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ORIGINAL ARTICLE

Improving workflows of neuro-interventional procedures with autostereoscopic 3D visualization of multi-modality imaging in hybrid interventional suites

J. Perhac[1] · J. Spaltenstein[1] · V. M. Pereira[1] · K. Schaller[1] · O. Brina[1] · I. Cabrilo[1] · O. Ratib[1]

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Abstract
Purpose Recent developments in interventional neuroradiology techniques, medical imaging modalities, endovascular stenting and embolization materials lead to an increasing number of patients with cerebral aneurysms and arteriovenous malformations that are eligible for endovascular treatment and have opened new perspectives for novel ways for patient treatment in general. In this paper, we describe a software tool for 3D image fusion of multi-modal acquisitions to assist endovascular treatment of cerebral malformations. The software and an autostereoscopic 3D display were implemented and tested in clinical applications in a hybrid interventional suite that is used for radio-interventional as well as neurosurgical procedures. Our hypothesis is that fusion of image data acquired prior to intervention procedures with images acquired during those procedures should allow better visualizing and navigating through complex cerebral vasculature. This should also improve workflows of neuro-interventional procedures.
Methods Preoperative and intra-operative acquisitions of vascular images of the brain were performed and transferred to a dedicated imaging workstation to be processed with our image fusion and visualization software tool. The tool was developed as a plugin extension to the open-source DICOM viewer OsiriX and is based on a modular and scalable architecture. Several processing modules were implemented to allow spatial co-registration and fusion of preoperative and intra-operative modalities. A special extension was also implemented for interactive autostereosopic, glass-free 3D visualization of fused results.
Results The software platform was validated and evaluated in nine in vivo procedures by expert users. All patient cases were related to interventional treatment of neuro-vascular diseases. The emphasis was laid on the added value of spatial co-registration and fusion of preoperative and intra-operative modalities, as well as the overall impact on workflow during the intervention. The co-registered and fused images were visualized on an autostereoscopic 3D monitor installed in hybrid interventional suite. All experiments were evaluated and scored by interventional physicians and technicians.
Conclusions Displaying 3D–4D representations of brain vascular anomalies based on multi-modal acquisitions on a 3D autostereoscopic display is beneficial for the workflow and efficiency of interventional radiologists. The implemented software tool fulfills the premise of applicability of an open-source platform for more advanced, multi-modal visualization and processing of brain vascular structures for image-guided therapeutic interventions.

Keywords Multi-modality imaging · Stereoscopic · Visualization · Aneurysm · AVM · Open-source · Osirix

Introduction

Vascular aneurysms and other vascular abnormalities such as arteriovenous malformations (AVMs) are frequently diagnosed in patients suffering from recurrent headaches, neurological symptoms or as a result of a hemorrhage or seizures [1]. Hemorrhage has high morbidity and mortality rates, with a 5–25 % chance of death within 1 year and a 25–40 % risk of permanent neurologic deficits [2]. Treatment of aneurysms and AVMs can be performed using open surgery or minimally invasive procedures such as stereotactic radiosurgery or

✉ J. Perhac
jan.perhac@gmail.com

1 University Hospitals of Geneva, Geneva, Switzerland

endovascular embolization therapy [3]. Recent developments in stereoscopic rendering, medical devices imaging, endovascular embolization materials, as well as new interventional neuroradiology techniques with an increasing number of intravascular devices such as stents and embolization coils have increased the number of patients that are eligible for endovascular treatment (EVT), and they have also opened doors for novel and less traumatic ways for patient treatment in general [4].

Initial diagnosis of AVMs and arterial aneurisms is obtained from 3D tomographic images obtained from high-resolution MRI or CT angiography. These images allow identifying of the localization and topology of vascular anomalies prior to EVT [4]. Higher spatial resolution images for description of nidus, arterial inflow, venous outflow and general angioarchitecture of AVMs and vascular aneurisms are obtained from conventional X-ray angiography by super-selective catheterization of the arterial feeders of the AVM that are routinely performed before embolization [6].

