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Short Paper

VRIDAA: Virtual reality platform for training and planning implantations of occluder devices in left atrial appendages

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Abstract

Personalized anatomical information of the heart is usually obtained from the visual analysis of patient-specific medical images with standard multiplanar reconstruction (MPR) of 2D orthogonal slices, volume rendering and surface mesh views. Commonly, medical data is visualized in 2D flat screens, thus hampering the understanding of 3D complex anatomical details, including incorrect depth/scaling perception, which is critical for some cardiac interventions such as medical device implantations. Virtual reality (VR) is becoming a valid complementary technology overcoming some of the limitations of conventional visualization techniques and allowing an enhanced and fully interactive exploration of human anatomy. In this work, we present VRIDAA, a VR-based platform for the visualization of patient-specific cardiac geometries and the virtual implantation of left atrial appendage occluder (LAAO) devices. It includes different visualization and interaction modes to jointly inspect 3D LA geometries and different LAAO devices, MPR 2D imaging slices, several landmarks and morphological parameters relevant to LAAO, among other functionalities. The platform was designed and tested by two interventional cardiologists and LAAO researchers, obtaining very positive user feedback about its potential, highlighting VRIDAA as a source of motivation for trainees and its usefulness to better understand the required surgical approach before the intervention.

CCS Concepts

• ***Human-centered computing*** → *Information visualization;* • ***Applied computing*** → *Interactive learning environments; Health care information systems;*

1. Introduction

Teaching or planning surgical procedures have historically been difficult due to the high complexity and variability of human anatomy, being critical clinician's experience and the availability of good quality medical imaging data. The first (and commonly the only one) visualization and analysis of medical imaging data is always performed with the visualization tools provided by the scanner manufacturers, usually as 2D images and standard multiplanar reconstruction (MPR) visualization viewed in 2D flat screens. Off-line image analysis can be performed with numerous tools including Open-Source software such as 3D Slicer [KPV14] or commercial solutions, usually tailored to specific imaging modalities of type of pathologies. Most of these imaging tools are stand-alone softwares but web-based frameworks with Cloud-based engines are becoming modern and more flexible alternatives. We recently developed VIDAA (Virtual Implantation and Device selection in left Atrial Appendages), which is a clinician-friendly web-based platform to support the pre-operative planning of left atrial appendage occlusion (LAAO) interventions [AOY*19], characterizing and visualizing the morphology of the LAA and allowing clinicians exploring the LAA anatomy with different LAAO devices.

However, the VIDAA platform and most state-of-the-art tools are still limited to visualize and analyze imaging data with the standard MPR, volume rendering and surface mesh views in 2D flat screens, thus with limited degrees of freedom interaction and preventing a correct perception of the 3D nature of the studied anatomy (e.g. depth, scaling). Three-dimensional printing is becoming a routine tool in certain cardiology fields, especially when dealing with abnormal heart anatomies such as in congenital heart disease and pediatric applications [FHR*19], to provide the clinician a better understanding of 3D cardiac anatomy. There are several studies that have evaluated the added value of 3D printed models for training and planning of LAAO interventions (e.g. [BOC*17]). Recently, Conti et al. [CMM*19] compared 3D-printing recommended and implanted devices, with an agreement of only 35%, and with a overestimated device size derived from the 3D printed model of a 10%. Moreover, computational costs and time required for models to be printed with realistic materials are not negligible.

Augmented, mixed and virtual reality (AR, MR and VR, respectively) are nowadays becoming attractive technologies since they enable more intuitive and effective ways of visualizing and in-

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teracting with complex medical data, with potential in education, training, pre-operative planning and intra-operative support. Cardiology has not been an exception and recent studies (e.g. [SSRS18]) have reviewed the added value of advanced visualization of cardiac data, including in specific applications such as in congenital heart disease [SFL*20, GPY20] or transcatheter mitral valve replacement [KWS*20]. Regarding VR applications for cardiac devices, some proof-of-concept studies have focused on transcatheter closure of cardiac defects such as ventricular septal [MHHV18] or sinus venous defects [TBB*19]. Recently, Nam et al. [NHL*20] used new functionalities of the 3D-Slicer Open-Source software (i.e. link with VR headsets) to develop a tool for the virtual testing, selection and placement of transcatheter device closures of atrial and ventricular septal defects. As for LAAO devices, the EchoPixel True 3D Virtual Reality Solution (EchoPixel, Inc., Mountain View, California, United States) allows to to visualize CT scans and perform a "device-in-anatomy" simulation for LAAO pre-procedural planning [SL19]. Zbronski et al. [ZRS*18] visualized CT-derived LA anatomies before and during the occlusion procedure with the AR Hololens headset being a useful enhancement according to clinicians. Finally, some work [LANMA18, LN19] is currently under development for VR-based device sizing from the visualization of 3D echocardiography images with VR headsets.

