Visual Analytics for Planning Left Atrial Appendage Occlusion: A Case Study on In-silico Hemodynamic Assessment

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Abstract

Clinicians are encouraged to integrate both structural and functional information when making medical decisions, but often lack the necessary visualization and analysis tools. For patients with atrial fibrillation undergoing left atrial appendage occluder (LAAO) implantation, interventional cardiologists must consider the variable anatomy of the left atria and blood flow patterns to select the optimal LAAO device settings. While commercial tools exist to assist with LAAO implantation, they only offer morphological information related to the left atria (LA). Conversely, advanced visual analytics tools have been developed to understand blood flow patterns in cerebral aneurysms. This preliminary study aims to investigate the potential of adapting these visual analytics tools to LAAO applica for the analysis of hemodynamics in the LA obtained from fluid simulations. The resulting platform, LAAOVis, enables the comparison of different LAAO device configurations to identify the most optimal ones for a specific patient. Domain experts have assessed the potential of LAAOVis and identified additional features that would enhance its suitability for planning LAAO device interventions.

CCS Concepts

• ***Applied computing*** → *Life and medical sciences;* • ***Human-centered computing*** → *Visualization;* • ***Computing methodologies*** → *Modelling and simulation;*

1. Introduction

Atrial fibrillation (AF) is widely acknowledged as the most prevalent type of human arrhythmia, affecting millions of individuals worldwide [CHN*14]. It is characterized by rapid and irregular electrical impulses in the atria, resulting in an irregular heartbeat. Consequently, blood flow within the atria becomes turbulent, increasing the risk of blood clot formation.

Patients diagnosed with AF who are unable to undergo anticoagulant therapy often receive treatment through a procedure called the left atrial appendage occlusion (LAAO), where the left atrial appendage (LAA) is closed to prevent the formation of blood clots in LAA, which is the most common site for thrombus formation [CGFS*19]. Various LAAO devices are available, each with its specific design; the most common ones are the Amulet Amplatzer (St Jude Medical Abbott), the OMEGA (Eclipse Medical), the Lambre (Lifetech Scientific), and the Watchman family (Boston Scientific). During the LAAO procedure, the cardiologist must select the appropriate type, size, and placement of the device.

This task poses a challenge due to the considerable variability in LAA morphologies. Sub-optimal implantation of the LAAO device can result in potential complications following the intervention. For example, if the device is inadequately sized or positioned, a thrombus may form around it after implantation, leading to a condition known as device-related thrombosis (DRT) [SJL*21]. Consequently, visualizing and analyzing the most relevant indices to mitigate the risk of thrombus formation is essential for optimizing patient outcomes.

The conventional tools used by interventional cardiologists for decision-making in LAAO involve multi-modal images in different 2D views, such as echocardiography and X-ray scans. However, existing computational tools primarily focus on LAA morphology assessment, neglecting the assessment of fluid flow complexity, which is crucial for proper occluder selection [MMM*22,BOC*17, EW18,GIA*20]. Discussions with domain experts and literature revealed that multiple hemodynamic indices and their correlations indicate an increased risk of DRT formation, with regions exhibiting low blood flow velocities and high complexity being of particular interest. As blood flow is dynamic, it is essential to analyze these indices at each time step of the cardiac cycle to determine the highest risk of DRT formation. Moreover, occluder implantation affects surface-based hemodynamic indices, and the impact of different occluder configurations on blood flow needs to be explored, which can be mentally exhausting. Therefore, techniques are needed to visualize differences between the indices before and after LAAO, as well as to compare different device configurations.

