Automatic Generation of Context Visualizations for Cerebral Aneurysms from MRA Datasets

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0. Abstract

Purpose: Cerebral aneurysms are dilatations of cerebral arteries and result from a local weakness of the vessel wall. They bear a high risk of rupture, leading to intracranial bleedings. Since these structures are parts of a complex vascular system, the adjacent vessels and the aneurysm position convey important contextual information for diagnosis and treatment planning. We concentrate on the automatic extraction and visualization of context information that include main cerebral arteries and the fine vessels that can emanate from the aneurysm body. This information is needed to estimate, if an aneurysm is accessible by means of minimal invasive treatment techniques and if it can be sealed without major disruption of the cerebral blood support.

Methods: We apply an automatic filtering approach to extract the context information from MRA datasets. Intensity values, connection information and anatomical knowledge about the vessel locations are utilized. The filtering result is used to create a hybrid rendering: the context information is presented by means of direct volume rendering; the focus structure is given by a polygonal model of the aneurysm and its parent arteries.

Results: The automatic filtering was successfully applied to 8 different MRA datasets. Two different color maps are presented for hybrid rendering: A DSA-like color map that resembles the visual impression of digital subtraction images radiology experts are familiar with, and a blue-to-orange color map that is adequate for emphasizing small, low intensity vessels close the aneurysm.

Conclusion: If a polygonal model of an aneurysm is given and the brain is centered within the volume dataset, our technique can be used to efficiently visualize additional context derived from the underlying MRA TOF dataset.

1. Introduction

Cerebral aneurysms result from a congenital or evolved weakness of stabilizing parts of the cerebral arterial vessel wall. These widened vessel parts bear a high risk of rupture, leading to intracranial bleedings with fatal consequences for the patient. Due to an increase of performed MR scans, the number of accidentally found aneurysms is rising. Since the treatment bears a certain risk for the patient, the hazardousness of an aneurysm has to be carefully estimated [1]. Morphological indicators like body-to-neck-ratio, size and the existence of local high curvature areas (indicates possible former bleedings) on the aneurysm surface convey important information for risk assessment. Current research aims at supporting this decision process, by the inclusion of local blood flow simulations [2]. For computer aided (semi-) automatic evaluation of morphological indicators as well as for the FEM-based flow simulation, the aneurysm and its parent artery / arteries are reconstructed as polygonal 3D-models.

For the following steps, the definition of simulation boundary conditions, the interpretation of local morphology and simulated flow, and the treatment planning itself, more information about the surrounding vascular system is required than is provided by the local polygonal reconstruction. In order to decide if an aneurysm can be treated minimally invasive by a catheter-based intervention, its accessibility through the main cerebral arteries has to be evaluated. The access could be blocked by deformed or narrowed vessel parts. Such deformations also give important hints for the risk assessment, since they could be the cause for the aneurysm in the first place. Besides this information derived from the main arteries, knowledge about the existence of small vessels, emanating from the aneurysm body, is relevant. These vessels could be blocked, if the aneurysm is sealed by the usage of coils. Brain tissue necrosis caused by reduced or interrupted blood supply would be the consequence.

In this paper we present an approach for the automatic filtering of the aforementioned contextual information from MRA TOF (time of flight) datasets with contrast enhanced vessels. Main arteries are accentuated while irrelevant structures like brain tissue and the skull are automatically removed. Additionally a distance transformation is utilized to smoothly preserve scalar volume data near the aneurysm. Hence an observer can visually determine if small vessels are emanating from the aneurysm. The final visualization is hybrid, containing a direct volume rendering (DVR) of the filtered MRA data as context and the polygonal reconstruction of the aneurysm and its parent arteries as focus. As a result of discussions with expert radiologists, two color maps are applied to the direct volume rendering: A grey color map that resembles the familiar look of the digital subtraction angiography (DSA) and a colored map that improves the 3D perception and the distinction of the low contrast features that are preserved near to the aneurysm.

