

# Sketching 2D Vessels and Vascular Diseases with Integrated Blood Flow

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**Abstract:** In this paper, we present a sketch-based interface, which allows medical doctors to illustrate different vascular diseases and treatment methods as well as fluid behavior. With this sketching interface, we provide the physician with an effective tool to illustrate different medical cases, which is important in the complex field of vascular diseases with respect to patient education. We use techniques from sketch-based interfaces and GPU-based computational fluid dynamics by considering usability aspects. We provide a concept and a prototypical implementation whose usability is tested with quantitative and qualitative methods. Additionally, we interviewed a physician to assess the benefits of the tool with respect to patient education.

SCIENCE AND TECHNOLOGY PUBLICATIONS

## 1 INTRODUCTION

Vascular diseases are a complex field with a large amount of deaths comprising 31% worldwide (see (Mendis et al., 2011)) and a big impact on economics about €196 billion in Europe (see (European Heart Network, 2012)). The treatment of such a disease leads to discussion about prevention, diagnosis, and therapy not only with colleagues, but also with patients. Most important, the patient education gives the patient an insight into the complexity and risk of the possible outcome. An informed patient can benefit in various aspects from comprehensive patient education (see (Keulers, 2008)):

- they need less medication,
- the time of treatment may be reduced,
- they are more active in dealing with their diseases and act more responsible, and
- they are more independent from their treating physician.

Therefore, a tool that supports physicians to discuss and communicate vascular diseases is very useful for patient education. In this paper, we present a program that helps the physician to easily create different vascular diseases and to show various treatment options that may help the patient in understanding their disease. This tool is inspired by the work of Zhu et al. (Zhu et al., 2011) about sketching tubular shapes and simulating liquids. Their method has several limitations with respect to sketching vascular structures and

diseases. Furthermore, it is not optimized for tablet devices, which could be integrated well in the process of patient education. The physicians need an effective tool to sketch patient-specific cases and to illustrate the different treatment options for educating the patient, see Figure 1. Hence, we make the following contributions:

- We present appropriate methods to sketch vessels, vascular diseases, and treatment options, which are usable by medical doctors and understandable by patients.
- We introduce a plausible representation of blood flow in real time.

## 2 MEDICAL BACKGROUND

This work focuses on the vascular diseases of arteries, which are vessels transporting blood from the heart to the peripheral capillary of the body. A common reason of those diseases is arteriosclerosis, which leads to a hardening of vessels by deposition of blood fat, thrombi, and lime (Kutikhin et al., 2013). This deposition affects vessels in two problematic ways:

1. A weakening of the vessel wall.
2. A narrowing of the vessel (*stenosis*) up to a complete occlusion.

The weakening can lead to a dilation of the vessels that may result in an aneurysm. A possible outcome

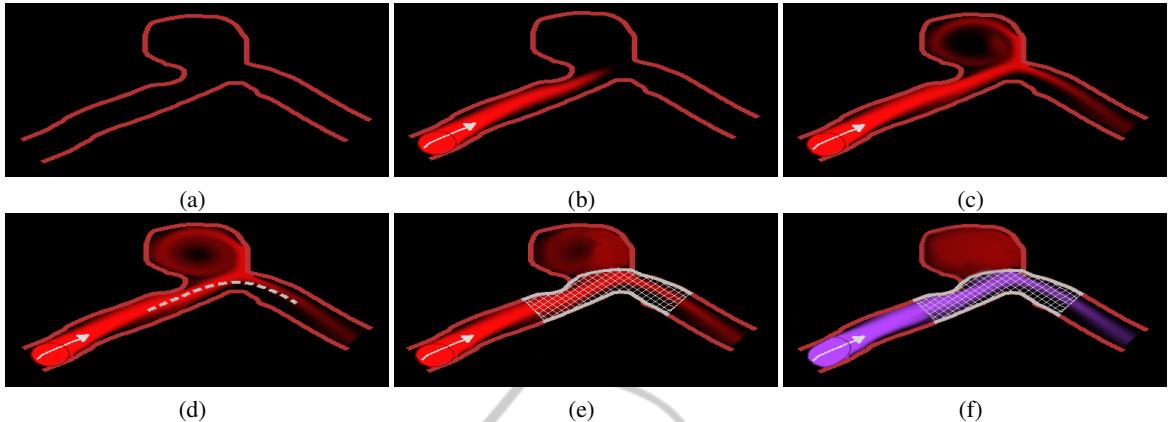


Figure 1: Illustration of blood flow before and after a stenting treatment. First, the physician sketches a vessel with an aneurysm (a). Afterwards, he manipulates and visualizes the underlying fluid simulation to illustrate the blood flow (b-c). The consequences resulting from the stent treatment (d-e) are illustrated with another color (f).

might be a clot formation inside the aneurysm or a rupture. A *stenosis* can lead to an undersupply of involved structures or can cause a clot formation. Another dangerous effect is an increased risk of rupture of an aneurysm in cerebral areas (Neugebauer et al., 2010) with a mortality rate of 40-60% (Bederson et al., 1994). In Figure 2 an aneurysm and a stenosis are illustrated. For the medical treatment of such vascular diseases, the physician can use several methods, see Wong et al. (Wong et al., 2011) for an overview. The choice of the treatment depends on parameters such as location, anatomical access or pathology. In particular, this work focuses on *clipping* as an example of an extravascular treatment method as well as *coiling* and *stenting* as examples of intravascular methods.

