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# Medical Animations: A Survey and a Research Agenda

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**Abstract**

*Animation is a potentially powerful instrument to convey complex information with movements, smooth transitions between different states that employ the strong human capabilities to perceive and interpret motion. Animation is a natural choice to display time-dependent data where the dynamic nature of the data is mapped to a kind of video (temporal animation). Clipping planes may be smoothly translated and object transparency adapted to control visibility and further support emphasis of spatial relations, e.g. around a tumor. Animation, however, may also be employed for static data, e.g. to move a camera along a predefined path to convey complex anatomical structures. Virtual endoscopy, where the virtual camera is moved inside an air-filled or fluid-filled structure is a prominent example for these non-temporal animations. Animations, however, are complex visualizations that may depict a larger number of changes in a short period of time. Thus, they need to be assessed in their capability to actually convey information. In this paper, we give a survey of temporal and non-temporal animated visualizations focussed on medical applications and discuss the research potential that arises. To be employed more widely, cognitive limitations, e.g. change blindness, need to be considered. The reduction of complexity in temporal animations is an essential topic to enable the detection and interpretation of changes. Emphasis techniques may guide the user's attention and improve the perception of essential features. Finally, interaction beyond the typical video recorder functionality is considered. Although our focus is medicine, the discussion of a research agenda is partially based on cartography, where animation is widely used.*

Categories and Subject Descriptors (according to ACM CCS): Animation

## 1. Introduction

Computer-generated animations have a long tradition. Powerful animation tools were developed already in the 1980s, primarily motivated by the needs of the film industry. Computer-generated animations are created based on metaphors from traditional films, like a *story board* and *key frames* that are interpolated to achieve smooth transitions. Animation provides enormous flexibility. A virtual camera may be rotated in a fixed distance around a pathology to assess its morphology (orbiting). The virtual camera may display a region around a pathology, zooming in particularly interesting regions, e.g. to assess an infiltration, or it may zoom out and move to another interesting viewpoint. The camera may also be moved inside structures, e.g. in bronchoscopy or colonoscopy [LJK95]. Animated displays provide motion parallax, an essential depth cue that supports the interpretation of volume rendered images and maximum intensity projections that are otherwise difficult to interpret [SGS95].

Animation may also be used to smoothly change parameters of a transfer function and thus to display or hide structures, to change colors or textures for emphasis of focus objects and to adjust clipping planes or more complex resection geometries. Virtually every parameter of a static display may be smoothly changed to a different state. While most animations are restricted to one viewport, multiple synchronized animations may provide different perspectives—similar to multiple coordinated views for interactive data exploration. Synchronized visualizations of internal and external 3D views are typical for virtual endoscopy [JLS*97].

Animations may be used for surgical planning and training [ÇK00, MBP06], and for anatomy education [HH95, PRS96]. Also the use of animations for patient education [KKSP08, McG10] and forensic use cases [Fis08, VOH17] was extensively studied. While forensic use cases require a high degree of realism (referred to as *scientific animations*), patient education benefits from plausible, abstracted visualizations where also aesthetic aspects are considered. In contrast, animations for medical education are driven more by learning-theoretic considerations, e.g. motivational aspects and cognitive load theory.

Like static medical visualizations may benefit from carefully chosen default values, the parameters that guide an animation may be re-used in similar cases, e.g. to report cases with a similar pathology in a reproducible manner [IHT*02, MP10b]. In addition to these animations, where no dynamic process is visualized, animation is a natural choice to display dynamic medical image data, such as simulated or measured blood flow [dHJEV16], motion of the heart wall [JAES87] and other functional processes. "Animation let us observe how an object changes its shape, size, and position … over time" [AWM10].

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Animated visualizations may be completely predefined with no or only basic interaction. At the other end of the spectrum, highly customized animations may be created on demand where the user has full control over all parameters. Thus, the purpose ranges from *communication of known facts* with predefined, often carefully prepared animations to *exploratory data analysis* [DMKR92].

Medical visualization comprises both direct volume rendering controlled by a transfer function and (polygonal) surface rendering. These two families of visualization techniques also occur in medical animation. However, surface-based rendering is clearly prevailing. This is due to the large flexibility to adjust polygonal models, e.g. by smoothing or simplifying them [McG10]. Another argument for the use of surface models is that medical animations often contain additional elements, such as surgical instruments or crime weapons in forensic animations that are represented as surface model.

So far, there is no survey article on animation in medicine. Animation in other areas, however, was discussed in a number of survey articles. The most recent of these articles relate to character animation, in particular to muscle modelling [CRPPD17], hand and finger modeling [WWS*15], and more general to physics-based approaches to character animation [GP12]. There is a slight overlap to the topics discussed in these articles with respect to biomechanics. However, the specific examples of animation using principles from biomechanics are different: We consider examples in forensics that were not part of previous surveys. Other surveys focussed on the application of animation to photorealistically generated images, e.g. Wald et al. [WMG*09]. The survey of Kreiser et al. [KMM*18] describes projection-based medical visualization techniques. It is briefly mentioned, since flattened visualizations may be animated similar to animated maps in cartography. However, Kreiser et al. do not discuss any animated technique.

**Organization.** In this paper, we give an overview of animation design (Sect. 2) and discuss how these methods can be applied to medical visualization. Patient-specific animations are useful for diagnosis and treatment planning. However, the effort to generate animations must be strongly reduced in clinical medicine. Therefore, we discuss strategies to re-use animations in Sect. 3. In Section 4 we discuss temporal medical visualizations with a focus on animated blood flow. Non-temporal animations are discussed in Sect. 5. In Section 6, we discuss application areas, including medical education, virtual endoscopy, and forensics. A crucial issue is the interaction to steer animated displays. This issue is described in Section 7. Finally, we discuss a research agenda (Sect. 8). The ideas for future work in this area are largely inspired by cartographic animation—an area that is more mature and involves systematic research on cognitive limitations in the interpretation of animations.

## 2. General Principles for Animation Design

In this section, we provide a high-level discussion of perceptual and cognitive issues involved in the interpretation of animations, including motion perception, change blindness, and cognitive load (Sect. 2.1). Since medical animations often aim at educational purposes, we also briefly discuss learning theories. As a second ingredient in animation design, we discuss principles from film making that were applied to computer-generated animations (Sect. 2.2).

Other areas of visual perception, such as color and contrast perception, shape and depth perception as well as flow perception are also relevant for animation design. For the sake of brevity, we do not discuss these other areas. As a starting point for dealing with the role of perception in visualization, we recommend the work of COLIN WARE [War12]. Since a large number of medical animations has been created with general purpose software instead of dedicated systems for medical use, we mention major tools in Sect. 2.3.

### 2.1. Cognitive and Perceptual Basics

The design of animations has to consider a number of aspects related to perception, cognition, motivation and learning theory. The effectiveness of animations may depend on [RCL09]

- the actual content to be displayed,
- the specific processes that are shown,
- learner characteristics, such as domain knowledge and spatial abilities as well as
- the context in which the display of animations is embedded, e.g. verbal instructions.

Research in this area is not comprehensive and in particular medical animations are not investigated well. Thus, our discussion also considers non-medical animations. The amount to which experiences from other areas, such as cartography and mechanics, can be generalized towards medical use cases is currently not clear.

**Motion perception** is the rather low-level process of identifying and assessing movements. An essential aspect is the ability to detect changes at all. In a series of experiments, it was demonstrated that users may miss even movements of larger characters known as *change blindness* [SL97]. Change blindness has a number of reasons, including saccadic eye movements that occur when a new region in an image is fixated. For a period of up to 200 ms, humans are blind during these eye movements [Gre15]. Not only that humans do not reliably detect changes, they are also not aware that they have not fully understood a video sequence. Thus, even users who miss essential changes report to be certain in their decision—a phenomenon called *change blindness blindness* [LMDIS00]. For animation design, emphasis techniques, such as arrows and the use of colors that grab attention, may be considered. Change blindness also depends on the speed of presentation. Neither very slow nor fast movements are beneficial to support the detection of changes.

Correct interpretation of an animation not only requires that users detect changes, they also should interpret the character of a change, e.g. whether a quantitive value has increased or decreased and to what extent the value changed compared to the original state. Thus, perception researchers use change detection (CD) levels, where

- CD 1 relates to the detection of a change,
- CD 2 to the direction of change, and
- CD 3 to the amount of change [GB09].

Evaluations in cartography animation reveal that humans make errors when they should answer CD level 2 and CD level 3 questions. Thus, users may notice changes despite having not enough time to figure out what exactly changed. Perceptual research indicates that the problems are more severe when it is necessary to pay attention to different regions in an image. This *split screen attention* situation reduces the human change detection ability [AW05].

**Cognitive load theory.** Cognitive load theory considers the limited resources of the human brain to process information. Short-term memory is limited and as a consequence information overload may interfere with learning [Swe04]. Researchers investigating cartographic animation therefore suggest to restrict both the complexity and the duration of animations [Har07]. Animations should be rather short, typically below one minute. Also based on cognitive load theory, Ruiz et al. [RCL09] discussed evidence that breaking an animation into smaller chunks reduces cognitive load and is beneficial for learning. They recommend that the information should remain available at the end. Cognitive load is further distinguished in *intrinsic* cognitive load that comprises the information that need to be processed, and *extrinsic* cognitive load that comprises other information that consumes cognitive resources without any effect on learning. Obviously, extrinsic cognitive load, e.g. anything that may distract, should be minimized [Swe04].

**Learning theory.** We will see that a considerable number of medical animations serve educational purposes. The use of animation in educational settings is driven by the attempt to “increase student interest in the subject material” [Fis08]. Fisk continues by saying “Today’s students have been raised in an environment rich in videos and visual stimulation. As a result, animated demonstrations of scientific topics may be more familiar and engaging for younger viewers” [Fis08]. While there is broad consensus about this motivational aspect, the evidence that animations indeed improve learning and are more efficient than learning with other media is controversial. Obviously, animations do not automatically have a substantial educational value. Excessive details and animations that are primarily decorating may be distracting. Instead, animations should be consequently designed and evaluated with specific educational goals in mind, where the dynamic character is likely beneficial.

Fisk [Fis08] discusses investigations by other authors that indicate the importance of an adequate preparation. Basic introductory information should be given to students prior to observing an animation. Also during the animation, “narration should be used to explain the events occurring in the animation” [Fis08]. Audio recordings or text embedded in the animation can be used. While audio recordings have the advantage that spoken text can be better perceived concurrently to an animation, displayed text requires visual attention to be split between observing the animation and reading text.

Ruiz et al. [RCL09] summarize research on animations that are effective for learning. They conclude that movements similar to those, a learner is expected to perform later, are highly effective. As a consequence, the actual handling of instruments and the conduct of steps in surgery can be learned better based on animations. Less effective—according to this theory—are animations that explain, for example, how a machine or the heart works. Ruiz et al. [RCL09] argue that even the best animations may not ideally serve their (learning) purpose if they are not carefully embedded in an overall learning strategy, comprising more *active* types of learning.

