Eurographics Workshop on Visual Computing for Biology and Medicine (2021)
K. Nieselt and T. Schultz (Editors)

Short Paper

Vologram: An Educational Holographic Sculpture for Volumetric Medical Data Physicalization

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Abstract

Real-world sculptures that display patient imaging data for anatomical education purposes have seen a recent resurgence through the field of data physicalization. *In this paper, we describe an automated process for the computer-assisted generation of sculptures that can be employed for anatomical education among the general population. We propose a workflow that supports non-expert users to generate and physically display volumetric medical data in a visually appealing and engaging way. Our approach generates slide-based, interactive sculptures—called* volograms*—that resemble holograms of underlying medical data. The volograms are made out of affordable and readily available materials (e.g., transparent foils and cardboard) and can be produced through commonly available means. To evaluate the educational value of the proposed approach with our target audience, we assess the volograms, as opposed to classical, on-screen medical visualizations in a user study. The results of our study, while highlighting current weaknesses of our physicalization, also point to interesting future directions.*

CCS Concepts

• ***Applied computing*** → *Life and medical sciences;* • ***Human-centered computing*** → *Scientific visualization; Visualization systems and tools;*

1. Introduction

Screen-based visualizations and augmented or virtual reality solutions are the most common approaches for anatomical education [PS18]. However, real-world physical representations—*physical visualizations* or *physicalizations*—are still widely employed [DCW*21], as they convey a unique sense of scale and channel information in an engaging way [ZM08]. As public demand for information rises, an increase in the popularity of engaging physicalizations has been documented [DSMA*21]—also for anatomical education.

The rise of 3D printing offered an alternative to expensive and difficult manual techniques for anatomical physicalization, such as traditional wax casting [MMŽ10]. Several attempts have been made to employ this technology for medical education [ADSv15] and surgical planning [HL16]. In most of these approaches, medical imaging data are employed to create models of anatomical structures and functions (e.g., models of the heart and the blood flow) to provide a durable, artificial alternative to cadaveric materials for patient data exploration. Alternatively, modern 3D scanning technology has been used to reproduce existing surgical dissections [MQMA14]. However, 3D printers are still not easily accessible to the general public, being quite costly and demanding pre-processing experience. Additionally, common 3D prints do not provide much interactivity, as they are inherently static.

Alternative forms of interactive volume visualizations with more readily available materials and technologies were proposed recently, opening promising directions for medical data physicalization [DSMA*21]. Cost-effective and easily reproducible ways to create anatomical models have been researched mainly for the education of laypeople and informed patient consent (i.e., patient-doctor communication). Such recent approaches include *Vol2Velle* [SB17], the *Anatomical Edutainer* [SWR20], and *Slice and Dice* [RGW20]. All three methods focus on creating simple and cost-effective, printable medical data physicalizations, where localized visualizations of patient data communicate anatomical structures or pathological conditions.

The *contribution* of our work is the design of a medical data physicalization workflow that supports non-experts in learning anatomy by generating interactive sculptures that physically represent volumetric medical data. The sculptures synthesized with our approach are called *volograms*, as they resemble holograms of the underlying volumetric medical data. To further support users to customize the volograms, we provide a stand-alone application that guides their design through an interactive interface. To assess the value of the volograms, as compared to on-screen visualizations, we perform a user study with 10 laypeople.

2. Requirements and Goals

The target audience for our approach consists of laypeople. We do not focus on a particular age group, although the physical and hands-on nature of physicalization might be a positive factor for a young audience [NMA12]. Still, elderly users, who are more likely to undergo medical treatment and are often not as proficient with computer technology, might similarly profit from such

DOI: 10.2312/vcbm.20211341

learning aids. Medical experts, such as medical practitioners, or researchers, are not the target audience of our work. Based on these observations, we formulate the following requirements:

- **R1** The application should cater to the target group's needs for anatomical education.
- **R2** Data selection and processing should be feasible and automatized for people not knowledgeable about medical visualization and image processing.
- **R3** The application should convey basic human anatomy.
- **R4** The input data are volumetric medical data, such as Computed Tomography (CT) or Magnetic Resonance (MR) images.
- **R5** The employed materials should be affordable and available to the general population.
- **R6** The generated physical models should be affordable, easy to generate, and quick to assemble.
- **R7** The on-screen visualization and the generated physical models should be optically comparable.