2. Related Work

In [3] a cerebral vessel extraction is presented, that works on TOF MRA datasets. They perform two segmentation steps: first potential vessel voxels are selected based on a mixture distribution model, resembling the physical blood flow. Then, this initial segmentation is refined by the inclusion of structural connectivity information, utilizing hysteresis thresholds. Thus, small artifacts like wrongly selected voxels are removed. Since this approach was only tested on two datasets, it remains unclear, if it is capable of reducing larger artifacts, like parts of the skull. Instead of using a local operator to select correctly chosen voxels, our approach utilizes high level anatomical knowledge.

In [4] a broad overview of state-of-the-art vessel segmentation techniques is given. Level-Set methods are common for vessel segmentation since they are applicable to complex topologic structures. Starting from a seed point, a surface propagates until it resembles the vessel surface. The propagation is steered by constraints, based on image properties like grey values, gradients or the propagation direction itself. The result is an explicit polygonal surface. In our case, no explicit surface description is needed, since we only want to create anatomical context information. In order extract anatomical context information on a broad range of MRA datasets automatically, we concentrate on less sophisticated filtering concepts, with few parameters. Their setting is based on global dataset information and assumptions about the anatomical configuration (see section 3). In [5], an example for an implicit filtering is presented. Instead of anatomical knowledge they apply a size based transfer function to distinguish between different sized volume elements. The concept of distance based reduction of details is applied in [6]. They link the contextual importance of anatomical structures with their distance to the focus area. In [7] DVR is used to depict context structures whereas focus structures are rendered as explicit polygonal surfaces. The fuzzy look of DVR allows the presentation of additional information without distracting the observer from the focus structure. Additionally, DVR represents the scalar volume data in a more direct manner than polygonal surfaces. Given a well chosen transfer function, it enables the observer to find low-contrasted or partially represented structures (e.g. small vessels) that probably would have been filtered during the surface reconstruction process.

3. Characteristics of MRA Datasets

We concentrate on MRA datasets since MR is the modality of choice for evaluating anomalies of the cerebral vasculature. Due to the increased number of performed MR scans, aneurysms are found accidently, even if the scan was motivated by afflictions not related to an aneurysm. Hence, datasets containing unruptured cerebral aneurysms are primarily available as MR scans. In contrast to CT scans, no standardized intensity values are available. Nevertheless, due to the contrast enhancement, vessels exhibit high intensity values. Depending on the imaging parameters, this can be also true for other anatomical structures like skin or parts of the brain matter. MR scans of cerebral aneurysms cover, often partially, a vertical area (along the transversal axis), beginning at the *Arcus Aortae* and ending at the skull cap. The finally chosen part of this area depends on the position of the aneurysm, whereas the brain normally forms the central part and is fully included, at least in the axial slices. Important context structures are *Arteria Carotis Interna* and *Arteria Basilaris*. Cerebral aneurysms normally occur there or at branching vessels. Therefore these vessels form landmarks for position determination and are important for accessibility analysis in case of minimal invasive treatment. Due to the angiographic imaging, it can be observed that these vessels bear a high contrast. Additionally, they are clustered and situated near the middle transversal axis of the cubic volume data (see Fig. 1B). We apply these general and therefore robust criteria for our automatic vessel extraction.

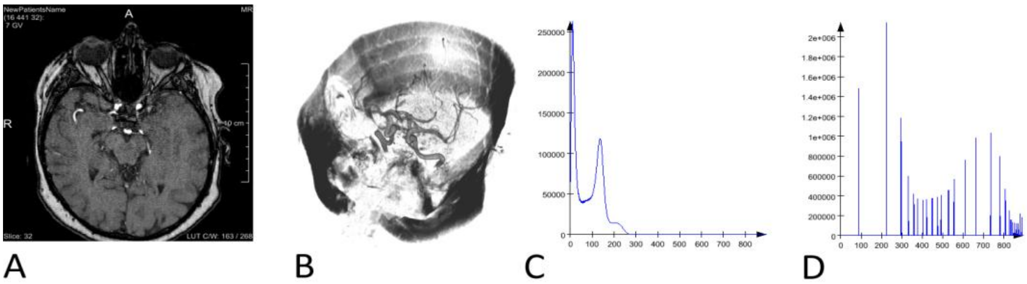


Figure 1: *A slice of a MRA dataset (**A**), a volume rendering that shows the clustering of important arteries close to the middle z-axis of the volume (**B**), the intensity histogram (**C**) and the equalized intensity histogram (**D**)*

