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Sketching and Annotating Vascular Structures to Support Medical Teaching, Treatment Planning and Patient Education

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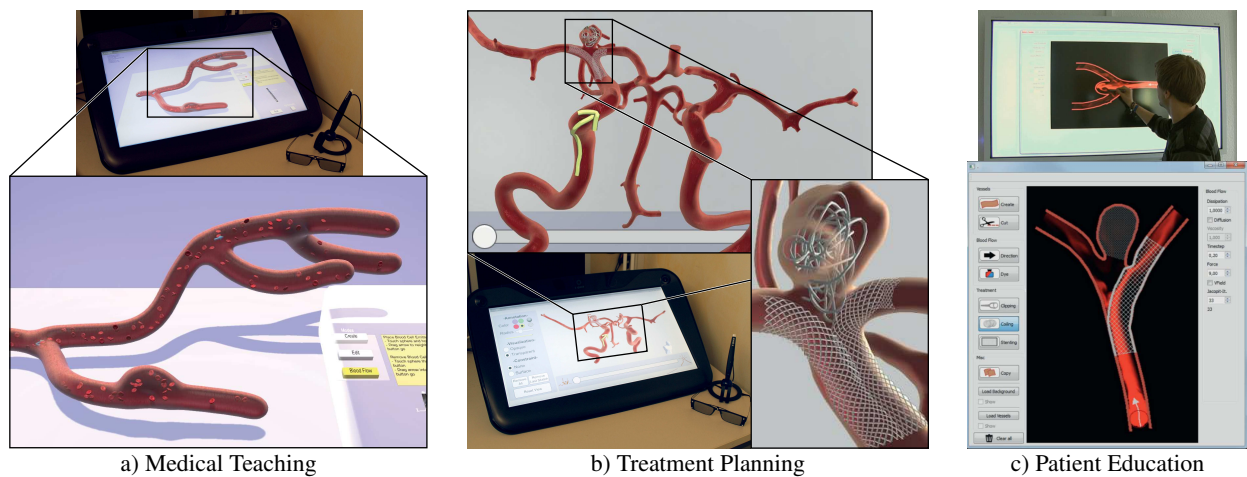a) Medical Teaching   b) Treatment Planning   c) Patient Education

Figure 1: Using sketching and annotations to create and enrich vascular structures and blood flow for supporting three medical domains.

Abstract

In clinical practice, hand drawn sketches are employed to express concepts and are an efficient method for the discussion of complex issues. We present computer graphic methods to improve and support the creation and annotation of complex sketches, resulting in a more clear, expressive and understandable result. For this, we consider the medical areas of teaching, treatment planning and patient education. Our applications allow students, educators, physicians and patients to sketch and annotate vascular structures, their pathologies and treatment options as well as to simulate and illustrate blood flow. The used sketching approaches take advantage of semi-immersive environments as well as interactive whiteboards to enable the creation of vessels either in their spatially complex 3D representation or as a simplified 2D illustration. We evaluate our work in interviews with physicians and user studies to assess their usability and to reveal their benefits to support the respective medical domain.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: —J.3 [Computer Applications]: —

1. Introduction

For the expression of ideas and concepts, sketches are a favored choice without the necessity to draw precisely. They do not only convey the author's thoughts, they also form an efficient tool for the discussion and communication of complex issues. In clinical practice, sketches are employed for a wide range of applications, e.g., documentation [RS06] and segmentation [HMTH13].

We use sketches to create and annotate vascular structures, their pathologies and treatment options as well as to illustrate blood flow. The focus on the vascular system is reasoned by its importance due to the associated fatal pathologies. Cardiovascular diseases lead to approximately 17.5 million deaths annually worldwide.

We describe the benefits of sketching and annotations in three medical domains: (1) teaching, (2) treatment planning, and (3) pa-

tient education. For **teaching**, we present a semi-immersive environment to support anatomy and pathology education by creating 3D vessels with integrated blood flow [SSPOJ16]. Anatomy educators can create and explain complex spatial relationships of interlinked vascular structures and blood flow behavior. For supporting medical **treatment planning**, we present the FAUST framework, which allows physicians to spatially sketch annotations on 3D planning models in a semi-immersive environment [SGB*16,SGBP17]. The physician can sketch different treatment options and access paths on an interactively unfolding vascular structure, where the annotations adapt accordingly. For **patient education**, we present an interactive application, usable on tablets and interactive whiteboards, to illustrate 2D vessels, pathologies, treatment options and blood flow [SBP*15,SBP*16]. Our sketching techniques have been evaluated in collaboration with physicians and anatomists.