## 2.2. Theories and Principles for Animation Design

Animation design involves unique aspects that go beyond modeling for interactive use. A geometric model with fine details may be appropriate for exploration but when moved with moderate or even high speed, the details may be unnoticed. Since the viewing directions are determined by an animation author, parts of a geometric model may always be hidden or appear too dark, based on the lighting specification which the viewer typically also cannot influence [HH95]. *Temporal coherence* is an issue: Visualization techniques that involve stochastic sampling or slight inaccuracies may lead to distracting flicker if tiny elements show up and disappear suddenly. As a consequence, animations must be iteratively developed, carefully checked and refined to reduce the risk of unwanted effects as much as possible.

Hand-drawn character animation provides an essential basis for animation design. Lasseter [Las87] mentioned eleven principles based on an in-depth analysis of literature in this area. While some principles apply primarily to facial expressions and other peculiarities of character animation, the following principles are also relevant for (non-temporal) medical animations.

Animations should be plausible with respect to mechanical laws which means that animated objects should be guided by gravity and inertia. Viewers will use such knowledge to interpret an animation, e.g. an object that can be accelerated very fast must be light, whereas heavy objects make slower movements. Objects are stretched and squeezed during motion, at least if they are not completely rigid.

**Anticipation.** The principles described by Lasseter [Las87] further explain that the actual movement shown in an animation requires preparation, as we discussed in Sect. 2.1. In the language of film, this is referred to as *anticipation*. Lasseter gives the example of a boy kicking a ball: The foot must be pulled back before the ball can be kicked. In a similar way, also a step of a surgical intervention can be prepared. Otherwise, viewers tend to miss the essence of a movement. “Anticipation is a device to catch the audience’s eye, to prepare them for the next movement and lead them to expect it. . . . Anticipation is also used to direct the attention . . . to the right part of the screen at the right moment.” [Las87].

**Staging.** After the anticipation, the core of a movement takes place. Lasseter argues to show just one movement at a time to support focussed attention on this movement. If an animation should convey different movements, these should be serialized [Las87, Fis08]. In a “busy” animation with many moving objects, Lasseter argues, that the eye tends to focus on relatively still regions—missing the dynamics completely [Las87]. According to the staging principle, the moving object should further be emphasized and thus differ from other objects. The aspect of guiding attention in an animation was emphasized by many authors, also related to medical animation, e.g. Fisk [Fis08]. In essence, with careful anticipation and staging, the author of an animation can effectively guide the viewer to certain objects in a certain sequence—exactly what is desirable to realize a communicative intent, e.g. for an educational purpose.

**Arcs.** Another principle, briefly referred to as *arcs*, relates to typical camera movements: cameras typically move along arcs and only rarely along straight lines. The camera orientation changes only slightly. Traditional animation is based on keyframes and thus

3D computer animation systems often follow this principle as well. Catmull [Cat72] presented the first such system. In this paper, also the first scripting language, the *Motion Picture Language*, was introduced to define animations. It supports accelerated and decelerated movements as well as concurrent or overlapping processes. To realize camera movements along arcs, animation systems employ spline-based interpolation techniques [KB84].

Animations have a number of essential characteristics:

- *Duration*. Typically, animations for presentation purposes are rather short, mostly below a minute.
- *Speed*. The speed determines how much time users have available to detect and interpret changes. The preferred speed may vary considerably and should be adjustable.
- *Temporal Scale*. When dynamic data is displayed, a certain *world time* interval is mapped to a certain *display time* interval.
- *Interpolation*. The specific interpolation method used for the transition between states or positions, e.g. linear or cubic. The interpolation determines the smoothness of camera movements.

There are three types of motion in an animation [Zet13, Sto17]:

- *Primary motion*. Movements of the actual actors, e.g. a car, or a cat escaping from a dog. In medical applications, growth processes, or changes due to a contrast agent that diffuses over time are examples for primary motions.
- *Secondary motion*. Movements of the camera, e.g. pan, tilt, and dolly, and movements of the lense elements, e.g. zooming. Also adaptations of illumination settings or transparency in a computer-generated animation belong to secondary motions. In medical animations, also transfer function parameters may be animated.
- *Tertiary motion*. Switches from one shot to another, i.e. transitions, such as fade, dissolve and wipe.

Primary motions are the core of temporal animations, whereas secondary motions occur primarily in non-temporal animations. Tertiary motions are relevant, e.g. for longer non-temporal animations to provide smooth transitions between strongly different shots.

As a final classification, based on Parent [Par12] and Stollfuss [Sto17], we mention

- *Artistic animation* "in which the animator has the prime responsibility for crafting the motion" [Par12].
- *Data-driven animation*, "where live motion is digitized and then mapped onto graphic objects" [Par12].
- *Procedural animation*, "in which there is a computational model . . . used to control the motion. Usually, this is in the form of setting conditions for some type of physical . . . simulation" [Par12].

We will see example for each of these categories.

### 2.3. Tools for Animation Design

Animations are often created with professional general purpose animation software. In the articles discussed in this paper, 3D studio max [MZL10], Cinema4D [Her02], Maya [COH*02] and Caligari TrueSpace [LBR04] are mentioned. These animation tools are intended for digital artists and animators. They provide support for keyframe animations, e.g. the author defines a set of keyframes and may choose among different strategies to create smooth animations based on an interpolation scheme. These interpolation-based techniques are often summarized as "Tweening" [Sak06]. The complex tools aim at efficient support for professional users instead of an easy-to-use lean interface for casual users. We found a number of animations created by physicians for educating students or patients. Cutting et al. [COH*02] used Maya from Alias Wavefront for creating animations to support surgical training (cleft lip surgery). Herman [Her02] used Cinema4D to create animations for patient education. Lim et al. [LBR04] used Truespace to provide educational material for regional anesthesia training examples. In Sect. 6, we discuss these and other examples.

### 2.4. Scientific and Non-Scientific Animations

Medical animations can be used to convey physiological properties, e.g. the pulsatile blood flow and the resulting vessel wall movement. Also biomechanical properties, e.g. the range of motion of the shoulder, can be effectively communicated with an animation. This leads to a further useful discrimination of animations.

- *Scientific animations* are based on the laws of physics, such as energy conservation and kinematic laws. Scientific animations aim at a high degree of realism and correctness.
- *Non-scientific animations* in contrast aim at a plausible depiction of movements without any guarantee that the behavior is correctly shown. Non-scientific medical animations may be used for patient education or more generally for educational processes.

Scientific animations are primarily used in medical research and in selected diagnostic processess, such as rupture risk assessment of an aneurysm based on an unsteady simulation of blood flow.

## 3. Re-use of Medical Animations

Medical animations created for anatomy education, patient education or surgical training may be unique, i.e. exactly *one* animation is generated and frequently used (as it is). They are often based on data of a healthy and "normal" person, e.g. the Visible Human dataset, abstracting from any anatomical and pathological variations of a patient. Re-use in the sense of adapting the animation to a similar situation is of minor importance in these educational situations. However, in routine diagnosis and therapy planning, only patient-specific animations are meaningful. It is essential that they can be created in a cost-effective manner, e.g. without a large amount of user input. The idea of re-using an animation is conceptually similar to *example-based animations* [WL08]; a concept that was used, for example, for clothing animation [WHRO10]. Although similar, the concepts are not identical. Wang and Lee [WL08] use different animations to compose a new animation. We consider re-use, as defined by Muehler et al. [MP10b], as the transfer of a single animation to similar datasets.

In addition to effectiveness, standardized approaches to animation generation also ensure *reproducibility*, e.g. animations are less dependent on the actual user. There are considerable efforts in all areas of radiology to standardize documentation, e.g. with respect to protocols and sequences as well as terminology. The incorporation of 3D visualization and 3D animation in (standardized) documentation obviously requires also to standardize the use of algorithms and parameters of (dynamic) visualizations [HNN*03], including transfer function specifications, viewing directions and clipping planes. Ideally, the expert knowledge of a physician is only necessary to create a first or very few animations and further animations are automatically *adapted* based on these examples. We found two publications driven by this goal related to the use case of cerebral aneurysm diagnostics [IHT*02] and planning surgery in case of neurovascular compression syndromes [HNN*03].

A simple type of animation frequently used for diagnosis and reporting is "a rotating cineloop to convey the 3D structure" [SSN*98], which is primarily applied to maximum intensity projection (MIP) images [SGS95] and local MIP [SSN*98]. In these loops, the virtual camera is moved horizontally around the center of the dataset, thus displaying the relevant vascular structures from a large number of viewpoints. Most vascular structures appear unoccluded in one of these views. The precise coordinates of the viewpoint depend on the bounding box of the dataset. In this section, we discuss attempts to create animations that are adapted to other cases as automatically as possible. We start with a special example from neuroradiology, the diagnosis of cerebral aneurysms (Sect. 3.1) and go on with examples from surgery planning (Sect. 3.2).

### 3.1. Re-use of Animations for Cerebral Aneurysm Diagnostics

For diagnosis, it is essential that a pathology is detected, that its shape can be recognized and assessed in detail and that the shape can be quantitatively assessed, e.g. its size or volume is determined. Based on such information radiologists report on the existence of a pathology and the stage or severity of a disease. 3D visualizations and animations may be beneficial in case of pathologies with a complex shape that are partially occluded or otherwise difficult to assess, e.g. vascular pathologies. Vascular pathologies include plaques, stenosis, aneurysms and arterio-venous malformations (AVMs). We describe the (re)use of animations for diagnosis aneurysms that may occur in the whole arterial system, e.g. abdominal aortic or cerebral aneurysms.

Cerebral aneurysms are dilations of a cerebral artery that are relevant due to the involved risk of rupture. Iserhardt-Bauer et al. [IHT*02] created standardized animations to support a systematic search for such aneurysms based on locations where most aneurysms occur. A posterior overview and different lateral views are chosen to analyze selected cerebral arteries. CT angiography datasets are employed and subvolumes are extracted in a standardized way. Clipping planes are inserted at specific landmarks and the transfer functions are adapted to a new case in a clearly defined manner (the basic strategy for this adaptation is a histogram analysis involving also derived data, such as gradient magnitude). Instead of one large video sequence, five smaller sequences are generated. Each consists of circular 360 degrees flight around a subvolume. The videos are rendered on a graphics server and distributed via web clients. In an evaluation, it could be shown that 18 out of 19 aneurysms (in patients) were found by analyzing the automatically generated video sequences. The aneurysm that was missed was occluded by bony structures—a situation where even expert radiologists may miss an aneurysm in slice-based visualizations.