The evolution of minimally invasive surgery and image-guided procedures has led to the development of hybrid interventional suites (surgical rooms), which integrate several imaging technologies and devices that can be used during surgical and therapeutic interventions [5]. These intra-operative imaging devices allow surgeons and interventional radiologists to acquire images at different stages of the therapeutic procedure and adjust their treatment accordingly.

Holographic imaging has emerged with 3D screens that require special (active or passive) glasses for getting the perception of depth from volume rendered images. Latter generations of 3D holographic screens provide a glasses-free solution, one of which is called autostereoscopy [6]. This technology is more appropriate for surgical environments and can be used in operating rooms where 3D glasses interfere with the surgeon's work in a sterile environment. The rationale for implementing autostereoscopy in the OR is to improve the three-dimensional perception of complex structures such as the vascular tree. This has implications not just for perception of the geometry and topology of different objects in space objects, but also for a better visualization of complicated anatomical structures such as the brain vasculature. The human brain can better perceive information from a 3D image, compared to a 2D projection image, as shown in Fig. 1.

In this paper, we present an open-source software tool that we have developed to allow modular combination and visualization of different imaging modalities and techniques required for minimally invasive neuro-vascular interventions and neurosurgery procedures in hybrid interventional suites, equipped with real-time angiographic equipment. We have also adapted our tool to provide autostereoscopic, three-dimensional image visualization and analysis of the angioarchitecture and EVT of brain aneurisms and AVMs.

Methods

Several research studies were focused on quantifying the contribution of glass-free 3D autostereoscopic visualization in medical use [6,12]. However, all the studies had in common the usage of just a single modality (CT or high-resolution MR) acquired at a given time prior to a procedure, providing surgeons with a 3D projection of patient's anatomy that was static in time and without any addition visual information related to the spatial position of medical instruments used during a procedure. Our approach is focused on providing surgeons with 3D projection of patient's anatomy enhanced with dynamic, 4D (2D + time) navigation allowing a better positioning of different interventional devices (e.g., position of catheters, stents or coils).

Hardware setup

We benefit from a hybrid interventional suite (Phillips Allura FD20 mono-plane system, Philips Healthcare, Best, the Netherlands) that is designed to provide 3D rotational angiograms (3DRA, using the Xtravision workstation) and cerebral angiogram (DSA) with acquisitions in one orthogonal incidence.

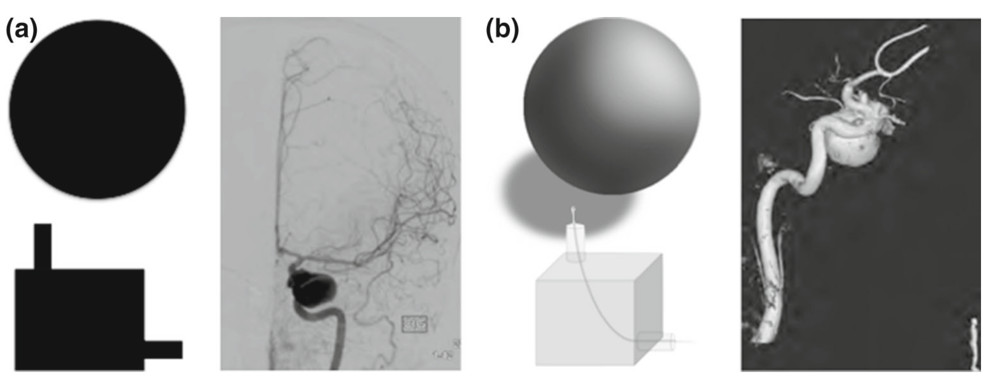

Fig. 1 Representation of geometrical objects and vascular structures in 2D (**a**) and (pseudo) 3D (**b**) space

We also benefit from having several preoperative imaging devices for high-resolution CT and MR acquisitions (GE Discovery CT750 HD, General Electric, Fairfield, Connecticut, USA; Siemens Biograph 64 and Biograph 16, Siemens Healthcare, Erlangen, Germany).

The workstation used for the purposes of the presented work was a MacPro 2012 (from Apple, Cupertino, California, USA), equipped with 2× Intel Xeon (Hexacore) CPU (24 cores available for the OS), 16 GB RAM and 1 TB hard drive.