The **clipping** procedure, e.g., for treating a cerebral aneurysm, starts with a craniotomy to disclose the aneurysm. Afterwards, a titanium clip is placed across the aneurysm neck to stop the blood from entering into the aneurysm (Gasteiger, 2014). **Coiling** is performed by entering an artery from the *inside*. The coil, a small titanium wire, is used to fill the aneurysm and to induce a thrombus formation (Teitelbaum et al., 1994). The **stenting** method can be used to treat both stenosis and aneurysms through an intravascular approach. Similar to the coiling procedure, a catheter is moved to the affected position from the inside. Afterwards, the stent is expanded and forces the vessel to expand to treat the stenosis. For treating aneurysms, stents can help to support the involved vessel during, e.g., a coiling procedure.

Further descriptions of different forms of vascular diseases, their treatments, and possibilities for visualization and exploration are mentioned by (Gasteiger, 2014). A historical overview of different treatment

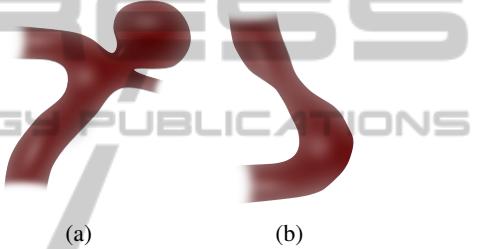


Figure 2: Illustrations of a saccular aneurysm (a), which is the most common type, and a stenosis (b) caused by a narrowed vessel.

options can be found in the work of (Wong et al., 2011).

### 3 RELATED WORK

This work involves two main topics: computational hemodynamics and Sketch-based Interfaces (SBIs), a form of user interface (UI), which deals with sketching. The following parts name related work for the *latter topics*.

#### 3.1 Computational Hemodynamics

To simulate the behavior of blood, it is necessary to imitate a *non-Newtonian fluid* (a fluid with varying viscosity). Furthermore, in terms of fluid dynamics, blood is *compressible* and *inhomogeneous*. Such a simulation is not only complicated, but also expensive regarding the calculation time (Bridson, 2008). We consider blood as an incompressible, homogeneous *Newtonian fluid* to achieve a real time simulation. Examples for methods to calculate non-Newtonian fluids can be found in (Ciarlet et al., 2011) and (Ferziger and

Perić, 2002). To describe the state of a fluid, there are two possibilities: the Lagrangian (a particle-based) and the Eulerian (a grid-based) description. We use the Eulerian description because the grid-based character is well suited to be calculated with fragment shaders on the GPU. Examples for the Lagrangian description can be found in (Müller et al., 2004; Qin et al., 2010). Both deal with particle-based simulation of blood flow in vessels to support surgeons in virtual surgery scenarios.

### 3.2 Sketch-Based Interfaces

The usefulness of SBIs to communicate ideas and concepts is described among others in (Jorge and Samavati, 2011). The communication of complex issues is possible without the necessity to draw precisely and accurately. This advantage, however, is a disadvantage for the computer, which tries to interpret the sketch. As a consequence, several works deal with the interpretation of sketches, see (Jorge and Samavati, 2011) for an overview and examples. The foundations of were laid by Ivan Sutherland (Sutherland, 1963) with the program *Sketchpad*. Sketch-based interfaces can be seen as a part of post-WIMP (windows, icons, menus, and pointers) UIs because the sketching is performed with direct input, e.g., a pen or touch (Preim and Dachselt, 1998). So the pointer component of the WIMP paradigm is no longer necessary (van Dam, 1997). (Xu et al., 2002) and (Naya et al., 2007) showed the advantage of reality-based interfaces (such as SBIs) by comparing WIMP-based interaction with reality-based interaction and presented two findings: first, the users preferred the sketch-based approach and second they were more efficient with it. SBIs contain three processing steps: *resampling* of the input data, *beautification*, and *recognition*. This paper only deals with the resampling of the input data. Examples for the second step (beautification) can be found in (Igarashi et al., 1997). There, line segments were analyzed according to geometric constraints such as perpendicularity and parallelism. After that, the program recommends different options of how to interpret the lines. The user chooses an option by clicking on it. The processing step *recognition* describes a procedure where the sketch is compared with an internal representation of symbols. The similarity is expressed with a parameter. If this parameter exceeds a value, the sketch is interpreted as the compared symbol (Jorge and Samavati, 2011). A simple way to integrate recognition in an application is described with the *1<sup>c</sup> Recognizer* (Herold and Stahovich, 2012).

An important use case of SBIs is geometric mod-

eling, i.e., the creation of 3D structures. An example of an SBI for modeling (SBIM) medical structures is (Pihuit et al., 2010). There, methods are described to sketch and model branching vessels. To maintain the sketch-based look of 3D models, it is possible to visualize them with non-photorealistic rendering. A comparison of different rendering styles in the medical domain can be found in (Lawonn et al., 2014b). Contrary to SBIM, the following work addresses the creation of 2D vessels.

## 4 METHODS

Our sketch-based interface consists of different concepts to create vessels with interior blood flow based on intuitive sketch-based gestures. In the following, we describe the methods and the implementation.

### 4.1 Blood Flow Simulation

We use the Eulerian fluid simulation, which is described in (Stam, 1999; Bridson, 2008; Harris, 2004). For the fluid simulation, we use the Navier-Stokes equations for *incompressible* and *homogenous* fluid, which are based on Newton's second law of fluid motion:

$$\frac{\partial u}{\partial t} = -(u \cdot \nabla) u - \frac{1}{\rho} \nabla p + \nu \nabla^2 u + F, \quad (1)$$

and

$$\nabla \cdot u = 0. \quad (2)$$

Equation 1 (*momentum equation*) describes the behavior of the velocity vector field  $u$  under influences like advection, diffusion, pressure, and external forces, which will be described in more detail in the following. Equation 2 (*continuity equation*) ensures the incompressibility by defining  $u$  as a divergence-free vector field.