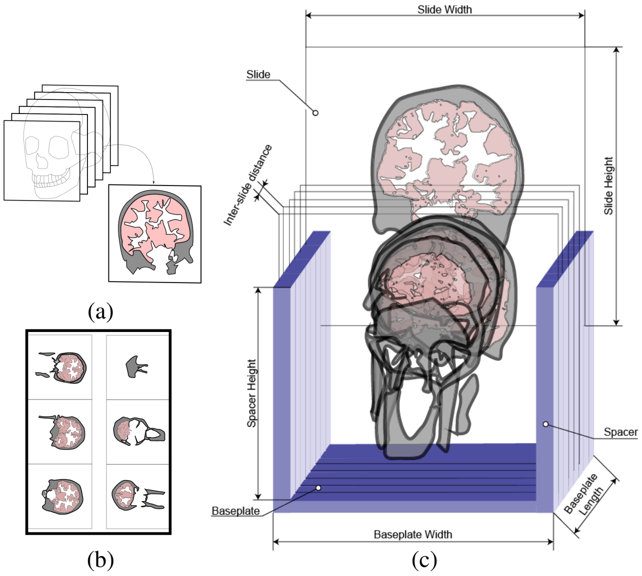
Based on these requirements, we summarize our specific goals. The *first goal* is to find a suitable physicalization concept for volumetric medical data, covering all requirements **[G1]**. The *second goal* is to develop a computer-assisted workflow that supports non-professional users in creating the anatomical physicalizations **[G2]**. For this, it is crucial to consider the target group, their abilities to use a computer, as well as their limited literacy in medical visualization **(R1-R4)**. Users should be able to construct the physicalization with relative ease, and the materials should be affordable and readily available **(R5-R6)**. The *third goal* is to assess the value of our physicalization **[G3]**, as compared to an on-screen visualization, to identify if either approach provides an advantage **(R7)**.

3. Identifying a Suitable Physicalization Concept [G1]

Concept: Approaches like *Vol2Velle* [SB17] and *Slice and Dice* [RGW20] have made use of transparent materials, which are easy to purchase and use. Inspired by the latter approach, we conceptualized *vologram* to achieve a 3D holographic appearance of a volume rendering. A vologram (Figure 1) consists of two parts: (i) the *semi-transparent slides* that contain the actual imaging data (i.e., the sliced volume rendering) stacked equidistantly in parallel, and (ii) the *receptacle* to support the slides. Unlike *Slice and Dice*, a vologram does not undergo a complex octree partitioning and the subsequent (optimal, but complex) placement of the octree slices on the printable material. Instead, it is a simple slice-based approach, analogous to the slice-based viewing of medical images.

To facilitate the creation of a vologram, the users can select parts that they wish to include in the sculptures through an *accompanying interactive application*. Parameters, such as the scale, inter-slide distance, and viewing angle, can be adjusted by the users in the application to accommodate their viewing preferences. The volume data are then transformed into individual slices (Figure 1 (a)) that are arranged on slides on a printable template, which is printed on overhead foils, using inkjet or laser printers (Figure 1 (b)). The individual slides are then cut out and inserted into the pre-assembled receptacle to create the vologram (Figure 1 (c)).

Volograms provide an inside view of structures, as a whole or through the individual slides. The assembly of the sculpture is straightforward and quick. The receptacles can be reused, saving a significant amount of time for the construction of the sculptures. An important feature of the approach is that the individual slides support interactivity. They can be easily removed and examined individually to provide a sequential overview of the different anatomical structures on a specific plane. The slide distance can be varied to create bigger volograms at the cost of resolution. Occlusion caused by sub-optimal foil quality can be countered with the usage of a backlight.