DOI: 10.2312/evs.20241065

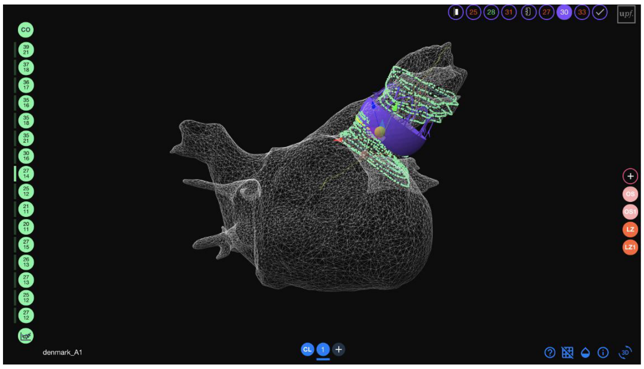

Figure 1: *3D visualization of the left atria and virtual implantation of a left atrial appendage occluder device in the VIDAA platform.*

This study aims to address these issues using and adapting a visual analytics platform to allow experts to analyze hemodynamic indices and their correlations over the entire cardiac cycle in two cases simultaneously, while also providing the possibility to explore specific LAA surface regions of interest.

2. Related Work

The VIDAA platform is a web-based tool for exploring 3D LA images, shown in Figure 1 [AOY*19], utilizing computerized tomography (CT) scans and meshes for morphological analysis and device selection. It enables virtual device implantation and adjustment, supporting pre-operative evaluations. Additionally, it has been integrated into AR/VR environments for enhanced visualization [MAM*20].

Examining LA and LAA morphology is key for setting device parameters. 3D images require manual rotation for a full view, but 2D flat maps from 3D meshes simplify this process. These 2D projections make multi-modal data analysis more accessible, allowing for easier interpretation and more efficient LA analysis [NGBA*20, AMC21, KMM*18]. However, existing LAAO platforms focus only on morphology, overlooking the importance of hemodynamic data from in-silico models crucial for assessing thrombus risk in the LA. Studies link low flow velocities and stagnation to higher DRT risks [AKM*11].

Clinically, LA hemodynamics analysis often relies on simplified echocardiographic measures, like the end-diastolic velocity at the LAA ostium (i.e., interface with the LA main cavity) [MHL*21]. Computational fluid dynamics (CFD) simulations offer a more detailed alternative, capturing complex blood flow patterns around LAAO procedures [MHL*21]. Open-source tools like Paraview are popular for CFD analysis, but fully capturing the 4D dynamics of LA blood flow demands advanced visual analytics due to its complexity.

Mill et al. [MMM*22] assessed computing technologies, including AR, VR, and fluid simulations, for LAAO pre-planning's clinical potential and highlighted the need for the development of advanced visualization methods for in-silico hemodynamic indices, Researchers have developed tools like MuscaVis [MGB*18] for analyzing hemodynamic data, focusing on cerebral aneurysms. These tools merge statistical analysis with interactive visualizations, aiding in the exploration of aneurysm features and the assessment of rupture risks and treatments [MWPL20].

In this work, we would adapt the visualizations tools developed for cerebral aneurysms, *MuscaVis* [MGB*18], to the particular characteristics and needs for the LAAO use case, including different device visualizations as well as choosing different relevant in-silico haemodynamic indices, decided with domain experts. The new tool, so called LAAOVis, enables a comprehensive comparison of two different device configurations, allowing for the simultaneous examination of multiple in-silico hemodynamic indices. LAAOVis, incorporates interactive visualizations and statistical methods, which empower users to gain a deeper understanding of the characteristics of the LAA. This tool facilitates the personalized selection and placement of occluder devices, ultimately leading to improved patient outcomes.

3. Data

Retrospective pre- and post-occlusion CT images of three nonvalvular AF patients were obtained from Hôpital Haut-Lévêque (Bordeaux, France) with approval from the ethical committee and informed consent from the patients. Patient-specific geometrical information and simulated blood flow patterns were derived from binary mask segmentation of the CT images. The implanted devices in the analyzed patients were positioned deep in the LAA, exposing the pulmonary ridge, manually obtained by clinical experts in the hospital. Consequently, a different device positioning approach was assessed, aiming for placement closer to the ostium and covering the pulmonary ridge. A total of six simulations were run to test the platform, where two occluder device configurations were deployed in each of the three patients. The Omega device was used for one patient, while the Watchman FLX was used for the remaining two. Within the VIDAA platform, the recommended LAAO device size for this alternative configuration was estimated based on anatomical measurements [AOY*19].