To achieve a real time fluid simulation, the grid size is an important factor. While a small grid size accelerates the calculation time, details like whirls may be lost. Another problem are obstacles. To enable the blood flow to react on these, it is necessary to model them in the simulation grid. This is achieved by marking grid cells as occupied. So the grid resolution also affects the possible level of detail of the obstacles. To allow a high spatial resolution of grid cells, the simulation is performed on the GPU. For the GPU-based calculation, we used the fragment shader similar to (Harris, 2004).

To solve the equations for the differential operators, the finite difference method is used. Furthermore, Equation 1 needs to be split up in single terms, which are calculated separately.

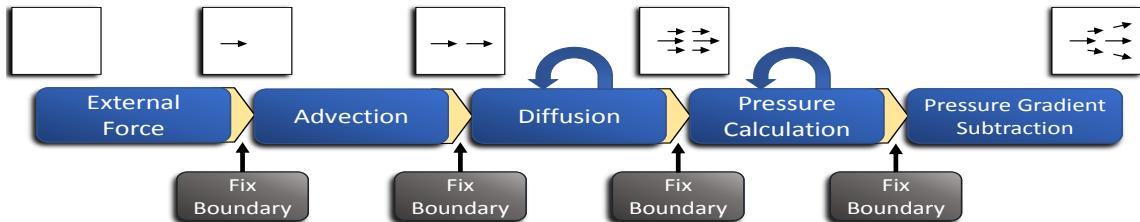


Figure 3: Overview of the calculation pipeline for the fluid simulation including the influence to the underlying vector field. Each step is realized with a separate fragment shader program. The steps provided with self-referencing arrows show the steps which are calculated with an adjustable amount of iterations. Here, a trade-off arises between accuracy (high amount of iterations) and calculation time (low amount of iterations).

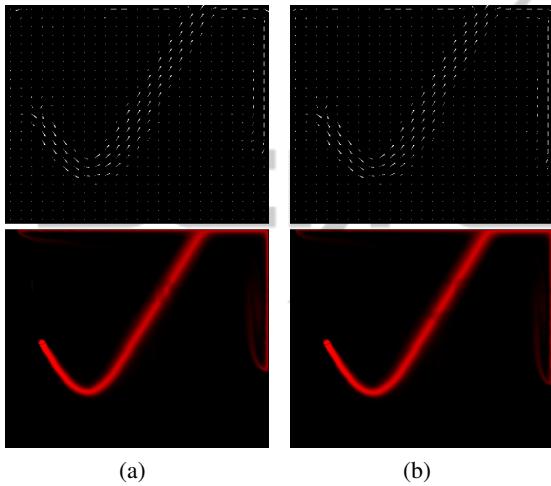


Figure 4: Comparison of the Euler (a) and Runge-Kutta 4 (b) integration methods with a step size of 0.3. Both methods are visualized with a modified arrow plot visualization (top) and a scalar field visualization (bottom), which looks similar to a streakline visualization through the continuous placement of ink during the simulation. Since the differences between both methods are small, the faster Euler method is used.

An overview of the calculation steps is illustrated in Figure 3. In the following, we describe the mathematical terms and their effects in the fluid simulation.

The first term  $-(u \cdot \nabla)u$  describes the self-advection of the fluid, which is the process of moving the velocity itself through the fluid. Here, the self-advection is realized with semi-Lagrangian advection (Stam, 1999). Mostly, fluid simulations use the Runge-Kutta method (Butcher, 1996) for the integration, which is less error-prone than the simpler and faster Euler method. Interestingly, as illustrated in Figure 4, the differences between both methods are small, due to the small step size used in the application. Therefore, we used the Euler method to decrease the calculation time.

The pressure, a force that gradually spreads from regions with high to regions with low pressure, is described with the second term  $\frac{1}{\rho} \nabla p$ . The factor  $\rho$  is

a constant to describe the density. Furthermore, this term also ensures the incompressibility of the velocity vector field, and thus simultaneously ensures the Equation 2. To achieve this, the term is calculated at the end. For a description of the derivation, see (Bridson, 2008). To calculate this term, it is necessary to solve a Poisson equation. This is accomplished by the Jacobi approach because it can be mapped directly to GPU facilities. For a discussion of different approaches, see (Krüger and Westermann, 2003).

The third term  $v \nabla^2 u$  expresses the physical process of diffusion, i.e., the property of mixing materials without external forces. Here,  $v$  is a constant that describes the viscosity. The calculation of the diffusion also requires the solution of a Poisson equation. A disadvantage of diffusion is the resulting smoothing effect on the applied vector field, which causes a loss of details. Therefore, the choice whether diffusion is applied is left to the user.

The last term  $F$  describes external forces, which allows the user to influence the simulation dynamically. Normally, such forces are steady, so the influence of the force to fluid is constant over time. This approach would not reproduce the pulsating character caused by the contractions of the heart. This pulsation can be imitated by applying a factor to the force, which changes over time. Therefore, we approximate the function measured by an electrocardiogram with the following formula:

$$f(x) = -\frac{3}{4}e^{-\frac{1}{2}(-\frac{1}{2}+x)^2} + 1, 12e^{-\frac{x^2}{2}} - \frac{1}{4}e^{-\frac{1}{2}(1+x)^2} + 1. \quad (3)$$

This equation was determined by combining three Gaussian functions with varying heights and widths. In Figure 5, the difference between a constant and a pulsating force is illustrated.

