Volume visualization in the clinical practice

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Abstract. Volumetric data is common in medicine, geology and engineering, but the O(n^3) complexity in data and algorithms has prevented the widespread use of volume graphics. Recently, 3D image processing and visualization algorithms have been parallelized and ported to graphics processing units. Today, medical diagnostics highly depends on volumetric imaging methods that must be visualized in real-time. However, daily clinical practice shows that physicians still prefer simple 2D multiplanar reconstructions over 3D visualizations for intervention planning. Therefore, a very basic question in this context is, if real-time 3D image synthesis is *necessary* at all. This paper makes four main observations in a clinical context, which are evaluated with 24 independent physicians from three different European hospitals.

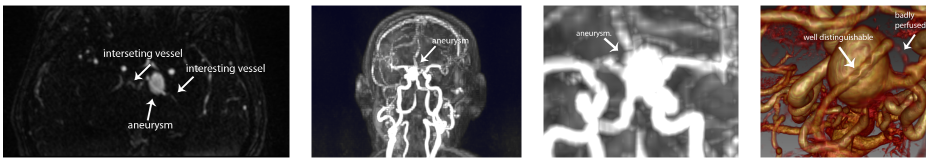
Keywords: medical visualization, evaluation in clinical practice

1 Introduction

Hundreds of highly sophisticated three dimensional medical visualization algorithms have been presented since the the first volumetric scanning devices came up in the clinical practice. However, when working in the clinic or in close collaboration with medical doctors, one might have the impression that none of these algorithms ever found their way into daily use. Diagnostics and treatment planning is done on 2D slices of the scanner's raw data by radiologists and surgeons. Three dimensional visualization methods, Virtual Reality (VR) or Augmented Reality (AR) approaches seem to be completely unknown.
This paper tries to solve the question when 3D visualization is useful or even indispensable in medicine. We show that there is indeed a *need* of 3D image synthesis for diagnostics and we investigate why those methods are not yet commonly used and expose their problems in the current clinical routine. We provide a medically motivated taxonomy of rendering methods and we substantiate several observations in the upcoming analysis with a survey amongst 24 medical

doctors (54% radiologists, 29% surgeons, 8% internists, 4% radiology physisits and 4% general practitioners) from all over Europe, of whom 50% have more than 5 years of professional experience. These observations are considered as application-oriented hypotheses (AOH) in this work.

Motivation by example: The main source for volumetric data in medicine is radiology. Therefore, it would be obvious that radiologists are the target users for volumetric visualization. However, radiologists are trained to gather information from 2D image slices, originating from medical scanners. 3D image synthesis is rarely integrated into a radiologist's work flow. Furthermore, radiologists often do not trust direct 3D image synthesis methods. The general opinion of all radiologists we have been working with during the past years is that 2D slices do not *make up* information about the shape and appearance of a structure, and thus 2D representation are the preferred diagnostic source for imaging sequences, where a direct 2D slice based assessment is possible. Angiography forms a suitable example to discuss this problem in detail:



(a) Axial slice through a MRA of the subject. The aneurysm and one interesting vessel are marked with arrows.

(b) Maximum Intensity Projection (MIP) of the MRA from (a). The arrow is indicating the cerebral aneurysm of this subject.

(c) Closeup of the aneurysm in (b).

(d) DVR of the same scene as shown in (b) and (c).

Fig. 1: A human subject suffering from a cerebral aneurysm. (a) shows an axial slice through a Magnetic Resonance Angiography (MRA) of contrast enhanced vessels with a subtracted previous native scan of the brain to get rid of low perfused image parts. This view would be used by radiologists for diagnosis. The reason is obvious when (a) is compared to (b) and its closeup in (c). Note that the marked vessel in (a) is hidden by the aneurysm in the MIP (b) and (c). However, the MIP can be freely rotated and gives a better impression for e.g., possible surgery access paths for clinicians. The MIP is replaced by a DVR method in (d). Structures of similar intensity are now distinguishable but badly perfused vessels are still only identifiable on 2D slice representations of the original data.

