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Is there a Tornado in Alex's Blood Flow?
A Case Study for Narrative Medical Visualization

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Abstract

Narrative visualization advantageously combines storytelling with new media formats and techniques, like interactivity, to create improved learning experiences. In medicine, it has the potential to improve patient understanding of diagnostic procedures and treatment options, promote confidence, reduce anxiety, and support informed decision-making. However, limited scientific research has been conducted regarding the use of narrative visualization in medicine. To explore the value of narrative visualization in this domain, we introduce a data-driven story to inform a broad audience about the usage of measured blood flow data to diagnose and treat cardiovascular diseases. The focus of the story is on blood flow vortices in the aorta, with which imaging technique they are examined, and why they can be dangerous. In an interdisciplinary team, we define the main contents of the story and the resulting design questions. We sketch the iterative design process and implement the story based on two genres. In a between-subject study, we evaluate the suitability and understandability of the story and the influence of different navigation concepts on user experience. Finally, we discuss reusable concepts for further narrative medical visualization projects.

CCS Concepts

• ***Human-centered computing*** → ***Empirical studies in interaction design; Visualization design and evaluation methods;***

1. Introduction

Storytelling to share knowledge is a powerful technique for communicating complex relationships and insights to a broad audience. Modern media enables the incorporation of data-driven storytelling with interactive graphics, which is described as *narrative visualization* [SH10]. Narrative visualization is already used in several scientific areas, such as astronomy [BAC*19], climate research [BKVR*20], and cell biology [HSFT18] to communicate scientific insights to broad audiences in a comprehensible manner.

Conveying information to broad audiences is crucial in medicine. Patients and relatives want to be educated on conditions and their understanding of procedures is vital for informed consent. Consequently, media outlets, such as newspapers, TV channels and websites of health organizations provide information on preventable risk factors, diagnostic approaches and treatment options for a wide range of diseases. Static or animated content is contributed by medical illustrators to such media outlets. It describes normal and pathological processes or treatments in the form of a story to encourage engagement and empathy. While the use of narrative visualization is common in such media outlets, research on the use and value of medical narrative visualization is unexplored.

Recently, Meuschke et al. [MGS*21] introduced concepts for designing data-driven medical stories about diseases. Although they created a storyboard about a vascular disease, cerebral aneurysms, it remained open how associated blood flow data and derived characteristics could best be communicated to a broad audience. There has also been no research on which genre and corresponding navigation strategy are best suited for interactive medical stories.

In this paper, we discuss the design of data-driven stories about blood flow on the example of measured data in the aorta. In collaboration with the Heart Center Leipzig, we focus on the most common congenital heart defect: the bicuspid aortic valve (BAV) [War00]. In BAV, the morphology of the aortic valve is altered. This can cause vortices in the aorta and lead to dangerous secondary diseases. A key storytelling goal is to provide an understanding of blood flow vortices as important indicators of the severity of a BAV and to educate on potential dangers and possible treatments. We create two versions of our storyboard comparing the *Slideshow* [SH10] and *Scrollytelling* genre [SZ18], where navigation works via clicking and scrolling, respectively. Our aim is to understand the influence of different interaction methods with the story and related design decisions. In summary, we make the following contributions:

- A storyboard to communicate blood flow data that is enriched with interactive visualizations of medical data.
- Adaptive implementation of the storyboard with regard to two genre types: *Slideshow* and *Scrollytelling*.
- A comparative user study to evaluate the suitability of these genres, regarding the navigation and interaction.

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2. Related Work

This section discusses related work regarding visualization considerations for broad audiences, narrative structure and strategies, and narrative visualization for medicine.

Visualization for broad audiences. A broad audience includes people without domain-specific background knowledge who differ in terms of age and culture [BKVR*20]. Broad audiences require design and narrative choices to convey a clear, engaging, and understandable message [GMF*21]. Cognitive studies show that broad audiences find data more exciting and memorable when it is embedded in a narrative [MLF*11], or when an appropriate degree of interactions is provided [BKVR*20]. Therefore, complex scientific relationships need to be summarized to essential findings that are conveyed through comprehensible visualizations [BKVR*20].

Narrative structure. A visual data story consists of four essential components [Dyk19]: the **content**, **narrative characters**, such as real or fictitious people leading through the story, a **conflict** describing the problems that the characters must solve, and a **structure** that controls the flow of the scenes and the interaction with the story. The story content is composed of visualizations of the most important facts to be communicated with data [LRIC15]. These visualizations are complemented by story elements such as labels, arrows, motion, audio and textual explanations to emphasize the facts [KM13, HD11]. A story can be structured into a series of acts which are encompassed by a story arc defining the progression of the story. Typically, three to seven acts are used, framed by the Aristotle's tension arc [Mad08]: (1) an introduction, (2) a climax, and (3) a denouement. Each of these acts is divided into scenes, where transitions (e.g., animation, interaction) are needed between the scenes [SH10]. In addition, a story path describes the order of scenes (e.g., linear or elastic, i.e., several paths to choose from). Yang et al. [YXL*21] examined the use of the classical narrative structure of Aristotle's tension arc to narrative visualizations.

Narrative visualization strategies. Several genres exist to define how the user is guided through the story. They are used to arrange the story pieces and scenes. Segel and Heer [SH10] discriminate seven genres: *Magazine Style, Annotated Chart, Partitioned Poster, Flow Chart, Comic Strip, Slideshow* and *Film/ Video/ Animation*. Those genres are not mutually exclusive and can be combined. One of the two implementations of our storyboard is based on the *Slideshow*. The frames of a *Slideshow*, the slides, can be static or contain animations. Research on slideshow-like stories includes the work by Hullman et al. [HDR*13] on the choice of sequencing in narrative visualization. They describe how slides are ordered and which types of transitions may connect them. Besides, Seyser and Zeiller [SZ18] introduced the *Scrollytelling* genre, which is a long-form article rich in images and multimedia that is common in online journalism. In contrast to *Slideshows*, where the user navigates through the story in a discrete manner by clicking, here, the user navigates continuously through the story by scrolling.