The original approach was later refined by Roessler et al. [RWIB*07] who provide a GPU-based solution for the effective computation of the video sequences. Thus, the computation of transfer function parameters, the direct volume rendering and video encoding are carefully distributed to achieve optimal load balancing.

### 3.2. Re-use of Animations for Surgery Planning

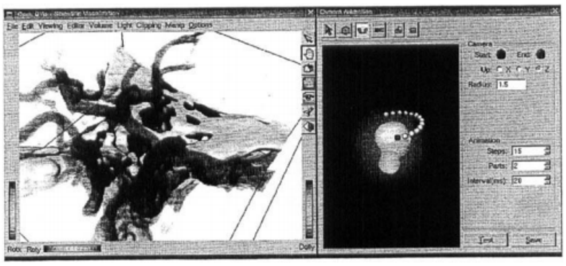
Surgery planning has similar requirements than diagnosis: A precise understanding of the pathology and the spatial relations around it is essential for surgery planning as well. Additional requirements relate to the discussion of different surgical strategies, e.g. the selection of an implant, the selection of an access path or the choice of a more or less radical intervention.

Muehler et al. [MP10b] discussed the use of animations for surgery planning (oncologic neck and liver surgery planning). They emphasized that animations may summarize a longer individual planning process for collaborative discussions, e.g. in a tumor board. This requires an easy generation of animations and the re-use of one animation for similar cases. For tumor surgery planning, access planning and the assessment of infiltrations are typical examples. Access planning can be supported by an animation that moves the camera gradually from outside closer to the tumor, eventually combined with fading out occluding structures. The assessment of potential infiltrations requires to study the tumor and nearby structures, such as vascular structures. A careful investigation from many different viewpoints is necessary, i.e. an animation where the infiltration of all potential risk structures is displayed sequentially. For each structure, a rotation around the tumor from a fixed distance (orbiting) in an appropriate speed is needed. If such an animation is defined once, e.g. for a neck tumor, it can be adapted to many similar cases.

The system described by Muehler et al. [MP10b] provides substantial support for animation generation. Automatically generated and manually selected viewpoints can be employed to define a smooth camera path. So-called *key states* can be defined and stored for later re-use with a different dataset.

**Slice-based animations.** Muehler et al. [MP10b] also considered slice-based visualizations and provided means to animate them. Thus, the system navigates the user within the slices and emphasizes important pre-segmented structures with either colored contours or a certain fill style. The slice-based animations may be structured in meaningful parts, e.g. assessment of lymph nodes of a particular region. The re-use requires that the same structures indeed are assigned the same labels.

**Planning neurovascular compression syndrom surgery.** The neurovascular compression syndrome is characterized by vascular structures that touch the intracranial nerve which may lead to considerable pain that requires neurosurgical treatment. Vega et al. [HNN*03] use the techniques developed in the same group (recall [IHT*02]) to create standardized videos for surgery planning. The videos were used for rehearsal in the operating room where they could be watched via a laptop. The animation generation could be controlled by parameters, such as the temporal resolution, the number of steps and the radius of the sphere on which the virtual camera rotates [HNN*03] (see Fig. 1). In the terminology of diBiase et al. [DMKR92], this represents an *on-demand computation* of an animation that is primarily used to explore the data.



Radius: 1.5

Steps: 15

Parts: 2

Interval(ms): 20

**Figure 1:** *Animation generation: The small spheres on the right indicate the camera path. The size of the sphere, the number of steps and the temporal resolution can be adjusted. The left view serves to test the current specification (From: [HNN*03]).*

## 4. Temporal Medical Animations

According to the terminology used in cartography [KEM97], we discriminate *temporal* and *non-temporal* animations. A temporal animation (in cartography) depicts spatio-temporal patterns, such as the development of crimes in different regions (*crime mapping*), population growth, migration patterns or the spread of an infectious disease. Thus, the depicted changes indicate how values in different regions change over time. A non-temporal animation (in cartography) presents static data focussing on different regions, typically combined in a smooth movement. As an example, to study large scale phenomena, a globe is slightly rotated to display geo-referenced data in different parts of the world. Thus, geometric transformations, such as rotation, zooming, and translation, as well as emphasis techniques, such as modifications of colors, are typical examples for non-temporal animations. In the terminology of Parent [Par12], temporal animations are primarily *data-driven*, representing *primary motion* captured in dynamic medical image data. We also consider *procedural animations*, e.g. animations resulting from biomedical simulation. For the visualization, the simulated character is often not directly addressed. The generated animations strongly depend on assumptions and parameters guiding the simulation. Thus, a procedural animation may also be employed to study the plausibility of the underlying simulation model.

### 4.1. Temporal Animations of Raw Medical Image Data

Temporal animations in medicine primarily relate to dynamic medical image data, such as MR perfusion, 4D PC-MRI data, and 4D angiography data. Animation is a also natural choice to present the results of unsteady simulations, e.g. in hemodynamics, biomechanics or biophysics.

Compared to cartographical animations, one major challenge in the animation of dynamic medical image data is due to the fact that a living patient is imaged. Thus, breathing, pulsatile blood flow, muscle relaxation and other physiological processes hamper the interpretation of four-dimensional data (3D+time). As an example, if the contrast enhancement in the female breast is analyzed to characterize a suspicious lesion, the lesion is moved primarily due to breathing and therefore a voxel with coordinates $x, y, z$ at time $t_i$ often does not correspond to a voxel with the same spatial coordinates at time $t_{i+1}$. Motion correction, actually a type of image registration, is therefore necessary as a pre-processing step [POM*09]. We will not discuss motion correction here. Instead, we assume that these problems are either not severe and can be ignored or they are already solved with appropriate methods.

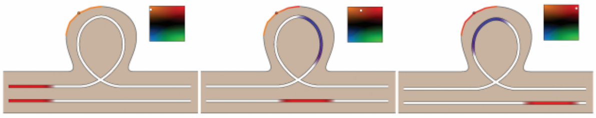


**Figure 2:** *Animated pathlines represent simulated blood flow over time. In the scheme, one pathline enters the aneurysm whereas the second remains in the parent vessel. The part of the pathline that corresponds to the current time is emphasized by color. A Gaussian was used to modify the color saturation with a peak at the current time point (From: [LGP14]).*

**Animated Display of Blood Flow Data.** Lawonn et al. [LGP14] animated pathlines, representing simulated blood flow in cerebral aneurysms, i.e. dilatations of the cerebral arteries (recall Sect. 3.1). The animation conveys differences in speed which is essential for risk analysis. High-speed flow that enters the aneurysm and hits the wall is related to an increased risk. The display of the pathlines is adjusted such that regions of the pathline that are close to the vessel wall are emphasized by appropriate colors (see Fig. 2). This is valuable since the spatial relation between the pathline and the wall of curved vessels may be difficult to perceive, e.g. due to occlusion. Whether these animations correctly convey all relevant information or are too difficult and cause change blindness, was not tested.

**Adaptive Temporal Scale.** Temporal animations are typically characterized by a constant temporal scale, i.e. a factor that translates world time to display time. This is usually beneficial, in particular if users are accustomed to such animations, e.g. physicians that routinely analyze dynamic medical image data. However, a constant temporal scale implies that some parts of an animation are less interesting, e.g. because the rate of change is low or the changes are not essential for the diagnostic task. On the other hand, other parts of the same animation may be considered too fast to recognize and interpret changes. When analyzing cardiac blood flow data, for example, physicians look carefully when vortical behavior is visible and wait when no such behavior occurs. Based on these observations, Koehler et al. [KPG*16] described the choice of an adaptive temporal scale based on an appropriate "interestingness" measure. The system is applied to 4D PC MRI data and the interestingness measure is based on vorticity, e.g. more time is spent on temporal intervals with a large amount of vortical behavior, whereas intervals where the flow is laminar are displayed faster. The underlying algorithm is inspired by histogram equalization, i.e. it aims at a constant amount of feature visibility over the whole animation.

The feedback from physicians was positive in general. The physicians emphasized that it is necessary to have an option to disable this adaptive behavior. Thus, the adaptive temporal scale may not replace the constant scale, but it gives a valuable additional perspective. Another aspect of the physician's feedback was that the adaptive character needs to be communicated by an appropriate legend. In particular, because constant scale animations are so widespread, users need to be made aware if a different scale is employed.

This strategy may be applied to a wide range of dynamic image data and interestingness measures that may be interactively adjusted. As an example, also other flow features or the maximum speed may influence the local temporal scale.

**Dynamic Contrast-enhanced Perfusion Data.** Perfusion data represent the contrast enhancement over time. They are acquired, e.g., to analyze the perfusion of the brain after an ischemic stroke or to analyze the perfusion of the heart muscle after an infarction. In these examples, the temporal resolution is rather high and therefore an animation can be generated that represents sufficient temporal continuity. The animations cycle through the time frames and are valuable "to assess image noise and artifacts, but especially for the assessment of enhancement patterns" [POM*09]. The use of animated functional image data for quality control was also emphasized by Choyke et al. [CDK03].

**Estimating and Visualizing Heart Motion.** In the diagnosis of the coronary heart disease, animation is also used to study the ventricular wall motion. The most abnormal behavior is represented by *akinetic regions* that do not contribute to the wall motion, typically since this tissue is ischemic after an infarction. Heart motion is usually assessed with 2D echocardiography where physicians analyze the wall motion in a few selected slices and mentally combine their impressions to a model of the complex movement and its pathological variations. Already in 1987, Jilin et al. [JAES87] described how the information extracted from individual slices may be combined in a smooth 3D animation. Jilin et al. suggested to manually contour four slices representing two longitudinal and two cross-sectional slices (both at end-systolic and end-diastolic state) and to interpolate between them with splines.

The visual inspection may be enhanced by a quantitative analysis of the velocity magnitude and direction. Suehling et al. [SAJ*03] introduced optical flow methods to fit velocity distributions to echocardiography data and superimposed either velocity magnitude (color-coded) or velocity direction (using arrows) on the animated display. Since then substantial research was carried out to improve motion estimation. However, no recent publication discusses visualization techniques to display the results in appropriate animations.

### 4.2. Temporal Animation in Functional Anatomy

Functional anatomy comprises an understanding of the relation between anatomical structures and their function. This includes the movement of joints (biomechanics), the pumping of the heart muscle and the pumping of the Eustachian tube [HH95]. Computer-generated animations to convey these functions are typically based on an explicit modeling of these movements. Thus, in contrast to measured or simulated blood flow, there is no predefined and precise temporal scale. However, we consider these animations also as *temporal*, since a dynamic process is displayed and the modeling typically aims at realistic and physically-based movements.