Finally, boundary conditions are used to simulate the behavior of the fluid at the vessel wall and the boundary of the draw area. These conditions are necessary for the *velocity* vector field and for the scalar field, describing the *pressure*. For the velocity vector field, a Dirichlet boundary condition is

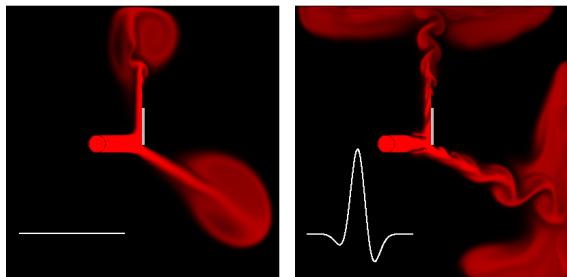


Figure 5: In (a) a constant force is applied to the vector field. In (b) a heartbeat-like function is applied as a factor, which mimics a more realistic behavior. The corresponding functions are plotted at the left bottom.

used, which states that the velocity drops to zero at boundaries. For the scalar field, a Neumann condition is used, which states that the derivatives are zero. To calculate the derivative, the normal of the boundary is necessary. The normals of the top, right, bottom, and left image boundaries are defined as  $(0, -1)$ ,  $(-1, 0)$ ,  $(0, 1)$ , and  $(1, 0)$ , respectively. For determining the normals of arbitrary boundaries, we use the neighborhood of the obstacle. That means that for each grid cell, which is an obstacle, eight neighbors are analyzed. Depending on the state of these neighbors (obstacle or no obstacle) the normal is approximated to one of eight possible directions. This approach is described in more detail in (Wu et al., 2004).

## 4.2 Blood Flow Visualization

To illustrate the unsteady vector field that represents the blood flow, we implemented two visualization concepts: (1) a direct and (2) a sparse flow visualization, see Figure 4. The direct visualization is a modified line plot on which fans are drawn on an adjustable grid. Fans are used because they facilitate a fast realization of the flow direction for the user.

Especially for patients, a scientific visualization method for vector fields may be inappropriate. Thus, an additional method is used. It aims to be easily understandable to visualize the behavior of blood in areas such as aneurysms and stenoses in a descriptive way. The used scalar field visualization is inspired by the idea to place *colored ink* in the vector field (also known as *dye injection*). By diffusion and advection, this ink is transported through the vector field. The amount of ink is color-coded with a black-to-hue scale with different colors. This allows using multiple colors, e.g., to show how blood mixes in an aneurysm before and after a treatment, see Figure 1.

The colors are taken from the *Lab color space*, which allows choosing colors that are roughly per-

ceptually linearized regarding hue and brightness. To determine different colors, the approach of (Glaßer et al., 2014) is used. If the ink is placed continuously over time, the visualization technique is similar to streaklines. In contrast to streaklines, the placed ink is not connected, but if the amount of placed ink is high enough, there is the impression of connectivity. A difficult task by sparse visualization techniques, namely to identify suitable seed point positions, is left to the user, i.e., the physician or the patient.

## 4.3 Sketching

The obtained data from the input device inherits noise, which is caused by the conversion from the analog signal to a digital signal (quantization) as well as the imprecise input from the user. Especially the quantization, also depending on the sampling rate, reduces input information during fast input movements from the user. To remove the resulting noise and obtain equidistant input information, the received data of the input device is resampled and smoothed. These steps are commonly applied after the user finishes drawing, which causes abrupt changes in the sketch. To avoid these sudden changes, we use on-the-fly methods that are applied during sketching. This presents challenges regarding real time capability. Ideally, the user did not even realize these steps. First, the resampling should reduce the obtained sample points. To achieve this, we use a simple strategy: we ignore all points that are too close to the last accepted point. We use the Euclidean distance to measure the distance of two points, see Figure 6.

A disadvantage of this approach is that it is prone to draw zigzag lines. This can be neglected, because vessels, vascular diseases, stents, and coils usually do not have those shapes. To smooth the accepted sample points, a local Gaussian filter similar to (Taubin, 1995) is used. More precisely, the 1-neighborhood of the accepted points is used to adjust the points with a Gaussian distribution. The filter is only applied to the *pre-last* point, which was accepted to prevent the line segments from shrinking, see Figure 6.

## 5 APPLICATION

The application should be as flexible as possible regarding the used direct input device. More precisely, it should be possible to control the application with touch and pen-based input. This implies the following limitations:

- Special functions from pen-based input devices like pressure sensitivity or additional buttons are

not supported.

- Multitouch input is not supported.

Through these limitations, the used concept is theoretically usable for a mouse with a left button only. Furthermore, the application is designed according to major usability criteria, such as "suitability for the task", or "self-descriptiveness". The evaluation of the application revealed possibilities for improvements, which were partially implemented. Improvements based on the quantitative part, the qualitative part, or the interview, are marked and discussed. The application can be downloaded under [wwwisg.cs.uni-magdeburg.de/~patrick/application/SketchingVesselS.zip](http://wwwisg.cs.uni-magdeburg.de/~patrick/application/SketchingVesselS.zip).

## 5.1 Sketch Vessels and Vascular Diseases

Mainly, drawing a vessel requires two lines representing the border of the vessel. Unfortunately, drawing each line separately leads to strong variations in the resulting vessel structures. Therefore, we use a *create tool* that creates both lines simultaneously by using the sketched path as the *center line* and drawing the vessel wall around it. The general advantage of this process is that uniform vessels can be drawn easier and faster. We fix the width of the vessel to simplify the application. In contrast to (Zhu et al., 2011), where it is possible to draw vessels under and over already existing ones through a 2,5D sketching canvas, this work limits the sketching area to a *2D canvas*. This decision is reasoned by considering what could happen if the user sketches over an already created vessel. Besides the possibility to draw the vessel over or under the existing ones, it is possible to *merge* the new vessel with the old ones. This offers the possibility to create more complex structures like branching vessels and aneurysms without changing the drawing

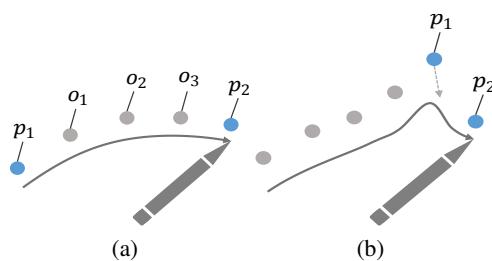


Figure 6: (a) The new point  $p_2$  has exceeded a specific distance to  $p_1$  and thus, is sampled. The points  $o_1$  -  $o_4$  are too close and thereby omitted. (b) shows the smoothing approach. In the moment  $p_2$  is sampled, the pre-last point  $p_1$  is smoothed. By sampling the pre-last point, a shrinking of the line is prevented.