The network in the OR consisted of 1 Gb ethernet connection between PHILIPS Allura Xper and the Mac Pro.

Network interconnection between the hybrid interventional suite and the workstation was established, and the DICOM push functionality of the hybrid suite was enabled to send DICOM images to the workstation immediately once they are available. The process is semiautomatic. A surgeon uses the hardware pedal connected to the hybrid suite to mark the start point (stepping on the pedal) and end point (releasing the pedal) of the sequence of image data during the actual acquisition of intra-operational DSA. Once the sequence is marked, the images are sent automatically to the workstation.

Software platform

The possibility to acquire high-resolution preoperative and real-time intra-operative medical data, together with having state-of-the-art network infrastructures for data transfer, has lead to the development of our open-source, DICOM-standard compliant, processing-pipeline-based software tool for real-time manipulation and visualization of medical data. Support for autostereoscopic 3D output was also implemented.

The developed software tool is based on the OsiriX software platform and its plugin SDK [7]. It also utilizes Apple's Cocoa frameworks [8] for implementing its core processing pipeline architecture. ITK frameworks [9] are used for processing modules, and VTK [13] is used for output visualization. The tool runs on a 64-bit version of OS X operating system (10.7 or later).

The decision to use OsiriX and its SDK as the main development target was also due to its DICOM network abilities and wide adoption among radiologists and surgeons. OsiriX can act as a DICOM server/listener with full support for DICOM query/retrieve/send PACS commands, as well as direct gathering of DICOM images from imaging devices via DICOM push. This was essential for our project and for the developed tool to enable near real-time acquisition and processing of images acquired intra-operatively.

The software plugin architecture

To fully support a multi-modality-based workflow, several design and architectural choices were made. To be easily usable with multiple imaging modalities, a simple user interface was designed to easily manage the processing and visualization tools. Different modalities require different processing tools. This has led to the development of a modular and scalable architecture in the form of a software "pipeline" that can be used to select specific sequences of processing algorithms to be applied sequentially to different types of images. The developed pipeline architecture has many advantages compared to traditional approaches. It allows to add, remove or alter the sequence of processed modules on-the-fly and also to change the parameters of individual active modules in real-time and visually assess the effect of these algorithms on the resulting image.

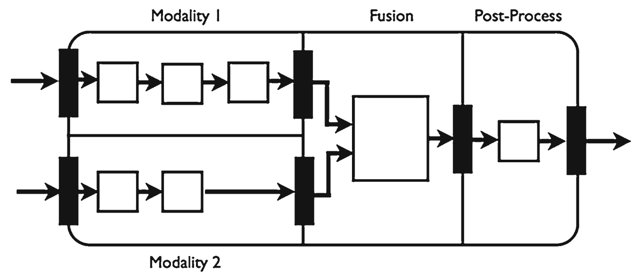

Fig. 2 Pipeline overview showing four pipes filled with seven modules

The pipeline architecture consists of four separate pipes, each of which is dedicated to different stages of processing (namely Modality 1, Modality 2, Fusion and Post-Process). Its general architecture is depicted in Fig. 1.

Every pipe is able to operate with zero, one or more processing modules. A processing module is a single-purpose unit, which can have one or more inputs and one output. The current version of the tool allows working with two inputs, but the modular and scalable architecture allows extending the number of inputs to a higher one as well (Fig. 2).

The user interface

The user interface consists of three main elements: a window for selection of *acquisition modalities* (Fig. 3a), a *main* processing and rendering *window* (Fig. 3b) and an *inspector panel* (Fig. 3c) for setting the parameters of the pipeline. Every processing module is linked with a unique user interface that is show as a drawer in the *inspector panel* to set its parameters. A simple drag-and-drop paradigm was introduced for adding new modules into specific pipe. The strength of the pipeline architecture is in the ability to test the same set of data with different processing modules by simply enabling/disabling or adding and removing them.