Functional anatomy is not only essential within anatomy education but also in areas, such as forensics, where possible reconstructions of body posture may be important to understand possible scenarios of a crime [MZL10]. An essential basis for the animation of biomechanical movements is the H-Anim ISO/IEC standard that comprises a model of the human anatomy consisting of joints and segments [JB08].[†] The movements resulting from using H-Anim are based on Newtonian's laws of motion (*scientific animations*). They are employed, e.g. for forensic investigations [MZL10]. Based on H-Anim, data from a CT or MRI scanner can be employed to extract a skeleton and match it with the abstract data incorporated in the standard. Then, the model may be animated displaying correct movements. The H-Anim standard incorporates a hierarchy of joints, e.g. when the arm is moved, the hand is moved as well. The joints are modeled at four "levels of articulation" [MZL10]. The coarsest model consists of an 18-joint skeleton; more detailed levels comprise 71, 94 and 144 joints respectively. H-Anim also provides a Web3D-capable motion viewer that may export animated films. H-Anim is used in particular to move the whole human body—not just the skeleton. Thus, skin vertices for example are also moved in a realistic manner when associated joints are moved.

### 4.3. Temporal Animations of Map-Based Medical Data

In medical visualization, projection-based (or map-based) techniques are often used to reveal the distribution of parameters at a glance, i.e. without occlusion problems inherent to 3D visualizations [KMM*18] For dynamic data, e.g if the results of an unsteady flow simulation are projected, map animations arise. Value changes, e.g. pressure or blood flow velocity, are typically color-coded leading to dynamic heat maps. Like other temporal medical animations, the temporal scale needs to be carefully chosen. Also other aspects, e.g. the use of temporal smoothing to avoid short-term fluctuations, require careful consideration. While in similar cartography animations considerable experience exists how to reduce map complexity [TM18], we found no medical map-based visualizations taking map complexity into account.

Spatial epidemiology is an area that is at the intersection between medicine and geosciences. In spatial epidemiology, the incidence of diseases, health disorders, such as fatty liver, and potential risks, are depicted on maps (typically with data aggregated over administrative units, so-called choropleth maps). Such maps reveal *disease clusters* and enable an in-depth analysis [CRN*08]. Typically, the underlying data is time-dependent and thus temporal visualizations, such as change maps or animations are generated. General issues of animated choropleth maps are discussed by MacEachren et al. [MD91]. MacEachren et al. [MBHP98] show medical examples of map animations. Animations in their system are generated on the fly after the user specified a temporal interval that should be shown. Moreover, attributes, such as the incidence of heart diseases among man and the unemployment rate, may be chosen. Such bi-variate map animations require to discretize the values or even to binarize them, e.g. regions with elevated numbers and numbers below a threshold are distinguished—leading to four different value combinations.

Iqbal et al. [IHN*16] focussed on cancer prevention analyzed associations between chronic diseases, such as diabetes, and common

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[†] `http://www.web3d.org/working-groups/humanoid-animation-h-anim`

**Table 1:** *Major temporal animation systems in medicine (ordered chronologically).*

| Data | Application and Major technique | Key Publications |
|---|---|---|
| 2D Echocardiography | Diagnosis of heart motion, interpolation | [JAES87] |
| Video-captured data | Anatomy education, Eustachian tube | [HH95] |
| 2D Echocardiography | Diagnosis of heart motion, motion estimation | [SAJ*03] |
| Functional image data | Quality control | [CDK03] |
| Spatial health statistics | Spatial edidemiology, map animation | [CRN*08] |
| Modelling with H-Anim | Forensic investigation | [MZL10] |
| Simulated Bloodflow | Aneurysm Diagnosis, animated pathlines | [LGP14, MEB*17] |
| Measured Bloodflow | Cardiac diagnosis, adaptive temporal scale | [KPG*16] |

types of cancer, e.g. for breast and colon cancer. They displayed these associations for the entire population (based on 782 million patient visits in Taiwan) and for persons of different age groups. The animation in their CAMA (Cancer Association Map Animation) system conveys how the prevalence of chronic diseases and cancer change depending on age. Inspired by Hans Roslings dynamic bubble charts, they employ circular glyphs that change their position in the scatterplot to represent the dynamic character. The glyphs represent the co-morbidities of chronic diseases and cancer.

**Temporal Re-expression.** An idea from cartographic animation that is potentially useful for medical animation is to change the presentation order to convey relations and trends not easily recognizeable in the original sequence of data. Kraak et al. [KEM97] suggest to display periodic data aggregated over the months of the year, such that firstly all January measurements are shown, then all February measurements and so on. For epidemiology data, such animations would reveal the variability of the incidence of influenca within a season, whereas a conventional display would emphasize the seasonal differences. Data that is dependent on the heart beat may be re-expressed such that all peak systolic data are displayed sequentially and all peak diastolic data as well. Table 1 summarizes temporal animation systems.

## 5. Non-Temporal Medical Animation

A wide variety of animation techniques have been developed that use animation to convey the complex spatial relations within the human anatomy. In the terminology of Parent [Par12], these animations are *artistic*, they are neither data-driven nor procedural (guided by a simulation). Most of the non-temporal medical animations are based on surface models derived from segmented medical image data. But also animated volume renderings have been employed, e.g. for virtual endoscopy or for presenting different possible variants of the anatomy as a result of uncertainty characterization. In this section, we discuss algorithms that are essential for medical animations without details about specific applications. We start with the computation of good viewpoints (Sect. 5.1) and continue with camera path planning (Sect. 5.2), which comes in two flavors: the computation of a path to show a patient model from outside and the computation of a path for a fly-through, e.g. inside the bronchial tree. We discuss strategies to annotate (medical) animations (Sect. 5.3) and we discuss scripting languages that were developed to translate high-level instructions in the low-level commands for a graphics library (Sect. 5.4).

### 5.1. Viewpoint Selection

For non-temporal animations a camera path is valuable to show a complex anatomy virtually from different perspectives. The definition of a camera path can be supported by algorithmic components. The overall task breaks down in the selection of good viewpoints and the combination of these viewpoints to a smooth movement. Finally, the speed of the camera movement may be adapted, e.g. close to a key viewpoint the camera may slow down, pause a few seconds and speed up again. The selection of good viewpoints can be guided by geometric considerations. Some target structures should be visible at least to a large extent and their projection should not be too small. Viewpoint entropy, a measure from information theory, turned out to be a good quality criterion for selecting good viewpoints [VFSH01]. In essence, a minimum set of viewpoints is selected that conveys the maximum amount of information. Since viewpoint entropy is highly sensitive to the triangulation, Sbert et al. [SPFG05] suggest another measure based on the Kullback-Leibler divergence.

Viola et al. [VFSG06] and Muehler et al. [MNTP07] sampled a sphere around the scene of the relevant anatomy to determine good viewpoints. Viola et al. [VFSG06] determine one characteristic viewpoint for each object in a pre-processing step.

Muehler et al. [MNTP07] also integrated preferences of surgeons, e.g. views that are familiar to them. Furthermore, a *stability* criterion was incorporated: A viewpoint is only selected if possible viewpoints in the neighborhood are appropriate also. Thus, the camera stays for a while in a beneficial region, e.g. to see a tumor and its surrounding. This stability criterion also supports the interactive exploration, i.e. if the animation is interrupted and the user initiates incremental changes of the camera, the target structures remain visible. Viewpoint selection algorithms are also available for volume-rendered images, e.g. [ZAM11]. There is a large variety of viewpoint selection methods, see the survey article by Bonaventura et al. [BFS*18].

Once viewpoint candidates are determined, a selection can be computed taking into account that the resulting set should be as diverse as possible. Thus, it is ensured that a target structure is really seen from significantly different perspectives. Viewpoints are also characterized by the distance to the interesting structures. Often, it is desirable that the camera maintains a fixed distance—a type of navigation known as *orbiting*.

### 5.2. Camera Path Planning

Finally, the selected viewpoints need to be ordered, e.g. a meaningful sequence is established. This sequence of viewpoints is connected, typically along a path computed as a spline, following the *arc* principle stated by Lasseter (recall [Las87] and Sect. 2.2). There are many variants, how viewpoints may be connected to a camera path. Muehler and Preim [MP10a] discuss the following criteria:

- The path should be as short as possible.
- A path should be chosen where relevant information is displayed during the whole camera movement.
- Unfamiliar or uncomfortable viewpoints should be avoided.

Obviously, trade-offs are necessary. The shortest geodesic path between a set of points on the surrounding sphere does not necessarily reveal relevant information. It may also contain unfamiliar viewpoints. Thus, a weighted combination of the criteria may serve as objective function for an optimization process. Camera path planning may be combined with adjustments of transparency to ensure the visibility of essential anatomical structures. As an example, if a pathology should be shown, occluding objects are rendered semitransparently as long as they actually occlude the target object. Viola et al. [VFSG06] discuss primarily how two viewpoints $v_1$ and $v_2$—each serving to emphasize one structure—may be connected also restricting movements to the surrounding sphere. Their major idea is to carefully determine a *contextual viewpoint* $v_c$ that is traversed along the path, i.e. the geodesic movement between $v_1$, $v_c$ and $v_2$ is used for an animated transition to a new focus object.

The definition of a camera path is also an essential part of fly-through animations inside anatomical structures (*virtual endoscopy*, see Sect. 6.3). However, the requirements and solutions are fundamentally different, since the virtual camera in these applications always remains inside and the target structure is automatically visible. Instead of visibility information, centerlines guide the camera path planning in virtual endoscopy. In virtual endoscopy, *collision avoidance* is of highest importance, e.g. the virtual camera should remain inside the (elongated thin) target structure.

### 5.3. Annotating Animated Visualizations

Labeling is essential in medical education and surgical planning [MP09]. Textual annotations, measures, arrows, and other metagraphical symbols may be used to emphasize certain structures. While labeling static medical visualizations was extensively analyzed [OP14], only one publication [GHS07] describes the special problems and possible solutions related to labeling animated objects.

Labeling animated objects requires real-time capable layout algorithms [GHS07]. Moreover, *temporal stability* of label positions and, if present, connection lines needs to be ensured. An internal label that is embedded within the related graphical object is moved with that object which is perceived as natural [MD08]. However, strong changes of the viewing direction may hide the label and strong zooming operations lead to very large or very small labels. External labels that are connected via a reference line to the related graphical object may stay at a constant position. Thus, only the connection line needs to be updated. The potential drawback of this strategy is that the place occupied by labels may be subject to relevant changes in the data. Thus, while labels may be placed at regions where they initially do not occlude important parts of the data, they may later occupy salient regions, e.g. where a vortex arises. Goetzelmann et al. [GHS07] suggest the use of video processing techniques to identify *calm regions* with little changes that may serve for label placement. Their paper employs examples from engineering, e.g., labeled animations that explain complex engines. The strategies can be translated to 3D models of a patient anatomy.

### 5.4. Scripting Languages

Modern visualization toolkits, such as Amira [SWH*05], contain simple and general scripting facilities to generate camera movements and object transformations. These, however, are not sufficient, e.g. to effectively explain the anatomy in a particular region or to support a tumor board discussion on the resectability of a tumor. In the following, we describe more powerful mechanisms for animation generation, including scripting languages.