Tetrahedral volumetric meshes were generated to solve the fluid domain, incorporating the deployed LAAO devices and LA geometry obtained from VIDAA [AOY*19]. CFD simulations were performed for two cardiac cycles, with analysis focused on the second cycle to avoid initialization inaccuracies. Additional details on image processing and simulation setup are available in the supplementary material, where the whole modeling pipeline is depicted.

The time-averaged WSS (TAWSS), oscillatory shear index (OSI), and endothelial cell activation potential (ECAP) were calculated based on the wall shear stress (WSS) at the LAA wall. TAWSS represents the average shear stress over time, while OSI qualifies the degree of flow oscillation. ECAP is the ratio between OSI and TAWSS, indicating flow complexity and low-velocity magnitude. To identify areas with high thrombogenic risk the WSS, absolute pressure, and the ECAP were assessed on the LAA surface in all time steps of the second cardiac cycle.

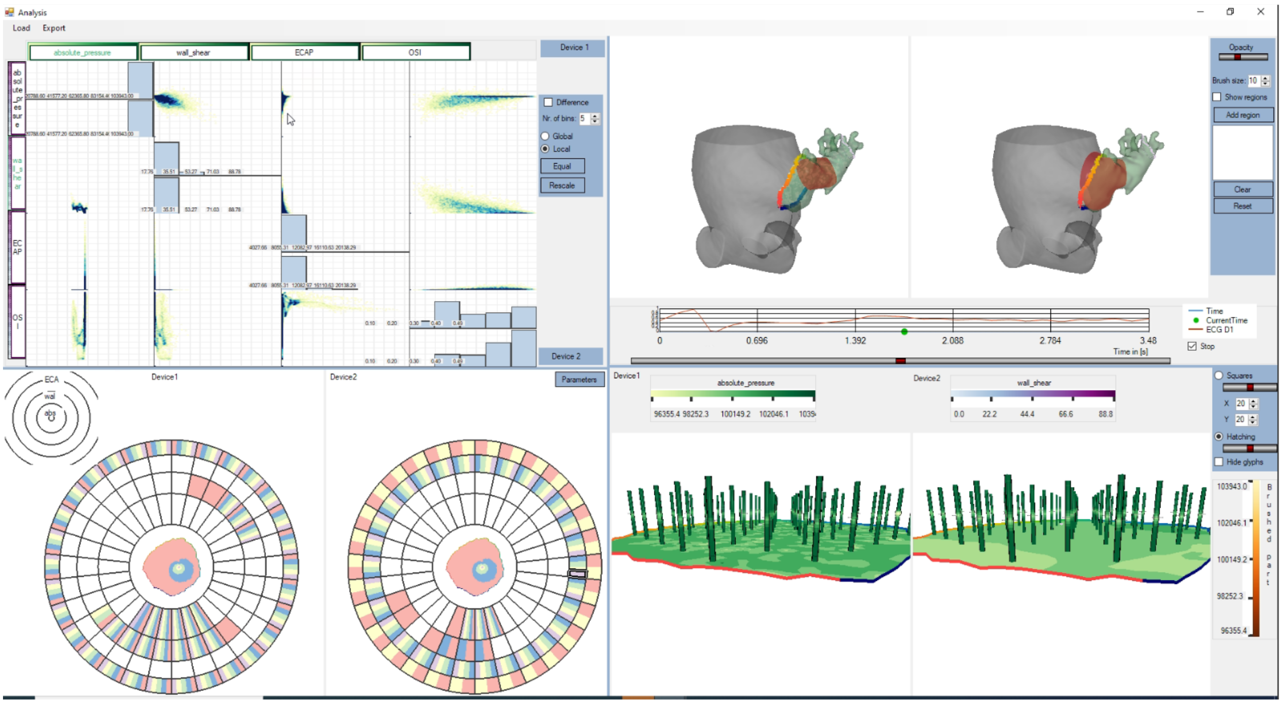

Figure 2: *LAAOVis platform including four views for one case with two different device configurations. Statistical graphs in the upper left view; 3D reconstruction of the left atria (grey) and its appendage (green) with an implanted occluder device (red) in the upper right view; 2D flat LAA surface maps with glyphs in the lower right; bull's eye plots in the lower left.*

