A Visualization System for the Clinical Evaluation of Cerebral Aneurysms from MRA Data

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Abstract

This paper details a work-in-progress application under development as part of a clinical visualization project. The software has been designed to meet the specific needs of interventional neuro-radiologists evaluating the suitability of intracranial aneurysms for endovascular coiling and also when planning the procedure. Providing rapid (real-time) interaction with high resolution iso-surfaces derived from Time-of Flight (ToF) Magnetic Resonance Angiography (MRA) data will enable the clinician to quickly assess the ability of the aneurysm to accept a coil, with greater reliability than exisiting, 2D film techniques. Simulating the interface of the C-arm angiography system, used during the procedure, allows the clinician to evaluate various surgical strategies, potentially reducing procedure times and therefore patient radiation dosage. The first release of the software is currently under-going clinical evaluation.

1. Introduction

Brain haemorrhage is one of the commonest causes of sudden death in adolescents and young adults. In most cases it results from the rupture of a weak spot on one of the arteries that feed the brain with blood. These areas of weakness expand due to the high pressure of arterial blood to form small balloon like protuberances known as aneurysms. The wall of the aneurysm is very thin, weak and prone to spontaneous rupture. Rupture of the wall causes sudden loss of consciousness and in 40% of people death occurs within an hour. In the remaining 60% emergency treatment is required to stop subsequent re-bleeds which are far more common immediately following the initial episode.

Currently, one of the commonest forms of treatment involves packing the aneurysm with a small platinum coil. This is introduced into the body by a catheter inserted into the femoral artery in the groin and fed up into the brain and eventually into the aneurysm itself. The tiny flexible platinum coil is pushed through this tube into the aneurysm, the coil retains a *memory* of its original shape and expands to fill the aneurysm, though it can take several coils to fill a large aneurysm. The platinum promotes clotting and eventual healing of the aneurysm without the need for invasive brain surgery.

One of the major technical difficulties in endovascular coiling is the accurate identification of the shape, size and origin of the aneurysm and in particular the relative proportions of the aneurysm neck to the aneurysm itself, (figure 1).

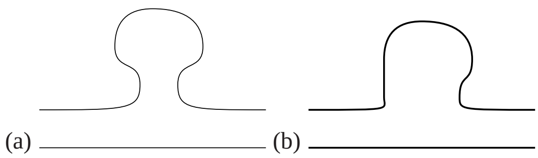

Figure 1: *Aneurysms form as swelling on the artery wall due to the high blood pressure in the vessel and a localised weakness the wall. The aneurysm in a) has a well defined neck that is suitable for coiling. However in b) the aneurysms has a wider neck and a coil may not stay in place*

Imaging techniques have become a vital component in this pre-operative stage, assisting in the assessment of the shape, size and location of the aneurysm as well as its position relative to surrounding vascular structures. However, much of the surgical planning relies on two-dimensional information from sources such as X-ray images, digital subtraction angiography (DSA), multiplanar reformatting (MPR) or maximum intensity projection (MIP) of contrast enhanced Computer Tomography (CT) or magnetic resonance angiography (MRA) data. The clinician is often left with uncertainty in their assessment due to ambiguities resulting from the projection of a complex 3D environment onto 2D. Further, during the coiling procedure the clinician relies on angiography to monitor the introduction and positioning of the coil. The clinician must identify at least two view angles, one showing the neck of the aneurysm and a perpendicular view to check alignment of the catheter. Obtaining these views can take many attempts which expose patient to additional radiation doses.

This project has developed a visualization application that aims to provide renderings which simplify and accelerate the process of assessing the shape, size and position of the aneurysm and for selecting the optimal aneurysm views for the coiling procedure. Two Magnetic Resonance Imaging (MRI) acquisition methods have been considered, Time of Flight (ToF) and Black Blood (BB). ToF produces a signal proportional to the blood flow through the vessels, conversely, in BB sequences flow produces a signal void. Both methods have their advantages and disadvantages however, as many aneurysms appear near bone and bone also presents a signal void in BB sequences, ToF is the preferred method in this work [1]. Figures 2 and 3 show example images from ToF and BB sequences respectively.

