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Spatio-temporal Visualization of Regional Myocardial Velocities

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Abstract

Cardiovascular disease is the leading cause of death worldwide according to the World Health Organization (WHO). Nearly half of all heart failures occur due to the decline in the performance of the left ventricle (LV). Therefore, early detection, monitoring, and accurate diagnosis of LV pathologies are of critical importance. Usually, global cardiac function parameters are used to assess the cardiac structure and function, although regional abnormalities are important biomarkers of several cardiac diseases. Regional motion of the myocardium, the muscular wall of the LV, can be captured in a non-invasive manner using the velocity-encoded magnetic resonance (MR) imaging method known as Tissue Phase Mapping (TPM). To analyze the complex motion pattern, one typically visualizes for each time step the radial, longitudinal, and circumferential velocities separately according to the American Heart Association (AHA) model, which makes the comprehension of the spatio-temporal pattern an extremely challenging cognitive task. We propose novel spatio-temporal visualization methods for LV myocardial motion analysis with less cognitive load. Our approach uses coordinated views for navigating through the data space. One view visualizes individual time steps, which can be scrolled or animated, while a second view visualizes the temporal evolution using the radial layout of a polar plot for the time dimension. Different designs for visual encoding were considered in both views and evaluated with medical experts to demonstrate and compare their effectiveness and intuitiveness for detecting and analyzing regional abnormalities.

Categories and Subject Descriptors (according to ACM CCS): I.3 [Computing Methodologies]: Computer Graphics—

1. Introduction

The heart is one of the most critical organs in the entire human body. It supplies oxygenated blood carrying essential materials, helping bodily functions, and removes deoxygenated blood carrying waste products. If the heart stops pumping blood, the body begins to shut down and eventually dies. The left ventricle (LV), one of the four chambers of the heart, plays a crucial role in the performance of the entire heart. The abnormal motion of its wall muscle (myocardium) is an important indicator for multiple cardiac pathologies [JFB*06]. According to the World Health Organization (WHO), cardiovascular disease is the leading cause of deaths worldwide [FAF13]. Nearly half of all heart failure cases occur due to decline of the LV performance [JFB*06]. Therefore, the early detection, monitoring and accurate diagnosis of left ventricle pathologies is of paramount importance [JFB*06].

Global cardiac function parameters such as ejection fraction, ventricular volume, etc., are routinely used to assess cardiac motion. However, when using global parameters, regional abnormalities are often overlooked. For instance, nearly 50% of heart failure patients have abnormalities in the diastolic function despite having a normal ejection fraction [WN09]. The regional alterations in heart motion are an important biomarker of many cardiac pathologies such as coronary artery disease, cardiomyopathy, or hypertrophic heart disease. According to the recently updated American College of Cardiology/American Heart Association guidelines [JAC*09], one of the key questions that must be addressed in assessing patients with heart disease concerns the structure of the LV [KFM*09].

The advancements in cardiac magnetic resonance imaging (MRI) technology over the last few decades have enabled the investigation of flow and motion such as that of blood and the wall of the LV. With novel techniques such as MR phase-contrast velocity mapping or tissue phase mapping (TPM), myocardial motion can be investigated in great detail with high spatial and temporal resolution [JSM*04]. It enables the extraction of myocardial velocities in all three spatial dimensions (radial, tangential/circumferential, and longitudinal). The three-dimensional nature of TPM is particularly well suited to the study of the complex motion of the LV, allowing an independent analysis of the regional heart function [JSM*04]. It is a relatively new technique and not much has been done in visualizing the data it provides. Current representations do not depict the dynamics of the heart's movement over time.

The primary objective of this paper is to enhance the visual analysis of the cardiac motion to improve the understanding of the physiology and pathophysiology of the heart. We analyze the design space for visual encodings and propose novel methods to vi-

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sualize the data using radial layouts for locally aggregated spatial and spatio-temporal encodings. The spatial encodings represent all information of a single time step, while the spatio-temporal encodings couple 2D spatial with temporal information. The different encodings can be applied individually or in a combined side-by-side fashion using coordinated views. We evaluated our visual analysis methods with leading domain experts in the field to compare the design choices we made against each other and against the state of the art. We were able to demonstrate that our new visual encodings represent the relevant information more effectively and more intuitively and that our interactive visual analysis system can improve the analysis of cardiac motion to detect pathologies.

2. Related work

A variety of tools have been developed for the regional assessment of the ventricular wall motion such as tagging [ZPR*88], displacement encoding with stimulated echoes (DENSE) [ADBW99], diffusion-weighted (DW) [KC07] and TPM [PSY*94] MRI. We distinguish between two types of visualization techniques: techniques that visually represent each time step individually (*spatial encodings*), and techniques that show the temporal evolution of an entire cardiac cycle (*temporal encodings*). The spatial encodings have been used heavily in the literature, while temporal encodings have not gotten much attention.

Spatial encodings. One of the early works on the visualization of the LV wall motion was conducted by Guttman et al. [GZM97]. They used MR tagging to measure the wall movement and visualized the LV as a 3D polygonal mesh with Gouraud-shaded quadrilaterals. They also developed an animation of the 3D mesh to visualize the abnormal contractions highlighted with colors over an entire cardiac cycle. Gilson et al. [GYF*05] used a combination of 3D and 2D vector fields to show the myocardial displacement measured by DENSE MRI. Liu et al. [LWG*09] also used the 3D model of the LV to show the reconstructed 3D model of the LV, and its motion from DENSE MR images. An inherent major problem of visualizing the LV in a 3D space is occlusion. The problem in animating the mesh is that the viewers might have to watch the animation several times to grasp the temporal evolution.