The generation of animations based on a scripting language was first described by Catmull [Cat72] and later by Zeltzer [Zel91]. Zeltzer [Zel91] refers to the level on which an animation is specified as *the task level* where *visualization goals* are formally described. An example for a task may be ”show object <name>”. As a prerequisite for using such scripts, a 3D model with an object structure is needed and each object should be assigned a meaningful name, e.g. the name of an anatomical structure.

To bridge the gap between such high-level task specifications and the low-level commands of a graphics library, where precise coordinates for cameras, light sources and other objects are needed, *decomposition rules* are used. These rules represent knowledge how to achieve a communicative intent with a vido sequence. Several authors describe decomposition rules that are inspired by traditional filmmaking. An early example of such an animation system is ESPLANADE (Expert System for PLANning Animation, Design and Editing) [KF93]. Karp and Feiner [KF93] employ a 4-level-hierarchy with tasks on the top level, and sequences, scenes and shots at the lowest level. ESPLANADE provides support for primary, secondary, and tertiary motion (recall Sect. 2.1). The sequence level contains tertiary motions, such as dissolve and wipe.

ESPLANADE was employed to illustrate technical models, such as engines. The animations also include exploded views and cutaways that ensure the visibility of essential objects. It is straightforward to apply the same principles to datasets consisting of medical surface models where tumors and their local surrounding, e.g. possible infiltrations are displayed instead.

Butz [But94] presented a scripting language for animation generation that was integrated in a larger presentation planning system which comprises also text and static image generation. In his BETTY system, an animation is hierarchically represented as a sequence of components that may be further decomposed in subsequences. One node in this hierarchy may have several subnodes—representing components that are shown in parallel. Thus, several movements may be carried out simultaneously. Also BETTY was applied to generate (dynamic) technical illustrations and involves rotations of objects, camera movements, and the generation of exploded views.

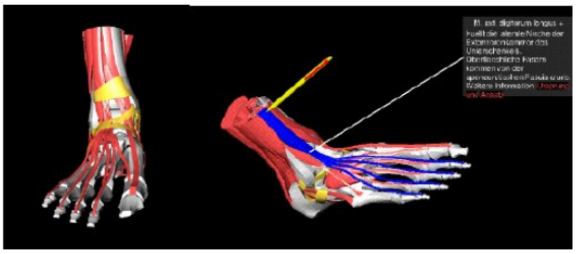
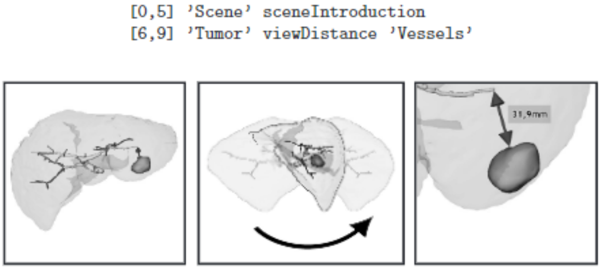


**Figure 3:** *Two screenshots from an animation for anatomy education: The initial view of the foot anatomy is rotated; a pen points at the origin of a muscle and a ligament that partially occluded the muscle was made transparent. A textual explanation is displayed. In the further course, arrows follow the different branches of the muscles guided by its centerline (From: [PRS96]).*



```
[0,5] 'Scene' sceneIntroduction
[6,9] 'Tumor' viewDistance 'Vessels'
```

**Figure 4:** *The two instructions (on top of the images) specify an animation. The numbers in brackets specify the temporal interval. The "sceneIntroduction" creates a horizontal rotation. The "viewDistance" statement creates an animation that zooms to the two specified objects and integrates the display of their minimum distance (From: [MBP06]).*

Preim et al. [PRS96] adapted these strategies to generate animations for anatomy education. In addition to the objects of the scene, also meta-graphical symbols, such as arrows could be used to explain anatomical structures. Moreover, textual labels and multiline explanation were available and could be integrated in a smooth animation. For this purpose, continuous zooming techniques were employed to provide the space to include the textual components. At the task level, authors could specify which objects or groups of objects should be explained. Their IllustratorControl language provides commands to further specify how objects should be explained, e.g. whether an arrow should be used to show an object (see Fig. 3). The basic idea of this language was to generate expressive animations even with very short descriptions, but to enable more fine-grained control optionally. In particular, authors can specify with how much detail an object is explained. The author does not need to specify timings—the inbuilt rules compute how much time is needed for certain changes based on observations of what can be interpreted. However, this also represents a limitation, since authors may want to deliberately deviate from the default animation speed. The IllustratorControl language supports primary motions, e.g. motions of arrows and other pointing devices and secondary motions, but no tertiary motions.

The interpretation of the script controls an Open Inventor program, where primarily the support for interpolation was employed. In addition to camera movements and transformations of objects, also the appearance could be adapted, e.g. in a smooth transition. As an example, the transparency of an object could be increased to enable the recognition of an occluded object and to fade out an outer object, e.g. an organ.

Muehler et al. [MBP06] also provide a scripting language for generating medical animations with a focus on intervention planning. They also incorporate movements of clipping planes, the presentation of slice-based visualizations and simple animated volume renderings based on changes of 1D transfer functions. Clipping planes may be selective, e.g. they may be applied to a subset of all anatomic structures. Like in other systems, camera positions are specified relative to objects instead of using absolute coordinates. The time in this scripting language is explicitly specified as an interval, i.e. an instruction starts and ends at an absolute time (in seconds). Thus, the execution of instructions may overlap, e.g. a second instruction specifies a movement that starts two seconds later and ends at the same time as a first instruction. Figure 4 gives an example for an instruction and screenshots from the generated animation. The terms used in the scripting language are related to therapeutic questions. Also the scripting language of Muehler et al. supports primary motions, e.g. motions of clipping planes and secondary, but no tertiary motions.

**Discussion.** Although individual scripting languages provide considerable support specialized on a number of medically relevant tasks, they are not comprehensive. As an example, no medical animation system provides support for tertiary movements, e.g. typical transitions between scenes.

### 5.5. Navigation-Assisted Animation Design

Liao et al. [LHM14] introduced a completely new approach to animation design. Instead of keyframing or scripting languages, they exploit characteristics of the exploration process of domain scientists to create animations. This is surprising first, because an exploration process with a considerable amount of trial-and-error differs strongly from a presentation situation that *summarizes* the findings. However, the trial-and-error phases are removed and it turns out that users created animations with a similar quality like with a keyframe-based system in a shorter period of time. The use case considered there was the analysis of a time-varying hurricane dataset.

## 6. Selected Applications

In this section, we give an overview of applications where animation was employed to support medical education, diagnosis, treatment planning and also forensic use cases. We comment, if possible, on the specific animation design and evaluations that assess the value of animation, typically by comparing with other modes of information presentation.

### 6.1. Medical Education

Animations were developed and evaluated in a variety of medical education applications, including anatomy education, embryology (neonatal development), surgery training, histology, cellular processes and regional anesthesia teaching. The survey article by Ruiz et al. [RCL09] lists 13 papers using animation for medical education. Animations for educational purposes should be designed with the findings of learning theory on the reception of animation in mind (recall Sect. 2.1).

**Anatomy Education.** The use of 3D visualization for anatomy education was widely discussed including commercial systems [PS18]. However, only very few systems provide animations or explicitly discuss their use for anatomy education. Pioneering work was carried out by Habbal and Harris [HH95]. They argue that the potential of animation is particularly high for displaying functional anatomy (recall Sect. 4.2). In their pilot study they employed drawings of the human heart, imported them in a professional tool (3D Studio Max) and used keyframing to create animations that depict the complex relation between the valves and the ventricles. They included movements of incompetent heart valves to illustrate this pathological process. The whole animation design fulfils their philosophy: “A successful animation requires three mutually dependent components: good artistic modeling, high quality images and a story to tell” [HH95]. Most of the paper deals with strategies to cope with the hardware limitations at that time.

Based on the scripting language described in Sect. 5.4, Preim et al. [PRS96] discuss the process of generating animations to convey the spatial relations between bones, muscles and ligaments, using examples from the foot and knee anatomy. The animations contain rotations to show particular structures, the display of instructional text, e.g. the innervation and origin of a muscle, and emphasis by changing colors. Inspired by the way lecturers explain elongated structures, such as muscles, pointing devices are used to illustrate the course of such structures (recall Fig. 3). The underlying geometric models consisting of a few dozens of labeled anatomical structures were created by digital artists and acquired from a commercial vendor. Thus, the models are not patient-specific—an aspect that was considered essential for educational aspects [McG10].

We briefly discussed the use of animated exploded views for technical illustration (recall Sect. 5.4). The same principles have been employed in an anatomy education system to reveal spatial relations [RPDS00], see Fig. 5. Exploded views may be achieved by slightly scaling down anatomical structures, thereby increasing the gap between them. Animating the transition between the original state and the exploded view reduces the mental effort to understand the relation between both.

Vernon et al. [VP02] discuss teaching aids, including 3D models and (only briefly) animation for medical teaching. The paper provides recommendations, largely focussed on commercial tools and their use. Keyframe animation and motion capture to support biomechanical animations are emphasized. Compared to the large number of systems that provide interactive exploration of 3D models for anatomy teaching (recall [PS18]), the use of animation in this area is limited. Fisk [Fis08] discusses the value of animations for various medical disciplines. With respect to anatomy education, he emphasizes the possibility to display objects from unusual viewpoints that are hardly possible, e.g. when dissecting a cadaver.

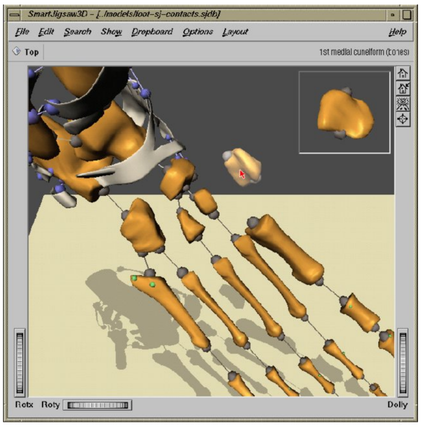


**Figure 5:** *An exploded view of the skeletal anatomy of the foot was created in an animation. The exploded views are embedded in a comprehensive anatomy education system (From: [RPDS00]).*

**Surgical Training.** Dynamic presentations play an essential role in surgery training. However, intraoperative video is the presentation mode. As an example, WebSurg (`https://www.websurg.com`) provides thousands of videos for explaining a large variety of surgeries. The videos are structured according to major steps of the surgery and contain textual explanations in the style of PowerPoint slides. In addition, computer animations often show slice-based visualizations and related annotations that make the user familiar with the pathology and the surrounding anatomy.