Despite the limited amount of VR-based solutions adapted for LAAO interventions, the experience in other medical areas suggests that VR technology can also provide added value to existing visualization tools in LAAO applications, both for educational purposes and to better understand the required surgical approach before the intervention. Beyond the additional source of motivation for trainees when using VR headsets, already observed in human anatomy students [TSN*20], the enhanced interaction with 3D objects (i.e. LA geometry and device) and depth/scaling perception available in a VR system may offer useful insights for improved LAAO-related decision-making.

In this work, we present VRIDAA, a VR-based platform for the visualization and analysis of LAA anatomies and the most appropriate occlusion devices to be implanted, with potential uses as a training platform for surgery trainees or as a pre-operative planning tool. The VRIDAA platform allows the user to interact with the LA geometry, jointly visualize it with patient-specific medical images in standard MPR format and relevant morphological indices, to finally virtually place the LAAO device of choice (i.e. different designs, sizes) in any position. Additionally, the user can also plan the optimal location for introducing the delivery catheter in the LAA, freely manipulating a catheter model together with an endoscopic view to facilitate the visualization of the LA interior.

2. Methods

As a preliminary step before using the VR headset, the web-based VIDAA platform is used to generate some morphological measurements (e.g. centerline) on the LAA anatomy and have an initial set of appropriate devices (see Section 2.1), which are imported to VRIDAA. Afterwards, the VR-based platform is launched, allowing two different types of users: student for training and clinician for pre-operative planning. Depending on the user mode, different information will be visualized. The main scene in VRIDAA allows the visualization of the left atrial anatomy as a 3D surface, with relevant images displayed in a MPR format, and the menu with the different platform functionalities. Standard surface manipulation including mesh clipping and transparency changes are possible as well as browsing along the CT scan slices. Morphological measurements imported from VIDAA can be displayed such as the centerline and a graph with the associated LAA contour diameters. Several LAAO devices, with different designs and sizes, can be virtually positioned along the LAA centerline, allowing the user to freely move it for optimal positioning and exploration. A catheter model is also available in the platform, including endoscopic view, for simulating the device delivery. Any device configuration can be stored, which can be used for the evaluation of training exercises. Some of these visualization models are shown in Figure 1.

2.1. VIDAA platform

First, the LA geometries were semi-automatically segmented from the CT scans of the studied patients using region-growing and thresholding tools available in 3D Slicer, creating LA binary masks before applying the Marching Cubes algorithm to create a 3D surface mesh. Both CT scans and the LA meshes were then introduced to the VIDAA platform for visualization and morphological analysis. Several landmarks, relevant to LAA interventions (e.g. circumflex artery), can be manually selected by the user, including a point on the LAA to guide the centerline computation. Perpendicular contours along the obtained centerline are then obtained to obtain morphological measurements on the LAA (i.e. maximum and minimum LAA diameters). The user can also define the ostium and landing zone landmarks with small spheres along the centerline. Finally, based on the estimated measurements, the VIDAA platform proposes a set of appropriate LAAO devices for the studied LAA geometry. These devices, the landmarks and the morphological measurements are subsequently imported by VRIDAA, together with the 3D surface LA mesh and original CT scans.

2.2. 3D geometry interactive visualization

The left atrial meshes were imported into VRIDAA from the processing of 3D Slicer and VIDAA. Once uploaded, the user can interact with the 3D meshes by using the HTC Vive Pro controller to freely move it (6 degrees of freedom, i.e. rotations and translations) or zoom it in order to navigate inside the patient's LA. Mesh transparency allows to visualize the interior of the mesh from outside, but the user is able to change it in a menu option. We have also implemented the option to clip/slice the LA mesh, by grabbing a little movable sphere that will always be present in the scene. These features allow the user to exploit the potential of VR for interactive exploration of 3D objects and have a better understanding of its geometrical characteristics.

The left atrial meshes are visualized with relevant landmarks (e.g. centerline, the circumflex, ostium and landing zone in Figure 1) that were selected by the user to guide to the subsequent device implantation. It needs to be pointed out that when the VRIDAA platform is in training mode, the ostium and the landing zone will not be visualized so that students can be evaluated on how well they define these landmarks.