4. Extraction of Context Vessels and Distance Based Detail Preservation

As a result of the automatic filtering process, the bigger cerebral arteries and small vessels near to the aneurysm have to be preserved, while irrelevant structures like skin and brain tissue have to be removed. Thus we avoid a visual occlusion of the context structures and the polygonal focus model. The segmentation and creation of the polygonal model is described in [8]. The automatic extraction pipeline takes the volume dataset and the polygonal model as input and consists of the following steps: An adaptive threshold for initial separation of relevant and irrelevant information, a connected component analysis and volume based filtering and a distance- and cluster-based distinction between context vessels and remaining artifacts. Based on the polygonal model, a Euclidean Distance Transformation (DTF) is used to smoothly remain details in the local surrounding of the aneurysm. The result of the extraction pipeline and the DTF are combined to a mask that is applied to the original MRA dataset.

Initial Threshold: We apply a threshold *T* to initially select voxels that presumably belong to the main arteries. Since no standardized intensity range is available, *T* is chosen relative to the intensity maximum I_{max}. Tests on several MRA datasets have shown that $T = 0.25\ I_{max}$ is a good initial guess. To refine *T*, we include the grey value distribution. For this, we generate an equalized histogram and choose the half of the mean value position as *T*. Since the equalized histogram offers a more even distribution of intensity values but still contains an adapted histogram profile we get $T = 0.25\ I_{max} * a$, whereas *a* influences *T*, depending of the overall contrast between vessels and other tissue. The resulting image contains all the main vessels, parts of high intensity brain tissue and skin (see Fig. 2B).

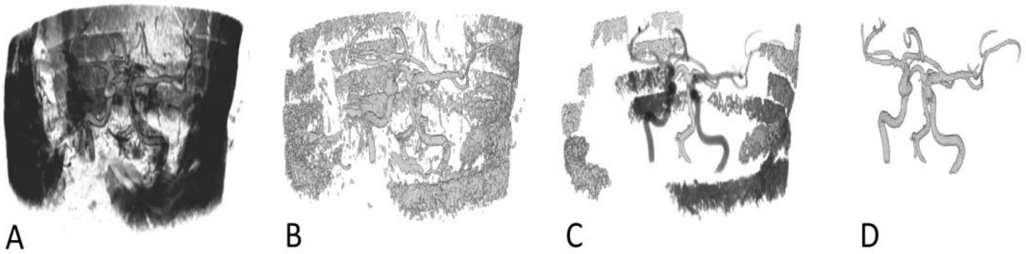


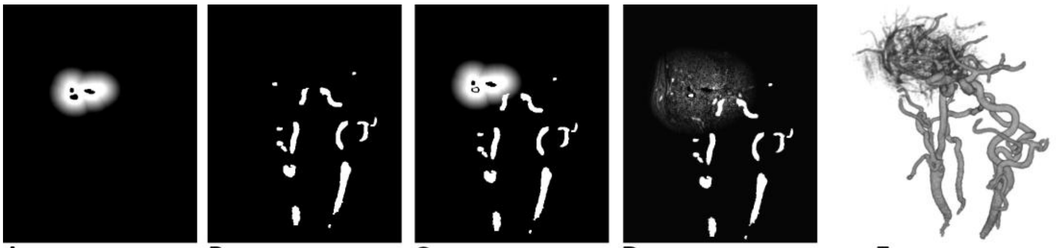
***Figure 2:** The initial MRA dataset (**A**), the result after applying the threshold T (**B**), the result of the connected component filtering (**C**) and the result after removing components according to their distance and cluster characteristics (**D**).*