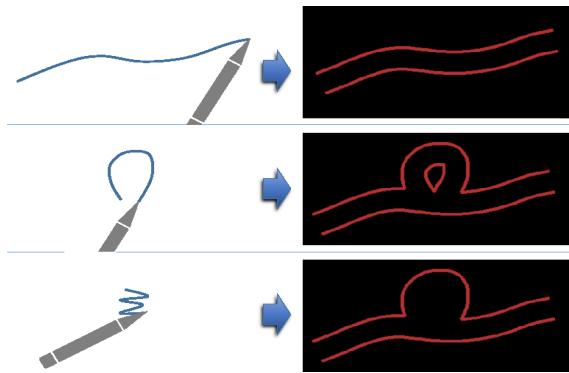


Figure 7: As illustrated, the merging behavior can be used to draw a vessel containing an aneurysm by simply sketching on top of the previous drawing.

mode. The merge behavior is illustrated in Figure 7 and is realized with an already implemented polyline-based functionality in the used framework.

Additionally to the possibility to draw aneurysms, the application offers a possibility to draw stenoses. A *cut tool* is used to allow the user to create irregular non-symmetrical stenoses in a consistent sketch-based way. To prevent problems during cutting, e.g., ambiguity (see (Heckel et al., 2013)), the user does not only see his sketched contour, which is used for the cutting process. The start and end point of the sketched contour are connected, and thus span a cutting area to support the user. This area is subtracted from the existing vessels (see Figure 8).

This tool does not only allow the creation of stenoses; in combination with the *create tool*, the user has a generic sketching tool, which allows the creation of any 2D structure under the usage of only two different modes. To support the medical expert during the sketching process, it is possible to load images in the background. The physician can use this function to load a slice of patient-specific MRI or CT data, which contains, e.g., the vessel structures of the patient. In addition frequently used vessel structures, such as the Circle of Willis, can be loaded (see Figure 9).

During the evaluation, some participants suggest a possibility to load vessel structures. This could

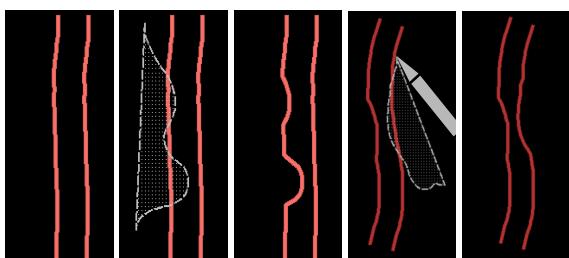


Figure 8: The *cut tool* is used to remove structures from the already sketched vessel to create a stenosis.

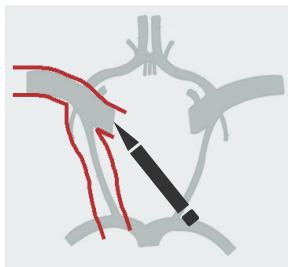


Figure 9: The medical doctor has loaded a background image of the Circle of Willis which supports the sketching process.

help because it allows the physician to not only load standardized structures, but also patient-specific data. The functionality is implemented by loading a monochrome black-and-white image. Every black pixel is interpreted as a vessel and every white pixel as free space, where blood is able to flow. This approach has, however, a disadvantage. It is only possible to show bloodflow in the loaded vessel structure, but not to use the other tools, e.g., cutting or treating the vessel. This disadvantage can be avoided by implementing an object-based save and load mechanism instead of an image-based, which could be added in the future.

## 5.2 Manipulate and Visualize Blood Flow

As described in Section 4.1, the flow can be manipulated with a force term, which is represented with a 2D vector field. To allow the user to influence this field in a flexible and easy way, a *direction tool* is used, which also works in a sketch-based way. After the *direction tool* is selected, the user can sketch lines, that are represented by arrows directing in the draw direction. This arrow represents the influenced force on the vector field.

To transfer the sketched arrow to the vector field, it would be obvious to manipulate only the vectors directly under the sketched arrow. This behavior is not desirable, because it only allows to manipulate the flow in small areas. Instead, the force is applied in a *region* around the sketched arrow. The size of this region is adjustable and is initially set to the width of a vessel. To achieve a natural effect, the force is slightly decreased at the border of the region by applying a Gaussian distribution, resulting in a strong force at the center and a weak force at the border.

To visualize the flow, the user can use a *dye tool* to place ink (blood) in the fluid region. A circle of ink is placed by just tipping on the canvas or drawing over an area. The ink is interpreted as a source of in-

finite amount of ink, which is added in every render frame. The width of the ink area is adjustable, but set to the vessel width to allow the user to fill a vessel with ink in a fast way. Under the assumption that the physician wants to show the mixing behavior of fluid by repetitive using of the *dye tool*, a new color is used after each usage of the *dye tool* with the approach explained in Section 4.2.

## 5.3 Treating Options

To show the patient how to treat aneurysms and stenoses, we implemented the following treatment methods:

- coiling,
- clipping,
- and stenting.

First, we implemented the *coiling tool* such that the user should fill out the aneurysm. This coil was illustrated with a line, which occurred during the drawing process. Generating the coil with this approach is not applicable, since it takes too much effort and is too time-consuming, which was stated by the participants in our evaluation. Therefore, we implemented another approach to improve the coil placement.