Narrative visualizations can be *author*- or *reader-driven* [SH10]. An author-driven story, often intended for live presentations, comprises static visualizations with a linear ordering and no interactivity. In contrast, reader-driven stories have no strict ordering and exhibit extensive interactivity. Thus, it is debatable whether reader-driven stories belong to narrative visualization, since the author cannot ensure that a message is conveyed if the user has considerable freedom in what to look at. Interactive visualizations lie between these two orientations, combining and balancing aspects of both. A structured narrative is supported by limited interactive elements. Segel and Heer [SH10] defined an interactive *Slideshow* as having an encompassing author-driven format with reader-driven interaction in each slide. In addition, various hybrid orientations have emerged such as the *Martini Glass* structure, which begins the story author-driven and opens up later to reader-driven free exploration. However, the author-driven beginning ensures that the user looks at specific story content before free exploration begins.

In designing individual scenes and visualizations, Hullman and Diakopoulos [HD11] proposed a framework to classify elements of narrative visualizations. They differentiate multiple editorial layers, starting from the data and continuing up to user interactions. Furthermore, they describe rhetoric techniques, including visual metaphors, individualization, and filtering. Also, a story can be told in different ways, such as compelling or emotional, depending on the audience and the intent of the author. Bach et al. [BSB*18] introduced eighteen narrative design patterns for telling data-driven stories. Edmonds and Bednarz [EB21] most recently built on these works to derive a categorical classification of narrative visualizations in terms of the strength and persistence of traditional narrative structures, e.g., Aristotle's tension arc.

Narrative visualization for medicine. While narrative visualization has become popular and accessible for information visualization [TRB*18, GP01], there is little research on combining medical visualization with narratives [MGS*21]. Höhne [HÖ97] presented a first approach for interactive exploration of volume data in the context of a museum exhibition. Wohlfart and Hauser [WH07] introduced an authoring tool for generating interactive medical stories based on volume data. However, medical data includes many other types of data, such as non-spatial data, 3D models, and flow data that are of interest to a broad audience. Sallam et al. [SSLM*22] studied the effect of data-driven medical videos on users' attitudes toward making their lifestyles healthier. Accordingly, such videos should convey concrete solutions to medical problems as well as adapt the level of threat in the messages to the users' perception of risk. Recently, Meuschke et al. [MGS*21] discussed narrative visualization in medicine. They proposed a template for the narrative visualization of disease data and explored this template in three case studies. Our work builds on the concepts proposed by Meuschke et al., using the same tension arc as well as certain parts of the proposed template such as the presentation of a patient and introduction of treatment methods. In addition, we propose approaches to communicate blood flow information in an understandable way. Furthermore, we investigate the role of different genres for navigation in a comparative user study.

3. Medical Background

The number of deaths due to cardiovascular diseases (CVDs) is steadily increasing [TAA*22]. Assessing individual patient risk and the severity of their disease is important to provide timely and appropriate treatment. To determine the severity of CVDs, such as valve defects, physicians investigate the vessel morphology and internal blood flow [FSS*12, GMH*12].

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Patient-specific blood flow information can be measured non-invasively with four-dimensional phase-contrast magnetic resonance imaging (4D PC-MRI) [MFK*12]. For every voxel, 4D PC-MRI provides the flow direction and strength in three directions (x, y, and z) at different time steps during the cardiac cycle. The data sets used in this work were acquired with 3T Siemens Magnetom Verio MR scanner with a maximum expected velocity (V_{ENC}) of 1.5 m/s per dimension. The spatio-temporal resolution is $1.77 \times 1.77 \times 3.5$ mm^3 \ 50 ms with a 132×192 grid for each of the 19 to 35 slices and 18 to 33 time steps.

CVDs lead to deformation of the vessel geometry, which can cause quantitative and qualitative changes in blood flow [KYM*93]. One pathology that 4D PC-MRI helps to detect and characterize are aortic aneurysms, which are local dilations of the vessel wall [HMW*07]. Aneurysms may rupture and cause serious damage or death to the patient. This risk can be reduced by preventive treatment of the patient. However, the treatment carries also considerable risks. Therefore, an accurate risk assessment for the individual patient is critical.

While a number of pathological conditions can cause an aneurysm, our case study focuses on BAV. Where a healthy aortic valve has three leaflets, in BAV, two of the leaflets are fused. The fused leaflets alter the behavior of the aortic valve, often leading to vortices of blood flow in the ascending aorta. These vortices, in turn, change the forces acting on the vessel wall, which can lead to aneurysm formation [DSGTT*19]. Due to the higher risk of impaired heart function and aortic wall problems, patients with BAV must be monitored regularly [BGB*05].

4. Generating Alex's Blood Flow Story

Our goal was to develop a data-driven story that educates a broad audience about aortic blood flow vortices, with which imaging technique flow information are measured, and why vortices can be dangerous. The story should also convey the research experience of the clinical partner with respect to the development of sequences for measuring aortic blood flow efficiently [EHK*19], for validating the measurements [EDK*20], and for establishing age-dependent normal values related to parameters derived from blood flow measurements [EKA*22]. A major focus was to extract as much information as possible from real patient data in order to minimize the manual effort required to create illustrations and thus provide a way for non-artists, such as medical professionals, to inform a broad audience about medical topics. Moreover, we want to assess different interaction techniques to navigate through the story w.r.t. the user experience. We chose a common heart disease, BAV, whose severity and treatment success are related to the occurrence of vortices. For this purpose, we worked closely with a radiologist at the Heart Center Leipzig with the vision of providing the final story as an interactive exhibit in the form of a touch display at the Heart Center. Thus, we designed an asynchronous story without a narrator [LRIC15].

In the following, we first discuss our process for measuring and preparing the blood flow data, see Sect. 4.1. We then summarize how the major story ingredients were implemented with a list of content priorities about which information is to be provided, see Sect. 4.2. Afterwards, we explain major design decisions including how designs of individual scenes were adapted during the iterative design process, see Sect. 4.3. This results in the final blood flow story, see Sect. 4.4, which was implemented based on two genres: *Slideshow* and *Scrollytelling*, see Sect. 4.5.