The user interface was designed in a way that respects the OS X human interface guidelines [8] providing a separate inspector panel with specific settings of tuning parameters for each tool. These settings can then be saved as "preference"

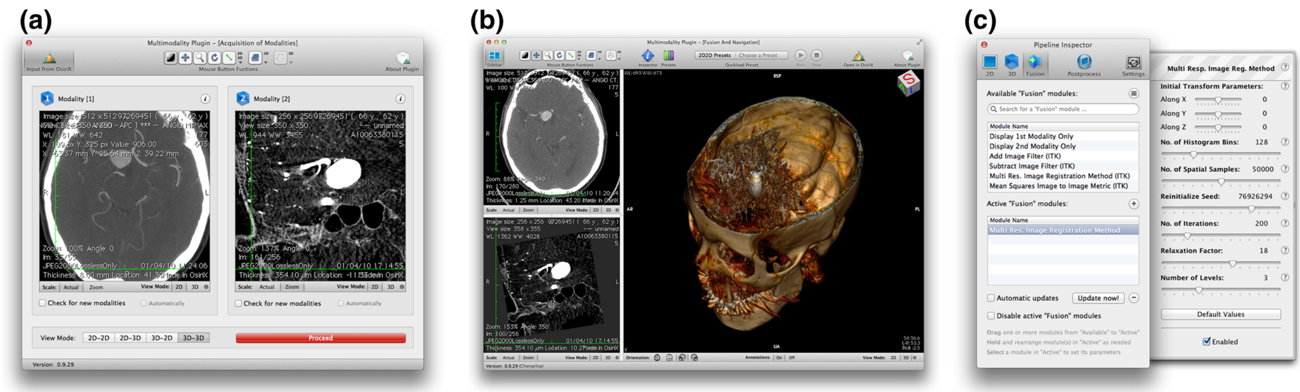

Fig. 3 The tool's user interface: **a** acquisition of modalities, **b** main window, **c** inspector panel

settings that can be reloaded and applied to other sets of image data.

Image processing and the stereoscopic 3D screen

Depending on the type of imaging modalities and the desired rendering and fusion mode, several modules were developed to deal with different preoperative and intra-operative modalities. Regarding preoperative modalities, high-resolution CT and MR modalities had to be co-registered and fused with each other and/or with a 3DRA modality, acquired at the beginning of every interventional procedure. Accurate 3D–3D registration and fusion were performed with a processing module based on feature-based mean squares metric method from the ITK library obtained from $N \times 2D \rightarrow 3D$ projection as dimensional correspondence strategy [10]. In intra-operative modality, dynamic DSA sequences were co-registered and fused with the corresponding preoperative modalities. With its temporal dimension, DSA is in nature 4D image data (2D + time). The 3D–2D registration and fusion were performed with a processing module based on intensity-based mutual information metric method from the ITK library with $3D \rightarrow N \times 2D$ projection as dimensional correspondence strategy. In case of misalignment, the user is able to use the *inspector panel* to correct the specific registration and fusion process either by altering its parameters or by aligning the modalities manually.

The 3D screen

The 3D screen installed in our hybrid suite is a 42″ (107 cm) autostereoscopic LCD display made by Alioscopy [11]. It is equipped with Alioscopic solid–glass lenticular lens with 0.01 μm accuracy, which allows 8 viewpoints that can accommodate multiple viewers (up to 40) over a wide angle of field of view (up to 100 °). The required display resolution of the screen is 1920 × 1080. The screen is positioned in the surgeon's "field of view" across from the operating table. The holographic effect of the screen at the distance of 4 m is accurate, immersive and the surgeon does not need to reposition himself to get the proper 3D depth effect while doing the procedure, instead of perceiving the output as a 3D visualization on a flat 2D screen. A special extension of our software tool was implemented for autostereoscopic, 3D visualization of the fused images with support for eight simultaneous view points calculated in real time allowing interactive rotation and panning of the 3D data.

Patient studies

After internal validation of our techniques and software platform on phantom studies, nine patients were selected for multi-modal acquisition and processing using our software program. Several acquisitions of different modalities were performed prior (CT, MR) and during (3DRA, DSA) the endovascular procedures.