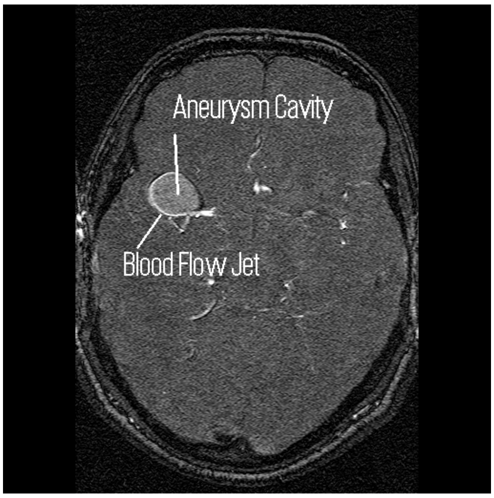

Figure 2: *Time of Flight MRI image which shows the signal fall off in the aneurysm cavity due to the turbulent flow of blood and the jet entering the aneurysm*

The work in this paper outlines the current capabilities of the software and how we intend to complete development. The software is currently undergoing the first stage of evaluation by our clinical partners using PC hardware with an

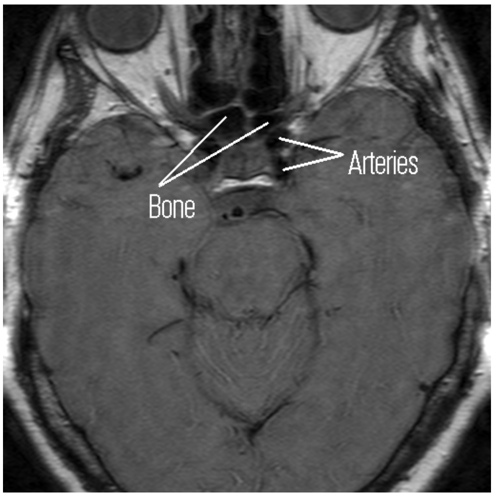

Figure 3: *BB MRI image, both the flowing blood and bone are shown as signal voids*

Intel PIII 600Mhz, 256Mb RAM and an nVidia Geforce 256 graphics card.

2. Previous Work

Several studies have investigated methods for extracting vascular structure from ToF sequences [2,3,4]. These techniques attempt to segment the data using either a statistical or structural model of the data. Although attractive rendered images often result from such techniques there is no attempt to assess the validity of the results. In any model based method it is important to know to what degree the prior expectation of the model is dictating the final result. What needs to be known is how the different pre-processing techniques effect the clinical choices and ultimate outcome of the procedure. Until the affects of the segmentation techniques are understood we are reluctant to make use of algorithms which utilise as much prior information. The metric performance of these algorithms is also poor, taking many hours to segment typical datasets on standard PC hardware.

An automatic optimal view selection method has been suggested [5], this used an adaptive thresholding method [2] to segment the vascular structure from ToF. A skeletonization method was then employed to create a path from the artery into the aneurysm. Radial image maps were created at approximately sixty points along the path, each contains the distance from the point to the vascular wall. These maps were then used to determine the position and orientation of the aneurysm neck. The results presented appeared good although there was no evaluation of the performance of the technique in clinical situations. Further, given the ready availability of accelerated graphics hardware for PC platforms it is now possible to present high quality 3D surface and volume renderings in real-time at minimal cost. Together with the experience of the clinician whose knowledge of the vascular structure and familiarity of the problem enables them to interpret the data even though it may be incomplete leads us to conclude that optimal view selection is best done manually.

Currently in our partners clinical environment, MRA data is analysed on a Philips EasyVision system which provides good 2D image manipulation but has poor 3D performance. Only a small volume of data can be rendered as a surface which can take several minutes to prepare. The renderings are of low resolution, with basic user interaction available at low frame-rates (typically <1fps). Clinical staff often spend in excess of half an hour studying a single case using this system and then only in conjunction with angiography data.

We have set out to the provide an application that will take the user through from MRA acquisition to data preparation and then visualization. The software will allow them to make concise judgements on the structure of the the aneurysm and then to plan the surgical procedure. Finally we provide them with 3D visuals to aid in the procedure itself. The application makes use of the hardware currently available to provide an interactive environment that gives to user as near to real-time feed back as possible.