4.1. Data Extraction and Preparation

We used the software *Bloodline* [KGGP19] to generate visualizations of the aorta and internal blood flow from 4D PC-MRI data before and after BAV treatment. Doing so requires several pre-processing steps. Artifacts, in particular movements due to pulsatile flow character, are corrected automatically. Subsequently, the thoracic aorta is segmented using the Graph Cut algorithm. From the segmentation mask, a polygonal vessel surface is extracted using Marching Cubes, which is post-processed by smoothing and reduction. Based on the 4D PC-MRI data, the complete flow is automatically calculated within the aorta. Qualitative flow patterns, i.e., vortices are extracted to evaluate the heart function [KGP*13].

4.2. Story Ingredients

A visual data story consists of four basic ingredients: content, characters, conflict, and structure (recall Sect. 2). The **content** of our story includes the presentation and effect of blood flow vortices in BAV, where the **main character** is a patient, who we call Alex. We introduce this character with a name to engage and generate empathy between our fictional story character and the audience. Based on discussions with our collaborating radiologist, the main points of content that the story should convey are:

- **Blood flow measurements:** The story should introduce 4D PC-MRI data. Moreover, the difference between CT and MRI should be explained on-demand, since many people are not aware of this difference and may be fearful of getting an MRI.
- **Blood flow vortices:** The story should convey what vortices in blood flow are and why they can be dangerous. Here it should become clear that both heart-healthy people and patients with heart pathologies have vortices in the aorta, but they differ in size and strength. It should be conveyed that vortices can lead to diseases such as aneurysms, which can be dangerous.
- **BAV:** The story is intended to illustrate the construction of a healthy aortic valve and how it is altered in the case of BAV. Optionally, detailed information about a BAV, such as symptoms or effects on the closing behavior of the valve, should be provided.
- **BAV treatment:** A novel promising treatment method in case of BAV is the replacement of the diseased valve by an artificial aortic valve. The user will be taught the essential steps of this minimally-invasive treatment.
- **Blood flow changes:** To illustrate the positive effects of the treatment, it will be shown how the strength of vortices changes as a result of valve replacement.
- **Further information:** Additional information that might be of interest includes pre-processing steps related to 4D PC-MRI data, information about departments of the Heart Center Leipzig, as well as information about the story authors.

Although we are aware that prior studies recommend incorporating *voice over* [MvWHS15] into story, we did not follow this sug-

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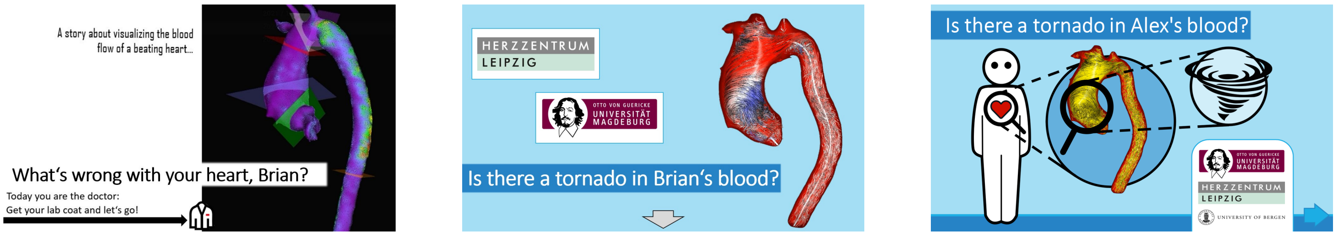


(a) (b) (c)

Figure 1: *Design progression of the opening where (a) shows the first draft, (b) a midway stage, where new design decisions were implemented and (c) the final design with Alex added to the story, due to their mention in the title.*

gestion, since we intend to display the story primarily as an informational resource in a clinical waiting area. The inclusion of voice could be perceived as disruptive by others in the waiting room.

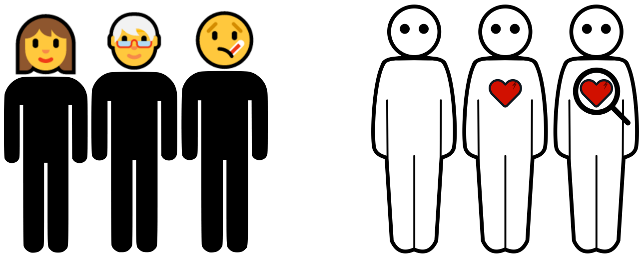
The **conflict** is described by our patient, Alex, who has dangerous vortices in the aorta and whose goal is to become healthy. For the **structure**, we used the *Freytag's Pyramid* an extension of the Aristotle's three-act model, which divides the story into five acts: exposition, rising action, climax, falling action, and denouement [Mad08]. To motivate people, we place a hook in the form of an *interesting starting point* at the beginning.

Each act comprises multiple scenes. Within the scenes, we aim to combine 2D/3D representations with textual descriptions arranged in the *partitioned poster style* [SH10] to explain blood flow aspects in a way that is brief and easier to remember than, e.g., long form text descriptions. Following the *structuring by revealing data* pattern [BSB*18], elements within a scene were to be revealed sequentially to avoid visual overload for the user. We use two interactive genres, *Slideshow* and *Scrollytelling* to compare their relative strengths for user navigation and interaction. *Slideshows* are common and familiar across a relatively wide range of age groups for presenting information. Because of widely available powerful standard tools, *Slideshows* are easy to create. In contrast, *Scrollytelling* is an attractive method of presenting findings, especially for younger people. Compared to clicking, scrolling is potentially more engaging and well suited for a wide range of current devices (tablets, cell phones, larger touch displays) [ZSRB14].

4.3. Iterative Story Design

The design of the story was an interdisciplinary process involving computer scientists, medical experts, an interaction designer, and a medical illustrator. Based on the content brief from the radiologist, the following key design questions arose:

Q 1. How can we design an interesting opening?
Q 2. How many characters should be in the story and what is their design (realistic people vs. illustrative drawings)?
Q 3. How do we explain 4D PC-MRI?
Q 4. How can we convey the phenomenon of blood flow vortices?
Q 5. Which blood flow visualization techniques do we use?
Q 6. Where in the story do we need illustrations, i.e., custom or hand-crafted illustrations, instead of data-driven models?
Q 7. How do we compare pre- and post-treated flow visualizations?