Cutting et al. [COH*02] discuss the use of 3D animations for surgery training and provide evidence that 3D animations are valuable for surgery training. They deal with cleft lip and palate surgery and developed an animation based on polygonal models of skin, bone, cartilage and muscles. The models were smoothed, and simplified and imported in Maya (Alias/Wavefront, Toronto, Canada). The animations show the action of a scalpel.

The major problem is that the use of a scalpel changes the geometry radically: Incisions alter the topology of the underlying geometric models. Maya and other commercial animation systems do not provide support for adequately treating such topology changes. As a consequence, Cutting et al. prepared many small animations (without topology changes) and combined them in a final step [COH*02]. Since the anatomic model contains different layers, transparency is used to display the skin and inner layers, e.g. the nasal cartilage complex, simultaneously. Movements of the skin are propagated to the (linked) inner layer representing cartilage and muscles. The animation is actually a hybrid between temporal and non-temporal animations. The temporal component is a simulation of the pump mechanism of the Eustachian tubes, whereas camera movements and zooming operations represent the non-temporal component.

**Endoscopic Ultrasonography.** Endoscopic ultrasonography is an essential imaging technique that requires considerable experience to be used effectively. Burmester et al. [BLH*04] developed a training system that supports the understanding of this imaging technique. The system was based on the VOXELMAN, a comprehensive anatomy education system, that employs the Visible Human dataset. Ultrasonography images were simulated to create appropriate animations. The basic functions to control a video, e.g. playing forward and backward, were supported.

**Regional Anesthesia Teaching.** "Regional anesthesia requires clinical skills of patient positioning, surface marking, and needle manipulation" [LBR04]. Lim et al. observed that training opportunities largely depend on suitable patients and decreased over time. In their specific example, they aim at a training of the interscalene brachial plexus block, a regional anesthesia that is indicated for arm and shoulder operations.

Lim et al. prepared a number of small animations, lasting between 2s and 8s, showing individual steps of the procedure. TrueSpace from Caligary was used (the system is no longer available). A neck model was prepared and used for selecting good viewpoints to demonstrate surface landmarks and the needle movement. Similar to Cutting et al., Lim et al. [LBR04] emphasize the importance of transparency to convey the spatial relations. They also emphasize the role of incorrect handling of the needle and their consequences as part of the generated animations. All animations were integrated in a PowerPoint presentation to convey the overall process.

The evaluation was carried out with 24 users ranging in their experience from those with no experience in this area to experts. The large majority (21 users) stated that the animations enhanced their anatomical and technical understanding. Users also had to set surface markers for needle placement. Those with little to moderate experience improved their performance significantly after the presentation with the integrated animations, leading Lim et al. [LBR04] to the conjecture that "less advanced trainees would probably benefit more from didactic teaching. Therefore, we chose a less interactive approach." The realistic evaluation is a strength of the paper. Unfortunately, little details about the animation design are given. Thus, it is not clear which decisions lead to this favorable outcome.

**Discussion.** 3D animations are particularly useful for training procedures where they are used to explain individual steps or the composition of a procedure based on these steps. Carefully designed animations use different viewpoints that provide an unobstructed view to the relevant anatomical structure and instruments, including viewpoints that are impossible to realize when preparing a real video. Transparency is another powerful mechanism in a 3D animation to convey spatial relations, e.g. within a transparently rendered organ. Moreover, the visual display in an educational 3D animation is clearer and easier to interpret compared to an intraoperative video. For interventions, such as anesthesia teaching, a video could not show interesting internal details. Cutting et al. [COH*02] argue that animation supports an *early stage* of learning, whereas more experienced learners benefit more from active types of learning, e.g. solving tasks in a virtual reality simulation system.

## 6.2. Patient Education

Complex spatial information needs to be conveyed in the process of patient education before surgery or interventions. The information comprises major steps of the intervention and the risk for associated complications. In the following, we describe three animation systems for patient education.

Hermann [Her02] compared the quality of patient education with 3D animation with a conventional approach based on textual information only. The regional anatomy around the thyroid gland and basic steps of surgery are shown in an animation created with Cinema4D. The specific complications that may arise related to anatomical structures, e.g. nerves, in close proximity are also displayed. The control group had 10 minutes time to read a textual explanation carefully adapted to patients. The animation group (both groups comprise 40 patients each) reported significantly better subjective understanding and more trust. The patients considered an abstract graphical display also as superior to a video sequence showing the actual surgery. The description, however, is not comprehensive. No details about the specific design of the animation, e.g. duration, speed, camera paths, are given. The screenshots indicate that the visualizations are rather simple and clear with high contrast. The anatomical structures are strongly smoothed and thus easy to perceive. The animated anatomy is not patient-specific. It was prepared once and re-used often to justify the expense of around 20.000 Euro.

We already described the SinusEndoscopy system (recall [KKSP08]). This system was also used for patient education. Thus, the surgeon explained the surgery and associated risks based on the specific data of that patient. The virtual camera moved along a precomputed path leading to animations that last about 40 seconds. The animations were presented by the operating surgeon on a large 40 inch monitor to explain the surgical strategy to the patient. The evaluation revealed that the large majority of 127 patients found these animations helpful. Additional comments reveal that patients gained trust in the procedure. The medical implications are described in a medical journal paper [SLF*09].

McGhee [McG10] describes an approach to generate animations that emphasize aesthetics, appeal and artistic proficiency to engage learners or patients. As an example, material properties and shaders are carefully tweaked to achieve highly reflective vessel visualizations (derived from clinical MR angiography). They contain blood cells and indicate blood flow during the cardiac cycle (see Fig. 6). McGhee also emphasizes the "narrative", the story that is conveyed by means of dynamic images to "engage students and improve their understanding of disease ... and treatment" [McG10]. McGhee also provides a discussion of further evidence that pictorial content is beneficial for patient education. In conclusion, animation is beneficial for patient education in case of planned surgical interventions.

## 6.3. Virtual Endoscopy

Virtual endoscopy, where a camera is moved inside the human body, is probably the most important area for generating animations in medicine. Virtual endoscopy is an umbrella term:

- Virtual angioscopy relates to virtual endoscopy in the arteries,
- virtual bronchoscopy to the inspection of the bronchial tree, and
- virtual colonoscopy addresses the search for polyps in the colon.

An animated "fly-through" is generated to inspect the walls of tubular structures. Due to the complex shape of structures, such as

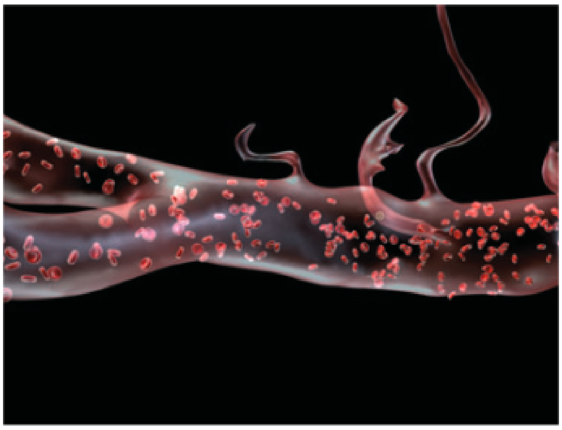


**Figure 6:** *The human aorta and some of its side branches extracted from MRI data and combined with a particle simulation with blood flows (From: [McG10]).*

the colon, a keyframe animation based on user-selected key viewpoints is tedious [JLS*97]. Instead, the generation of a "fly-through" requires little user input, i.e. the user selects a start point and an endpoint in the target structure, e.g. the colon.

**Camera path planning.** Based on an automatic segmentation and centerline determination, a path is created that connects the start and endpoint. All points along this path are inside the target structure, approximately in the middle. For strongly curved self-intersecting structures, this is not easy to achieve. A focus of path computation is to avoid collision with the wall of the target structure. The centerline may be post-processed to better serve as a camera path. It is often smoothed to avoid sudden changes of the camera direction. However, collision avoidance always has higher priority. The centerline may contain many branches caused by bulges in the target structure.

All these processes may be performed with default parameters in a predefined manner and as a result an animation is created that smoothly connects the start and endpoint to enable the physician to inspect the wall of the colon or the bronchial tree. The sensitivity in the detection of polyps along the wall may be improved considerably if the physician watches a second animation that displays the path from the end to the start point. Some folds are better visible if the camera looks at them from the opposite direction. Path planning for virtual endoscopy was first discussed by Lorensen et al. [LJK95]. They adapted concepts from robot motion planning to derive a path where the camera does not collide with anatomical structures. Hong et al. [HKW*95] and Rubin et al. [RBA*96] are other early examples for the generation of offline animations serving as fly-through endoscopy.

Hong et al. [HMK*97] described the first comprehensive virtual colonoscopy system including a careful discussion of useful interactions. The user is guided from the start to the target point and *glides* in the colon center—a navigation inspired by the *submarine metaphor*. Bartz [Bar05] gives a survey on the first decade of virtual endoscopy developments.

**Synchronized animation.** In virtual endoscopy it is typically not sufficient to provide the relevant information. A virtual camera that moves inside a complex structure, such as the bronchial tree, reveals the *local* detail of the bronchial wall surface but does not convey where the camera is in relation to anatomical landmarks, i.e. the *global* context is missing. Virtual endoscopy systems therefore typically generate *synchronized* animations that display the endoscopic view and a 3D view from outside indicating the current camera position and orientation. An alternative to this type of synchronization is the display of 2D slices along with the endoscopic view, where the currently displayed 2D slice contains a cross-hair cursor to indicate the current camera position. A split screen display where external 3D views and 2D slice views are synchronized with the virtual endoscopy view was already suggested by Jolesz et al. [JLS*97]. Even the three orthogonal slicing directions (axial, sagittal, coronal) are often displayed simultaneously with the endoscopic view to support the interpretation of the current camera position and orientation in context (see Fig. 7). On the other hand, this split-screen situation raises interpretation problems of its own (recall Sect. 2).

**Surgery planning.** Virtual endoscopy is also useful for planning endoscopic surgery [ÇK00, KKSP08]. The different target user groups lead to slightly different requirements related to the interactive exploration of the data. Surgeons may use an animated fly-through to define a position where they cut in the tissue. Thus, they do not only want to interrupt an animation but also to mark a position or draw a line. Radiologists, on the other hand, may also annotate an endoscopic view when they see a suspicious region.

Cakmak et al. [ÇK00] created textured geometric models from the Visible Human dataset and assigned mechanical properties to realistically deform medical tissue when forces, such as instruments, are applied. Mass spring models are employed for modeling the dynamic changes. Such functional animations may convey complications, such as bleedings, and the smoke when tissue is ablated [BGG98].