4. Visualization Platform

The LAAOVis is designed with four linked views of LAAO data. The platform with its views is depicted in Figure 2 and described in detail in supplementary material. The views are connected using brushing and linking to enable users to interact with the data and focus on regions of interest. The selected hemodynamic indices, WSS, ECAP, OSI, and absolute pressure, and their correlations can be visualized and explored in each view.

The bull's eye plot (BEP) is a commonly used tool in clinical settings to visualize quantitative functional data of the left ventricle [oMSfCIC*02]. Since clinicians are already familiar with this tool, it was adapted to represent possible correlations between indices over time in the lower left part of the platform.

The upper left part of the platform consists of statistical plots. In the non-diagonal entries of the matrix, scatter plots provide an overview of the data's distribution. On the diagonal entries, histograms visualize the individual distribution. This allows users to examine the frequency and range of values for each parameter combination separately. The data for one device configuration is displayed in the upper part above the diagonal, while the data for the second device configuration is shown below.

The right side of the platform displays 2D and 3D visualizations of the left atrial appendage, to provide a detailed exploration of high-risk regions throughout the cardiac cycle. Each view is divided into two sections, showcasing two cases with different device configurations. To establish spatial connectivity between the views, the ostium area is highlighted as a reference point. Details on individual functionalities of each view and their brushing and linking capabilities are described in [MGB*18].

The tool has been adapted to facilitate the comparison of two cases with different device configurations by dividing the visualization window into two parts. The link between the views and two device configurations ensures that the visualization remains consistent across all views as the data is observed over time. Furthermore, visualization of an electrocardiogram (ECG) signal over the the cardiac cycle is added to the 3D visualization view to provide temporal information on different stages of the cardiac cycle.

5. Domain Expert Evaluation

In this preliminary study, the evaluation process involved the participation of four experts, three CFD engineers, and one interventional cardiologist, with 2 to 7 years of experience in LAAO intervention and computer-aided evaluation of simulated blood flow in medical data sets. All evaluations were considered equivalent.

Before the evaluation, the experts attended a demonstration session to familiarize themselves with the LAAOVis platform and its interactive capabilities. During the session, they received an overview of the platform and its features, followed by an opportunity to explore it independently and ask questions to enhance their understanding of its functionality. Subsequently, the participants completed an evaluation two-part questionnaire. The first part aimed to quantitatively assess the usability of a specific vi-

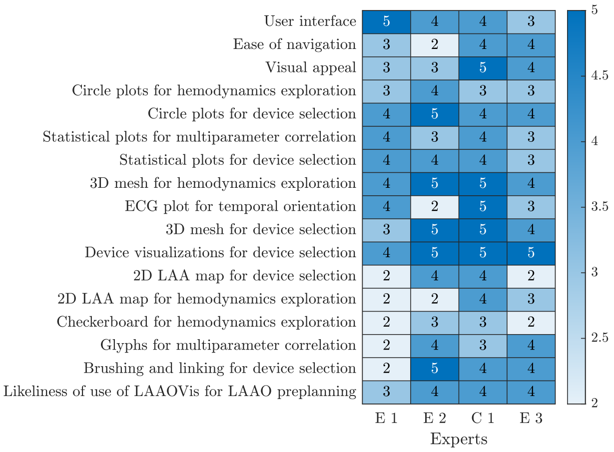

Figure 3: *Quantitative evaluation responses of three CFD engineering experts E 1, E 2, E 3, and a clinical expert C 1.*

sualization method, with 17 items rated on a 5-point Likert scale to gather objective feedback on the effectiveness and user-friendliness of the visualization method. The second part consisted of open-ended questions to gather additional information about the participants, their current routines, and their perspectives on the implementation of the platform in their work.