The following table (Table 1) describes which modalities were used for each patient for testing our tool for co-registration and fusion of these images. The different imaging modalities were acquired according to the clinical pathway for each patient as part of their standard medical workup. Therefore, different combinations of imaging modalities are explored and tested.

Results

The software tool was tested in clinical practice with a specific emphasis on its ability to provide improved visualization of co-registered fusion of preoperative and postoperative images. Special attention was given to overall workflow and ease of use in the operating room. The ability of physicians and technical staff to master and use the software was evaluated and monitored during clinical procedures. Subjective evaluation and objective assessment of the software platform were obtained from all the users. Furthermore, the added

Table 1 Summary of modalities used per patient case

	Preoperative data 1	Preoperative data 2	Intra-operative data 1	Intra-operative data 2
Case 1	CTA	–	3DRA	–
Case 2	–	–	3DRA	DSA
Case 3	CT	–	–	DSA
Case 4	CTA	–	3DRA	–
Case 5	MR	–	3DRA	DSA
Case 6	CT	MR	3DRA	–
Case 7	MR	–	3DRA	DSA
Case 8	–	–	3DRA	DSA
Case 9	MR	–	3DRA	–

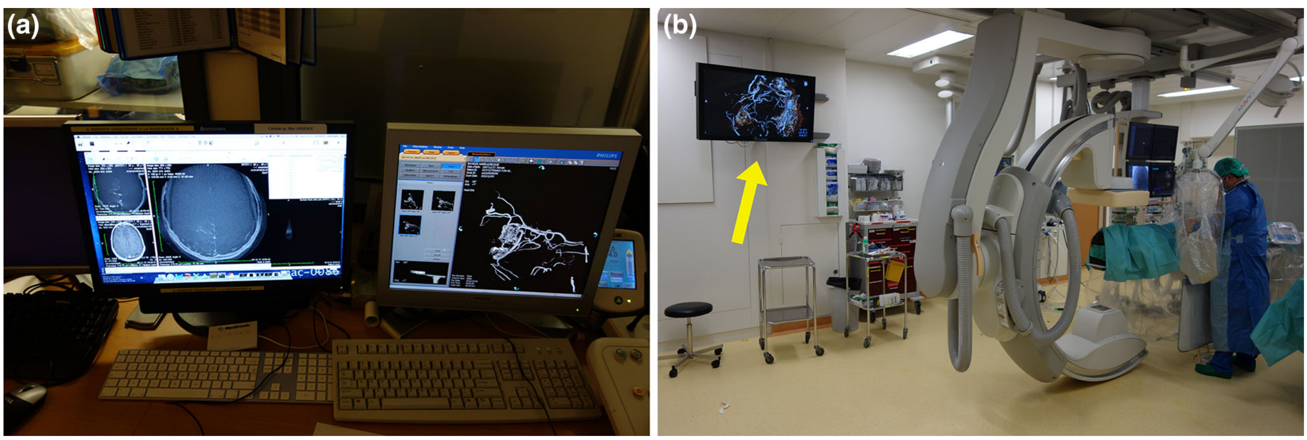

Fig. 4 The software tool as seen in the OR's control room (**a**) and in the on the 3D autostereoscopic screen (*arrow*) (**b**)

value of 3D autostereoscopic images was compared to more conventional display of angiographic images for accurate localization of vascular structures and assessment of the best surgical path for the intervention.

The clinical validation experiments were performed on 9 patients (6 men and 3 women), aged between 26 and 74 (mean 42) scheduled for intravascular interventions. Preoperative modalities were transferred to the imaging workstation from our PACS; the intra-operative modalities were transferred to the imagine workstation directly from the X-ray angiography unit located in the hybrid interventional suite, through a direct DICOM-based communication protocol. Image sequences with the best spatial resolution were selected from preoperative modalities by trained radiologists (Fig. 4a). Images from intra-operative modalities were acquired by the software platform automatically or manually when needed, depending on their suitability for interventional procedure. Depending on the type of input modalities, the tool was used by trained technicians to co-register and fuse them with intra-operative images and to display the resulting composite images on the autostereoscopic 3D screen (Fig. 4b).