First, an area is sketched, e.g., on the vessel wall of an aneurysm. After the user raises the pen, every sample point analyzes its neighborhood with a specific adjustable distance. This is performed by sending eight rays in a circular manner, starting at every sample point. Significantly less rays would result in an inaccurate vessel wall detection and more rays would not improve the result. We test every ray for intersecting the vessel wall. If more than one ray collides with the wall, the ray with the shortest distance is chosen. After that, the corresponding sample point is placed on the intersection point of the ray. If no collision occurs, the point keeps the current position. The underlying grid cells are then treated as obstacles and thus, the blood flow changes dynamically corresponding to the drawn coil. Figure 10 illustrates this algorithm.

The *clipping* method was inspired by the line drawing method used in *Sketchpad* (Sutherland, 1963). The point where the user starts drawing represents the first point of the clip. As long as the user draws with the pen, the current pen position represents the end point of the clip. These two points are connected with a dashed line to give the user a preview of the clipping result. After the user finishes drawing and raises the pen, the clip is placed and the blood flow simulation is affected by it.

The stent placement algorithm is inspired by the real treatment. Here, a balloon catheter is inflated to dilate the stent in the vessel. We use this inflating process for providing a stent placement algorithm. The user draws a line in the center of the vessel with the *stenting tool*, which represents the position of the balloon catheter. After the user finishes the sketching process, the application calculates the dilation of the stent. The difficulty to achieve this behavior is to dilate the stent in the relevant vessel, but not to enter the aneurysm. Since the structure is not differentiated semantically (i.e., in vessels and aneurysms), the described behavior must be achieved in another way. To accomplish this, the surrounding region of the sketched stent is analyzed. The algorithm is described in more detail in Figure 11. This method is more robust according to various input lines. The best results regarding visual aspects are achieved by drawing a line, which is as close as possible to the center of the vessel. Inaccurate lines may lead to penetration of the stent inside the aneurysm. A disadvantage of the described method is that it depends on four control points obtained through the start and the end point. If

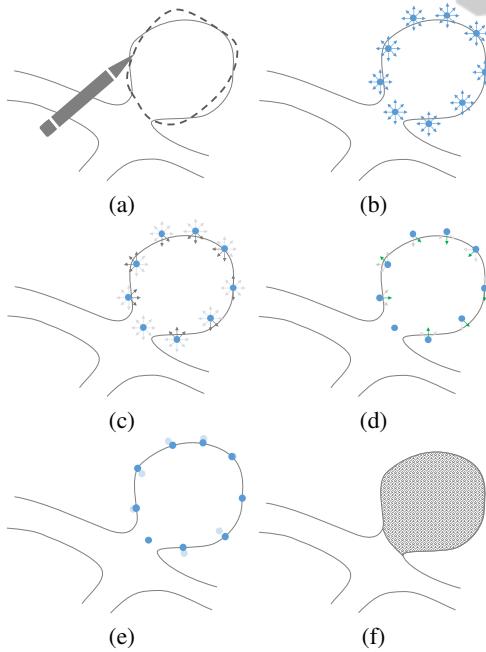


Figure 10: (a) - (f) shows the algorithm to calculate the coil area. In (a) the physician sketches imprecise over the vessel wall of the aneurysm. (b) shows the captured sample points as well as the rays, which are sent in a circular manner from each sample point. In (c) all rays that collide with the vessel wall are highlighted, from which those with the shortest distance are chosen (d). The sample points are moved to the intersection point or remain on their position if no intersection occurred (e). The adjusted sample points build the new area for the coil, which lies precisely on the vessel wall.

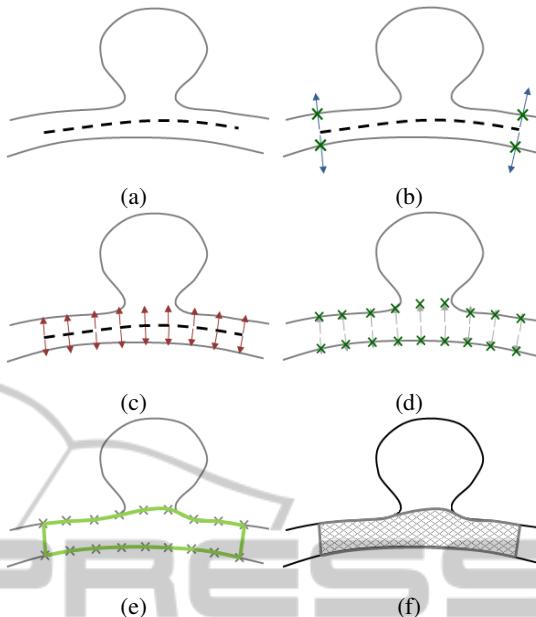


Figure 11: (a) - (f) illustrate the algorithm to calculate the stent dilation. The user input is illustrated as a sketched line in (a). After the user finishes the stent, the normals of the start and end point are determined (b). The normals have the length of the vessel width. All four normals are tested if they intersect the vessel wall. If not, the stent is discarded. Otherwise, the distance  $l$  is determined, which is the longest length of the normal start point to its intersection point. Now, for every point of the sketched line, the normals with length  $l$  are determined (c). All of these normals are tested for intersections with the vessel wall. If they intersect, they are shortened to the intersection point, otherwise they keep the length  $l$  (d). The achieved end points of the normals are connected (e) and form the border of the stent, visualized in (f).

not all control points could be determined, e.g., if the vessel is too wide, not all normals are calculated and so the stent will not be placed. Similar to the coiling and clipping method, the grid cells under the stent are marked as occupied and thus, influence the fluid simulation.