(a) (b)

Figure 2: *Originally three characters, Emma, Alex, and Brian, were planned for the story (a). Later, the story focused on examining the blood flow of one patient, Alex, with a heart defect (b).*

Q 8. How do we deal with different levels of user knowledge?
Q 9. What interactions do we provide?
Q 10. How can we phrase textual descriptions so that their intended message comes across to our target audience?
Q 11. How can we encourage trust in the content shown?

In an iterative process that included weekly meetings between all team members, we first created a storyboard using the freely-available software Miro. We extensively discussed how to address the design questions, which led to new inspirations and adaptions of the story design. In the following paragraphs, we summarize the solutions to the design questions and how parts of the story were adapted over several iterations in the design process.

Q1: Story opening. The design of the first scene was revised several times, see Fig. 1, to generate a eye-catching and interesting opening. Therefore, we chose a static image of an aorta reconstructed from the imaging data, showing a prominent vortex in the blood flow (Fig. 1(b)). It contains bold colors and presents the user with a familiar metaphor (see Q4) that is not explained at this time, but introduces an element of uncertainty and provokes interest with the question, "Is there a tornado in Brian's blood?" Later, the design (Fig. 1(c)) was edited to reduce the size of the logos and focus more on the story content within this scene. Since the imaginary patient "Alex" is mentioned, they are shown so that the user can connect with them. Moreover, the depiction of the vessel had to be adapted to keep it consistent with other parts of the story (see Q5).

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Q2: Character definition. In the initial design stage, three characters were introduced: Emma, Alex and Brian. This was done to be able to convey different states of vortices within the blood of healthy young (Emma) and elderly (Alex) people, and to compare these to an unhealthy case (Brian) (Fig. 2(a)). During a later stage, the focus of the story shifted to examining the blood flow of one patient with a heart defect and how it can be treated. This was done in part to restrict the length and complexity of the story. Furthermore, we discussed whether to use real photographs of characters similar to Meuschke et al. [MGS*21] or illustrated patient characters. Deciding that using a realistic looking character would compromise relatability, we used a very simple pictogram, see Fig. 2. The more detailed and refined a character becomes, the more features can distinguish the potential user from it. Skin color and gender, in particular, can therefore make relatability difficult. Moreover, we decided to introduce a gender-neutral patient character since all genders are affected by BAVs. Therefore, Brian was renamed "Alex" which is a gender neutral name. The face of the patient was also changed from a sick to a neutral expression, because the disease does not necessarily make you feel uncomfortable.

The *pictogram* representing Alex is kept identical in its main features, however, there are three variations, see Fig. 2(b). First there is a basic outline. A second depiction shows them having a break in their heart, representing their heart defect. And lastly Alex is shown with their broken heart to be examined with a magnifying glass. Each model is used depending on what type of content a scene depicts in relation to them.

Q3: 4D PC-MRI. Our original intention was to explain how 4D PC-MRI works. However, later discussions revealed that this might be too complex for a non-expert. In addition, the focus shifted to include a patient experience to explore audience engagement and empathy with the story. Therefore, instead of demonstrating the theory behind 4D PC-MRI, important aspects of the examination were added. *Icons* are used to make important information about the examination more memorable. Additionally, the collaborating radiologist commented that MRI is often confused with CT, because of similarities between the apparatus. Therefore, additional clarification regarding this misconception was inserted on an optional scene deviating from the main story path.

Q4: Vortex explanation. To explain vortices, we asked the radiologist how he explains them to patients. He used the *metaphor* of vortices in the blood flow as tornadoes. Tornadoes are a type of vortex that can be considered common knowledge and show similar visual flow characteristics as blood flow vortices. Tornadoes are also dangerous, just as vortices in the blood flow can be dangerous. In contrast, there are harmless swirls in nature, e.g., swirl in a glass with liquid while stirring, that correspond to physiological vortices in the aortic arc in heart-healthy people.

Q5: Data-driven blood flow visualizations. The visualizations created using *Bloodline* [KGGP19] show the blood flow extracted from 4D PC-MRI data. We decided to exclude the anatomical background because the gray-scale MRI data is difficult to interpret. Instead, an initial scene shows the blood flow visualizations in an abstracted illustration of the surrounding anatomy. The surrounding anatomy is not shown in the subsequent visualizations as the

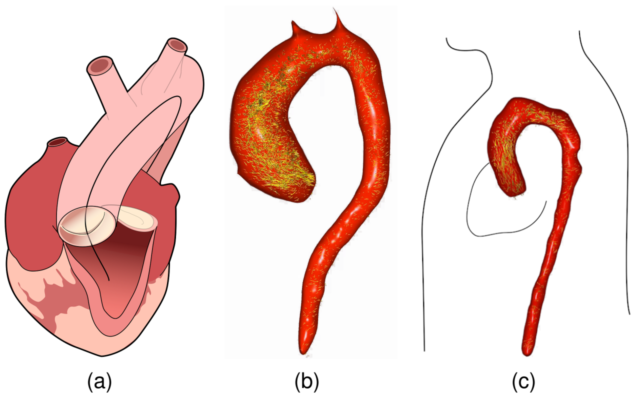

Figure 3: *Illustrations (a,c) are designed to convey a clear message in a simple style, with views chosen such that the aorta is recognizable as the same aorta in the 3D data-driven visualization (b).*

additional width and height would require a substantial downsizing of the visualizations. We initially visualized blood flow using *animated pathlines* with encoding the blood flow direction by a red-to-blue color scale. However, a pilot study with five non-experts showed that they not interpreted this color coding correctly. The colors were often confused with different types of blood cells. Therefore, we finally colored the pathlines uniformly. However, to support depth perception and thus the perception of vortices, we enabled *ambient occlusion* on the pathlines [KGGP17], see Fig. 4.