Examples of 3D–3D registration and fusion of selected CTA and 3DRA studies and of 2D angiography with 3DRA are shown in Figs. 5 and 6, respectively.

Evaluation scoring questionnaires were submitted to three surgeons and five technicians that have participated in the clinical validation and completed after every patient case, to better evaluate the impact of the software on the workflow in the procedure. The questionnaire for the technicians consisted of ten questions focused on the use of the tool during a procedure. The questionnaire for the surgeons consisted of six questions relevant to the medical use of the tool, especially on enhancements of perception of anatomical structures. The scores obtained for most relevant questions for this paper are presented in Figs. 7 and 8 showing the evaluation results of the questionnaires and the general satisfaction with the tool.

The software tool has received positive satisfaction between the technicians. The modular architecture of the tool allowed it to adapt its pipeline modules for each patient in accordance with the different imaging modalities used and the average satisfaction with "ability to adapt to a new patient" was rated by the technicians between *Medium* and *High*. *Medium* and *High* ratings were given to "stability of the system." The accuracy of the co-registration and fusion modules was rated from *Low* to *High*. The satisfaction of the user interface was rated between *Medium* and *Very High* and so was the satisfaction with the 3D output capabilities.

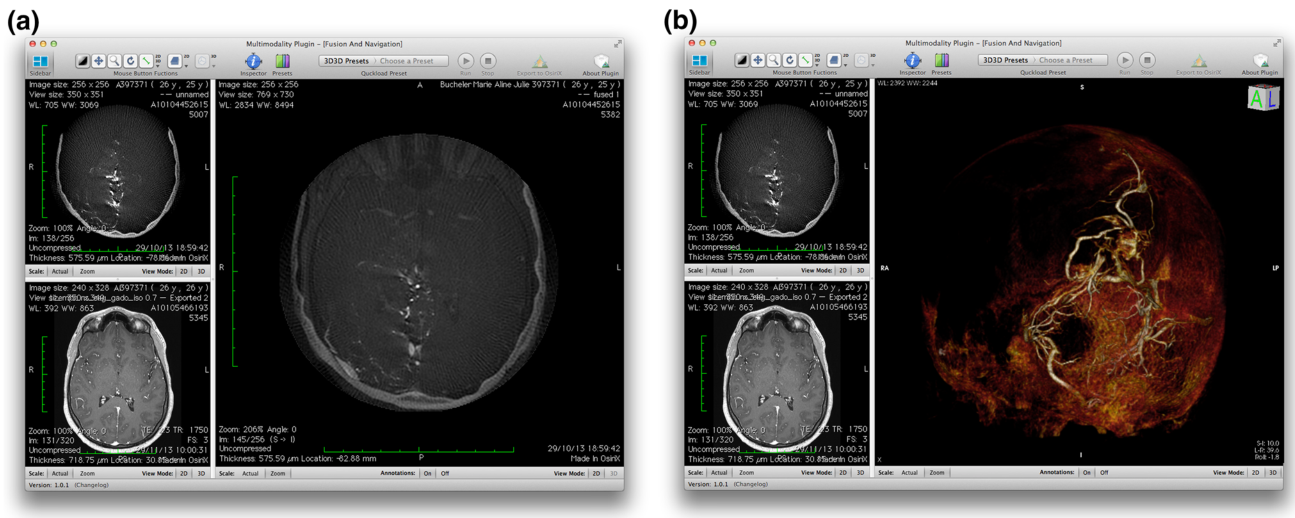

Fig. 5 3D–3D registration and fusion patient case 1 (CTA + 3DRA) in 2D (**a**) and 3D (**b**) output mode