Ennis et al. [EKH*04] visualized the myocardial strain using super-quadric glyphs. Chitiboi et al. [CNS*15] also designed a glyph-based visual encoding to map the radial, longitudinal, and circumferential velocities to a barycentric 3D glyph space. The issue with glyph-based representations is that the changes in orientation and shapes of the glyphs over time can be very complicated to understand, and the 3D layout also suffers from occlusion.

In 2002, the American Heart Association (AHA) standardized the myocardial segmentation and nomenclature for the tomographic imaging of the heart in order to improve the cross-modality clinical patient management and research [Cer02]. For the evaluation of results, they defined a standard model for the representation of the LV based on 16 segments. This model represents a discrete 2D projection of LV slices onto a plane perpendicular to the long-axis visualized as a bull's-eye (BE) polar plot (see Figure 1). The AHA-based visualization model has been used frequently in the literature, e.g., [dMG08].One major issue with this representation is that it does not visualize the myocardium into enough number of segments for it to be useful for the effective analysis of regional myocardial motion – the AHA model divides the basal and mid-ventricular slices into six each, and apical slice into four segments. We follow the idea of Föll et al. [FJS*09] to subdivide each slice into a larger number of segments (24) to provide a more adaptive description of LV performance. An additional problem of standard AHA-based visualizations is that the three velocity components (radial, circumferential, and longitudinal) are visualized separately and a large number of images are generated for a complete cardiac cycle. It is a challenging task to analyze all images separately and assemble the velocity changes in mind. Instead, we propose to combine all velocity components into one image for each time step.

The cardiovascular imaging group at Northwestern University performed several studies for the assessment of the myocardium structure and its function, e.g., [JFB*06]. In these studies, pixel-wise arrow plots were used for the in-plane velocity components (twisting/untwisting and contraction/expansion) and rainbow color-coded mapping for the longitudinal velocities. The rainbow color-coded maps were also employed by Staehle et al. [SJB*11] to visualize the myocardial acceleration. The rainbow color maps are considered perceptually harmful when applied to numerical attributes and may provide misleading information [BTI07]. Föll et al. [FJS*09] follow the same concept using an extended representationof the AHA-based model. Their segments towards the center (apical slice) are very small and look cluttered with overlapping 2D vectors and the in-plane velocity changes in the apical slice are hardly visible. We propose several extensions of this visual encoding in a first step and compare our visualizations with the work by Föll et al. in our user study. Moreover, we extend this encoding by encodings of spatio-temporal information which is then used in conjunction with the visual encodings of individual time steps using coordinated views.

Temporal encodings. To our knowledge, there has not been much work in the literature that visualizes the temporal evolution of myocardial velocity changes over an entire cardiac cycle while keeping the spatial context of the myocardium at the same time (spatio-temporal encoding). Yang et al. [YMMK07] used a similar encoding to compare the longitudinal contractility in a patient with ischemic heart disease with a normal healthy subject. However, they did not follow up on the visual encoding as it was not the focus of their work. Breeuwer [Bre02] used the time series plots to show the uptake of contrast agent in the myocardium over time for the perfusion analysis. In conjunction with the time series plots, he also showed the animation of the LV color-coded by the uptake. Likewise, Simpson et al. [SKF13] also used time series plots to visualize the temporal evolution of all three components of velocity vectors acquired with phase-velocity-mapping MR imaging. All velocity components in basal, mid-ventricular, and apical slices were plotted separately. Although the time series plots show the temporal changes in perfusion/velocities over time, they lose the structural and spatial context. Our approach uses coordinated views for navigating through the data space. One view visualizes individual time steps, which can be scrolled or animated, while a second view visualizes the spatio-temporal patterns by showing the temporal evolution within a spatial context. The spatio-temporal view applies the

general radial layout idea for the temporal dimension presented in *CircleView* [AMST11, KSS04] in the myocardial context.

3. Background

MR Tissue Phase Mapping (TPM). MRI allows for the evaluation of the heart's anatomy, the function of its chambers and valves, and the blood flow through major vessels, as well as other aspects in a non-invasive manner. The MR methods such as tagging [ZPR*88], phase-contrast velocity mapping also called tissue-phase mapping (TPM) [PSY*94], and displacement encoding with simulated echoes (DENSE) [ADBW99], provide the measurements of local myocardium motion with high accuracy. TPM has proven to be a robust technique in comparison with others for the assessment of regional myocardial motion. It offers high spatial ($< 2mm^2$) and temporal ($\approx 20ms$) resolution in comparison with other acquisition techniques [CHS*16]. Hence, within this work, we use TPM data, but the visualization methods proposed here are also applicable to the other imaging methods mentioned above, For this work, three short-axis slices (base, mid-ventricular, and apex) along the LV are selected according to the recommendations by the AHA, as shown in Figure 1. For each slice, a magnitude and three velocity encoded images (one for each x, y, and z directions) are acquired.

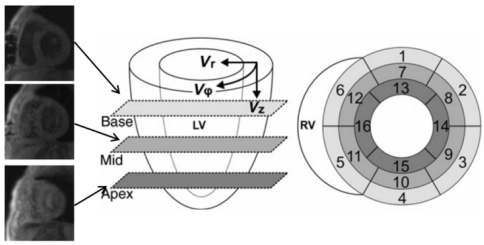

Figure 1: Acquisition of basal, mid-ventricular, and apical slices [CNS*15]

Myocardium segmentation and preprocessing. The images acquired using TPM requires a reliable way of segmenting the myocardium. In this work, we have employed a semi-automatic segmentation technique that uses smooth, iterative contour propagation and probabilistic segmentation using particle tracing based on the underlying velocity field [CHS*16]. The segmentation process provides a mask for all time steps that partitions the myocardium into multiple segments according to the standard AHA model. This mask is applied to all velocity-encoded images to extract the velocity measurements of the myocardial motion.