Q6: Illustrations. One hurdle in creating the prototype was creating a coherent graphic style for the entire story due to the limited availability of medical illustrations and the different media, i.e., 3D models, illustrations, and photographs. While the focus was to use data-driven blood flow animations, some explanations could not be realized without the use of medical illustrations. A medical illustrator created the necessary visualizations in a uniform style, which abstracts away irrelevant anatomical details to be understandable for a broad audience. The illustrations use a color palette that helps focus attention on elements of interest, i.e., high contrast and saturated colors are reserved for the surgical implements in the valve replacement procedure. Custom illustrations created for the story include key steps of the valve replacement procedure (Fig. 3(a)), a background illustration for the 3D aortic model (Fig. 3(c)), and a comparison of a healthy aortic valve versus a BAV (Fig. 5 (Climax)). We used contour-based renderings and Toon-shaded illustrations [LVPI18] of the heart valve and the aorta. Although their individual styles differ, i.e., all illustrations are 2D vector renderings while flow visualizations are 3D surface renderings (Fig. 3), when possible, we chose views such that the illustrated aorta was recognizable as the same structure as the 3D aorta. This ensures conceptual continuity across all media assets, which should help the user to remain immersed and engaged in the story.

Q7: Blood flow changes. After an explanation of healthy and abnormal vortices in blood flow, the user is asked to examine three examples of different strengths of vortices as seen in Fig. 4. These examples show that the intensity of blood vortices has a spectrum. The first example (Fig. 4(a)) belongs to a healthy aorta with a phys-

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Figure 4: *Three strengths of blood flow vortices are depicted, going from (a) small regular vortices, to (c) an extreme vortex that compromises the vessel wall stability, forming a bulge.*

iological vortex in the aortic arc. The second example (Fig. 4(b)) displays an unhealthy blood flow with strong vortices due to a BAV. The third example (Fig. 4(c)) depicts an aorta with an extreme vortex that has weakened the vessel wall, creating an aneurysm.

One of our goals was to enable users to compare the changes in the presence and strength of vortices, specifically before and after treatment. We used a side-by-side layout with identical vessel size and positioning at the end of the story to communicate treatment success. A close-up was added to limit differences in view elements to only the flow in the ascending aorta, where the dominant vortices occur in BAV before treatment and are reduced afterwards.

Q8: Background knowledge. To address the varying prior knowledge of users, we chose an *elastic story path*. The user can optionally obtain additional information at various points but is always led back to the main path. These optional scenes contain either background information that we expect not all users to be aware of, or information that we expect will be of interest only to specific users.

Q9: Interactions. First drafts were more exploration-based, allowing users to interact with the flow visualizations and compare self-selected pairs of data sets. However in discussions with clinical and design experts, we decided to reduce the amount of interaction. We aimed at high user engagement and content memorability, while enabling users with limited prior knowledge to follow the story without difficulties. Interactions kept include allowing users to decide whether they want to engage with the scenes to view additional information. Additionally, we attempt to keep the users attentive and interested by inviting them in Q7 to classify the strength of Alex's vortex. This adds an element of *gamification*.

Q10: Textual descriptions. One important step was writing the informational text for the scenes. We drew inspiration from popular public-facing health websites and related articles on aneurysms to find the appropriate balance of information without overwhelming the user with medical jargon. Here are some examples:

- How Tornadoes Work
- What is an Aneurysm?
- Bicuspid aortic valve

Medical terms were reduced as much as possible, so the average user does not get confused or discouraged. Where the use of these terms could not be avoided, they were explained by referring to known concepts and describing their function. For example, 4D PC-MRI is described as a technology to see if a heart condition worsens. *Bold fonts* and *colors* highlight the most important information.

Q11: Trustworthy content. For effective science communication, it is crucial to build trust, where expertise, honesty and good intentions are key [SEG10]. This is especially important in public-facing communication, where the intended audience may lack the expertise to question the information being presented. In the age of fake news, showing expertise establishes that we are a reliable source. We show our expertise through the inclusion of collaborating academic institutional logos, which demonstrate the necessary medical competence that is crucial for telling this story accurately. Also, the scientists and physicians involved in the story creation are shown at the end. Design quality, which includes aesthetics and clarity, play an additional role in establishing the trustworthiness of a visualization [LBS*18]. We employ a consistent, clean visual style and narrative for a high-quality design in order to increase trust.

4.4. Final Story

We created a story following the *Martini Glass* structure [SH10], which starts with a less interactive author-driven part, followed by more interactive elements and optional story paths, leading to a reader-driven ending. Therefore, the story starts with a motivating opening, followed by a traditional five-act tension arc, see Fig. 5. The aim was to introduce information gradually and only when it is inevitable to create facts to proceed. The reader-driven ending includes references, more 4D PC-MRI scans, a link to the website of the Heart Center Leipzig and information about the authors to address the content requirement of providing further information (recall Sect. 4.2) and enabling the user to continue exploring the topic on their own. In the following, the author-driven main story and its five acts will be explained.

First Act: Exposition. The story extends the *catching title question* described in Q1 by introducing the main character of the story, Alex, as described in Q2. The user learns that Alex has a heart defect and needs regular checkups. Thus 4D PC-MRI, Alex's upcoming examination, is introduced, following the content decisions described in Q3. This includes the optional path providing information on the difference between CT and MRI.

Second Act: Rising Action. Within this act, the tension should be built as to why vortices can be life-threatening. Leaving Alex's story aside for a moment, the tornado metaphor motivated in Q4 is introduced. Utilising the metaphor, vortices in the blood flow are presented, using the visualizations described in Q5. Vortices, the "tornadoes in the blood", are illustrated first in a harmless case of a healthy person and then showing a vortex causing serious health risks. Expanding on the potential harm caused by strong vortices, the danger of a rupturing aneurysm is outlined.