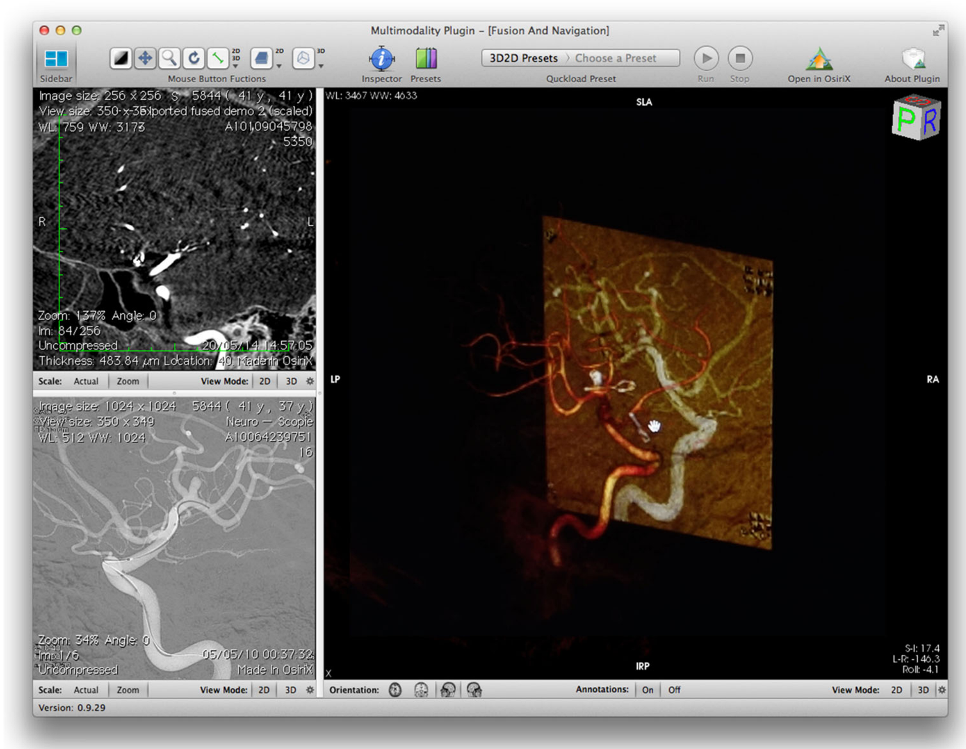

Fig. 6 3D–2D registration and fusion, patient case 2 (3DRA + DSA). The 3D volume provided by 3DRA was properly scaled and oriented to properly match the 4D (2D + time) DSA images updated intra-operatively

The software tool was also scored medium to high average satisfaction by the surgeons as well. The "perception of anatomical structures" was rated with *High* to *Very High* ratings, the "confidence during the procedure" was rated with *Medium* and *High* and the "time needed to finish the procedure" got ratings in the range from *Low* to *High*.

The higher ratings were given to satisfaction with user interface, manipulation with the tool and visual outputs on the autostereoscopic 3D screen.

The lower ratings were partly due to two patient cases with input modalities of lower visual quality. Both cases were based on MR imaging and while they had relatively high trans axial (X, Y directions) resolution, their resolution in axial direction (Z direction) was sub-optimal due to higher slice thickness. The co-registration and fusion algorithms and 3D volume rendering on the autostereoscopic 3D screen produced visual degradation, especially visible on thin anatomical structures. The users were instructed

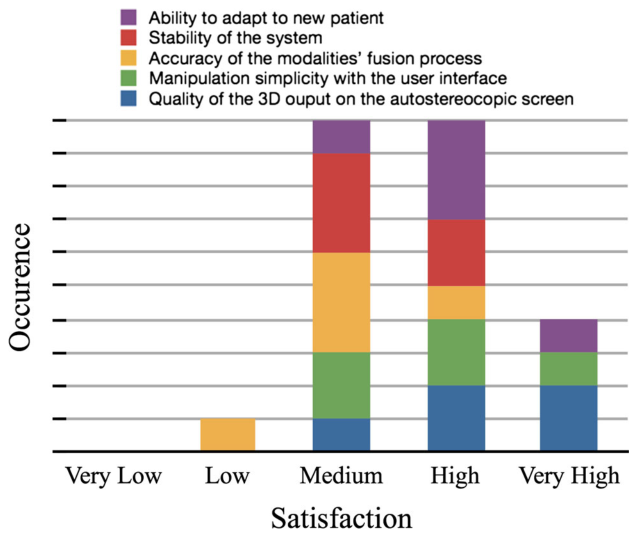

Fig. 7 Evaluation results of all patient cases: general satisfaction of five technicians