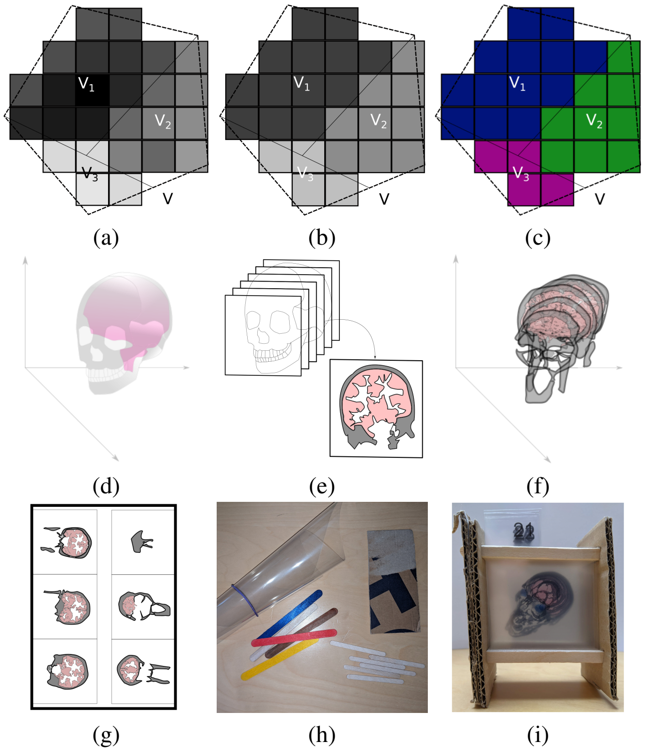


(a) (b) (c)

Figure 1: *Concept for the* vologram*: (a) Transformation of the volume. (b) Creation of printable. (c) Resulting physical model.*

The vologram fulfills all *requirements* discussed in Section 2. The proposed sculptures display anatomical data, captured with CT or MR images **(R4)**, in an accurate enough way for a layperson target group **(R1)** to convey the positions of organs and their spatial relationships in the human body **(R3)**. The used materials are inexpensive and widely available **(R5)**, while a quick and easy assembly is supported by the two-part design. The reusable receptacle can support multiple slide sets, and the slides are simply printed with desktop printers and can be cut out with regular scissors **(R6)**. The workflow requires little user input and is not dependent on a user's ability to navigate complicated medical visualizations **(R2)**.

Materials: For the realization of the vologram, we propose a two-part design: the slides and the receptacle (Figure 1 (c)). The *slides* are the core component of a vologram and are made of a transparent, printable material, such as overhead foils. To ensure that the 3D effect is achieved correctly, the slides must be aligned in parallel, keeping a constant distance. Users have to balance the ratio of scale to material usage, according to their own needs. Our prototype receptacles support slides of $90\,mm \times 90\,mm$ and $60\,mm \times 60\,mm$ by default, which creates palm-sized sculptures of sufficient level of detail with regard to the usual CT/MR spatial resolution. The advised slide distance is $2\,mm$ to $4\,mm$. The *receptacle* consists of two parts: the baseplate and the spacers. The baseplate provides a



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 2: *Schematic depiction of the workflow for the vologram generation: (a) Raw medical data are used as input to the framework. (b) The data are processed to create a data-dependent set of filters (V1-V3) for the users to decide which structures to include or exclude. (c) The intensity values of the data are mapped to adequate transfer functions. (d) Visual inspection of the rendering. (e) Selection of viewing direction, scale, and slide distance. (f) Vologram rendering before printing. (g) Pagination before printing. (h) Employed materials. (i) Assembled physicalization.*

plane surface for the slides and the spacers to rest on. For this, a rectangular hole is cut into the baseplate, and spacers are tightly inserted to support each other enough to be upright but loose enough so the slides can still be inserted. Therefore, the baseplate should be of durable material that can be easily processed, such as thick cardboard. Its width/height should exceed the sum of the slide width/height and the total spacer width/height. The spacers are required to be durable and firm to hold the slides onto the baseplate. Wooden sticks are a sufficient solution, and their height has to be equal to or greater than the slide height to ensure stability. The receptacle dimensions are a required user input in the application for the generation of the volograms.