3. Endovascular Surgical Planning Tool

The development environment for the application needed to fullfil the following requirements:

- to prototype the application in a short space of time
- to provide a professional look and feel
- to be able to make rapid changes as feedback from the clinicians was obtained
- to be flexible and extendable

AVS/Express was chosen over alternatives such as the open source Visualization Tool-Kit (VTK) for several reasons. Although VTK has an excellent array of functionality the Manchester Visualization Centre (MVC) has a lot of experience with AVS/Express; it hosts the International AVS Centre. The combination of the visual programming environment and the V description language, which defines AVS/Express applications, meant that rapid changes could be made to the software. AVS/Express applications are also trivially ported to other platforms. In addition Hardware volume rendering support is also being evaluated and it is expected that AVS/Express will provide support for these cards as and when then appear.

Since the software is being developed for clinicians who may not have a high degree of computer literacy and also have limited time, the UI has been designed to be as intuitive as possible. This means we have tried following established practices and procedures. The software has been developed with constant user input so that ideas can be quickly integrated into the system and make them aware of what the system is capable.

The system has been integrated with the MRI scanner which exports data in the DICOM medical image format. Data can be pushed directly onto the PC via the local network within a few minutes of the scan being taken. The DICOM file is parsed for pertinent information so that a simple database can be created that allows the clinician to be presented with a clear indication of the datasets present on the system.

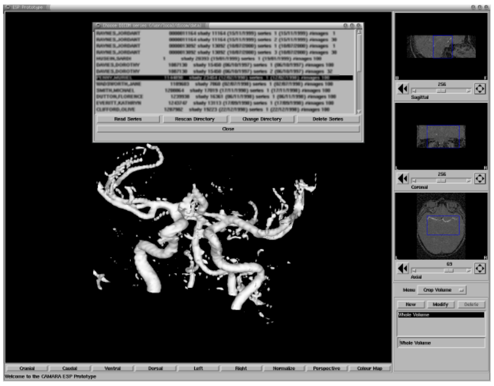

Figure 4: *Endovascular Surgical Planning tool showing data that has just been selected from the systems database and creation of an initial isosurface*

The ESP tool presents the user with a large main view to show the 3D visualization. Smaller 2D views provide the standard perpendicular slices through the volume, (figure 4). The user interface controls have been kept to a minimum to make best use of the screen space and let the clinician focus on the actual data. For each step the user selects the appropriate UI from a menu. Less frequently used controls have been moved to pop-up windows, though the number of these is kept to a minimum.

Once a scan has been acquired it is pushed to the system. The clinician can then select the volume to be read in from a list of patients with the date and size of their scan.

The ESP will initialise and attempt to *window* the data (clamping) using values that may be found in the DICOM header and set other parameters to sensible defaults. The clinician can then move back and forth through the slices, and pan and zoom to the region of interest, which is a standard practice for analysing MRA. The slice views can be redirected to the main view to make this task easier. Tools are provided to take distance and area measurements from these images.

Once the area containing the aneurysm has been identified a crop volume can be selected by marking the area in the orthographic views. Currently, only rectangular region can be selected but more sophisticated methods will be added to aid in removing objects that may obscure the aneurysm. An arbitrary number of crops can be generated.

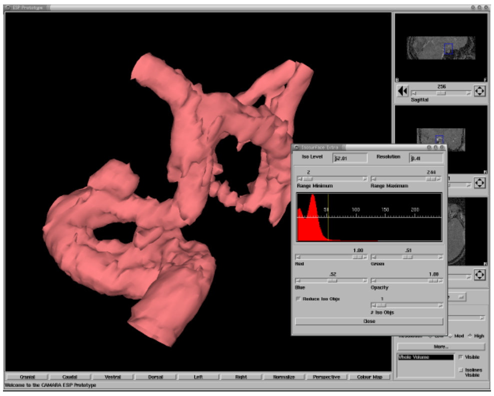

Figure 5: *The data is cropped to the region contaning the aneurysm and isosurfaced using the histogram tool. An object removal method has also been employed*

To visualise the aneurysm in 3D an isosurface can be created from each crop volume. An interactive histogram is available and a visual indication of the isosurface value on the orthographic views aids in selecting the correct value. The colour and opacity of each isosurface can be selected by the user.

