SSM was computed using
 139 singular value decomposition to obtain the modes of the centerline, which represent the principal
 140 components of its shape variability. The second, third, fourth and fifth standardized modes coefficients
 141 resulting from the projection of one centerline onto the SSM were used to describe each anatomy. Each
 142 of the reference and test centerlines were decomposed onto this SSM to obtain its corresponding modes
 143 coefficients. The centerline C of any case can now be reconstructed as: $C = \phi_1 + \sum_{i=2}^5 m_i \phi_i$, where
 144 ϕ_1 represents the mean centerline shape of the SSM, $\phi_2, \phi_3, \phi_4, \phi_5$ are the modes obtained from the
 145 SSM and m_2, m_3, m_4, m_5 are the modes coefficients. This compact representation highly reduces the
 146 number of scalar coefficients required to describe the centerline: indeed, a centerline originally
 147 represented by 40 3D points (requiring 120 scalars for description) is now described by its four modes
 148 coefficients.

149 The Euclidean distance between the modes coefficients vectors of two centerlines was used as a
 150 similarity metric. Aortas with similar geometries have comparable SSM modes, so a small distance
 151 indicates a high anatomical similarity. The distance between two anatomies a_i and a_j was computed as
 152 follows:

$$153 \quad d(a_i, a_j) = \|m_{vec\ i} - m_{vec\ j}\|$$

154 where $d(a_i, a_j)$ represents the distance between aortas i and j (noted a_i and a_j), $\|\cdot\|$ represents the
 155 Euclidean norm, $m_{vec\ i} = (m_2^i\ m_3^i\ m_4^i\ m_5^i)^T$ and $m_{vec\ j} = (m_2^j\ m_3^j\ m_4^j\ m_5^j)^T$ represent the modes
 156 coefficients vectors describing aortas i and j respectively.

157 III. Results

158 This section presents the evaluation results of the proposed method. The method is evaluated with three
 159 cases. For each case, the adequacy of the retrieved configuration parameters is confirmed using FE
 160 simulation.

161 A. Reference simulations

162 After a trial-and-error approach and a duration of 3h using 8 CPUs Intel Core i7 2.60 GHz for one
 163 simulation, the simulations for the three reference cases R1, R2 and R3 resulted in the determination
 164 of their respective design and navigation parameters. Over 20 simulations were necessary to identify
 165 suitable parameters for each aorta. The obtained parameters can be found in Appendix C.

166 B. Case-based simulation

167 a) Retrieved phase

168 The values of the distance metric between each test aorta T1, T2 and T3 and each reference aorta R1,
 169 R2 and R3 are given in Table 1.

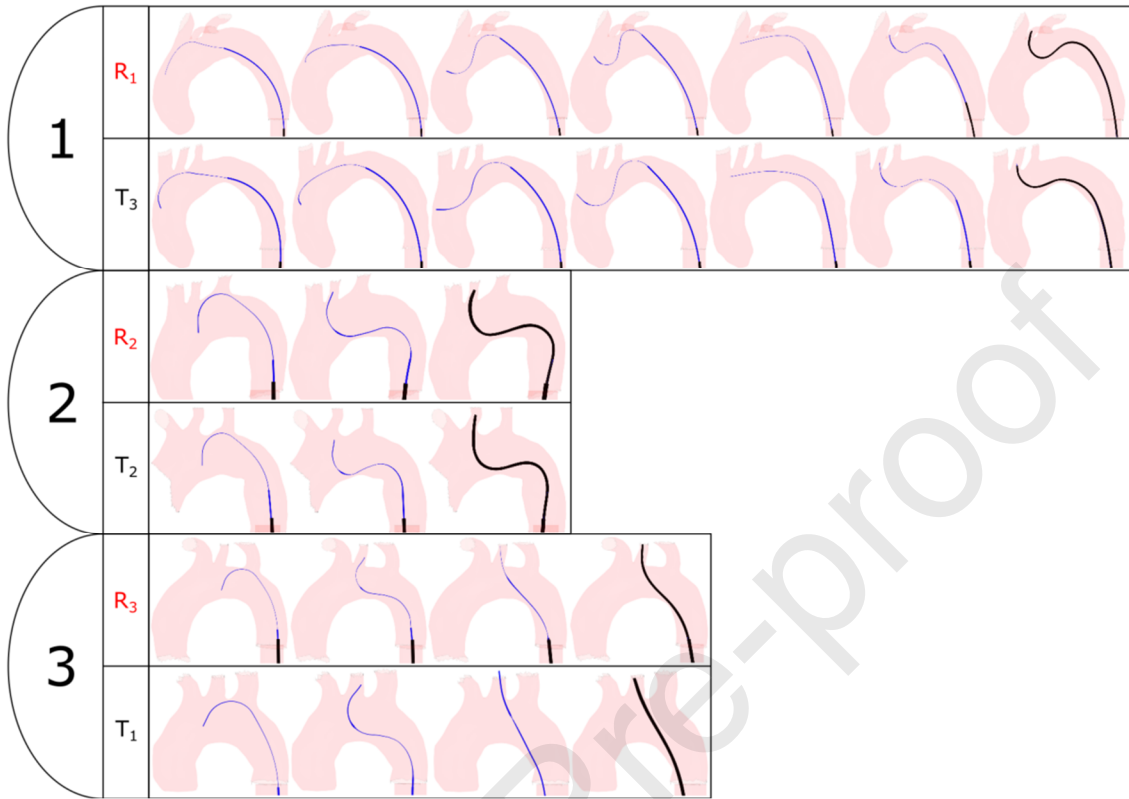
170 Table 1: Euclidian distance between test aortas and reference aortas represented by their SSM modes
 171 coefficients. A smaller distance indicates a greater similarity between anatomies.