Datasets: To generate the physical models, suitable datasets need to be selected (i.e., volumetric data with accompanying organ segmentations). For this work, we employ the well-known *Visible Human* dataset [ASSW95]. It contains volume data of a male human cadaver, comprising of photographs of the cryosected slices of the body, as well as CT and MR images. The male dataset has been used by Pommert et al. [PHP*01] to create a comprehensive segmentation of the human head and torso. Both datasets have a slice resolution of 573 × 330. The head dataset contains 255 slices, while the torso has 774 slices. Segmentations for many structures are provided separately. The Visible Human male dataset and the segmented inner organs from Voxel-Man have been kindly provided to us for use in the course of our work.

4. Developing a Workflow for Generating Volograms [G2]

The second goal **[G2]** is to develop a computer-assisted workflow that supports layman users in generating their volograms from volumetric medical data (Figure 2). In our workflow, we follow the physicalization pipeline introduced by Jansen et al. [JD13]. We describe the individual steps of the pipeline in the following section.

Data Processing: The first step is to transform the *raw data* (Figure 2 (a)) into *processed data* (Figure 2 (b)). Requirement **(R4)** states that the input for the proposed application should be volumetric medical data. Users, as stated in **(R2)**, are not expected to be proficient in medical visualization. Therefore, the data need to be prepared in advance in the form of pre-segmented organs and structures. Users should only have the option to select which of these organs or structures they desire to display. We provide *filters*, i.e., binary segmentation masks, for various areas of interest. Users select a set of regions to be displayed, and the volume data is automatically processed accordingly.

We propose two filtering algorithms that can transform the raw volume data according to a user-dependent structure selection: a discrete and a continuous filtering method. A *discrete filtering* method assigns individual intensity values, i.e., indices, to the included structures, which results in losses of intra-structural variations, as shown in Figure 2 (b). To mitigate this loss, we can use a *continuous filtering*, where the intensity values within each structure are remapped to a fixed interval. This ensures that a single pre-determined transfer function is needed for rendering the filtered dataset, regardless of which structures the user selects.

Visual Mapping: The next step in the workflow is the *visual mapping*, as shown in Figure 2 (c). In this step, the processed data are brought into a visual form. In our case, the visual form is fixed, as only volume rendering is considered. To this end, we employ a transfer function that maps the intensity data values of the filtered volume, as resulting from the previous step to color and opacity values. Users only choose color and opacity for each structure.

Visual Inspection and Physicalization Settings: In this step, the generated rendering can be visually inspected (Figure 2 (d)), and the final setup of the physicalization (viewing direction, scale, and slide distance) is selected (Figure 2 (e)). Initially, the users are presented with a rendering of the filtered volume data, using the transfer function created in the visual mapping stage. The scale is assigned a default value of 10, which is sufficient to transform a thorax CT into a roughly palm-sized vologram, and the viewing position is set parallel to the inherent z-axis of the volume, towards the center of the volume. This initial rendering serves for the *parameter selection* of the physicalization setup.

The users can specify a scale factor for their sculptures, depending on the desired size of the physical model, and an inter-slide distance, which represents the physical distance between individual slides. The latter depends on the chosen physical slide distance in millimeters, as well as the voxel spacing in the viewing direction. The viewing direction is chosen by altering the camera position of the rendering, using simple panning and rotation. The slicing direction is set corresponding to the final selected viewpoint. After selecting the parameters for the physicalization, the transformations are performed, as shown in Figure 2 (e). The volume data is resliced to align the voxel grid with the viewing direction. Then, we extract 2D volume slices at regular intervals corresponding to the selected inter-slide distance. As a result, we obtain a set of slices through the volume data at a user-selected viewing direction.