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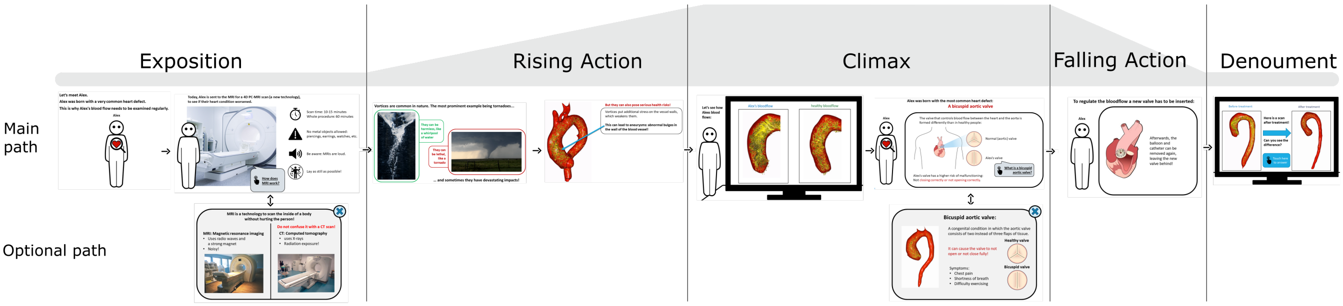

Figure 5: *Overview of the final story design, where screenshots are identical between the Slideshow and the Scrollytelling implementation. For each of the five acts, key scenes and optional story pathes are shown here as examples.*

Third Act: Climax. The climax of the story is the investigation if Alex has blood vortices. Back at Alex's blood flow, the user can compare the 3D representation of Alex's blood flow with those of a healthy person and a patient with an aortic aneurysm. In all three cases, the strengths of the vortices varies, following the design described in Q7. In order to explain why Alex has blood vortices, their underlying heart condition BAV is explained. The user can optionally get more detailed information about the defect and a list of symptoms. Then, Alex's blood flow is explained by pointing to the vortex in their blood and explaining that surgery is needed.

Fourth Act: Falling Action. Alex's recovery is shown by explaining the surgical procedure (Q6). This was added due to part of the target audience being family members and patients visiting the Heart Center Leipzig and getting examined or even getting the procedure themselves.

Fifth Act: Denoument. Finally, the flow visualizations before and after surgery are compared and the users are asked if they can spot a difference between both. After surgery, the amount of vortex flow is greatly reduced, concluding Alex's story and leading over to the reader-driven ending.

4.5. Genre Implementation

Two implementation media were chosen to create the story that we described above, based on two genres with different interaction principles. We wanted to investigate which navigation method is easier for a broad audience to use, whether the resulting transitions are perceived as pleasant, and whether the level of interaction is appropriate. The implemented prototypes can be found here for *Sildeshow* and for *Scrollytelling*.

4.5.1. Slideshow-Based Navigation

The first implementation was based on a traditional *Slideshow* where users interact by clicking to navigate through the slides. To create the *Sildeshow* we chose *Microsoft PowerPoint*. Each slide has a *title* to provide orientation and it contains a *navigation bar*. In addition, a small *progress bar* shows where the user is within the story, which can motivate the user to finish the story if the attention span is low. To access additional information, the user can click on *underlined text comments*. The transition to additional content slides is a *dialogue transition*: The text poses a question, which the user can click on to proceed to the answer on the next slide.

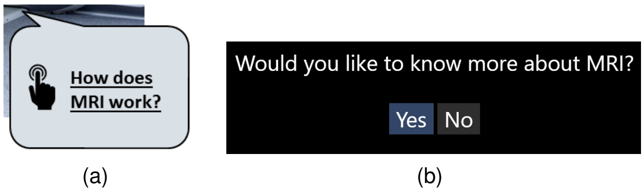

Figure 6: *Interaction design for deviating from the main path for the (a) Slideshow and (b) Scrollytelling version of the story.*

To visualize the blood flow, the animations created with *Bloodline* are converted to GIFs and inserted into the stories. This was done to prevent users from forgetting to activate a video. The GIFs start playing as soon as the slide is introduced, drawing the user's attention to the blood flow.

Using PowerPoint brought some limitations to the story design. The interaction functionality of PowerPoint mainly consists of different slide transitions. Limited functionality is provided for interaction within slides. PowerPoint's feature to move to the next slide when clicking on any non-interactive slide elements, makes accidental switching between slides very likely. Another challenge was overcoming PowerPoint's slide show design when using other transition techniques such as more gradual transitions. This was often just possible through clever slide design. For gradual transitions, slides were kept nearly identical with minimal changes, which, combined with morphing or inconspicuous slide transitions, creates a visual effect of continuous change within a slide.

4.5.2. Scrollytelling-Based Navigation

We chose to use the *ScrollyVis Editor* [MBS22] to create a story using *Scrollytelling*. The main interaction method here is scrolling, but some click interactions are added to choose story path branches. While the content of the two stories is identical, one main difference in interacting with the story is how the user moves outside the main story path. In *Scrollytelling*, the users must actively decide in a new scene whether they want to go an optional path or not (Fig. 6(b)). In contrast, branching in the *Slideshow* is integrated into

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a scene as an highlighted interactive comment (Fig. 6(a)). The visual design of the ScrollyVis implementation follows a dark theme, see Fig. 6(b). This was a design standard predefined by the editor and was not part of an active design decision. A main feature within the ScrollyVis Editor is the navigation tree on the side to follow the progress of the story. In addition, the implementation of the text structure differs between ScrollyVis and PowerPoint. In PowerPoint, slide text can be displayed sequentially in an animation, so that multiple text items can be displayed at the same time. ScrollyVis handles building up text through scrolling instead, so that a maximum of one text item is always displayed.

5. Evaluation

We conducted a user study to assess the suitability of the two genres, *Slideshow* and *Scrollytelling*, regarding the navigation and interaction. This section describes the study design and results.

5.1. Study Design and Participants

The study was performed with 24 participants of all genders and an age range from 8 to 57 (median age: 26). Most participants had a high level of education (high school diploma, a bachelor's or master's degree). We collected participants once at the *Long Night of Science*, a university event directed at the general public. Additional participants were recruited through invitations and announcements to university students, where we ensured that they were not taking medical courses.

Both implementations were presented on two Wortmann Terra All-in-One-PC 2211 with an Intel Core i3 with 3.4 GHz, 8 GB RAM, an Intel HD Graphics 2500. Each PC had a 21.5"touchscreen with Full HD (1920×1080) resolution.

We performed a between-subject design study, where each participant interacted with one of the two story implementations. Afterwards, they were asked to fill out a qualitative questionnaire. This questionnaire contained questions regarding participant demographics, user experience based on the navigation types (clicking and scrolling), as well as knowledge checks to verify if the intended messages were received. We observed participants navigating the story and documented what problems emerged using the *think aloud* method [FKG93]. The questionnaires are included as supplemental material.