The choice of isosurface is extremely important, low values are required to obtain as much vascular structure as possible but the noise in the ToF can cause the creation of a large number of artifacts that obscure the aneurysm, see figure 9. Re-sampling the crop volume to a lower resolution is an immediate help though there is the obvious loss of detail. The ability to use lower resolution data also means larger volumes can be rendered directly and adds some scalability to the software. Additional noise reduction methods are discussed in section 4.1.

Higher isosurface values can show the regions of fast blood flow. Where these blood jets occur and how they enter the aneurysm are of special importance as they can cause compacting of the coils once in place. Visualization of the blood flow is discussed further in section 4.3.

Though isosurfacing is used as the primary visualization method, due to its speed and ease of use, volume rendering of selected crop volumes can also be performed. The transfer function is described using the colour-map editor, (figure 6). The performance of the volume rendering can be adjusted to suit the hardware, using *fat* rays to render at a lower resolution and a bounding box for interaction. The nVidia Geforce chip-sets, however, have excellent texture map performance that allows interactive frame-rates (>10fps) to be obtained using a back to front composite texture map volume rendering method. The data must however be converted from the usual 12 or 16 bits to 8bits; the affect of this and the quality of the volume rendering is to be assessed. In addition, the MIP render method is provided, mainly as a comparison to the composite method, as it has been a standard 3D visualization method for MRI.

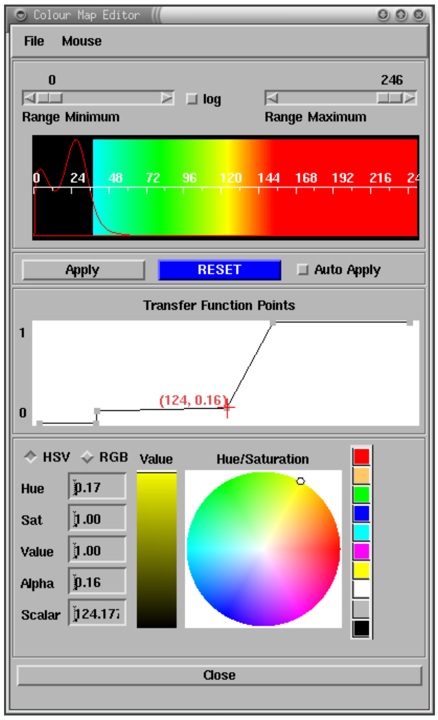

Figure 6: *AVS/Express' internal volume rendering methods are used with a simple to use colour-map editor to describe an appropriate transfer function*

Once the clinician has identified the aneurysm and created a visualization which clearly demonstrates the orientation and structure of the aneurysm neck and blood flow into the region, planning of the working views can then proceed.

The angiography machine consists of an X-ray machine mounted on a swivelling C-arm, (figure 7). The orientation of the X-ray source can be positioned in single degree steps set by dials on the machine's control panel. The table may also be moved in three directions.

There are three major arteries entering the cranium, however the contrast medium will only appear on part of the vascular structure. Therefore, the clinician creates a crop volume containing the vascular structure that will be visible during angiography. The ESP simulates the movement of the C-arm about the patient's head. To achieve this a common centre of rotation must be decided upon that can be found in the ESP and at the start of the surgical procedure. To co-register the position of the machine with that of the scanned cranium three intersecting planes are defined in the ESP using standard anatomical features as references. Once a working centre of rotation has been defined the ESP presents a

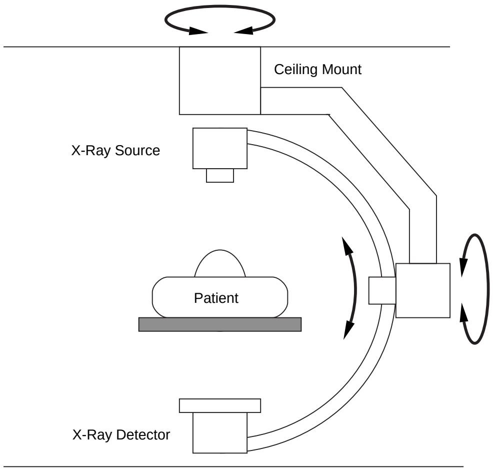

Figure 7: *General arrangement of the C-arm, the table can be moved in any direction*

simulation of the C-arm controls to allow the clinician to find the required views using the full rendering of the vascular structure to obtain clear and unobstructed views, (figure 8). The application visually warns the user, by changing the background colour, if the view will position the C-arm in an unattainable orientation i.e., coincides with the patient or the table. The patient can then be positioned in the machine according to the same anatomical references as used in the ESP, and the C-arm orientated to the position obtained from the simulation. An approximation to the projected angiography image is performed using and inverted MIP. This provides a rough structural approximation to the image which would be viewed by the clinician. A better simulation of the angiogram images is to be added to the application in the near future, using volume rendering.