Angiography is a medical imaging technique used to visualize the lumen (the inside) of blood vessels and organs. This is usually done by injecting a radio-opaque or magnetic contrast agent into the vessel of interest or into the whole vascular system by intravenous application. X-Ray based techniques such as fluoroscopy and Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) are subsequently used as image modality. The resulting image shows all vessel lumens (which are filled with contrast agent) with a high and distinct intensity value. Fig. 1 (a) shows one selected slice from a contrast enhanced image sequence for a human head compared to one of the most common 3D representations in clinical practice: Maximum Intensity Projection (MIP) [13] with the subtracted non-contrast enhanced native sequence, Fig. 1 (b). From image acquisition on, the further investigation of the dataset highly depends on the necessary treatment and therefore on the necessary medical personnel. Diagnosis – which is in this case usually done by a radiologist – is based on 2D slice analysis. The main reason for that is that if a vessel is not filled with contrast agent and therefore not projected with high intensity it is not displayed with a MIP or other 3D image synthesis algorithms (illustrated in Fig. 1). However, a missing vessel in 3D does not mean that the vessel does not exist. A vessel can be stenosed or thrombosed, resulting in a decreased blood flow or it can simply be hidden by a structure with a higher intensity. A trained radiologist is still able to perceive at least the remaining perfusion in the area of that vessel which depicts as non-linear small contrast changes in 12-bit encoded medical images. All standard volume visualization methods or vessel segmentation methods are not able to reflect these subtle image variations. This fact makes 2D slice-based volumetric dataset investigation still the method of choice for a radiologist in this example.

An interventional radiologist might not be able to perform the necessary treatment. In this case – e.g. extensive surgery – clinicians are consulted. Clinicians, often surgeons, are trained to navigate inside the human body, obviously a 3D task. For the angiography example, a 3D representation from medical scans (mostly MIP) is essential to provide a link between radiologists and clinicians and to illustrate pathological findings. Investigating an interesting vessel part from all sides without surrounding tissue is a vital procedure for e.g. vascular surgery planning in the current clinical practice. A MIP is simple and fast to compute but it has the severe drawback that structures of a lower intensity can be hidden by structures with a higher intensity as shown in Fig. 1. To overcome this problem, direct volume rendering (DVR) – e.g. ray casting [10] – can be used. Unfortunately, DVR algorithms show a tremendous algorithmic complexity and requires expert knowledge input for feasible diagnostic images. This is currently one of the main reasons, why more sophisticated direct 3D image synthesis algorithms find their way only slowly into the clinical practice. In recent years, hardware providing enough computational power became available also to normal clinical workstations. Besides that, imaging protocols and image synthesis have to be extensively tested and approved by health organizations as for example by the US Food and Drug Administration (FDA) to avoid wrong treatment decisions based on algorithmic shortcomings. This means for angiography that medical imaging devices supporting MIP representations have already been approved by the FDA in the early 1990th, whereas real-time DVR methods got first approved around the year 2000. However, the number of standard treatment procedures where DVR is used for intra-disciplinary communication rises. MRI-based angiography is one of them, not only because of the hidden structures problem but also because of the better image quality, as shown in Fig. 1 (c). Fig. 1 shows that a well utilized DVR shows also structures which are hidden in a MIP but that it still cannot display stenosed or thrombosed vessels which are not well filled with contrast agent.

2 Related work

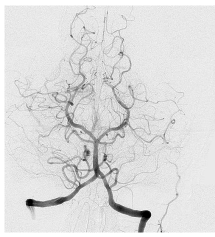
Basic questions like these in this paper are sparsely covered by literature. Liu et al. [11] and Elvins et al. [4] describe several clinically applicable visualization algorithms and their possible use. To the best of our knowledge, there is no comparable work in Computer Science which investigates the questions presented here. Medical literature usually evaluates more specific application questions. For example, Barish et al. [1] investigated how to use virtual colonoscopy with a questionaire with 33 participants. Early non evaluated statements about the usage of 3D visualization in the clinic can also be found in Robb et al.[14] and similar work. Their main focus is to describe usage scenarios for virtual reality surgery planning and rehearsal and not an analysis of their requirements.