2. Related Work

Annotations in medicine are commonly used as textual labels to support education. Mostly, they are automatically placed, either as internal labels on the structure's surface or next to it as external labels [OJP14]. In contrast, an *interactive positioning* of labels avoids the usage of a complex label layout algorithm, but introduces challenges regarding user interaction [SGP15]. For example, during an intervention, a gaze-based interaction can show labels for structures of interest without violating sterility [SMHP15].

Sketching is related to annotations in terms of enriching medical data with meta information. For example, it is used as an intuitive interaction technique to annotate medical reports [RS06] or to segment structures in 2D images [HMTH13]. Furthermore, sketching is used to create structures, such as 2.5D branching vessels [PCP10] which mimic blackboard sketches of medical educators.

3. Sketching 3D Vessels and Blood Flow for Teaching

Medical education is a challenging task for students as well as their educators. Students need a comprehensive understanding of the complex spatial relationships, shapes, and names of vascular structures, whereas educators need appropriate tools to convey these information. In lectures, educators present vascular systems through sketches on blackboards [PCP10]. Computer-assisted methods can support medical teachers and students in a variety of ways. For example, there are eight similar vascular system configurations for the supply of the liver. Here, methods to quickly create, copy and edit vascular systems and highlight spatial differences are beneficial. Based on our work [SSPOJ16], we present an approach to sketch a wide variety of vascular configurations in different body areas and illustrate the most common vascular diseases.

The sketching is implemented on the semi-immersive device *zSpace 100* (zSpace Inc., San Francisco, U.S.A.). It uses a full HD display with an update rate of 120 Hz. Stereopsis is achieved with polarized rendered images, which are filtered by glasses worn by the user. These glasses are tracked and allow six degrees of freedom (6DoF) head tracking. This combination of stereopsis and head tracking allows users to spatially explore medical structures. For user input, a stylus with 6DoF input is used. The interaction technique is ray-based, i.e., the orientation of the stylus is virtually

extended into the scene. The virtual ray allows an accurate definition of 3D points and, thus, sketching 3D lines. Our developed application, including the zSpace and stylus, is shown in Figure 1a.

Creating and Editing Center Lines. The vascular surface meshes are defined by center lines, which the physician can sketch with the stylus. The 3D positions provided by the stylus are irregularly sampled and noisy due to tracking inaccuracies and hand tremble. Therefore, the acquired points are resampled and smoothed by a Gaussian kernel. Each point is stored as a control point and connected to create a center line. The center line is editable by oversketching lines and an eraser metaphor. To build complex vessel trees with bifurcations, new lines can be attached to old ones. Hereby, not only vascular trees can be created, but also cycles, which allows to create systems such as the *Circle of Willis* (CoW).

Surface Creation with Metaballs. The vessel surface is created in real time around the sketched center line. For this, we use implicit surfaces, i.e., Metaballs. By placing Metaballs in close succession along the center line, they blend into each other, forming vascular structures with smooth surface transitions at branchings.

Creating Stenoses and Aneurysms. The illustration of pathologies is important in medical education to understand their implications for morphological vessel changes, their influence on the blood flow behavior, and finally, possible risks for a patient. Additionally, they improve the clinical relevance of the learning content and, thus, the students' motivation. The most important vascular diseases are stenoses (narrowing or occlusion of vessels) and aneurysms (bulging of vessels). To indicate stenoses, the Metaballs' size can be decreased by selecting them with the stylus and *pushing* the stylus forwards. By *pulling* it backwards, the Metaball size increases, yielding fusiform aneurysms. To indicate saccular aneurysms, a combination of sketching centerlines and adjusting the size of the associated Metaballs can be carried out.

Exploration of Real-Patient Data. The possibility to import vessel surfaces derived from real-patient data allows students to inspect rare conditions. In addition, it is faster compared to manually sketching complex structures. To preserve the benefits of our sketching approach, we allow importing center lines based on skeletonized segmented real-patient data.

Including Blood Flow. An illustration of blood flow, which dynamically adapts to the sketched center lines, supports students to understand relationships between vascular pathologies and their influence on the blood flow. We implemented a fast, but still plausible approach based on a particle simulation. We employ the vessel surface and centerline with a combination of collision detection on the surface as well a guidance along the center line for each particle.