Connected Component Analysis: To reduce the number of remaining, wrongly selected voxels and create data for the further refinement, a connected component analysis is applied. All components with a volume smaller than 0.01 % of the overall dataset-volume are discarded. The remaining components are the main cerebral arteries and parts of the skin. To distinguish between those two types of components, we utilize the center of their bounding boxes. According to the aforementioned dataset characteristics, we can assume that arteries are situated near to the middle z-axis of the dataset volume, whereas the skin parts are naturally located at more remote positions (see Fig. 2C). It also can be observed, that the main arteries are vertical structures that are located near to each other, which leads to a clustering of the x- and y-positions of their bounding box centers. The skin parts are located separately around the area of the brain and consequently exhibit a lower clustering rate. The orthogonal distance d_i of all bounding box centers are calculated and sorted in ascending order. Then the mean m_d value of the distances intervals $D_i = d_{i+1} - d_i$ is calculated. All components that belong to an interval $D_i < m_d * b$ are defined as context structures. Tests on several datasets have shown, that $b = 1.2$ is an adequate choice to describe the common cluster density of components belonging to cerebral arteries (see Fig. 2D).

Euclidean Distance Transformation: A DTF is applied to define a smooth volume around the aneurysm, where possible existing, small low-contrast vessels are not filtered. The input for the DTF is a voxelized version of the polygonal model. It is important, that the position of the polygonal model is aligned to the according data in the volume. Otherwise, the DTF-result cannot be utilized for masking the original data properly. This problem has to be considered during the creation of the polygonal model.

The result of the DTF is a distance field *F* with scalar values *f* between 0 and 1, where 0 describes the minimal distance near to the aneurysm surface. *F* is calculated over the complete volume with maximum distance values at the border of the dataset. To create a smooth ramp mask covering the local surrounding of the aneurysm, we first invert *F* and then generate a rescaled distance field *F'* with $f' = max(0, (f - 1 + (1 / c)) * c)$, whereas *c* is a constant. For all datasets, $c = 10$ led to a well sized ramp mask for the local aneurysm surrounding.

Final Mask Creation: The result of the connected component analysis is binarized. After that, a morphological dilation filter with a 3x3x3 kernel is applied. Thus we ensure that the vessel surface is represented completely when masking the original data. This mask is combined with the ramp mask by applying the arithmetic image operation *max*. The result is a mask that will preserve the main arteries and low contrast information near to the aneurysm surface, when multiplied with the original dataset (see Fig. 3D). In order to create this mask automatically, we utilize two defined constants: *b* and *c*. Both are independent variables and exhibit robust characteristics (for the tested datasets: stable results when altered +/- 20%). Their setting was determined empirically and could be successfully applied to all our datasets.



A B C D E

***Figure 3:** the rescaled distance field (**A**), the context vessel filter (**B**), combination of A and B with max operator (**C**), the result of multiplying C with the original image data (**D**) and a volume rendering of D, showing the preservation of details near to the aneurysm (**E**).*

5. Hybrid Visualization of Focus and Context

The final visualization consists of the filtered volume data, resulting from the applying the mask, and the polygonal aneurysm model. The color map has main impact on the visual representation of the volume data. Since the volume data serves as context information, low saturated colors should be used. Otherwise the context representation could distract the observer from the polygonal model, which forms the visualization focus. Visual cues describing shape and relative position of the context vessels depend on the chosen color map. Thus, it should be designed in a way that it supports the visual integration of the polygonal model and volume rendering. Interviews with radiology experts have shown that for simple cases an unsaturated color map that resembles the look of established angiographic imaging systems, especially the digital subtraction images (DSA), is suitable. Nevertheless, if the low intensity area around the aneurysm is of special interest, the usage of different colors improves the distinction between small vessels and surrounding tissue. Compared to the DSA-like color map, the three-dimensional impression of the context vessels also benefits from the usage of different colors. Thus, we propose blue-orange color map with a low saturation, in cases where the information conveyed by the DSA-like color map is not sufficient.