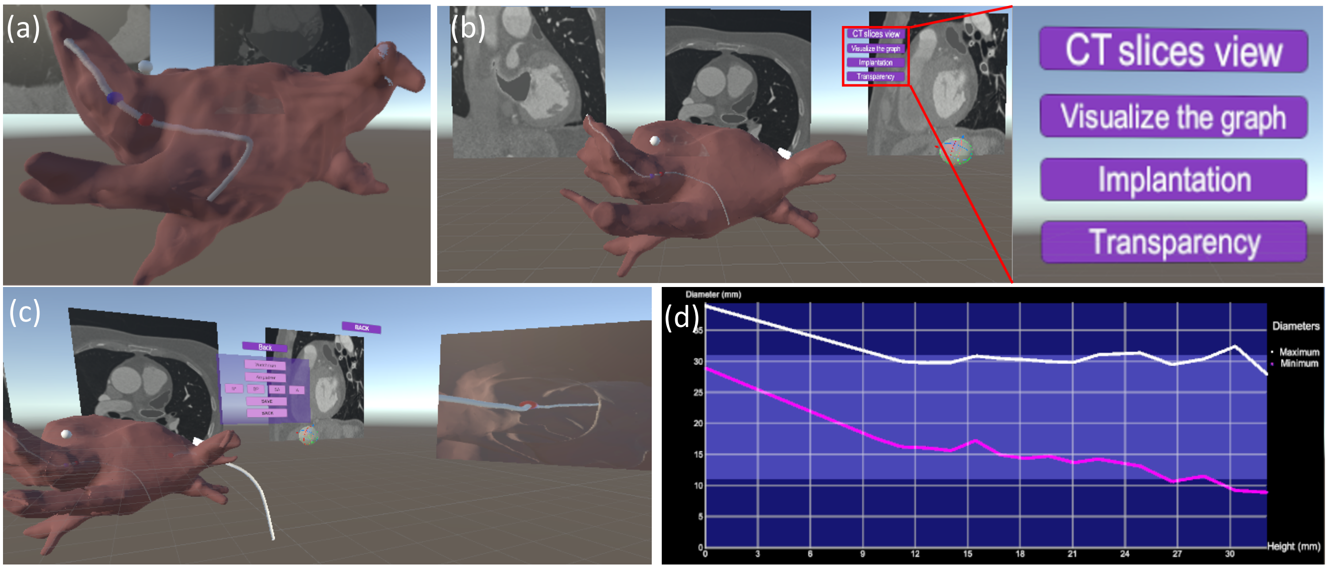

Figure 1: *Different visualization modes available at the VRIDAA platform. (a) 3D Rendering of the left atrial geometry including the centerline (in white) and relevant landmarks (circumflex, ostium and landing zone in white, red, and blue colors, respectively). (b) 3D geometry with axial, sagittal and coronal slices of medical images visualized behind, together with the navigation menu; (c) Visualization of the delivery catheter model (in white), including the 2D endoscopic view of the catheter's tip camera for LAA interior visualization. (d) Graph with morphological measurements to be viewed as a 2D panel.*

2.3. Visualization of 2D planar information

Multiplanar reconstruction (MPR) visualization of CT images and 2D graphs showing morphological measurements can also be displayed in the VRIDAA platform. Axial, coronal and sagittal slices centered in the LAA are initially shown as three different panels behind the 3D LA surface mesh, including the original CT grey-level images together with an overlay of the binary mask segmentation. The user can then browse through the different slices in any of the MPR views. The inclusion of the MPR visualization was chosen to support clinicians that are not very familiar with 3D geometry visualization, providing a more standard 2D slice-based view of the heart. Furthermore, a graph showing the maximum and minimum diameters of the contours along the LAA centerline is displayed in a 2D panel, since it gives intuitive information about the optimal depth along the LAA length of the device implantation.

2.4. Interactive device implantation

The virtual implantation of the LAAO device can be performed in VRIDAA with different types of devices. Simple Computer-Aided Design (CAD) models of these devices, covering the different available sizes, were built to be visualized in the VR platform, as shown in Figure 2. Once the type of device is chosen, a recommended size is given based on the computations from the estimated LAA diameters. However, the user is able to select and test a different LAAO size if needed. The LAAO device of choice is initially oriented perpendicular to the centerline and positioned at a certain distance from one of the selected landmarks (i.e. the LAA ostium). Afterwards, the user can move the device through the centerline by pressing a button of the VR controller to identify possible location candidates along the LAA geometry. Nevertheless, the user can grab the device with another controller option and move it freely in the scene (i.e. not necessarily following the LAA centerline), to find the position that betters occlude the LAA.