3 Application oriented hypothesis (AOHs)

The example of angiography and our overall experience with other clinical procedures lead to:
AOH1: ***Medical 3D image synthesis algorithms must speed up the information finding process to be accepted by medical doctors. For standard diagnostic procedures, 3D representations do not provide additional information to radiologists, but they are useful to illustrate pathological findings to other medical specialists, who use that information for opinion making and intervention planning.***
Following the DVR visualization attempt of the angiography example leads to another observation. The basic idea of DVR is to accumulate intensity values along viewing rays through a volumetric dataset. Each intensity value is looked up in a discrete transfer function, containing color and opacity values. All intensity values of one ray are subsequently accumulated in the resulting image pixel. Considering for example a linear ramp as transfer function, which maps low intensity values to transparent image regions and high intensity samples to opaque regions, makes DVR of an angiography highly comparable to a well established interventional imaging technique: C-Arm fluoroscopy. A C-Arm is a relatively simple X-Ray based device, which can directly display X-Ray attenuation at a certain view port. The image contrast can be enhanced by injecting contrast agent during imaging. Fig. 2 compares a linear ramp DVR to a fluoroscopy image during catheter based minimal intervention. The similarity of the

underlying principles (X-Ray attenuation vs. opacity accumulation) makes the DVR algorithm acceptable for clinicians and leads to:
AOH2: ***If a 3D image synthesis algorithm is comprehensible and if it is related to a familiar physical principle, 3D image synthesis is accepted as diagnostic valuable tool and integrated into the clinical workflow.***

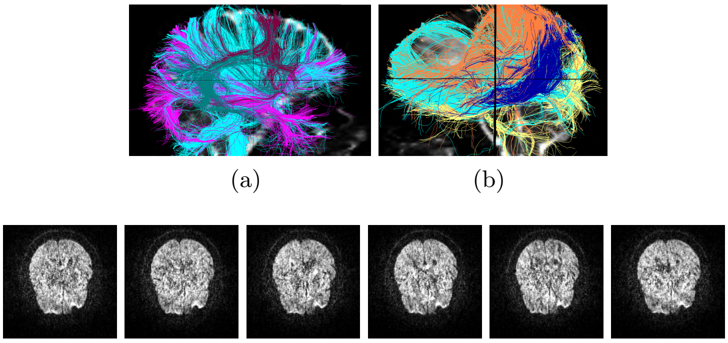
(a) Contrast enhanced MRA of the brain, displayed using DVR with a linear opacity transfer function.



(b) Contrast enhanced fluoroscopy of the brain, arteries

Fig. 2: (a) shows the same subject as in Fig. 1. The DVR in (a) is used with a linear ramp opacity transfer function to underline the similarity of the algorithmic principle to the physical principle in (b). (b) shows a fluoroscopy image made with a C-Arm during catheter based intervention. Contrast agent is injected into the vessel of interest.

Besides 3D assisted angiography, which was first proposed by Napel and colleques [13], there are also further examples showing the same evidence for the need of 3D image synthesis in clinical practice. One of the most common needs is 3D image segmentation. Even though segmentation results are not often used for diagnosis, they are essential for Computer Assisted Intervention (CAI) and CAI-planning. Clear 3D boundary representations are essential for nearly all intervention planning systems and patient studies, where organ specific measurements are required. Furthermore, most state-of-the-art advanced visualization algorithms cannot process volumetric data directly, but have to use a polygonal representation of clearly defined image regions and hence anatomical structures. So far, in this section, no clear evidence has been shown that 3D image synthesis is *essential* for disease diagnosis in clinical practice. As long as the used image modalities are simple most radiologists prefer a straight forward 2D slice-by-slice investigation given that *AOH1* and *AOH2* are not fulfilled. However, many modern diagnostic procedures require either more than one image modality or an imaging mechanism, whose result is too complex for 2D images or even both. Many MRI sequences for example do not only produce greylevel intensity images. They produce high dimensional matrix records for each sample, encoding different physiological conditions. A popular example is Diffusion Tensor Imaging (DTI) [9] which, results the diffusion movement of water molecules within a test body. Because water tends to move along nerve fiber bundles, this sequence allows to draw conclusions about the spacial distribution of nerve fiber bundles, for example inside the living human brain. Fig. 3 shows an example for the resulting spacial structures, which were derived from several dozens MRI sequences of the same subject. A direct 2D investigation of these sequences is not possible anymore.



(a) (b)

(c)

Fig. 3: These images show a 3D overlay over a 2D image of certain fiber bundles, which cross a certain area around a tumor in (a) and (b). The Diffusion Tensor Imaging (DTI) is therefore able to identify vulnerable structures, which must not be hurt during an intervention. Deriving this information from the raw image data is impossible. In this special case the raw data consists of 31 gradient direction DTI volumetric image sequences which allow no direct conclusion about the fiber direction. The bottom row (c) show some selected slice images from the raw data. The dataset is courtesy of Prof. B. Terwey, Klinikum Mitte, Bremen, Germany. Visualization has been performed with tools from MedINRIA [15].