DSA-like color map: By applying the color map shown in Fig. 4A, we get a context rendering that resembles a DSA radiology experts are familiar with. As can be observed in Fig. 4C, the context vessels are slightly transparent. Due to this and because they are not saturated, the visual focus lies on the polygonal aneurysm model. The disadvantage is a weak visual integration of the sharp edged polygonal model and the semi-transparent, fuzzy context vessels. The perception of low intensity voxels near the aneurysm can be difficult, especially when lying in front of the saturated polygonal model.

Blue-to-orange color map: This color map offers two significant characteristics: first, the distinction of low intensity voxels is supported by a change of color from blue to orange (see Fig. 4B). Since we apply low alpha values to low intensity voxels, their representation is low saturated while the occlusion of the polygonal focus model is minimized. The color of the focus model is complementary to orange. By this, it is still possible to perceive the semi-transparent low contrast voxels, even if they are in front of the polygonal model. For the high intensity voxels, that belong to the main arteries, we apply a orange-black-orange color ramp with low saturation. This visually emphasizes the vessel edges and leads to an improved three-dimensional impression (see Fig. 4D). The visual integration of the polygonal model and the volume rendered context is improved, whereas the visual weight of the polygonal focus structure is not as high as if a DSA-like color map is applied.

Interference during Hybrid Rendering: The aneurysm is represented as a polygonal model and is often included within the volume data that is used to create the context information. Thus, the aneurysm surface is described by polygons and voxels. This redundancy can lead to visual interference artifacts, since the polygonal surface slightly differs from the surface voxels it was created from (see Fig. 5C). In order to avoid those artifacts, we remove the voxel representation of the aneurysm and create a voxel free area near to the surface, by applying a morphological dilatation (3x3x3 kernel) to the voxelized polygonal model. We use the result to mask all corresponding voxels in the original volume data. Thus, we obtain a polygonal surface representation without interference artifacts (see Fig. 5D).

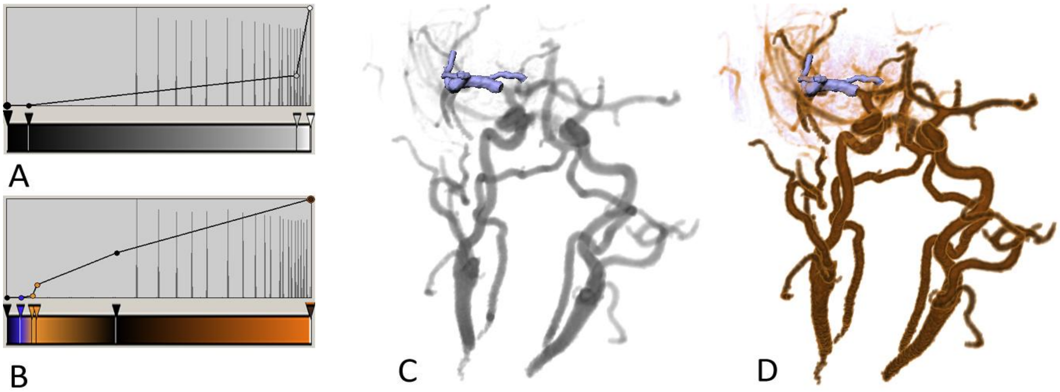


Figure 4: *the DSA-like color map (**A**) applied to the filtered data (**C**) and the blue-to-orange color map (**B**) applied to the filtered data (**D**), the polygonal model aneurysm model is also rendered (blue)*