TPM provides the three-dimensional velocity measurements (v_x, v_y, v_z) in a 3D Cartesian coordinate system. These measurements are transformed into a cylindrical coordinate system (v_r, v_φ, v_z) where the base of the cylinder is oriented and centered along the segmented myocardial contours [CHS*16]. As a result, v_r represents the motion along the radial (contraction/expansion), v_φ along the circumferential (clockwise/anti-clockwise), and v_z along the longitudinal (shortening/lengthening) directions. The description of the velocities in cylindrical coordinates is more useful in describing the performance of the LV.

In order to have a better resolved depiction of LV motion, we subdivide each slice into 24 angular regions [FJS*09]. Furthermore, each angular region is partitioned into epicardium and endocardium segments by dividing the myocardium mask along the radial direction. Myocardial velocities falling within one region are averaged which results in 48 radial, circumferential, and longitudinal velocity components for each slice (basal, mid-ventricular and apical). Eventually, it results in 3x2x24=144 velocity measurements for each time step.

4. Visual encodings and interactive analysis

4.1. Design space and design choices

The outcome of the preprocessing steps can be summarized as unsteady 3D vector fields, where (1) the spatial sampling is provided within a region of interest (LV myocardium) on three distinct 2D image slices (apex, mid, and base) and aggregated over 48 segments per slice, (2) the 3D vectors are given with respect to a cylindrical coordinate system, and (3) the evolution is measured over 30 to 50 time steps (up to one heart cycle).

Since the 3D spatial information is restricted to a segmented region of interest on three 2D slices, the 3D spatial information can be laid out in a 2D representation following the idea of the AHA model. Hence, the first design option is to visualize the three vector field components over 2D layouts depicting 3D spatial information. This spatial encoding represents all information about a single time step and interactive switching between time steps or animations are required to analyze spatio-temporal patterns. Most state-of-the-art approaches, see Section 2, fall into this category. The motivation behind this choice is that experts are already familiar with the AHA representation. We propose new ideas on how to encode the vector fields over such 2D layouts in Section 4.2.

An obvious extension of these layouts is to use the third dimension to encode the temporal evolution, i.e., having a 3D layout with the 3D spatial information depicted in a 2D layout and the time mapped to the orthogonal third dimension. This leads to obvious occlusion problems inherent to 3D visualizations. Opacity mapping can alleviate the occlusion problem, but cannot solve it.Thus, for an intuitive and effective visual analysis of an unsteady 3D vector field this option was discarded.

Another design option is to restrict the spatial information to a 2D slice (comparable to one ring of the AHA model) and combine that with temporal information within a novel 2D layout. We propose to use a radial layout for encoding such 2D-space-plus-time information, see Section 4.3. Such layouts would need to be investigated for each 2D slice individually (or in coordinated side-by-side views), but since there are only three slices that need to be investigated, this seems to be a suitable choice especially since spatio-temporal patterns can be observed more easily. Keeping the ring metaphor in a radial layout is motivated by the fact that the data is given over cylindrical coordinates. Exchanging the third spatial with the temporal dimension is motivated by the fact that we have many time steps in the temporal dimension but only three layers in the third spatial dimension. Thus, the number of 2D plots to be investigated is drastically reduced.

Finally, different visual encodings can be combined. While the

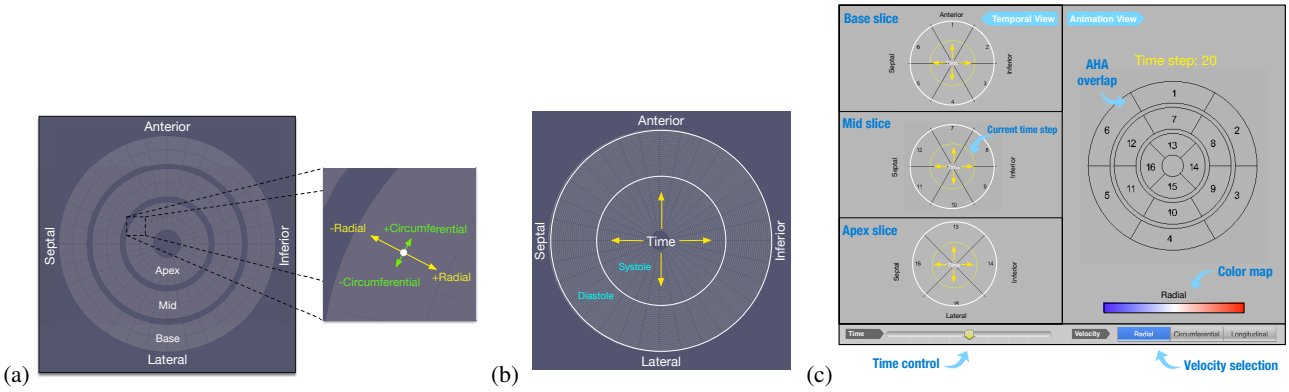

Figure 2: (a) AHA-inspired layout for the animation-based techniques. (b) Methodology of time-based method. Concentric rings labeled as 'Systole' and 'Diastole' show the phases of the cardiac cycle. Labels along the edges indicate the orientation of the LV. (c) Coordinated views.

first design choice includes all spatial information and uses an analogy to the AHA model, which the medical experts are familiar with, the last design choice allows for a correlation of space and time. Hence, we propose an interactive visual analysis system based on coordinated views of the two design choices effectively combining both relevant aspects, see Section 4.4.

4.2. 2D encoding of 3D spatial information

The goal is to represent all information of one time step in a 2D layout. The layout is inspired by the commonly used AHA model, where the base, mid, and apex slices are depicted as three nested rings. The layout is shown in Figure 2(a). Föll et al. [FJS*09] already employed such a layout. They split the AHA model into finer segments leading to a 3x2x24 segment model. Since the finer granularity of the segments allows for a better comprehension of the spatial distribution, we follow this idea.