5.2. Results

We first present the results of the questionnaires, then summarize participant feedback for the *Slideshow* and *Scrollytelling* versions as well as general feedback for both story versions.

Usability and knowledge questionnaire results. Fig. 7 shows the results from the usability questions. For both stories, the participants agreed that they could follow the central theme of the story (Fig. 7, statement 2). They rather disagreed when asked if they would prefer to interact less with the story (Fig. 7, statement 5).

Participants generally agreed that it was easy to interact with the story through scrolling or clicking, with higher agreement when clicking (Fig. 7, statement 1). The interaction with the story was

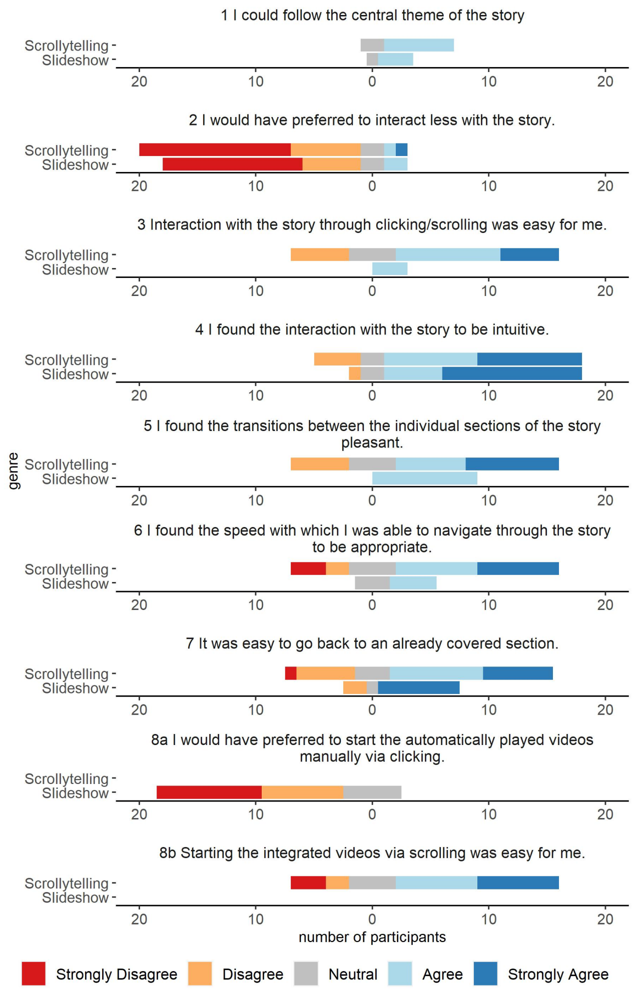

Figure 7: *Participant responses to usability questions for the* Slideshow *and* Scrollytelling *versions of the story.*

rated to be intuitive, again with slightly higher agreement in the *Slideshow* (Fig. 7, statement 6). The transitions between the individual sections were also rated slightly more pleasant in the *Slideshow*, but still with high ratings for both (Fig. 7, statement 3). The navigation speed was perceived as appropriate, with higher agreement in the *Slideshow* (Fig. 7, statement 4). It was additionally perceived as slightly easier to go back to an already covered section in the *Slideshow*, however, due to an implementation error, for the *Slideshow* the answers of the first 10 participants could not be included in this question (Fig. 7, statement 7). In the *Slideshow* the videos started automatically on each slide. Participants generally would not have preferred to start them manually via clicking (Fig. 7, statement 8a). The videos included in the *Scrollytelling* format started automatically when scrolling. Participants mostly were neutral or agreed that this was easy for them (Fig. 7, statement 8b).

The answers to the knowledge questions are summarized in Fig. 8. Users were able to remember the content shown well with

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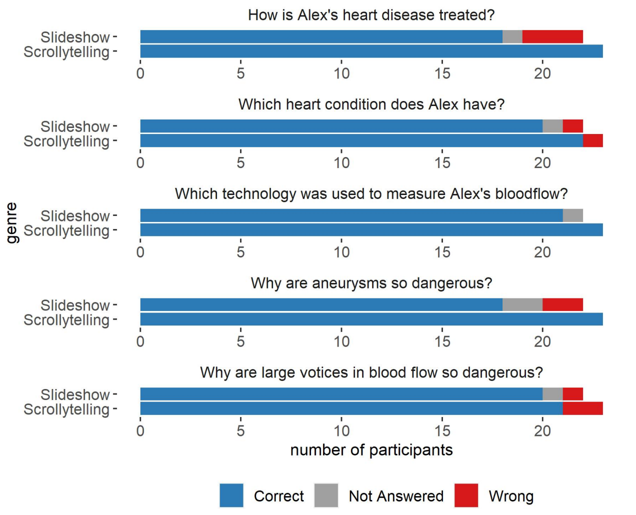

Figure 8: *Correct, incorrect and unanswered knowledge questions.*

no clear differences between *Slideshow* and *Scrollytelling*. The errors made were generally caused by a few people who left multiple questions unanswered, or who answered them wrongly.

General feedback. Participants reacted positively to both stories overall. Multiple participants stated they would like to look at such stories in their free time. Feedback included that the story was fun and that it reminded them of digital information boards in museums, where the length of the story was remarked as good. Some participants wanted more detailed information, e.g., how specific steps of the therapy worked or a more detailed explanation of terms like 4D PC-MRI. The visualizations of the blood flow in the aorta were hard to recognize for some participants and differences before and after treatment were recognized by vessel shape rather than blood flow. In both stories, smaller technical problems were discovered, such as confusing zooming behavior.

Slideshow-specific feedback. Comments about the *Slideshow* mainly concerned navigation. The transitions between slides were stated as good-looking by one participant and too slow by another. It was highlighted that navigation from left to right was aligned with the reading direction. However, participants wanted an option to switch directly between non-adjacent slides, such as an interactive menu bar to switch to specific key scenes. Slide numbers were commented by one participant as not necessary and were confusing when they jumped through the additional slides. Interaction with the story was sometimes perceived as sluggish. The arrows used for navigation could be included better in the overall slide design. One participant was confused by arrows not used for navigation.