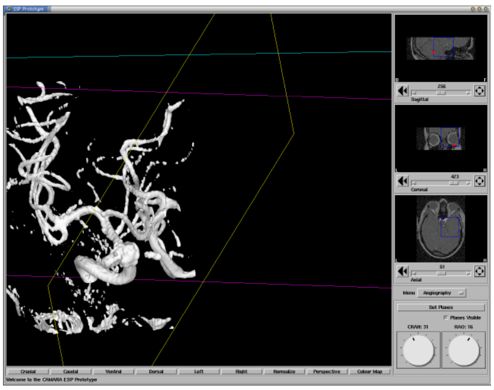

Figure 8: *With the reference planes defining the centre of rotation the operator can find the working views using the simulated C-arm controls*

Images of the main view can be saved out and a VRML model of the whole scene also generated. This allows remote consultation with other clinicians and provides a 3D guide to the clinician during the coiling procedure, this could be displayed on a laptop in the operating theatre when logistics make viewing from the ESP system impractical. Each session of work performed in the ESP may also be saved to file so that it can be referred to at a later date.

4. Current and Further Work

4.1. Filter Methods

As was mentioned earlier, we have investigated segmentation algorithms and concluded that, as yet, the performance of such techniques remains to be proven in a clinical context (see section 4.2). However, given the poor signal to noise ratio of ToF images we are investigating the performance of image based noise filtering techniques in order to reduce artifact clutter in the final rendering. Without any attempt to remove these artifacts the clinician is forced to reduce the iso-surface value until only the strongest signals remain, often losing many important vessels.

We have considered several image and volume filtering methods both 2D image based (Gaussian, linear sequential, median and tangential smoothing) and 3D volume based implementations of the median and tangential smoothing algorithms. All of these techniques have some effect on the data as well as the noise so we are currently evaluating these algorithms in terms of their noise removal and data modification behaviour. To achieve this we are measuring changes in cross-sectional area and circumference of known vessels at a given iso-surface value, as well as the number of noise artifacts removed. Preliminary indications are that the 3D version of the tangential smoothing algorithm has least effect on the vessel data, whilst reducing noise artifacts to an acceptable level. The tangential smoothing algorithm is designed to be edge preserving, smoothing along the edge (or plane in 3D) and not isotropically as many smoothing algorithms. Figure 9(a) and (b) show the before and after renderings at a fixed iso-surface for the 3D tangential smoothing.

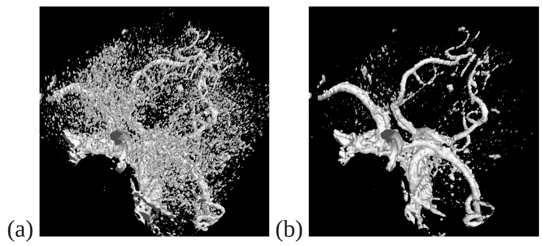

Figure 9: *(a) Isosurface of cranial vascular structure from raw ToF, (b) Isosurface after application of 3D Tangential Smoothing*

The filtering techniques described above have not yet been added to the ESP system. However a method for filtering out isosurface objects based on size (number of triangles) has been added and is available to the clinicians. This performs a recursive search through the arrays of vertices and triangles building up a list of topologically separate objects. The *N* largest objects in the isosurface can then be displayed. This feature has proved very helpful, though practically it can only be run on small isosurfaces. A more sophisticated method of selecting the objects to be displayed will be developed.