The remaining challenge is to visually encode the three vector components (radial, circumferential, and longitudinal) within that layout. Föll et al. [FJS*09] encoded in-plane motion (radial and tangential) using arrow plots, while through-plane motion (longitudinal) was encoded by color. In their encoding, the through-plane motion dominates due to mapping to colors, which is pre-attentive, while the in-plane motion cannot be recognized very well and leads to clutter towards the center. We propose four alternative encodings for the three vector components:

Warped segments. To better convey in-plane motion, we suggest to displace or warp the segments according to the corresponding in-plane velocity vector components (radial and circumferential). Figure 2(a) magnifies one segment to show the directions of radial and circumferential velocities. In addition, we still provide the option to depict in-plane motion using arrows anchored at the center of the segments. The through-plane velocity vector component (longitudinal) remains to be color-coded. Since the longitudinal vector components can be positive (shortening of the myocardium), negative (lengthening of the myocardium), or close to zero (no longitudinal motion), a three-point color map is the most suitable choice. Here, we chose to use a color map that smoothly transitions from blue (negative) over white (zero) to red (positive). This three-point color map is perceptually favorable over the rainbow color map for the numerical attributes [BTI07] that was used by Föll et al. [FJS*09]. Figure 3 shows this visual encoding (second row) in comparison to the one by Föll et al. when using our color map (first row).

Pins. Since the warped segments tend to overlap, we developed a pin map, where the pins replace the arrows above to depict the in-plane motion. The pin head is shown as the 2D glyph of a filled circle and encodes the magnitude of the through-plane motion using size. Since we need to distinguish positive and negative longitudinal motion, we, in addition, color-code the pin head using the same color mapping as above. By restricting the color-coding to the scaled pin heads, strong longitudinal motion is highlighted, while the position of the needle heads allow for an understanding of the in-plane motion, see Figure 3 (third row).

Warped lines. The warped segments and the pins encode the in-plane motion per segment. Since spatio-temporal coherence can be assumed, another choice is to connect the warped segments to a continuous representation. We do so by connecting the end of the arrows (or the position of the pin heads) using a piecewise linear line representation. The pins are still shown, but without their heads such that the longitudinal component is only encoded by mapping color to the line segments (color map as above). The warped lines clearly show the in-plane deformation, see Figure 3 (fourth row).

Warped lines and pins. Finally, warped lines and pins can be combined using the encodings as described above, see Figure 3 (fifth row).

As the visual encoding only represents one time step of the time series, the user is required to scroll through different time steps or use animation to investigate an entire cardiac cycle. This is a simple interaction mechanism, but mentally generating a spatio-temporal model requires a high cognitive load. Exploration of temporal data with animations has been shown to be inherently slower and less accurate at communicating information [SI10].