The VRIDAA platform also allows simulating the trajectory of the catheter bringing the device to the LAA from the right atria. It is one of the most delicate steps in the intervention since it requires creating a hole in the correct position of the wall between the two atria to move across the catheter and reach the LAA (i.e. transseptal puncture in medical terms). The user can freely move a catheter model to learn which puncture position in the inter-atrial wall (marked as a white rectangle in the 3D geometry) would be optimal for each geometry. Additionally, a camera is placed in the catheter's tip to visualize its endoscopic-like point of view in a 2D panel. Enabling free manipulation of the catheter with the VR controllers together with the visualization of the 3D geometry and the endoscopic view offer the user more detailed information to select the right approach to the LAA from the right atria.

3. Results

An initial set of six LA geometries of candidates to LAAO implantation from the Hospital de la Santa Creu i Sant Pau (Barcelona, Spain) were processed in the platform. The first prototype of VRIDAA was assessed by two interventional cardiologists, experts in LAAO devices, and three researchers with long-standing experience in LAAO computational tools. Initially, the participants were asked to freely play with the VR platform and to perform easy tasks such as grabbing the LA with the VR controllers and explore it. Then, they were guided to test all VRIDAA functionalities and fill

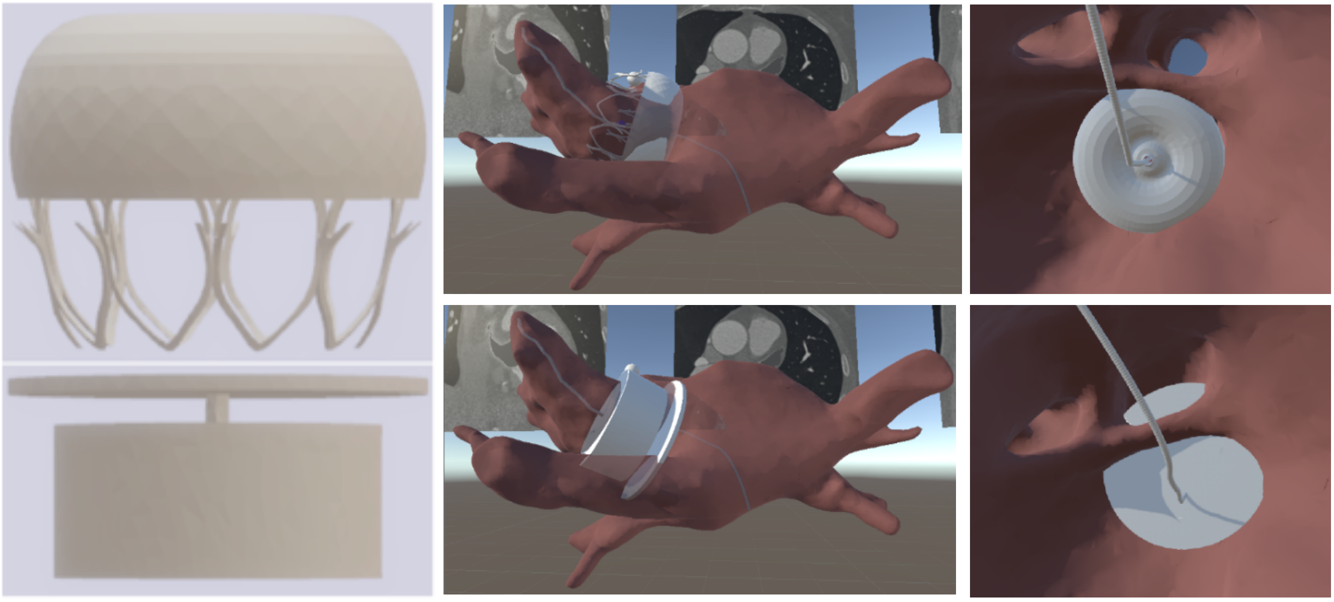

Figure 2: *Left column: CAD models of Watchman (top) and Amplatzer Cardiac Plug (bottom) left atrial appendage occluder devices. Middle and right columns: external and internal views of the implanted Amplatzer Cardiac Plug (top) and Watchman (bottom) devices.*

in a questionnaire to evaluate the appropriateness of the tool as a training or pre-operative planning tool, its easiness of use and other general questions.