These examples lead to:
AOH3: ***3D image synthesis gets crucial if the data input dimensionality exceeds normal human experience.***

AOH1, *AOH2*, and *AOH3* lead to the conclusion that 3D image synthesis is necessary and appropriate for clinical diagnostic and interventional practice. However, which shortcomings prevent modern image synthesis algorithms like direct volume rendering (DVR) [10] and highly complex (e.g. photorealistic) representations, from becoming an integral part of daily hospital procedures?

Is 3D image quality and interactivity already feasible for clinical applications? To answer this question, 3D image synthesis algorithms have to be classified more closely. For our context they can be roughly dived into five categories:
Low quality – acceptable rendering speed – huge input space: *Rendering of polygonal surface representations* is the oldest and most common technique. A

surface is generated by segmentation or iso-surface extraction and the resulting polygonal surface mesh is sent to the graphics processing unit (GPU) for rasterization. For simple and opaque models, this approach can be sufficient. However, high polygon count surfaces, as they result from vessel or organ segmentation, or many intersecting translucent objects are not feasible to be rendered at high resolutions with an interactive frame rate. Furthermore, surfaces tend to appear artificial because of very simple approximations of the surface illumination. Hence they are hard to integrate seamlessly into the real world experience of a surgeon or into AR environments, as sometimes used for inter-operative assistance. By using existing mesh simplification and smoothing algorithms, this approach can be considered as the most common for 3D image synthesis.

High quality – slow rendering speed – very limited input space: *Direct Volume Rendering (DVR)* [10] is not very common as diagnostic tool, although the technique is nearly 25 years old. The main reason for that is the high complexity of the algorithm and therefore low frame rates during image synthesis without image quality reduction. Furthermore, a higher input space compared to surface rendering is necessary to gain useful images. Whereas surface rendering requires only the definition of the camera and the lighting conditions for the simplest case, DVR requires additionally the generation of a full n-dimensional voxel-to-color-and-opacity transfer function. In recent years, the DVR algorithm has been ported to parallel GPU programming languages, which has mitigated at least the frame rate problem for interactive applications [5]. However, because of inherent limitations of the DVR algorithm, the vast majority of DVR rendering systems is not able to display more than one volume at a time or to intersect different datasets and volumes with geometry correctly. Note that this feature would be crucial for all state-of-the-art diagnostic methods which use multiple modalities.

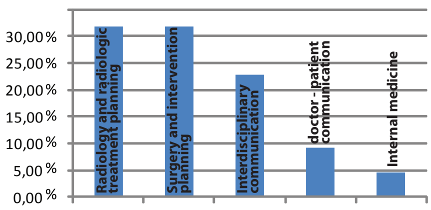
Reduced quality – high rendering speed – limited input space: Non-Photorealistic Rendering (NPR) stylization techniques are very popular for clinical AR applications. Firstly, most techniques reduce highly complex scenes to comprehensible images to avoid visual clutter and communicate the most important information in the simplest possible way [7]. Secondly, the majority of NPR techniques use very basic graphics operations (e.g., lines, strokes, and edges), which can usually be rendered at very high frame rates. However, a major problem of these attempts is the reduced or lost depth perception and the difficult estimation of *important* structures.

Very high quality - very slow rendering speed – limited input space: Photorealistic rendering of organic structures is common for endoscopic training simulators [8] and virtual colonoscopy [12]. Although these systems are well accepted by surgeons, the photorealism is restricted to *textured rendering of polygonal surface representations* illuminated with high specularity to simulate tissue moisture. "Real" photorealistic rendering algorithms, as for example ray-tracing [6], radiosity [3] etc., are not used at all in the clinical practice. Their extreme computational complexity and restriction to geometric objects has not allowed an interactive use so far.