Test aortas	Reference aortas		
	R1	R2	R3
T1	3.92	2.93	0.94
T2	3.34	1.67	1.86
T3	1.40	2.36	4.00

172 Then, design parameters and navigation sequences were extracted from the closest typical aorta using
 173 the CBS. Given the results, the configuration from the reference aorta R3 was retrieved for the test aorta
 174 T1, the reference aorta R2 was retrieved for the test aorta T2 and the reference aorta R1 was retrieved
 175 for the test aorta T3.

176 b) Simulation phase

177 Using the same design and navigation parameters for each pair of reference/test aortas (See Table 1),
 178 the hooking of the left carotid artery was successfully achieved for the test aortas, as seen in Figure 4.



179

180 Figure 4: Results of the simulations for the six aortas (references and tests). The names of the reference aortas
 181 are highlighted in red. Trial and error method was used to determine the parameters that enable successful
 182 hooking of the left carotid for the reference cases (results in Appendix C). The exact same set of parameters was
 183 applied to each test aorta, and hooking is visibly achieved, eliminating the need for additional simulations for
 184 these cases. The tool highlighted in blue is the active guidewire whereas the tools in black are the catheters.

185 IV. Discussion

186 This study introduces CBS, a novel approach to support active catheterization by building a case base
 187 of precomputed successful navigation cases, each associated with patient-specific features. For a new
 188 patient, CBS identifies the most relevant design and navigation parameters by retrieving them from the
 189 closest precomputed reference case, ensuring successful left carotid hooking. Validation on three test
 190 cases confirms the potential of this method to successfully guide navigation. While those results are
 191 preliminary, CBS lays the foundation for a real-time computational tool that identifies successful

192 navigation parameters for new anatomies. Unlike classical reduced-order models, it avoids the high
193 computational cost of training by focusing solely on key navigation scenarios [16], [17].

194 Despite promising results, several limitations exist. The identified parameters may not be truly optimal,
195 as multiple parameter combinations could achieve successful navigation. Additionally, a quantitative
196 comparison between navigation results of each pair of reference and test aortas was not established;
197 only visual hooking was considered in this work.

198 The retrieved configuration parameters should usually be applied directly. Nevertheless, if the
199 computed distance metric is too large, indicating a significant anatomical difference between the new
200 aorta and the closest reference aorta, a threshold should be set to determine whether the parameters can
201 actually be used. However, with a sufficiently large database, such cases should be rare. Another
202 limitation is the restricted number of aortic cases used to build the SSM (8) and the case base (3).
203 Expanding the dataset is essential for improving method robustness.

204 Clinically, CBS could improve preoperative planning by predicting successful device and navigation
205 strategies, reducing trial and error, and minimizing procedural time and radiation exposure [4]. This is
206 particularly relevant in stroke interventions, where rapid carotid access is crucial, aortic aneurysm
207 repairs requiring accurate catheter positioning, and renal artery catheterization where tortuous pathways
208 complicate navigation [18]. The next step is to expand the dataset and refine the CBS framework to
209 provide the clinician with interventional support. For clinical applications, experimental validation is
210 also necessary—testing the retrieved parameters in physical phantoms could help assess feasibility.
211 Ultimately, this tool could optimize complex vascular interventions by reducing procedural complexity
212 and improving efficiency.

213 **V. Conclusion**

214 This study introduces the new paradigm of case-based simulation to support active catheterization. The
215 general concept is to generate a case base made of the pre-computed successful navigation simulations
216 associated with describing features of several patient cases considered as reference cases, and to
217 retrieve, for a new patient, a set of appropriate design and navigation parameters. The method was
218 validated on three test cases. It paves the way for a comprehensive numerical tool that, for a new

219 anatomy, would enable a real-time identification of design and navigation parameters to guarantee the
 220 hooking of the left carotid artery.