Evaluation. We evaluated our approach with nine participants. Their task was to sketch a variety of common vascular configurations. We evaluated the usability and usefulness with appropriate quantitative and qualitative methods [GSB*16,SLB*17], i.e., questionnaires and the think-aloud method. All participants were able to reproduce the shape of the required vessel configurations and able to sketch into depth. The majority of usability questions were rated positively. The aspect *error tolerance* had the lowest rating, since participants often deleted the vascular system completely instead of correcting parts with the oversketching feature.

4. Annotate Vascular Structures for Treatment Planning

Sketches as annotations can be used for treatment planning and allow physicians to highlight regions, illustrate access paths, and visualize treatment options. Therefore, we developed the FAUST framework, which allows physicians to create annotations in object space as 3D sketches [SGB*16, SGBP17] (Fig. 1b). For the treatment of stenoses and aneurysms, the physician can use several methods, e.g., *coiling* and *stenting*. For *coiling*, a small wire is placed inside the aneurysm, possibly leading to an occlusion. The *stenting* procedure can be used to treat stenoses and aneurysms. The stent is inflated inside a vessel and forces it to expand. The choice of treatment depends on parameters such as anatomical access, size and shape of the pathology. This results in different access paths, stent lengths and coil types. We account for the huge variety of different configurations by letting the physician sketch freely.

As an example of a spatially complex vascular structure, we chose the CoW, which comprises a circular combination of arteries supplying the brain. The CoW is represented either in its anatomical, self-occluding state or in an unfolded, occlusion-free 2D illustration. To maintain a mental representation of both states including annotations, an interactive and seamless transition is realized.

Again, we developed our framework on the zSpace (cf. Sec. 3). The head tracking and stereopsis are important depth cues to support the physician in estimating sizes and relationships of anatomical structures [BHS*14]. The direct ray-based interaction with the zSpace stylus allows to freely create free-form 3D annotations as well as translate and rotate the vascular structure.

CoW Extraction, Unfolding and Visualization. We segmented the CoW from a healthy patient's MRI data and extracted a 3D surface mesh [GHV*16]. We use skeletal animation for the unfolding. Here, the center lines of the CoW were generated, used as the skeleton, and manually unfolded with 3ds Max (Autodesk, Inc., California, U.S.A). To allow the users to sketch inside the CoW, we let them choose between two visualizations: a fully opaque one and a shading technique which reveals the inside of the vessel.

Creating and Attaching Annotations. The free-form annotations are sketched with equidistantly resampled and smoothed points from the zSpace stylus. These points are algorithmically attached to the 3D surface. Thus, they adapt their shape during the unfolding of the CoW in real time. The physician can create three different types of annotations: generic annotations, stents and coils. For diverse tasks (e.g., highlighting regions and define access paths), our generic annotations are a flexible tool to sketch configurations. For the common treatment options, dedicated annotations can be used. For all types, we procedurally generate a cylindrical surface mesh along the sketched line in real time. This allows us to support depth perception by applying shading techniques to the surface. The radius of the cylindrical surface can be adjusted. Thus, the user can sketch stents with varying diameters for different vessels or place thin coils inside aneurysms. To aid the user in the process of sketching, annotations can be constrained to lay on the planning model's surface. This helps to, e.g., illustrate an access path along a vessel.

Interactive Unfolding. The CoW can be unfolded interactively with a slider widget. The value of the slider is mapped to the folded and unfolded keyframe states of the skeletal animation. By changing the value, the position of every skeleton's bone is interpolated to this value, resulting in a adaptation of the CoW and annotations.

Evaluation. We evaluated our framework by asking an experienced neuroradiologist to plan the Y-stenting procedure, where a thorough treatment planning is necessary. Hence, two guide wires are carefully positioned such that two stents can be released alternatingly. Both stents should end at the same position and should be adapted to the patient-individual vessel diameter. To further reduce the aneurysm's inflow, coils are deployed after the Y-stenting. In our framework, the physician starts by investigating the vascular structures and highlights pathologies with *generic annotations*. Then, the access paths are defined, where a completely unfolded CoW allows easier 3D sketching. Additionally, the constraining feature is used to constrain the annotations to lie on the surface. Now, the Y-stent is sketched to treat the aneurysm with a large neck size. Two stents with different diameters are sketched. Finally, the physician reduces the aneurysm inflow by sketching thin coils inside the aneurysm. The spoken comments and sketched results of the neuroradiologist indicate that our framework improves the spatial overview of vascular structures and supports the understanding of anatomical structures compared to conventional 2D images.