Krueger et al. [KKSP08] developed a virtual endoscopy system for surgery planning in the nasal cavity and patient education (recall Fig. 7). The risk is highly patient-specific, e.g. only in some cases surgery involves areas close to the optic nerve. Since there are no tubular structures that may guide the virtual camera, the camera path is manually defined, e.g. with selecting points in the slices. The surgeon used the generated animations for rehearsal. The information conveyed is highly welcome. On the other hand, the effort to prepare such patient-specific animations is considerable and thus the system was no longer used after the study.

We did not find any publications that describe a perception-based study in which information was actually extracted from such synchronized animations. Obviously, the cognitive load of interpreting synchronized animations is increased compared to the single endoscopic animation.

**Discussion.** Stollfuss [Sto17] discusses animated fly-throughs in detail including the influence of varying parameters that control illumination, texture and other aspects that influence the perceived realism. From a didactic perspective he emphasizes that animated endoscopy is based on data *and* many decisions of an author. We discussed already McGhee's work to characterize the potential of aesthetically pleasing and informative animations for patient ed-

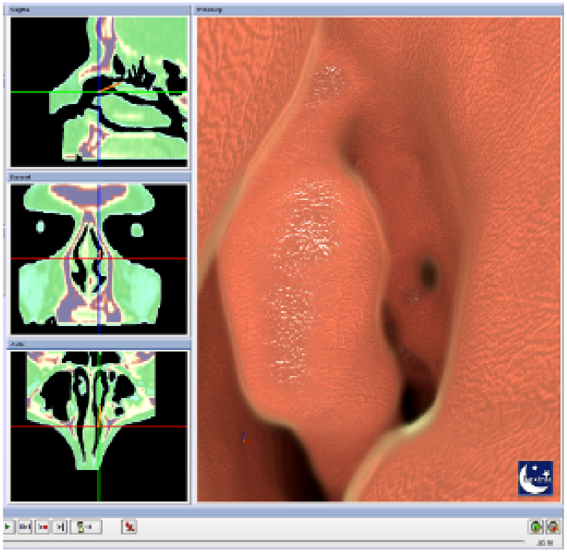


**Figure 7:** *SinusEndoscopy: A system that provides a fly-through the nasal cavities as preparation for surgery. The current camera position is indicated in three orthogonal slices (left), whereas the large right view presents the endoscopic view (From: [KKSP08]).*

ucation (recall [McG10]). Their focus was on *enhanced virtual endoscopy* applied to the vascular system.

### 6.4. Animation for the Diagnosis of Medical Blood Flow Data

In the field of medical visualization with respect to support the diagnosis and treatment planning of vascular diseases, the visual exploration of patient-specific blood flow data plays a crucial role. To assess the severity of a disease and find appropriate treatment, morphological and hemodynamic aspects have to be analyzed simultaneously to understand their interplay. This is a challenging task due to the complexity of the time-dependent data.

We discussed cerebral aneurysms already in Sect. 3.1. Here, we discuss how animations may be used to enhance this diagnostic process by incorporating simulated flow data. For this purpose, Meuschke et al. [MEB*17] developed an automatic selection of optimal viewpoints that are connected to a camera animation for the visual exploration of time-dependent blood flow data in cerebral aneurysms. With this system, suspicious surface, regions can be analyzed according to morphological and flow attributes without a time-consuming manual exploration.

The selection of viewpoints is modeled as an optimization problem. It consists of three major steps. First, a target function is formulated that should be optimized. Second, start points for searching appropriate views are chosen that serve as input for the optimization problem. In the last step, the resulting viewpoints are connected to a camera path. The target function considers visibility of the aneurysm surface part and an interestingness measure derived by two user-selected attributes, e.g. low wall thickness and high wall shear stress. For start point selection, an ellipsoid around the whole vessel surface is sampled discretely. To reduce the number of necessary runs of the optimization procedure, only the top 10 % of viewpoints are further processed. Moreover, a clustering algorithm is employed to group the remaining start points and a representative per cluster is used to determine an optimal viewpoint. Thus, views from different perspectives are generated around an aneurysm showing possible rupture-prone areas. Finally, a camera path gliding around the target structure at a fixed distance (orbiting) is used to create an animation. The evaluation indicates that the generated animation is considered useful for the assessment of the rupture risk. Manually selected views from medical experts showing interesting surface regions were quite similar to the automatically selected views with respect to camera position and view direction. However, manual exploration is required in addition, e.g. to explore small structures, such as blebs.

The interesting situation in this work is that temporal data is analyzed and camera flight, a typical technique for non-temporal animations, is used to focus the analysis to relevant regions and temporal intervals. Thus, the analysis of 3D + time data may also benefit from path planning.

### 6.5. Forensics

Animated visualizations in forensics are generated in case of shootings or other severe crimes. They may integrate different viewpoints, representing, e.g. the position of witnesses. Animations integrate *raw data*, representing the patient anatomy, gun, or knifes, other aspects of the crime scene and *reconstructed data*, e.g. the bullet path [MZL10]. The major use cases for such animations are to discuss possible reconstructions with respect to plausibility and likelihood and to demonstrate the results to the judges in the court room.[‡] "Physically accurate forensic animation may shed light on investigating what exactly happened at a specific crime scene, causes and effects that embrace the issue who is at fault or guilty." [MZL10].

This development is largely based on the increasing use of *virtual autopsy*, i.e. post-mortem CT and MRI data [TBB*05]. Since a cadaver does not move and radiation is not so strongly limited, the anatomy can be displayed in high spatial resolution and with a good signal-to-noise ratio. The data acquisition may be carried out as a whole body scan or as a scan of different body parts that are later combined [VOH17]. Due to the large size of the data, efficient rendering is challenging [LWP*06]. Figure 8 shows an example of a reconstructed crime based on post-mortem data.

Animations in forensics fall in this category. The whole animation generation process aims at faithfulness and credibility. Aesthetic considerations are not essential. Biomechanical animations are employed to discuss possible postures of a victim during a crime. The H-Anim standard is employed for this purpose, where a moderate level of detail (level 2 with 71 joints) is considered appropriate [MZL10].

### 6.6. Animated Display of Uncertainty for Diagnosis

In this subsection, we focus on a selected aspect of medical volume rendering. The display of medical image data involves considerable

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[‡] Ma et al. [MZL10] report that computer-generated animations are admitted in the courtroom in the UK if correctness is carefully analyzed.

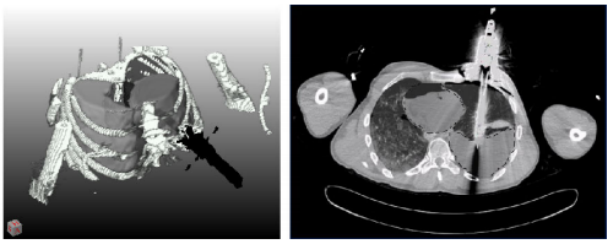

**Figure 8:** *Reconstruction of a crime scene. The cadaver dataset was imaged with CT and the puncture of the lung with a knife is clearly visible (From: [PCH*05]).*

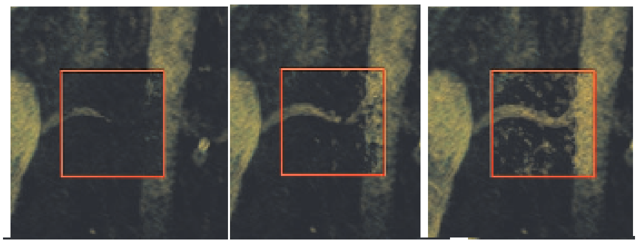

**Figure 9:** *Slightly different transfer functions strongly effect the appearance of a vessel. In a short animation, the possible visualizations are integrated and support an effective interpretation (From: [LLPY07]).*

uncertainty due to the noisy character of the images and further artifacts. Thus, a volume rendering with a certain transfer function (TF) leads to one possible display of the anatomical situation. Slightly modified transfer functions lead to a different but also possible interpretation. While small changes in the transfer function parameters may lead to similar small changes in the visualization, which indicates stability towards these parameters, small changes may also lead to substantial diagnostically relevant changes. This holds in particular for the display of vascular structures in contrast-enhanced CT data. Radiology textbooks inform physicians that the diagnosis of a stenosis should not be based on one setting of a transfer function. Instead, different parameters should be employed as well.

Lundstroem et al. [LLPY07] use animations to convey different TF settings. The border of a vascular structure is considered as an instance of a probability density distribution (PDF). Based on an appropriate sampling of the PDF, different instances are created, sorted according to similarity and combined in a smooth animation. A stenosis—based on this animation—is only diagnosed if it appears in *all* frames of the animation. A *sensitivity lens* is used to restrict the animation to a (small) region, e.g. the region where a static display suggests a stenosis (see Fig. 9). Thus, the foveatic vision is focussed on this area and reliably detects major changes if they would occur. Animation were used for visualizing uncertainty before in geovisualization [ESG97, Fis93]. Later, Akiba et al. [AWM10] discussed a *transfer function overview template* where the opacity TF is animated to reveal all structures in a volume dataset.

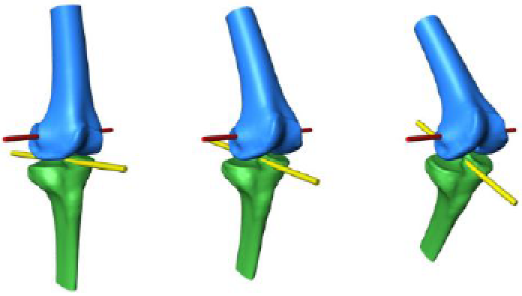

**Figure 10:** *An articulated shape model of the knee with two parts (From: [ALvTZ19]).*

### 6.7. Animated Display of Shape Spaces

Many applications in medical imaging benefit from statistical shape and appearance analysis. Based on a larger number of ground truth segmentations, often a principal component analysis is employed to represent the major modes of variation. Such models are primarily employed for image segmentation, but they also capture knowledge relevant for anatomy education (understanding the variability of anatomy) and for diagnosis (better understanding of the fuzzy boundary between healthy and pathological changes in particular for elderly patients). Ambellan et al. [ALvTZ19] discuss the idea to use animation as an educational visualization to convey the shape space. Instead of showing many instances as small multiples along the 1st, 2nd and 3rd mode of variation, shapes are interpolated (morphing) from the lowest to the highest value along an axis.

Based on the interpolation, a seamless transition can be shown in an animation. While numerous talks on statistical shape models contain such videos, this is hardly discussed in terms of animation design. The temporal scale needs to be chosen carefully, taking the amount of changes into account. Color may be used to emphasize strong deviations from the mean shape. Not only are the geometry of shapes different, but also the appearance, the "texture", e.g. of bones, differs, as an aspect of normal differences or diseases, such as osteoporosis. Animations may also be used to convey these differences. Some anatomical structures exhibit a complex topology, e.g. the hip or the knee. In these cases, shape models are derived for the individual parts and also the relative motion between the parts may be captured—leading to an articulated model (see Fig. 10). Animations may be used to convey both motions of joints (functional anatomy) and variability of the individual parts.