All users gave very good scores (4.3 over 5.0) to the VRIDAA platform as a training tool, especially for trainees using the platform with a teacher giving him/her support with another headset. Three out of five users would also use the tool with a group of students. The users also positively considered the VR as a source of motivation (4.8/5.0), with a bit less agreement on the added value of VR versus non-VR platforms (3.8/5.0). Evaluating VRIDAA as a pre-operative planning tool, users were also very positive (4.4/5.0). They similarly assessed the possibility of participating in future planning sessions with VRIDAA (4.6/5.0), its added value to define device settings (4.4/5.0) and the overall utility of the tool with additional improvements (4.4/5.0), being convinced on the added value of VRIDAA to minimize mistakes during surgery (4.4/5.0).

Regarding the ease of use, two participants felt some discomfort when using the headset, due to the blurriness. Plus, all participants evaluated the hand controllers to be easy to use. In addition, according to users the menu navigation was sufficient (3.4/5.0) and the easy-to-use level of the overall platform was good (3.8/5.0) but with improvements to be made. Finally, four participants estimated between five to ten minutes of VRIDAA use to perform a correct LAAO implantation (the remaining one with less than 5 min). Users also positively evaluated the use of VRIDAA for multi-disciplinary discussions (4.6/5.0), with the higher marks (4.8/5.0) rating the usefulness of the immersive VR environment to better understand the required surgical approach before the intervention.

4. Discussion and conclusions

The VRIDAA platform has been designed and implemented for providing new and complementary ways to explore the data required by interventional cardiologists and make clinical decisions involving LAAO devices. The uses as a training tool and as a pre-operative planning tool before surgeries were considered. VRIDAA allows to visualize and interact with the 3D LA geometry, virtually implant different LAAO devices and navigate through patient-specific medical images in MPR views, among other functionalities. User feedback on the platform, including from LAAO clinical experts without previous VR experience, confirmed the potential of VR technologies to impact the training and pre-operative planning of LAAO interventions; the highest scores were given to the platform as a source of motivation for trainees and on its usefulness to better understand the required surgical approach before the intervention, adding value to non-VR alternatives.

The current design and functionalities in VRIDAA were chosen in conjunction with LAAO clinical experts to take advantage of the unique possibilities of a VR environment. It provided a better understanding of the 3D nature of the left atrial anatomy, when compared to traditional exploration through orthogonal 2D planes or in 3D views on 2D flat screens, due to improved depth perception, 6 degrees of freedom interaction with 3D objects (both the LA geometry and the device) and views from the interior of the cavity (not easy to see even in 3D printed models), all points important for the device implantation. For example, it is challenging to truly grasp the depth and scaling of human organs and device sizes (as well as their relation) only from 2D screen visualization, generally causing astonishment when firstly explored with a 3D printed model or in VR. However, standard MPR image visualization of the studied LAA was included to help clinicians not familiar with 3D geometry manipulation. The visualization of relevant landmarks and morphological features (e.g. centerline and LAA diameter measurements) was useful for training and planning since they simplify the complexity of the 3D geometry and facilitate the task of deciding the optimal device size and positioning. The catheter model, including the endoscopic feature, provided views and interaction options with the 3D geometry difficult to implement in a non-VR environment, giving additional insight to optimize the path to the LAA from the right atria, which is the other critical decision in LAA interventions.

The current implementation of VRIDAA is in a relatively early stage and should be improved in some key points such as the menu navigation, linking the different visualization modes, allowing geometrical measurements and including wall-device interaction during device deployment. Additionally, an important aspect for the potential clinical translation of VRIDAA is to evaluate its cost-efficiency. In this regard, the associated costs of high-end VR headsets and the spatial requirements can be important barriers. However, more affordable VR headsets with reasonable performance and resolution, including wireless solutions without requiring much space (e.g. the Oculus brand) would be tested in the future. Long-term, it would also be interesting to explore other lines such as the adaptation of VRIDAA to augmented reality headsets. Additionally, 3D volume rendering could add a complementary and useful visualization model to the current 3D surface mesh view. Other technological aspects to be included would be the connection between the VR environment with Cloud-based processing servers and image processing libraries as well as the visualization of flow simulation results in VRIDAA to complement morphological information with haemodynamics patterns.

Finally, the evaluation of the platform was limited to a few cases assessed by a reduced number of users, due to the limited availability of clinicians these days. Nevertheless, a more thorough evaluation study of the VRIDAA platform is currently being conducted to evaluate its added value compared to standard MPR visualization, 3D printing, the web-based VIDAA platform and in-silico simulations, all technologies applied to a common dataset by the same users. Preliminary results of the comparative study confirm the uniqueness of VR systems for better understanding LAA anatomy.

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