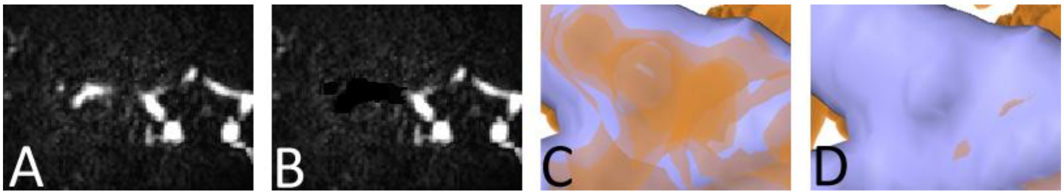


Figure 5: *the masking result including the aneurysm (**A**) leads to artifacts close to the polygonal surface (**C**), after filtering (**B**) the artifacts are removed (**D**)*

6. Results

The automatic filtering was successfully applied to 8 different MRA dataset. They were obtained from different scanning devices during clinical standard procedures. No non-standard image optimization steps were performed. In Table 1, the dataset characteristics are presented.

Dataset	Resolution (vox.)	Volume (mega vox.)	Mean Vessel Intensity	Max. Intensity	# Components / # Preserved Comp.
An_01	448x512x88	19.25	553	880	7 / 2
An_02	256x256x104	6.50	621	1094	9 / 3
An_03	256x88x384	8.25	766	1619	6 / 2
An_04	696x768x149	75.69	431	623	12 / 3
An_05	352x448x92	13.84	526	898	5 / 4
An_06	448x512x88	19.25	438	897	8 / 2
An_07	448x512x88	19.25	396	792	4 / 2
An_08	512x146x512	36.50	161	320	5 / 2

Table 1: *Dataset Characteristics, the last row contains the number of connected components before and after distance- and cluster-based filtering*

The scanned head area differs in all dataset, within the general constraints given in Section 3. Examples for the volume data before and after the automatic filtering are given in Figure 6.

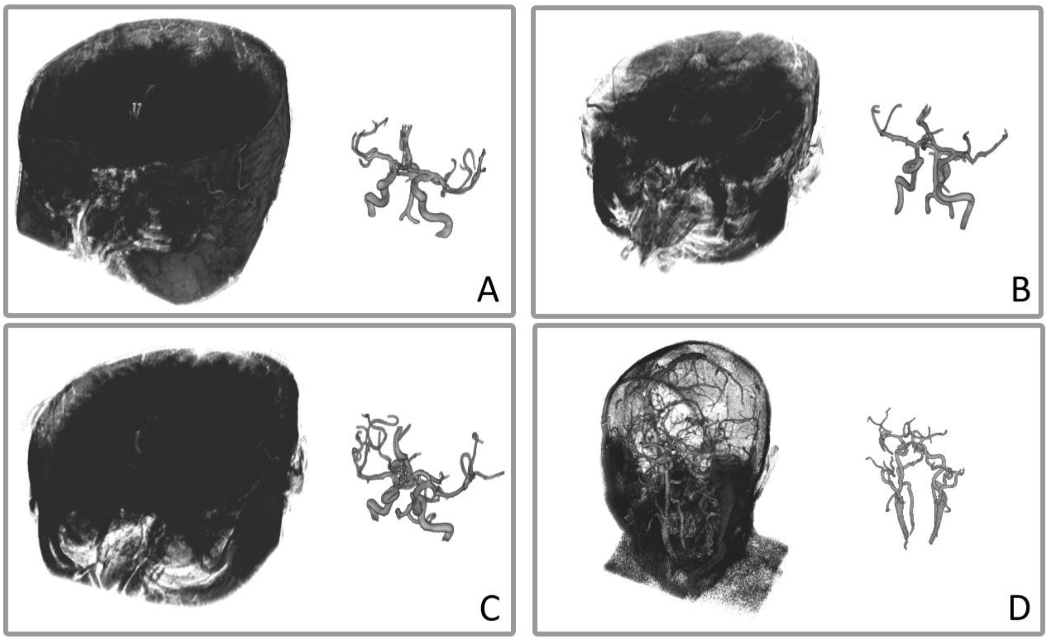


Figure 6: *examples for filtering results*

In all cases, the *Arteria Basilaris*, the *Arteria Carotis Interna* and branching vessels are preserved. No manual parameter setting was necessary to create these results. For all comparison images the same color map was applied. Figure 7 shows the final hybrid visualization after the automatic filtering process for two of the datasets. The preservation of low intensity details close to the aneurysm can be observed in Figure 7C.