Scrollytelling-specific feedback. When interacting via scrolling, more guidance was needed. Participants struggled at first with finding out that they should scroll to interact with the story. Some described this interaction as not very intuitive. Many participants felt that the scrolling speed was too slow. One participant did not recognize they could scroll up again. Some participants only scrolled on the right side of the screen, while scrolling was possible everywhere. Some participants did not understand that, after clicking on decision nodes they were supposed to continue scrolling, and expected something to happen directly. The graph on the side describing the structure of the story was appreciated; participants wished they could use it to navigate directly. Some participants were unsure when to continue scrolling when a video was shown, as the video started again when it was finished. A participant proposed to automatically show accompanying texts when a video is shown.

6. Discussion

Our patient-focused story on BAV incidence and treatment explored a concrete use case for narrative visualization in medicine. It exposes a number of interesting results to probe further in terms of story construction, presentation, and interactivity.

In general, interaction with the *Slideshow* was considered more intuitive than scrolling. This may be because clicking remains a more common and familiar way of interacting with *Slideshows*. The slow scrolling speed also negatively impacted user perception of scrolling. The study results in favor of clicking rather than scrolling could be interpreted to mean that clicking is the more favorable interaction mode. However, there are multiple ways to implement scroll-based storytelling and our evaluation considers only one of these. The implementation used for scrolling in this work deviates from scrolling in online news pages by first fading out a scene before showing the next one. This might have caused it to be perceived as unintuitive. News pages can be an important inspiration to address multiple of the negative comments of study participants. For example, if participants do not realize they are supposed to scroll at the beginning of the story, having text that only partially appears at the bottom of the screen could remedy that. This presents an opportunity for future work. The problem of participants not realizing that they should scroll after decision nodes could be solved by displaying the continuing text directly when a decision is made. The influence of the scrolling speed is also not researched yet. Simply assessing scrolling as less intuitive does not account for the success of scrolling in digital articles and social media [ZSRB14].

Conducting the study as part of a larger event meant that participants were not required to take the time to complete a questionnaire. This may bias our results in favor of people enjoying our story. This does influence our general study results, but does not affect the comparison of the two genres, as the bias applies to both cases. However, in future studies participants opting not to fill out the questionnaire should be counted and reasons collected.

The number of user comments on transitions indicates a large impact of ease of navigation on the quality of interaction. Our evaluation highlights the importance of easy and fast transitions between neighboring slides and ways to transition directly between non-neighboring ones. Comments of participants suggest that further research is needed on the impact of slide numbers as a navigational aid but also potential cause of visual clutter. It may also be further investigated how specific aspects of the story such as logos and ease of use affect user trust.

Designing blood flow visualizations for non-medical-experts is challenging as realism, visibility, and intuitive understanding have

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to be weighed against each other. Our monochrome visualization of blood flow did not cause any comprehension problems, but the perception of vortices should be further improved beyond the application of ambient occlusion. Using a color gradient for information such as flow direction does improve visibility of vortices, but was decided against in this work as test users misinterpreted this information. Future work should investigate compromises such as textual explanations of more complex visualizations.

The results present a good proof-of-concept. However, the ease of implementation and results were greatly impacted by the chosen software and their technical limitations. The development of these stories highlighted the need for specialized software that could, for example, support story design in multiple languages or provide easy-to-implement navigation controls to generate multiple story paths or switch directly between slides. In addition, the consistent integration of different media related to their style was a challenge that affected the perceived quality of the results. A corporation with professional illustrators who work, for example, for the New York Times, regarding fonts, color scales, and layouts used would improve the story. However, the focus of our proof-of-concept was more on narrative structures, e.g., grouping, sequencing, and narrative design patterns, as well as lessons that can be learned for similar projects.

7. Conclusion

We presented a case study on how narrative visualization and different interaction techniques can be used to explain medical blood flow data with vortices to the general public. The story was created in an iterative process involving medical experts, an illustrator, an interaction designer, and computer scientists with a background in visualization and human-computer interaction. Our major lessons learned from the design process can be summarized as follows.

Physicians not only may provide content and give feedback. Their experience in communicating with patients is particularly helpful designing narrative medical visualization. Moreover, we learned that metaphors, e.g., w.r.t. to natural phenomena familiar to the general public, seem to be a powerful option to explain characteristics of medical data, e.g., blood flow vortices. While the tornado metaphor could also be used to explain the risk of other vascular diseases, e.g., stenosis, it would be interesting to think about for which other medical aspects metaphors would be helpful and how these metaphors look like. In addition, we suggest to use gender neutral illustrations for patient characters, since many diseases are distributed between the genders approximately equally and thus not only one specific gender is addressed. We also found that user attention should be drawn to interesting flow features rather than showing the flow throughout the whole vessel. Possibilities for this are, e.g., the use of close-up views, arrows, outlines of vessel areas or filtering of uninteresting pathlines. In addition, it should be avoided to show only radiological images, as their interpretation requires a lot of medical knowledge. Instead, an understandable way seems to be to reconstruct 3D surfaces of the structures of interest from image data and combine them with illustrative context depictions. An alternative would be to highlight the most important structures directly in the image data, as in Meuschke et al. [MGS*21]. More extensive studies are needed in the future to evaluate which of these alternatives are more comprehensible to a broad audience as well as to evaluate the user's understanding of data-driven visualizations relative to illustrations. Since we cannot completely dispense with illustrations, powerful tools for creating medical illustrations for non-artists are needed in the future. Deep learning systems that generate comprehensible illustrations from a combination of text and sketches could help here.

We implemented the story in a *Slideshow* format with standard clicking interaction and based on *Scrollytelling* using a scrolling interaction. Study results favor interaction via clicking, yet, the scrolling interaction could be further optimized. It would be interesting to compare more interaction styles, such as a continuous data story when scrolling, instead of showing and hiding content. Different scrolling speeds should also be explored to improve ease of use. In addition, *Slideshow* formats can be compared with other genres, such as data comics and data videos.

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