5. Sketching 2D Vessels, Treatment Options and Blood Flow for Patient Education

In patient education, patients place particular importance on an understandable presentation of their disease and therapy. This results in various positive aspects [Keu08]: the time of treatment may be reduced, patients need less medication and they are more active in dealing with their diseases. To support patient education, we present an application that allows sketching different vessel structures, vascular diseases, and various treatment options [SBP*15, SBP*16] (Fig. 1c). In contrast to teaching and treatment planning, patients benefit from a simplified illustration of vascular structures. Therefore, we realized our work such that it is usable on a tablet or interactive whiteboard with touch or pen interaction. Furthermore, the vascular structures are sketched and illustrated in 2D.

Simulating and Sketching Blood Flow. For the blood flow simulation, we implemented a real time grid-based (Eulerian) Navier-Stokes simulation using fragment shaders on the GPU. The simulated flow can be manipulated by influencing a 2D vector field, used by the Navier-Stokes calculation. Therefore, the physician's sketched 2D paths are mapped to this vector field. The flow direction is determined by the sketching direction. For the flow visualization, an ink dropping metaphor is used, where the physician can sketch ink at any place. This allows emphasizing specific areas, which supports the patient's understanding. The underlying flow simulation then advects the ink in the direction of the sketched flow.

Sketching Vascular Structures. The physician sketches the center line of the vascular structure in a *creation mode* (cf. Sec. 3). The corresponding vessel wall is generated around it in real time. To edit existing vessels, a *cutting mode* is provided, which allows to sketch an area, that is subtracted from the vessel boundary. In combination with the creation mode, the physician can create a wide variety of 2D vessel configurations, e.g., irregular, non-symmetrical stenoses. Furthermore, by using the same sketch-based interaction

technique for both modes, the creation is easy to learn and follow by the patient. The physician is supported during the sketching process by the possibility to load background images, e.g., a patient-specific CT slice. Furthermore, it is possible to load pre-defined vessel structures of common pathologies. All changes to the vascular structures influence the flow simulation in real time.

Sketching Treatment Options. We realized the possibility to sketch common treatment options, i.e., clipping (a clip placed around an aneurysm neck), coiling and stenting. For each treatment option, a dedicated mode is available. Clips are illustrated with a gray line, which is spanned over the start and end point of the sketch. For coiling and stenting, a semi-automatic positioning approach is implemented. The physician roughly surrounds an aneurysm for coiling or sketches the center line of a stent. Afterwards, the neighborhood of every sketched point is analyzed. The sampled points are then moved to the vessel boundaries providing the impression of a completely coiled aneurysm or a fitted stent. All sketched treatment options influence the blood flow simulation directly. To provide the physician with an easy and fast possibility to illustrate more treatment options on the same vessel structures, a *copy tool* is available. Thus, the patient can see different behaviors of the blood flow, depending on the treatment option. This can help to understand why a specific treatment is favored.

Evaluation. We evaluated our application in a user study with 14 participants and interviewed a physician with 15 years of experience. In the user study, we assessed usability aspects with a questionnaire and the think-aloud method. The participants had to sketch pathologic vascular structures and treatment options on a 70″ *SMART Board* with pen interaction. Mostly, the participants were satisfied with the prototype and had no problems using the different tools. They highlighted the practicability of the semi-automatic behavior, e.g., the automatic expanding stents. In the interview, we asked the physician to compare hand drawn sketches for patient education against our prototype. The interview revealed disadvantages of *hand-drawn* sketches. To correct errors, a physician usually draws over existing sketches, which results in a cluttered image. The blood flow and the implications of a treatment are not drawn, because they are hard to illustrate. Our prototype allows a clear, more understandable illustration of vessels, because errors can be interactively corrected, different colors are used and vessels and treatment options are more expressive. The blood flow simulation includes novel information for the manually sketched vessels.

6. Conclusion

We presented the benefits of sketching and annotations in the medical domains of teaching, treatment planning and patient education. Supporting students during their education represents an important foundation to plan and perform interventions. Patient-individual vessels with pathologies require an excellent knowledge of the spatial variations and the 3D extent of the vascular system. Therefore, we used a semi-immersive environment, which allows an improved representation of spatial properties due to the additional depth cues and 3D interaction. For patient education, we choose another approach. Here, a simplified and easy-to-follow representation of vascular structures is necessary. Therefore, we restricted the interaction and visualization of the vascular structures to 2D. For future work, we want to combine the annotation and creation of vascular structures into one framework. The possibility to preserve a variety of annotations together with a 3D representation of the structure could greatly improve other fields, such as patient documentation.

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