Vologram Preview: After choosing the parameters and executing the data transformation, the vologram is rendered as a preview, using the same transfer function as the previous step's on-screen visualization. Users see a rendering resembling the final form of the vologram, as shown in Figure 2 (f). The set of virtual slides obtained in the previous step is used to construct a new volume dataset for this rendering. If not satisfied with the outcome, they can return to the previous step and alter the parameters.

Physicalization: The actual physicalization is rendered on printable overhead foils. For this, the individual slide data are rendered individually and automatically aligned on a printable page. For the rendering, orthogonal projection is used, as opposed to the perspective rendering of the preview. The position and size of each slide on the page have to be determined by a paginator (Figure 2 (g)), which is dependent on the receptacle size. Additionally, guiding bookmarks, in the form of rectangular tabs with indices printed on them, can be added to the slides. After printing, the slides are cut out and inserted between the receptacle's spacers, completing the physicalization. The materials employed for a vologram are shown in Figure 2 (h), and an assembled physicalization in Figure 2 (i).

5. Assessing the Value of the Volograms [G3]

The third goal **[G3]** is to assess the value of the volograms through initial experimental results. Additionally, we conduct a user study to determine whether the volograms demonstrate advantages over traditional, on-screen visualizations.

Experimental Results: We manually processed segmentation masks of inner organ data from the *Visible Human* male dataset in *MeVisLab* and used them as input for the creation of the volograms in our stand-alone *Python* 3.9.0 application. We created multiple volograms of different structures using different setup parameters. In this section, we show a vologram created from the male torso dataset. An additional example of the head dataset was shown in Figure 2 (h). We process the torso dataset to create filters for the most prominent anatomical structures. We exclude the colon, small intestine, and skin to prevent upper torso organs from being obscured for this prototype. The example uses the discrete filtering approach, where we provide distinct colors and opacities for each structure to create a more illustrative view of the data. Figure 3 (a) shows the visual rendering of the torso area, and Figure 3 (b) shows the selected upper torso region preview. We use a larger receptacle to display the larger region of interest and 90 $mm \times 90\, mm$ slides, with 4 mm inter slide distance. The transformation with the parameters selected for this vologram results in 14 slides, arranged over three pages in total. The final sculpture can be seen in Figure 3 (c).

User Evaluation: To assess the performance and user experience aspects of the vologram, in comparison to an on-screen visualization, we conducted a study with 10 participants. For this, we generated a visualization and physicalization that are comparable in the following aspects:

- **[A1]** They use similar visual cues, such as colors and opacities.
- **[A2]** They use the same source data, without any filtering methods.
- **[A3]** They only use interaction methods, inherent to their nature.

Our approach, by design, allows users to create a physicalization from a previously designed volume visualization from the medical data in a stand-alone application **[A1]**. Participants were asked not to use filtering methods provided by the interface, and we observed them to ensure this was kept **[A2]**. They were still allowed to manipulate the viewpoint of the visualization with the mouse. The participants were also encouraged to touch and manipulate the vologram, as desired **[A3]**. Subsequently, we compared the two modalities for user performance **(UP)** and experience **(UX)**.

The *test group* consisted of 10 people, between the age of 27 and 77 years. No children took part in the study, as this would require a different design and support from children educators, which was not possible at this time. The average age of the group was 43.7 years. Four participants are female, and six are male. None of the participants works in an occupation inside the medical field, and four of the participants have experience working with computers.

For the **UP** evaluation, we conducted controlled experiments with a set of 6 tasks. We measured error rates and task completion times of the users with the on-screen visualization, as compared to the vologram. The order of the tasks was randomized, and the order of the modalities was alternated to combat familiarization. The average task completion time using the physicalization and the visualization was less than 10 seconds apart, in favor of the visualization. For all organs except for the kidneys, the com-