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Journal Pre-proof

1 Abstract

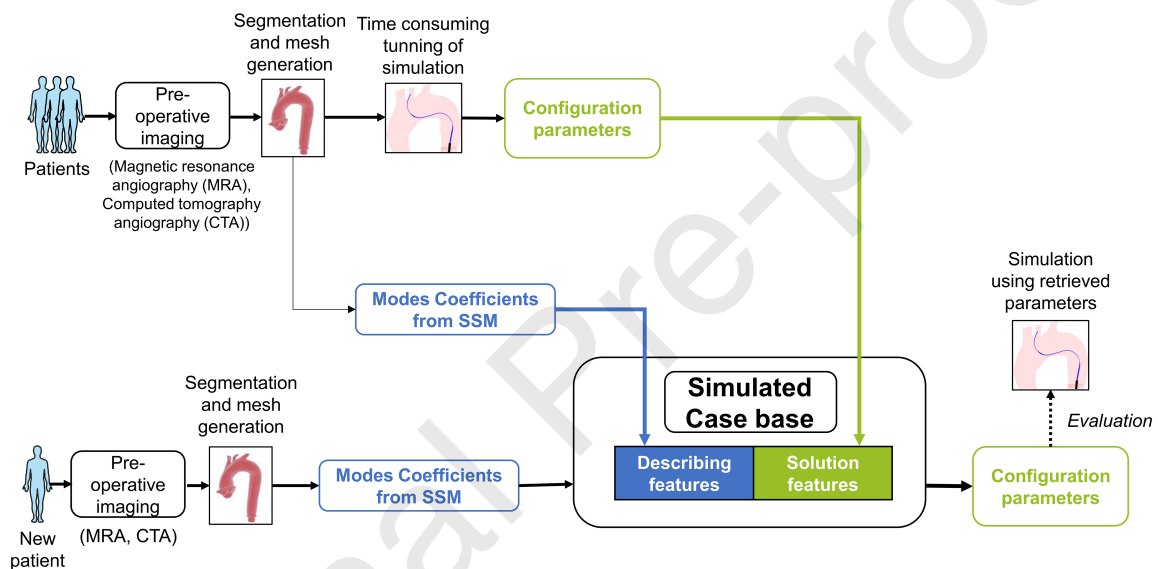
2 **Objective:** Active catheters are intended to support endovascular navigation in complex anatomies.
3 Nevertheless, their configuration and utilization are challenging. Finite element (FE) modeling
4 representing the navigation of active guidewires alongside catheters can be considered at an early stage
5 to identify the best parameters and support physicians in their planning and procedure. However, FE
6 simulations require significant computation time. We introduce the concept of case-based simulation
7 (CBS) to quickly find adequate configuration parameters for complex catheterization scenarios.

8 **Method:** Combining case-based reasoning and FE simulation, CBS approach is considered to reuse
9 design and navigation parameters from previous simulations. A case base is made of successful
10 catheterization simulations performed on reference aorta geometries. For a new patient, a distance
11 metric based on a statistical shape model is used to determine appropriate catheterization parameters
12 from previously simulated cases. The proof-of-concept of this method is performed in the case of the
13 navigation from the aortic arch to the left carotid artery. Among 11 patient-specific aortic arches, three
14 were selected for the reference FE simulations of the left carotid artery hooking to constitute the case
15 base and three others were selected for evaluation.

16 **Results:** The retrieved parameters allowed a successful simulated navigation in 100% of the test cases.
17 This demonstrates that the proposed approach can effectively and instantaneously determine
18 appropriate design and navigation parameters for complex catheterization scenarios.

19 **Keywords:** Catheter Navigation, Active Guidewire, Finite Element Modeling, Case-based Reasoning,
20 Statistical Shape Model.

How can the navigation and active guidewire design parameters be determined for a patient's specific anatomy?



Conclusion: This study introduces the concept of case-based simulation to enhance active catheterization. The idea is to utilize a case base composed of pre-computed successful navigation simulations, each linked to the descriptive features of several reference patient cases. For a new patient, this approach allows the retrieval of a set of optimal design and navigation parameters.

Author responsibilities, integrity, ethics



Article title :

Human and animal rights

The authors declare that the work described has been carried out in accordance with the [Declaration of Helsinki](#) of the World Medical Association revised in 2013 for experiments involving humans as well as in accordance with the EU Directive [2010/63/EU](#) for animal experiments.

Not applicable.

Informed consent and patient details

The authors declare that this report does not contain any [personal information](#) that could lead to the identification of the patient(s).

Not applicable

The authors declare that they obtained a written [informed consent](#) from the patients and/or volunteers included in the article. The authors also confirm that the personal details of the patients and/or volunteers have been removed.

Not applicable

Disclosure of interest

The authors declare that they have no known [competing financial](#) or [personal relationships](#) that could be viewed as influencing the work reported in this paper.

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