Quantitaive results: The questionnaire yielded valuable insights into the satisfaction levels of users with the platform. Overall, the platform received a satisfactory rating, with the majority of scores being 4 and 5 which indicate the high potential of the visualization platform for LAAO planning purposes. The specific components of the platform were evaluated individually which gives us insight into which ones are primary and which can be kept as complementary information. Full questionnaire and answers are provided in supplementary material, while Figure 3 shows shortened questions and experts' responses.

Experts found the user interface and design of the platform fairly user-friendly, while ease of navigation could be improved. For the exploration of hemodynamics and parameter correlation, experts found 3D LAA visualizations particularly effective. For the same purpose circle and statistical plots were deemed slightly less effective, while a 2D surface map and its components did not perform as well, which might be due to visual clutter. For the comparison of different device configurations, 3D LAA visualizations and circle plots were found to be the most effective, followed by statistical plots, which were slightly less effective, according to experts. The 2D surface maps received the lowest score, indicating lower effectiveness in this context too. The brushing and linking functionality, which allows users to interactively explore the data, was found to be useful by three out of four experts.

Qualitative results: During the session, the clinical expert provided valuable insights on improving the user interface. The main suggestion was to simplify the interface by adjusting the view sizes and focusing it on a data overview in the form of a 3D visualization while including other views as details on demand, which may be more optimal for complex cases. The expert emphasized that this approach represents a significant advancement in informed decision-making, enabling visualization and interaction with simulation results for two different device configurations. By utilizing linked views and interaction capabilities, experts successfully identified variations in blood flow in proximity to the device regions. The flat 2D map provides an overview visualization, which facilitated experts in the identification of key regions and subsequent marking using a brushing tool to select interesting regions and explore details in other views. Notably, their observation aligned with expectations, indicating that the device configuration covering the pulmonary ridge area is more optimal for implantation to minimize the DRT risk. Furthermore, all experts emphasized the importance of incorporating blood flow velocities in the form of streamlines under the device region to ensure a more comprehensive understanding of the hemodynamic data, which will provide a clearer picture of how the device interacts with the surrounding blood flow.

6. Discussion and Conclusion

In this study, we tested a visualization platform designed to explore the surface indices of LAA. The platform was evaluated by domain experts and found to have high potential to be applied in LAAO planning processes. It facilitated decision-making by providing linked views for the analysis of hemodynamic indices throughout the cardiac cycle, enabling experts to gain valuable insights and make informed decisions. Currently, there is no specific method to calculate the risk of DRT formation. To address this challenge, our platform focuses on targeted exploration of suspicious surface areas within the LAA and, by doing so, helps experts understand how specific device configurations can impact blood flow within the LA, particularly in cases with complex morphology. The platform also enables a direct comparison between different device configurations, supporting decision-making in LAAO treatments. By evaluating and comparing the effects of different configurations, experts can gain valuable insights that aid in making informed treatment decisions.

The platform, in general, was well-received by experts, particularly in the context of choosing an optimal LAAO device. In analyzing the low scores, experts suggested that the reason behind them may be the complexity of the visualizations rather than inefficiency. This implies that the users may have struggled to understand the visualizations and their relationships due to visual clutter.

Moving forward, our future work aims to expand upon this preliminary study and, based on experts' feedback, enhance the platform to provide a comprehensive understanding of hemodynamic processes in AF patients and assist in LAAO planning. It will be tested on numerous cases to further prove its applicability, assessing different device configurations and types of devices in a single patient. The evaluation will be performed by more experts where each will perform an individual case study. To address the issue experts had in understanding different views, in addition to demonstration experts will be provided with a documentation guide.

Acknowledgements The project that gave rise to these results received the support of a fellowship from the "la Caixa" Foundation (ID 100010434). The fellowship code is "LCF/BQ/DI20/11780021". This project has also received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101016496 (SimCardioTest).

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