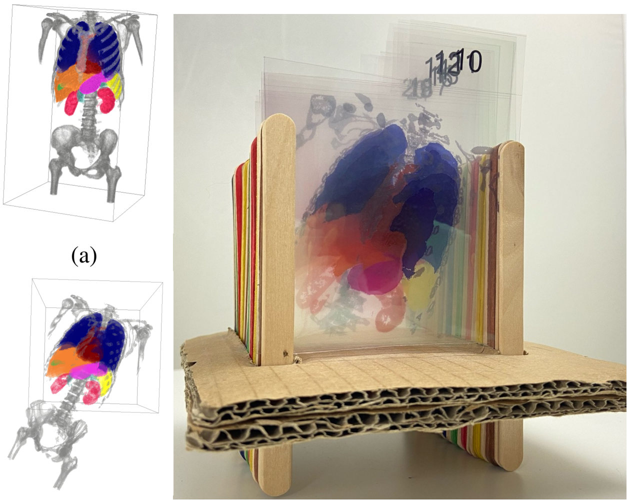

(a)
(b)
(c)

Figure 3: *Demonstration of the workflow for the generation of an upper torso vologram: (a) Visual inspection of the torso rendering. (b) Upper torso vologram preview. (c) Resulting physicalization.*

pletion time is shorter with the visualization. For example, using a vologram to find the spleen, which is located on the left side of the body, was not easy. Multiple participants reported that they had to remove individual slides to find this organ. Considering the error rate, users made more errors using the physicalization. This can be partly explained by the fixed size, as compared to the visualization. The screen-based visualization allowed participants to zoom in and out, making it easier to find small structures.

The **UX** evaluation consisted of an interview and a questionnaire. First, we employed a questionnaire to collect data about the demographics, such as age, prior knowledge, and occupation. Then, with a short questionnaire, the participant rated statements about their experience on a five-point Likert scale from “Strongly Disagree” to “Strongly Agree”. Additionally, we asked open text questions about what the participants did and did not like about either modality. Most participants reported preferring the on-screen visualization. Only one participant answered the opposite, reporting that he *”likes to work with [his] hands”*. None of the participants had seen a 3D visualization before the study, leading to a positive novelty effect. In the interviews, as well as in the informal feedback, many participants stated that they liked the handy size of the sculpture, as well as the playfulness of the concept. One participant remarked that they would like to show the sculptures to their parents. Another participant, who has young children, said that *”it would be a nice tool for children— they use the computer too much”*. On the negative side, it was often stated that the sculpture seemed unstable and that a good view is harder to achieve than on the screen. For the visualization, many participants reported positively about the concept and liked the freedom of movement for the camera controls.

6. Discussion

In terms of meeting our requirements, the study shows that the needs of the target group for medical education were sufficiently addressed by vologram **(R1)**. Data selection was not part of the study, but the user interface requires no prior knowledge to create meaningful visualizations. It provides an ample amount of preprocessed data, ready for laypeople to engage with **(R2)**. The shape and relative positioning of organs in the human body proved to be an interesting and engaging lesson for the participants **(R3)**. Real medical volume data were presented to medical laypeople in a way meaningful to them **(R4)**, in both an affordable and easy to construct **(R5, R6)** physical form, and an optically comparable screen-based visualization **(R7)**. The results of the evaluation clearly point out that our screen-based visualization was suited better for the task we imposed. The physicalization, however, also received some praise from the participants. We see a potential for both modalities for layperson anatomical education. They complement each other well: hands-on physicalizations can engage people more, while visualizations seem to be more versatile. Statements from different participants also point to applications for children’s education. Yet, we did not have access to a group of children of suitable age or an educator to design a suitable study. The study also pointed to potential use in communicating medical information to elderly patients. Physicalization could provide an opportunity to improve elderly patient education and their experience during treatment.

7. Conclusion and Future Work

We presented the physicalization concept of a vologram **[G1]** and designed a workflow for laypeople, to create personalized physical sculptures of medical data **[G2]**. We also conducted a study to examine the usefulness of our approach, as compared to screen-based volume renderings **[G3]**. While a classical screen-based visualization seems to have advantages over the Vologram, the lessons learned about the concept’s shortcomings open many exciting directions for future work in medical data physicalization.

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