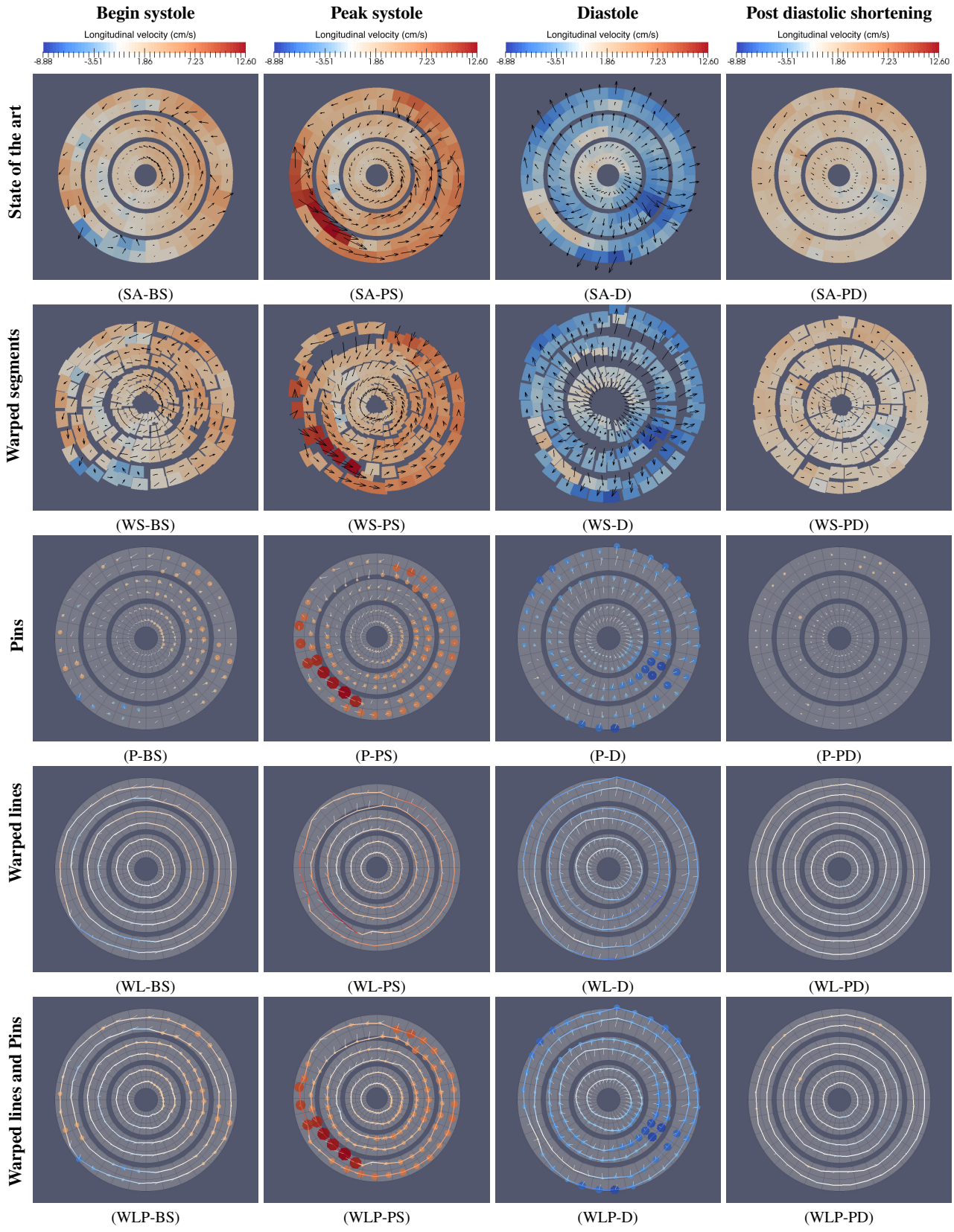

Figure 3: 2D encodings of 3D spatial information for healthy volunteer: Columns show visualizations of myocardial (radial, circumferential, and longitudinal) motion at different time points over the cardiac cycle. Rows show different visual encodings.

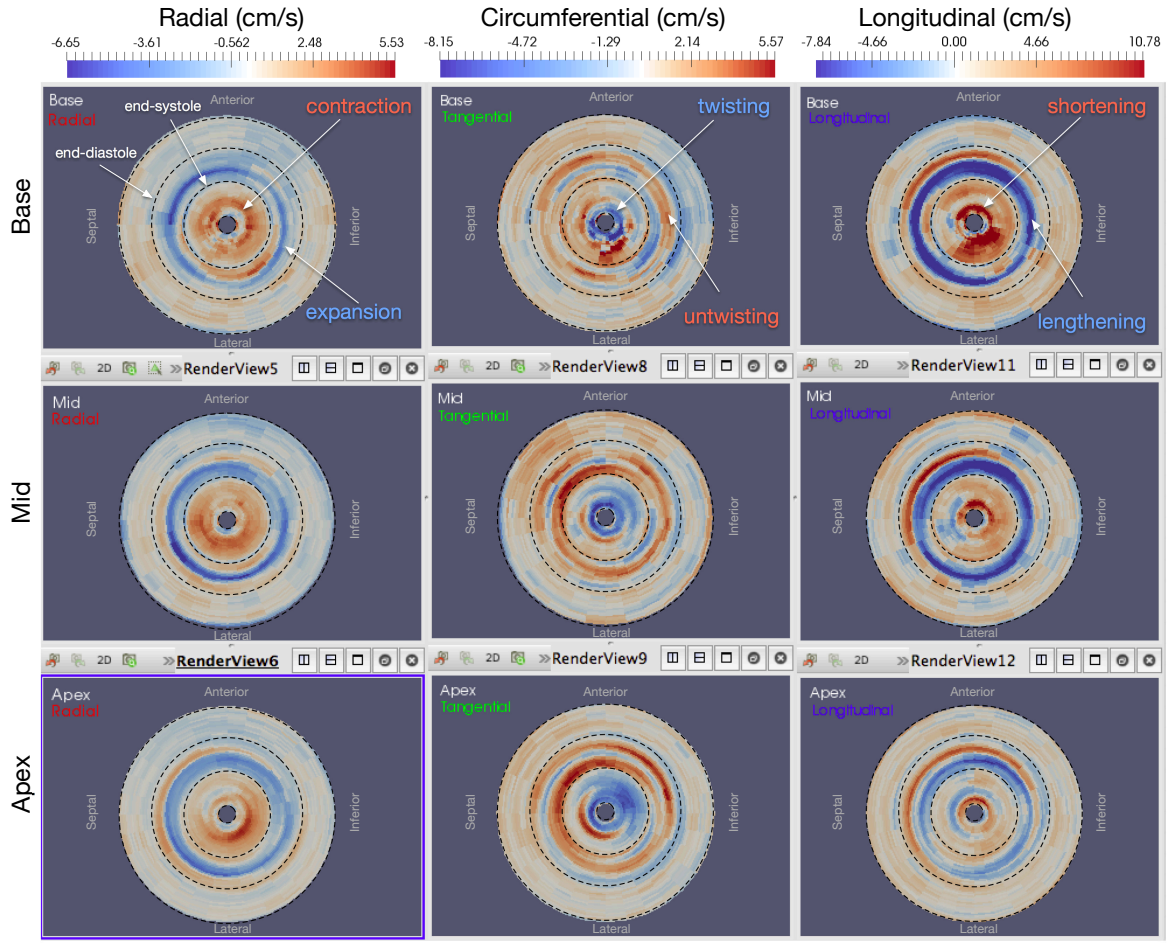

Figure 4: 2D encoding of 2D-spatio-temporal information for healthy volunteer. Columns show radial, tangential/circumferential, and longitudinal motion. Rows show the visualizations for basal, mid-ventricular, and apical slices.

4.3. 2D encoding of 2D-spatio-temporal information

To better support the analysis of spatio-temporal patterns and features within an entire cardiac cycle, we propose a novel 2D encoding that combines 2D spatial and temporal information. A radial layout in the form of a bulls-eye polar plot is used, where the segments of the chosen 2D slices are distributed along the angular direction as above, while the time dimension is mapped to the radial direction, see Figure 2(b). The visualizations are enhanced with rings and labels indicating the cardiac cycle phases (systole and diastole). Since this representation only encodes the spatio-temporal information of one of the three slices, we use three coordinated side-by-side views with the given encoding to investigate all three slices. Note that here we do not distinguish between epi- and endocardium.