4.2. Vascular Atlasing and Segmentation Algorithms

The best renderings will undoubtedly be achieved when only the vessel information is used. This would require prior segmentation and as we have stated the performance of such algorithms is not known. However, we have devised a technique to assess one aspect of the performance of these techniques in an automated atlasing system. This system is built on the existing 3D wireframe model matching software, which is part of our image analysis libraries called TINA [8], and is used to match a known wireframe model to data extracted from a stereo view (two camera) of an object [9]. By building a generic 3D model of the vascular structure we will be able to compare segmentation algorithms in terms of their ability to extract data suitable for the model matching process. Further, by labelling the regions with suitable markers it will be possible to automatically identify anatomical regions within the vessel structure.

4.3. Flow Indicators

As mentioned above the flow direction and speed of the blood is of interest as it has a direct affects on the placement of the coils within the aneurysm cavity. Secondary aneurysms can form on the back of the original aneurysm, often at the region under the most pressure from the blood inflow. Therefore it is of primary importance that this region is protected by the coil. Using ToF data the flow speed can be visualised with a volume rendering, (figure 10). By reducing the opacity of the slow flowing blood the observer can identify the faster flowing regions which likely act as the inflow jet to the aneurysm, and thus aim to protect the opposing wall. The current tool has this volume rendering capability.

Further, we intend to improve the visualisation of flow inlet by computing the minimum path derivative. Using the flow relationship in the ToF images we can compute the local voxel-to-voxel derivatives, and construct streamlines through the minimum energy paths, approximating the most probable flow directions. These can then be presented to the clinician as cues to the major flow directions.

5. Current Status

The software is currently undergoing initial evaluation by the end users at Manchester Royal Infirmary, Dept. of Neuroradiology. This involves a retrospective case study focusing on previous cases where the angiography and current MRA techniques were unable to resolve the structure, size or shape of the aneurysm. The study is also monitoring changes in radiation dosage new patients are subjected to, so that a comparison may be made when the system becomes fully operational.

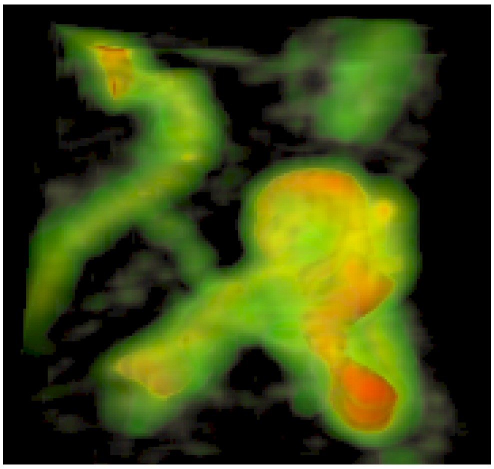

Figure 10: *Volume Rendering can provide a direct visualization of the flow intensities as they enter the aneurysm*

Early indications are very promising, the speed and easy of use of the system allows the clinicians to focus on the data.

6. Conclusions

We have been able to provide a system that conforms to clinician's standard working practices but integrates new and faster methods for examining and analysing MRA data than is currently available. Additionally we have enabled them to correlate the views and understanding of the aneurysm structure obtained in the application with the angiography equipment used during the coiling procedure. The clinician will have a clearer idea of how the coils should be placed to reduce the chance of aneurysm re-growth. Other benefits are a reduction in time in assessing each case and for the procedure. In turn this means a reduction exposure to radiation for the patient.

AVS/Express has so far proved adequate to the task, the first prototype being produced in four weeks (half of this being development of the DICOM image reader). The software has been ported to Windows NT/2000 and SGI Irix. It has also been adapted for use in the AVS/Express Multi-pipe edition which allows AVS/Express to run in virtual reality environments, such as caves, on multiple graphics pipes [6], and is provided as part of the demo suite provided by AVS. Standard, readily available PC hardware has been able to provide a system capable of providing the performance need for interactive and real-time manipulation of the data.

Recently, hardware ray-cast volume rendering[7] has become available, in particular the VolumePro* card from Real Time Visualization*. The first cards were considered at the start of the project but were found to have limitations. These would however be overcome in the second generation cards that will hopefully be available before the end of the project. Real-time performance provides the possibility of volume rendering becoming the primary visualization method rather than isosurfacing

* VolumePro and Real Time Visualization are registered trademarks of TeraRecon.

Acknowledgements

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