Table 2 summarizes temporal animation systems. It is striking that most systems are based on some kind of CT data which is probably due to the standardized intensity scale. Another interesting aspect is that there is only one recent publications with a focus on non-temporal medical animation.

## 7. Interactive Animations

Interaction is essential to control animations independent of the field of application. We employ cartography to discuss interactive

**Table 2:** *Major non-temporal animation systems in medicine (ordered chronologically).*

| Data | Application and Major technique | Key Publications |
|---|---|---|
| Geometric models of the foot anatomy | Anatomy education, scripting language | [PRS96] |
| Abdominal CT | Virtual colonoscopy, path planning | [HMK$^*$97] |
| Abdominal CT | Virtual colonoscopy, combined 2D and 3D views | [JLS$^*$97] |
| Abdominal CT | endoscopic surgical training tool, effects such as bleeding | [BGG98] |
| Clinical CT, MRI and Visible Human | Virtual endoscopy, surgery training | [ÇK00] |
| Abdominal CT | Surgery training, palate surgery | [COH$^*$02] |
| Geometric models | Regional anesthesia training, transparency adaptation | [LBR04] |
| Neck and abdominal CT | Surgery planning and education, scripting language | [MBP06] |
| CT angiography | Diagnosis of vascular pathologies, uncertainty lenses | [LLPY07] |
| Head CT | Virtual endoscopy, surgery planning and patient education, realism | [KKSP08] |
| Collection of clinical data and segmentation | Variational anatomy, shape spaces | [ALvTZ19] |

animation, since it is integrated and discussed in many cartography publications. In cartography, it is well-known that viewers are frustrated if they cannot control animation speed [MG94]. Ogao and Kraak [OK02] define the following interaction tasks for temporal cartographic animations:

- Adjust spatial and temporal resolution,
- Adjust spatial and temporal scale,
- Enable multiple linked (dynamic) views,
- Query temporal data, and
- Use mouse-over, e.g. show labels, measures, ...

While these interaction tasks are relevant for map-based (2D) animations, additional interaction tasks are essential for 3D animations. The user may stop an animation displayed in a 3D viewer and then interactively explore the data by zooming and rotation. Once the user is finished, a short animation may be generated to return to the initial state, before the animation is continued. The animations generated for anatomy education (recall [PRS96]) can be interrupted in this manner. Such a feature is even more important for virtual endoscopy, e.g. virtual colonoscopy (recall Sect. 6.3). The automatically generated animation leads the physician to a particular point along the centerline where she may notice a suspicious lesion. Then she should be able to explore this lesion, measure its extent, annotate it for a report and then "ask" the system to continue the fly-through.

The discussion of interactive control also comprises input devices. The joystick is a natural choice to control presentation speed [Sto17] but also to steer the camera, e.g. in virtual endoscopy. We found no research comparing input devices for steering medical animations in particular in endoscopy.

## 8. Research Agenda

In this section we focus on general aspects of medical animation and do not discuss in which particular applications animation generation may be promising. The interactive use of 3D visualizations for medical education and therapy planning is investigated quite well, including perception-based studies that characterize the shape and depth perception performance of users associated with these visualization techniques. In contrast, only few studies were carried out to compare different animation designs and their consequences on motion perception and human cognition. In the following we discuss the large potential for future research in medical animations.

**Perception- and Cognition-Based Medical Animations.** The major bottleneck for a widespread use of medical animations is probably not technological. Powerful software tools and computers may be used to generate and use medical animations, even if large medical volume data are involved. Instead, substantial research activities are needed to design animations that *directly* support essential tasks in medical education, surgery planning, forensics and patient education. The systems described in this paper focus on algorithmical details without any discussion of perceptual limitations. Moreover, no evaluation was carried out to investigate what was actually seen in these animations. Task-based experiments are often analyzed based on questions, such as what users have seen, whether a certain object was observed or how long something takes. For cartography animation, Fabrikant et al. argue that eye-tracking experiments should be carried out to better understand the viewing pattern [FG05]. Medical animations for educational purposes have very rarely been designed and evaluated with learning theoretic arguments in mind. Ruiz et al. concluded that "few studies have explored the effectiveness of animations in medical education" [RCL09]. This situation has not changed significantly.

**User Studies for Authoring Systems.** There is an obvious lack of user studies related to the authors' perception of an animation system. We discussed keyframing, scripting languages, and navigation-assisted authoring processes. Comparative studies are needed to understand which animation processes are more efficient, satisfying and provide the desired precision and control to realize the intent of an author.

**Semi-Transparent Medical Animations.** Several authors, in particular physicians creating animations for educational purposes manually (recall [COH$^*$02]) emphasize the unique advantage of displaying movements involving different layers with appropriate use of transparency. The generation of perceptually effective semi-transparent animations, however is challenging. It involves the afore-mentioned aspects of motion perception and the topic of transparency perception [SA02]. Designing and testing such animations is an open research challenge.

**Integrating Measures and Labels.** Therapy planning benefits from 2D and 3D visualizations combined with labels and measures, e.g. the volume or extent of a tumor or the minimum distance to a risk structure. Animations that show a pathology with their surrounding context enriched with this textual information may further support such processes. The textual information may be shown temporarily when the related visual information is visible well or even highlighted. Thus, the integration of textual elements benefits from a synchronization with the graphical elements of an animation.

**Combining Abstraction and Animation Generation.** Illustrative visualization provides us with a broad range of techniques that *abstract* geometric models, e.g. to feature lines [LGP14, VI18]. While abstraction is useful for the interactive exploration of medical surface models, it is probably even more important for animation. Animations are at a greater risk of producing cognitive overload and abstraction may allow to restrict the visual complexity to a level users can cope with. Thus, further research is needed to integrate abstraction in animation generation workflows and to assess the perceptual and cognitive effectiveness of such abstracted animations. Animations may also provide smooth transitions between different levels of abstraction, i.e. a morphing process supports the understanding of relations between different levels.

Temporal generalization, such as temporal suppression and temporal smoothing, from cartographic animations may provide a good source of inspiration. For readers interested in cartography animation, we refer to Maceachren et al. [MBHP98], Harrower [Har07, HF08] and Monmonier [Mon96]. Techniques from cartography animation are particularly relevant if medical projection techniques (see the survey from Kreiser et al. [KMM*18]) are used to depict time-dependent data.

**Combination of Animated and Static Visualizations.** Animated visualizations may give a good overview of spatio-temporal developments and support a goal-directed in-depth analysis. Since animations also have disadvantages, related to change blindness and limited capability to interpret detected changes, it may be combined with static displays that can be observed more carefully. Static visualizations may depict the state of dynamic data at selected temporal positions or *compare* the state at two selected positions. Such subtraction images are used for example in the analysis of perfusion data, to detect regions where the contrast agent arrival is delayed. Moreover, timeline-based visualization is a typical static variant of dynamic data display. It is also used for perfusion data to compare contrast agent enhancement in different regions, e.g. potentially pathologic and likely healthy regions.

The crucial aspect is that static visualizations and animations are linked with each other, e.g. when an animation is displayed it should be obvious where the current timepoint is in relation to a timeline-based visualization.

**Creating Animations to Convey Longitudinal Changes.** Severe diseases, such as cancer or aortic dissections, require monitoring of patients over time to assess growth, shrinkage or other changes of pathologies. Animations may summarize such changes—an idea that is described by Ambellan et al. [ALvTZ19]. Animations that convey longitudinal changes are also potentially relevant in developmental biology, where the stages of embryonal development are analyzed. The special situation with these longitudinal data is that they do not exhibit a regular sampling, i.e. there may be a 200 day interval between two examinations or a 500 day interval. Ideally, an animation that interpolates between the examinations, conveys the uncertainty involved, that is obviously larger for longer intervals.

**Non-Temporal Animating of Volume Data.** Volume rendering is essential for medical diagnosis and treatment planning. Therefore, it would be natural to develop (temporal and non-temporal) animations using the means of volume rendering, e.g. to enhance salient structures. While outside of medicine a number of essential developments were carried out to animate volume data and in particular to control highlighting of different portions [HZM13, RLH14, SRBG10, WS07], this area is under-represented in medicine. The only examples we identified is the work of Iserhardt-Bauer et al. [IHT*02] on aneurysm diagnosis and from Lundstroem et al. [LLPY07] on using animation for uncertainty animation.

**Integrating Animations in Storytelling Processes.** Storytelling for broader audiences becomes increasingly important also for medical applications such as health and patient education. Animation may be a crucial part of storytelling systems that may integrate interactive exploration and predefined video sequences to be interrupted for exploration. Pioneering work in this area was realized by Wohlfahrt and Hauser [WH07] who employed interactive volume visualization with animations. Similar concepts may be particularly useful for a wide range of educational applications in medicine.

## 9. Concluding Remarks

Animation is a useful presentation mode for medical image data and derived models of the human anatomy. The dynamics involved in animation may naturally display processes, such as growth processes and joint movements, and enable a deeper understanding compared to a sequence of static displays. On the other hand, animation design has to consider perceptual and cognitive limitations, related to motion perception, change blindness and cognitive load theory. According to these theories, animations should be rather short and exhibit a low or moderate complexity. Animations may be carefully integrated in overall workflows related to medical education and therapy planning. In educational settings, animations are particularly useful at early stages to make the learner familiar with certain processes. In therapy planning, animations may provide an efficient overview of the relevant patient anatomy, whereas the in-depth exploration of 3D visualizations and 2D slice-based visualizations support the actual decision process. Animations are not restricted to a presentation that is only passively observed: Animations may be generated on demand, they may be interrupted and even a sequence of observing a video and interactively exploring a region is possible.

Non-temporal animations typically employ different camera positions. The computation of candidates for a good camera position and the computation of a path that combines the selected candidates is an essential support for creating non-temporal animations.

A number of publications discuss the use of high-end animation software, such as Cinema 4D, for creating a single (expensive) animation. Since these software systems were not designed with use cases in medical education in mind, they miss important features for such use cases. The retraction of tissue for example cannot be plausibly represented with the deformers provided by Maya [COH*02]. Thus, substantial additional effort is necessary to simulate such a process. These animations are fine-tuned for a particular purpose and can hardly be adapted to new requirements, e.g. to display the use of another surgical instrument. Thus, widespread use of animations requires a streamlined generation process, including re-usable components like the templates introduced by Akiba et al. [AWM10]. In contrast, a number of computer scientists developed animation systems for a wide range of visualization tasks. Often, they are based on scripting languages. To illustrate the difference to the manually created animations: While the selection and combination of viewpoints in non-temporal animations is a tedious process in manually created animations, it is supported by viewpoint computation techniques in more general animation systems.

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