What remains is, again, to encode the 3D vectors of each segment and each time step. Since the radial direction is now encoding temporal and not spatial information, warping in radial direction would be misleading. Thus, we decided to encode the motion in the three different directions (radial, circumferential, and longitudinal) using three coordinated side-by-side views. As a result, we obtain a matrix of 3×3 coordinated views, i.e., one view for each of the three slices and each of three motion directions, see Figure 4. In each of the views, the respective (radial, circumferential, or longitudinal) motion is encoded using color with the color map described above. One option is to also use opacity-encoding such that motions with smaller magnitudes become transparent, see Figure 5. Another option is to use three different color transitions for the three motion directions such that the color scheme indicates which motion direction is visualized. For our experiments we used the blue-white-red color map from above for radial motion, magenta-white-green for circumferential motion, and cyan-white-yellow for longitudinal motion.

Finally, we also tried to use different encodings that reflect better the different motion direction. For the radial motion, color mapping is the only suitable choice. For the circumferential motion, we draw lines that connect the time points of different segments, where the lines are warped in angular direction according to the motion. The warped lines are also color-coded using a blue-white-red color

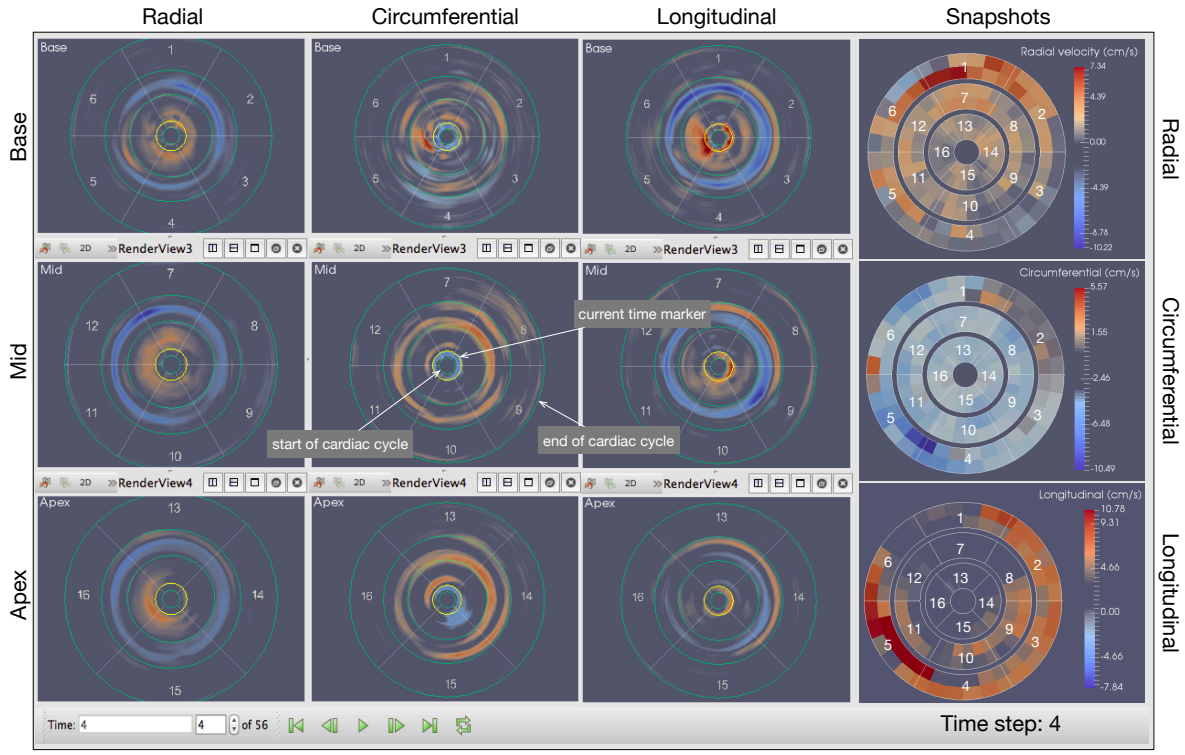

Figure 5: Coordinated views of spatio-temporal views of individual slices (3×3 views to the left) and 3D spatial views of selected time step (right column).

map. When additionally using opacities to remove low circumferential motions the remaining line pieces have the appearance of small arrows, see Figure 6 (middle). For the longitudinal motion, we connect the center of the segments to generate a surface in the form of a quadrilateral mesh. We apply a displacement map to the surface and render the result using lighting according to the Phong illumination model and Phong shading, see Figure 6 (right).

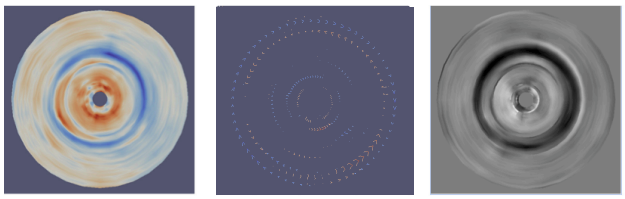

Figure 6: Alternative encoding:(left) Radial motion still encoded by color; (mid) circumferential motion encoded by color-and-opacity-mapped warped lines; (right) longitudinal motion encoded by displacement mapping.

4.4. Coordinated views

The visual encodings in Section 4.2 capture all information of a single time step and use a representation that the medical experts are familiar with and can easily relate to. However, it makes the comprehension of spatio-temporal behavior difficult. The visual encodings in Section 4.3 capture temporal evolution, but is an encoding the medical experts are not familiar with and may be confused with the AHA encoding first. To facilitate the understanding, we propose coordinated views that show both approaches side-by-side. In Figure 2(c), it is illustrated how the coordinated views work. The visual encoding on the right-hand side shows the 3D spatial information. The shown time step is chosen interactively at the bottom. In addition, labels according to the AHA model are overlaid. Any of the visual encodings presented in Section 4.2 can be selected. The coordinated views on the left-hand side show the 2D-spatio-temporal information for the three 2D slices. The currently selected time step is indicated by drawing a respective circle. Coordinated interaction assures that zooming or panning are applied to all views simultaneously, see accompanying video. Here, any of the visual encodings presented in Section 4.3 can be selected. Figure 5 shows our system with coordinated views during an interactive analysis.