#### 5.4 Edit, Delete and Copy Objects

The possibility to edit and delete objects such as stents and coils, is an important aspect regarding the controllability of the application. This is confirmed by the evaluation (see Section 6.1) in which the participants stated that a functionality to delete or edit objects would be useful. To realize this, it is necessary to implement a method to select already created objects. Since a requirement of the application is to control it with a pen without any further buttons, a suitable method is necessary. Besides the possibility of gestures or a double tap of the pen, the implemented ap-

proach is to press and hold the pen on the relevant object. Afterwards, the corresponding object is deleted. The possibility to edit objects, which is currently not implemented, can be realized with the same approach.

To provide the physician with an easy and fast possibility to illustrate more treatment options on the same vessel structures, a *copy tool* is added to the application. It allows to select an area, copy its content and paste it at another place. With this possibility, the patient can see different behaviors of the bloodflow, depending on the treatment option. This can help understanding why a specific treatment is chosen or why another is not possible.

## 5.5 User Interface

The structure of the user interface results from two considerations:

- The grid used for the fluid simulation is quadratic and
- a direct input device is used.

The first consideration implies that the canvas in which the user sketches is also quadratic. Through the horizontal format of current displays this means that there is potential free space on the sides of the canvas. This space is used for the menus. In detail, the space is divided in a left and a right region and used for a semantic differentiation of the functionality. On the left side, menus and buttons are placed, which are used to create and manipulate vessels, to sketch treatment options, and to visualize and control blood flow. On the right side, there are temporary menus to control simulation parameters such as the number of iterations for solving or to activate the diffusion process. The second consideration (using a direct input device) leads to the following requirements with respect to interaction. To achieve an easy interaction, all buttons have a bigger size and there are no sub-menus. Furthermore, classical WIMP input elements like spin boxes were omitted, since exact inputs would be hard with, e.g., a pen. In Figure 12, a screenshot of the user interface is shown.

## 6 EVALUATION

The evaluation is divided into two parts: in the first part, we used *qualitative* and *quantitative* methods for assessing the usability of the prototype. In the second part, we interviewed a physician to compare the procedure of typical patient education (with hand drawn sketches) with the prototype and investigate advantages and disadvantages.

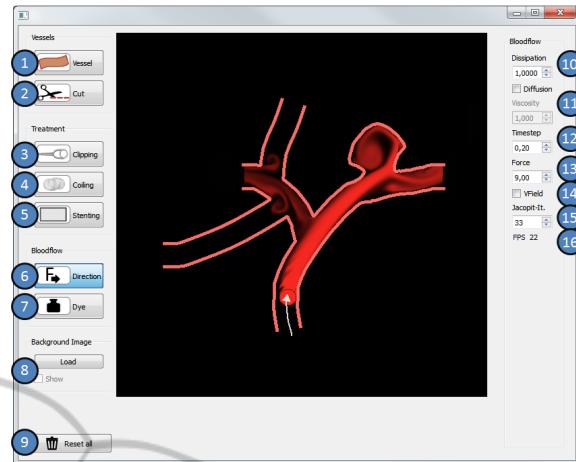


Figure 12: Screenshot of the prototype. Buttons (1-2) are used to create and edit vessels, (3-4) are used to manipulate and visualize blood flow, (5-7) are used to sketch treatment options, (8) is used to select the *copy tool*, (9) is used to load a background image to assist the sketching or load vessel structures out of a monochrome image and (10) is used to reset the whole canvas. On the right side the functionality to influence the fluid simulation in different ways is shown.

## 6.1 Usability

The **qualitative** part of the study was performed with the *think aloud method*, where the participants comment their activities while solving a problem. It is helpful to give insights into the misunderstandings of the participants as well as to understand how the participants predict the behavior of the prototype. This method gives hints for further refinements. The **quantitative** part of the evaluation was conducted with a questionnaire. The questions are inspired by a questionnaire for ergonomic principles from ISO 9241-110 (suitability for learning, suitability for the task, self-descriptiveness, conformity with user expectations, controllability, and error tolerance). The single questions were categorized in the different principles and could be rated with a 7-point Likert scale.

The evaluation started with a short introduction of the prototype on a SMARTBoard, a 70" screen which allows pen interaction. Here, all features were demonstrated and we asked to think-aloud and noted the spoken comments of the participants. Initially, the participants were asked to perform several tasks that were handed out in written form. For example, they should draw a vessel with a trifurcation; then, they should use the *cut tool* to change the vessel to a bifurcation. Furthermore, they were asked to draw an aneurysm and treat it with the *clipping*, *coiling*, and *stenting tool*. Finally, they should create and visualize the blood flow in a specific direction. Afterwards, the participants were asked to fill out the questionnaire.

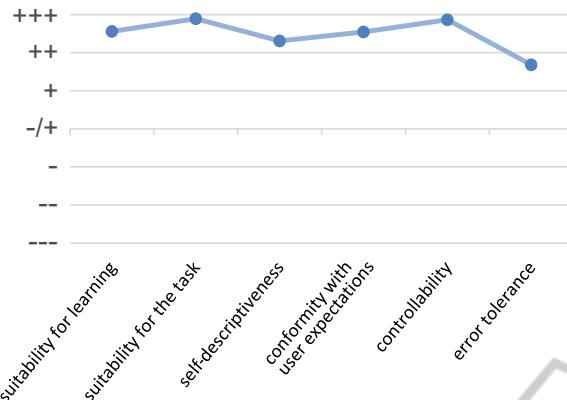


Figure 13: This figure shows the average results of the questionnaire for each category of the usability principles.

The evaluation was conducted with 14 researchers with medical visualization knowledge. We had three female and eleven male participants, aged from 25 to 44 with an average of 31 years. The participants are experienced computer users with an experience of 20 years on average (minimum: 14, maximum: 30). Ten participants were experienced with pen interaction. It took about 15 to 20 minutes to fill out the questionnaire. The statements of the participants are denoted with [P#].