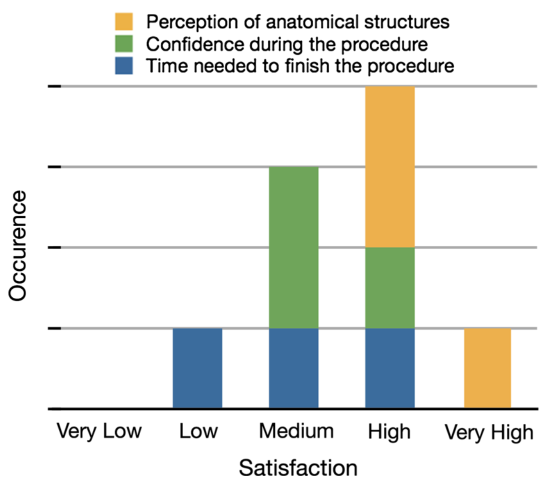

Fig. 8 Evaluation results of all patient cases: general satisfaction of three surgeons

to order higher-resolution MR imaging protocols with sub-millimeter slice thickness when possible to allow these data to be applicable for our tool.

The overall results from clinical validation of the software tool and the feedback from surgeons and technicians that have participated on the in vivo experiments have confirmed that the ability of having an autostereoscopic 3D screen installed in the hybrid interventional suite and used during interventions with adequate pre-intervention and intra-intervention data can improve the workflow of neuro-interventional procedures, by providing the surgeons with valuable additional visual information and better topological localization of the different vascular structures.

Discussion

The challenge of image acquisition in interventional procedures is real-time transfer of images that are being acquired intra-operatively. Most imaging systems will export image sequences as DICOM set of files, which is probably not the most efficient way of streaming data to a processing workstation. However, avoiding proprietary communication protocols we elected to stick to standard DICOM protocol despite its limitation in performance. In addition to the transfer delay of images, processing them for multi-dimensional fusion adds additional delays to the process. This requires image-processing workflow to adapt to users needs by allowing sequential processed images to be generated and displayed for guiding the users during the procedure.

Medical images (3D volumes) shown on an autostereoscopic 3D screen are highly dependent on the quality of input data of images acquired prior to the procedure. Preoperative images, whether CT or MR modalities come from different devices and institutions. MR modalities tend to be acquired with parameters that are often sub-optimal for 3D volume rendering and additional fusion with angiographic images. MR images are often acquired with lower resolution than CT, but most importantly with higher slice thickness resulting in poor spatial resolution in the axial direction. This, together with image reformatting and interpolation needed for autostereoscopic 3D monitor, has direct impact on the quality of 3D visual rendering. To overcome this, modalities with high resolution (ideally 512×512 and higher) and small slice thickness (ideally <1 mm) are preferable. Also the use of 4K autostereoscopic 3D monitors could also improve the visual output significantly. However, it is important to mention that higher resolutions of input data or output visualization devices are more demanding on the computational power of processing and visualization workstations.

Conclusions

The software tool was tested with multiple imaging modalities, acquired in different points of time and different imaging devices as well as with images acquired in real time, directly from the imaging device in the hybrid interventional suite. The tool was able to process the modalities in a user-friendly software environment and to display them on an autostereoscopic 3D monitor in a way that is more appropriate for the different types of procedures performed. The tool was highly valued by the users, and our preliminary evaluation with real-patient data in clinical practice showed its ability to provide adequate support for interventional procedures.

The clinical validation of the tool has also shown the limiting factors of working with different modalities. The differences in image quality, image resolutions between processed modalities contribute vastly to the quality of the co-registration and fusion results. For medical practice, these factors need to be evaluated in a larger set of clinical studies.

The implemented software tool fulfills the premise of applicability of an open-source approach for multi-modal visualization of image-guided therapeutic interventions and is available as open-source software on the following address: http://projet3d4d.hug-ge.ch/

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Compliance with ethical standards

Conflict of interest None.

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