5. Results

We present results from data acquired from one healthy volunteer (H_1) and two patients (P_1 and P_2). They underwent 2D TPM at basal, mid-ventricular (mid), and apical slices in short axis view. P_1 has 40% ejection fraction ($< 50\%$ is considered bad), with diagnosis of dilated cardiomyopathy. P_1 is known to have abnormalities primarily in the radial direction in the region between

left and right ventricles in all slices. P_2 has 60% ejection fraction with reduced motion in all directions and is diagnosed with inflammation. TPM consisted of a black-blood prepared cine phase-contrast sequence with 3D velocity encoding of myocardial motion ($venc = 25cm/s$, temporal resolution = $20.8ms$, spatial resolution = $2.0-2.4mm \times 2.0-2.4mm \times 8mm$). The data sets were segmented and preprocessed as described in Section 3.

We first report on how our visualizations document the cardiac motion for the healthy volunteer H_1. Figure 3 shows the output of the encodings for 3D spatial data at four different time points in the cardiac cycle: (1) begin systole, when the myocardium starts to twist, contract, and shorten to pump out the blood, (2) peak systole, when the shortening and contraction is maximum, (3) diastole, when the heart relaxes and expands to refill the blood, and (4) post-diastolic shortening, when the LV returns to its initial position.

We can observe that, at the beginning of the systole phase, when the myocardium begins to contract, twist, and shorten, the in-plane (radial and circumferential) motions are clearly visible in Figures 3(WS-BS) and (P-BS), while the red color indicates the shortening. However, in Figures 3(WL-BS) and (WLP-BS), the warped lines overlap with the drawn pins when the radial motion is low, making the circumferential motion hard to extract. In the peak systole, when radial contraction is strong, and in the diastole phase, when the myocardium expands and lengthens, the pins are visible clearly. The post-diastolic phase shows a little bit of shortening across the entire myocardium as indicated by the light red color of segments, circles, and lines in the last column of Figure 3.

Figure 4 shows the 2D encodings of 2D-spatio-temporal information for the three slices (base, mid, apex) and the three motion directions (radial, circumferential, longitudinal) in a 3×3 matrix of coordinated views using a blue-white-red color mapping. Red/blue colors indicate contraction/expansion in radial, clockwise/anti-clockwise twisting in circumferential, and shortening/lengthening in longitudinal velocities, respectively. The first column shows that, at the beginning of cardiac cycle, the myocardium contracts in radial direction (red color), while during the diastole phase it expands (blue color). The concentric dashed rings indicate the phases in the cardiac cycle such as beginning and end of systole, and end of diastole.

Figure 5 shows the coordinate views (using opacity-mapping) during an interactive analysis session. The left views show the spatio-temporal information encoding, here depicting the full 3×3 matrix of all three slices for all three motion directions. The right views show the encoding of 3D spatial information for a selected time step, here depicting the three motion directions in separate plots as known from the AHA model (and overlaid with respective labels). The controls at the bottom allow for the selection of the time step and for animations.

Having documented how our encodings reflect healthy cardiac motion, we want to document how differences to the regional motion can be observed when applying our methods to patient data. Figure 7 shows a comparison of spatio-temporal visualizations for the healthy volunteer H_1 (left) with the patients P_1 (middle) and P_2 (right) for the basal slice when considering radial (top) and longitudinal motion (bottom). While the radial motion for H_1 shows clear contraction rings in systole and relaxation in diastole, one can clearly observe a one-sided radial contraction and relaxation for P_1, i.e., not forming a ring. P_1 had a large myocardial scar in the septal region spanning from base to apex, which was confirmed by late gadolinium enhancement MRI. The scar impairs the local cardiac motion in the septal region, causing a reduced ejection fraction. This explains the detected abnormalities in the cardiac motion, i.e, we could effectively and intuitively be reproduce knowledge from prior studies. For P_2, we can observe that the overall radial motion is rather weak, i.e., much weaker than desired.

In the visualization for the longitudinal motion of H_1, one observes a pattern of first strong shortening in early systole, softer shortening in later systole, and relaxing in diastole. When applying the methods to P_1, one observes instead a much weaker motion with a left-sided half-ring shortening in early systole and further shortening later on in diastole with a simultaneous left-sided relaxation. This abnormal patterns is in line with the explanations given above. For P_2, one also observes reduced motion in the longitudinal direction. P_2 had been diagnosed with restrictive cardiomyopathy, showing signs of diffuse inflammation in the respective late gadolinium enhancement MR images. The anterior and septal regions of the myocardium showing the most severe inflammation correspond to areas with a reduced magnitude of the radial and longitudinal velocity that we observe in our visualizations. Furthermore, the impaired longitudinal motion is a specific characteristic of the restrictive cardiomyopathy pathology, thus our visual encoding provides essential diagnostic information.

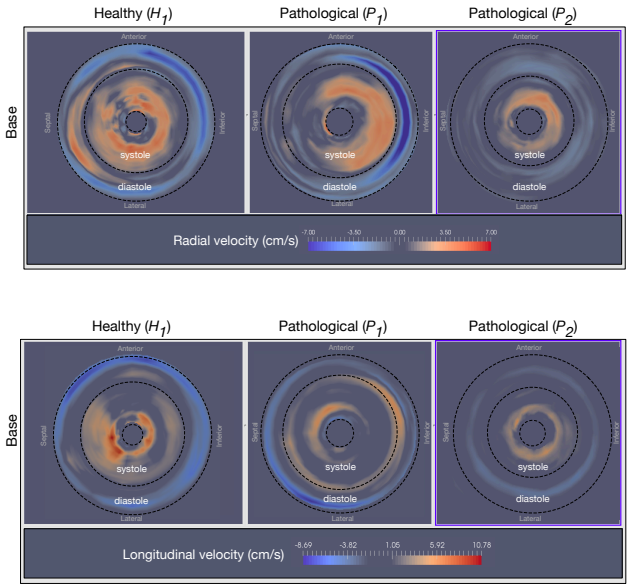

Figure 7: Comparison of two pathological cases (middle and right) with a healthy volunteer (left) in basal slice. Showing the radial (top) and longitudinal velocities (bottom).