**Think-Aloud Method:** Mostly, the participants were satisfied with the prototype: "it is possible to create vessels and aneurysms according to my own ideas" [P13]. Regarding the different tools, the majority of the participants had no problems using them. For example, it was stated that the *cut tool* "is more precise than conventional eraser tools" [P6]. Unfortunately, the *cut tool* leads to misunderstandings during the first use. This was caused by different expectations, e.g., some participants thought that it can be used as a conventional eraser. After some practice, the functionality was understood and the participants rated this tool as positive. Another example of a positively rated tool is the *stenting tool*. Especially the automatic expanding behavior was noted as useful. In summary, the participants were satisfied with the prototype. Furthermore, they were also pleased with the alignment of the tools, as it supports the typical workflow (generate vessel, treatment, and visualize blood flow). In general, they stated that this prototype allows a fast and easy generation of vessels with simulated blood flow.

**Questionnaire:** The results of the questionnaire were determined by calculating the average of every answer. For this, we assigned the symbols of the 7-Point Likert scale (- -- to + ++) to the values from -3 to 3. Figure 13 depicts the average for every category. The category *error tolerance* has the lowest rates. Here,

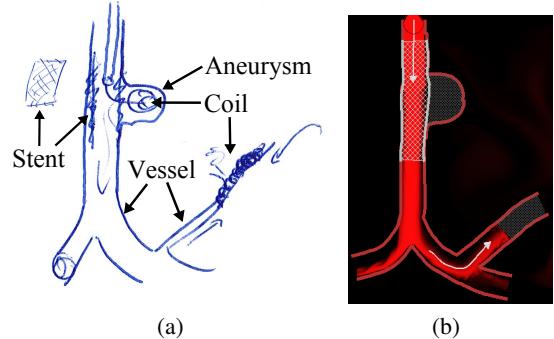


Figure 14: On the left side is the hand sketch of a physician with additional labels. On the right side are the same structures made with the application, which the physician assessed clearer and more understandable.

the users were asked if the effort to correct an inadvertently drawn error is significantly high. Mostly, the participants stated that it should be possible to delete drawn objects and the effort is high to manually correct them by redrawing. Thus, we added the possibility to delete drawn objects like stents and coils individually, see Section 5.4. However, with an average of 1.68, this category was rated well. In summary, the ratings of all categories were positive and the participants were satisfied with the functional range. For refinement, we used the results of the evaluation and improved the prototype according to the suggestions of the participants.

## 6.2 Structured Interview

We performed a structured interview of about 20 minutes with a physician, which has 12 years of experience in the field of vascular diseases and patient education. First, we asked the physician to explain typical patient education with an example and outline the typical education procedure. During typical patient education, the patient receives textual and image-based templates with respect to his disease. Additionally, the physician explains the intervention verbally and supports this with hand-drawn sketches (see Figure 14). These can help to illustrate specific medical cases and answer individual questions from the patient. The description of the physician revealed the following disadvantages of the *hand-drawn* sketches:

- To correct errors, the physician draws over the existing sketch, which results in a cluttered image.
- The blood flow and the implications of a treatment are usually not drawn, because it is hard to illustrate these and could lead to a confusing image.
- The physician only uses one color to draw all structures, which makes it difficult to distinguish between different elements.

- Some patients have problems to understand the sketch, because they find it difficult to imagine diseases and treatment options.

After that, we explained the prototype and asked to perform the patient education again using our application. Thereby, we let the physician compare his hand-drawn images with sketches from the prototype which showed the following:

- By using different colors, symmetrical, consistent and uniform structures (e.g., for the vessels or stents), the result is more clear, descriptive and plastic than the hand sketching, and thereby, the perception is supported.
- Due to the illustration of blood flow, the vessel structures, the effects of different intervention methods and possible complications are more understandable and imaginable.

Furthermore, the physician stated additional advantages of the prototype, e.g., due to the clearer resulting images, other persons, who were not involved in the sketching process, are able to understand the sketch. This is difficult with hand sketches, because of their cluttering nature. The physician rated the tool as easy to learn and use, which matches the results of our usability evaluation.

## 7 CONCLUSIONS AND FUTURE WORK

This work provided a concept and a prototypical implementation to sketch vessels, vascular diseases, and treatment methods. It is possible to interactively create and manipulate blood flow, which adapts itself in real time to change the sketch.

The quality and usability of the prototype was assessed with *qualitative* and *quantitative* methods. The positive feedback of the evaluation indicates that the proposed concept and prototype are suitable for sketching vascular structures and treatment options. The *structured interview* with the physician revealed further benefits compared to hand-drawn sketches and confirmed the idea to improve patient education and intelligibility by integrating animated blood flow.

A limitation of this work is the representation of the vessels and blood flow in 2D. The representation of vessels and fluids in 3D is a challenge with respect to visualization and interpretation (Lawonn et al., 2014a). An advantage of the 2D representation is its easier intelligibility as well as a faster calculation of details, which is important to achieve a real time simulation.

For the future, we want to investigate how the described concept and prototype can be used for collaboration between physicians. This collaboration can happen at different places where each medical doctor interacts with an instance of the application. The different instances could be connected and mirror the input from one place to another. Additionally, the communication could be supported with voice chat and webcams. Another way of collaboration is possible with only one application, where several physicians are sketching at the same time in front of a big screen and discuss a medical case.

Further analysis could investigate the possibility to lift the whole concept to the third dimension. This leads to challenges and questions regarding a real time 3D fluid simulation and visualization as well as creating the vessels. For 3D interaction, there are input and output devices which are more suited than pen or touch interaction. By lifting the application in the third dimension, the behavior of blood in vessels could be simulated more accurately, and thus, make the application more relevant for scenarios like operation planning and training.

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