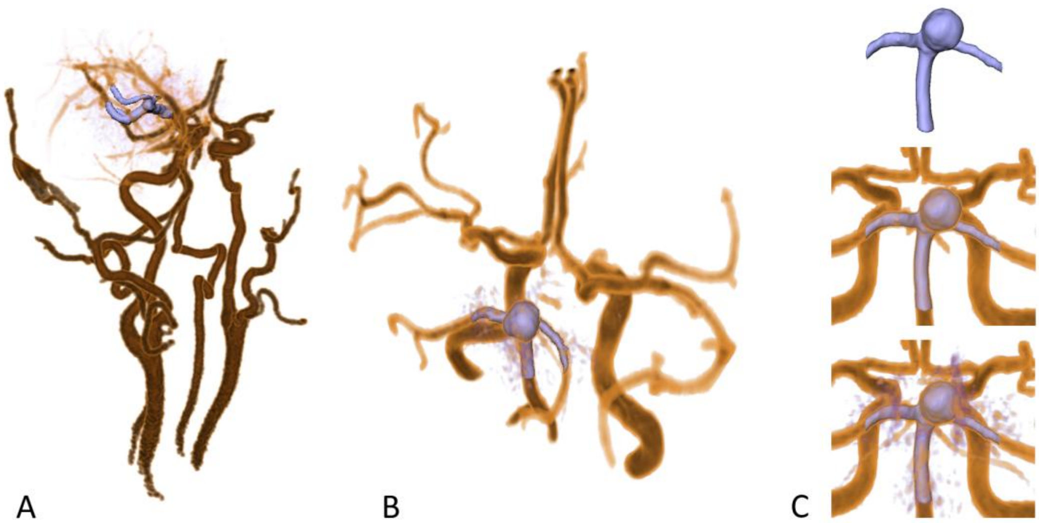


Figure 7: *the final hybrid focus + context visualization for two different datasets (**A**,**B**), after adding all context information, small vessel emanating from the aneurysm can be observed (**C**)*

7. Conclusion and Outlook

We described an approach for the automatic extraction of context information from MRA datasets. Our filtering technique is based on a few general assumptions. Thus, it shows a robust behavior, depending on only a few parameters. The filtering was successfully applied to several MRA datasets with different characteristics. The filtered information was used to create a hybrid focus + context visualization by combining it with a polygonal model that was created in a previous reconstruction process. Depending on the chosen color map, it properly conveys information about to spatial structure of the big context vessels and the small low intensity structure close to the polygonal aneurysm model.

If a polygonal model of an aneurysm is given, our technique can be used to efficiently visualize additional context extracted from the MRA dataset, the polygonal model was created from. If no polygonal model is present, the low intensity area close to the aneurysm cannot be emphasized, since no explicit information about the aneurysm surface and corresponding distances is given. Nevertheless, without a polygonal model, our filtering method can still be applied to obtain an unobstructed view on the main cerebral arteries. The filtering is based on general assumptions about the head area included in the MRA datasets. If this area strongly differs from our assumption (e.g. a small region of interest, containing only a portion of the cerebral arterial system), our filtering approach will fail. Nevertheless, a certain tolerance is given, since some of the successfully filtered datasets did not contain the whole axial brain area (see Fig. 6D).

In the current state, the main arteries are defined as contextual important structures. The structural characteristics of the *Circulus Willisi*, a circular connection between these main arteries, convey important additional information for treatment planning (e.g. the state of general blood support if the aneurysm is sealed). Future work will concentrate on the automatic accentuation of the *Circulus Willisi*, based on information derived from our filtering approach.

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