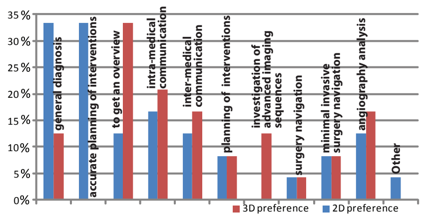
Very high quality - slow rendering speed – large input space: Hybrid approaches are sometimes used to provide different communication channels for multiple sources of information. Bruckner for example makes extensive use of NPR and DVR techniques to provide interactive illustrative volume visualization [2] for the effective communication of complex subjects and to provide a solution for the Focus and Context (F&C) problem. Their problems are formed by a combination of the shortcomings mentioned above.

The breakdown of 3D image synthesis algorithms and their outlined limitations as given above leads to:
AOH4: ***State-of-the-art 3D image synthesis algorithms are either not able to provide the necessary image quality or the necessary rendering speed, or they are restricted by the amount of input data. This prevents a common use of these techniques in the clinical practice and for clinical AR applications or for applications where the rendering result is used as intermediate result and where the overall result must be available within reasonable time.***

4 Evaluation and results



(a) Personal opinions on when 3D image synthesis from medical volumetric data is most important.



(b) The preference of 2D versus 3D for certain example applications. Multiple answers have been possible.

Fig. 4: Personal opinions on the importance of 3D image synthesis for certain applications.

To underline our general *AOHs* from Section 3, we have performed a survey with n=24 independent radiologists and clinicians (54% radiologists, 29% surgeons, 8% internists and 4% radiology physicists and 4% medical students), of whom 25% have more than ten, 25% have between five and ten, 33% have between two and five, and 17% have less than two years of professional experience. The specific knowledge of certain imaging modalities of the attendees has been 87.5% CT, 83.3% MRI (standard, e.g. T1, T2...), 75.0% X-ray (C-Arm, film...),

70.8% Ultrasound, 62.5% advanced MRI (e.g. fMRI, DTI, 4D...), 58.3% Scintigraphy, 45.8% PET, 37.5% SPECT, 25.0% 4D-CT, and 8.3% Thermography (e.g. mamma).
We used the opportunity to evaluate also personal opinions of the survey participants about 3D assisted procedures vs. 2D slice investigation and those situations when the attendees are used to use 3D images instead of 2D slice views. The personal opinions on the importance for certain tasks of 3D image synthesis algorithms are summarized in Fig. 4(a). The general preference of 2D or 3D clearly indicates that the required representation strongly depends on the kind of application (63% answered "it depends on the application", whereas 21% prefer always scrolling through slices.). The common use of 3D image synthesis versus 2D slice representation for certain examples is compared in Fig. 4(b).
Finally we have evaluated the overall agreement with *AOH1-4* from this work. The results are shown in Fig. 5. The results show evidence, that our hypotheses (cp., *AOH1-4*) are correct.

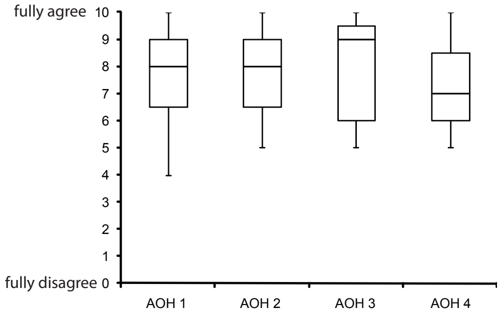


Fig. 5: The overall agreement of the survey participants with AOH 1 - 4. The ends of the whisker are set at 1.5*IQR above the third quartile (Q3) and 1.5*IQR below the first quartile (Q1).

5 Conclusion

We have tried to answer the sword-of-Damocles question of Computer Graphics in Medicine: Is 3D necessary for the clinical practice at all? This question is not necessarily obvious, but arises invariably when working closely together with experts from Medicine. 2D slice view investigation is the most common way for standard diagnostics and can also be efficiently done by trained experts. Furthermore, this method provides the highest level of accuracy and detail which makes it hard to compete with. However, we could show clear evidence by performing a survey amongst 24 experts from radiology and surgery that 3D image synthesis is indeed necessary and welcome in the clinic, but that it strongly depends on the kind of diagnostic or interventional application. We have summarized our main findings in four observations (*AOH1-4*), which have also been evaluated by the survey participants. A large majority agrees with our hypothesis and give also indication of the main medical areas of 3D image synthesis. The result can be summarized as follows: In most cases, 3D image synthesis is essential if the data input space gets too large for human cognitive abilities and for medical interdisciplinary communication (e.g., intervention planning between radiologists and surgeons).

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