6. Evaluation

We evaluated the effectiveness, intuitiveness, and utility of the proposed visualization methods by conducting a user study with three

domain experts (co-authors of the paper), all radiologists, with multiple years of experience in the field. Note that the participants did not contribute in development of the proposed visual encodings. The controlled user study was conducted over Skype and TeamViewer to allow the participants to interact with the visualizations. In a 20-25 minutes session, all participants were first introduced to the project. Then, the participants familiarized themselves with the visual encodings and interaction mechanisms using the H_1 data set. Eventually, the participants were asked to analyze the patient data within an interactive session. Afterwards, the participants were requested to fill in a questionnaire via an online form.

The questionnaire was divided into three sections. The first section included questions asking them to rate the visual encodings on a 5-step Likert scale (with 1 being worst and 5 being best) in terms of effectiveness and intuitiveness, and to share their remarks about each. The second section addressed the spatio-temporal visual analysis of healthy and patient data, and they were asked to describe their observations about the myocardial motion. Note that they were not familiar with the data sets and were not given any further information about the health status of the volunteer/patients. The last section included general questions about their preference, utility, and suggestions for improvements.

Concerning the comparison of the different encodings for 3D spatial information (see Figure 3), the feedback was mixed. One liked the spacing between the boxes in warped segments, others did not. They liked the scaling and coloring of the pins but one participant found it difficult to see smaller circles. None of them liked the warped lines, as they found it difficult to see the color. The combination warped lines and pins was regarded better than the separate versions. In summary, there was no clear winner, but the novel encodings we proposed got slightly better ratings than the state-of-the-art approach (but not consistently).

All participants appreciated the idea of the spatio-temporal encoding (see Figure 4). According to one of the participants, "this is the superior representation for R,T and L, but to imagine the time component of the heart movement by using the colors is a tough task". They also all liked the opacity mapping in the plots. One participant commented that "opacity mapping definitely increases the ability of the eye to grasp the essential information". Using three different color mappings for the three directions was not considered disturbing but also not beneficial (according to the ratings). The alternative encodings (see Figure 6) also got similar ratings.

The favorite concept of all participants though was the combination of both design choice using our system with coordinated views. One of the participant commented the myocardial motion is encoded most effectively using "temporal plots with opacity mapping coordinated with a representation of the AHA model, because it allows one to grasp the situation at once with the time-based views and then to go deeper into each time point to look in more detail what is going on". Moreover, another comment was that "once one gets the hang of it, it is actually easier to grasp the time-domain at once, it therefore requires less scrolling through data sets (time series)". Further comments were that "this gives the most comprehensive understanding of the movement" and that "I liked the coordinated views the best. It provides an overview and snapshot simultaneously which seems more intuitive to me".

Figure 8 shows the ratings of the three design choices. Since the variations of the ratings of the different alternatives within each design choice was low, we grouped the aggregated the ratings within each design choice. The coordinated views rated highest with respect to both effectiveness and intuitiveness. The spatio-temporal encodings were rated second and the spatial encodings that requiring animation were rated last with respect to effectiveness. In terms of intuitiveness those two design choices were rated equally good.

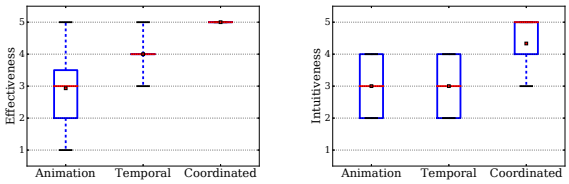

Figure 8: Effectiveness (left) and intuitiveness (right) of design choices on a 5-step Likert scale with 1 being worst and 5 being best. Coordinated views were ranked higher than spatio-temporal encodings (ranked second) and spatial encodings that require animations (ranked last).

When analyzing the patient data, all of the participants correctly pointed out the soft contraction in the affected region. They also reported correctly the delayed longitudinal shortening in the diastole phase: "The septal and lateral segments appear discoordinated" and "there seems to be much more transparency (opacity) in the systolic phase". Two of the participants reported that the weak and abnormal motion in the myocardium "may be concerning for septal pathology". The third participant did not explicitly report any pathology though. When analyzing the healthy volunteer data, they all correctly did not report any abnormal motion.

7. Discussion and Conclusion

The analysis of the complex motion pattern is a challenging task when one uses visualization that depicts for each time step the radial, circumferential, and longitudinal velocities separately, which makes the comprehension of the spatio-temporal pattern an extremely challenging cognitive task. In this work, we proposed novel spatio-temporal visualization methods for LV myocardial motion analysis with less cognitive load. Our approach uses coordinated views for navigating through the data space. One view visualizes individual time steps, which can be scrolled or animated, while another view visualizes the temporal evolution using a radial layout for the time dimension. Different designs for visual encodings were considered in both views and evaluated with medical experts to demonstrate and compare their effectiveness and intuitiveness for detecting and analyzing regional abnormalities.

Within this framework, we proposed several extensions of the state-of-art visualization method for encoding the three motion directions of a single time step in an integrated view. It was not seen as a major improvement by the medical experts, the reason being that the exploration of single time steps using scrolling or animation was considered the least effective design option. Instead, the spatio-temporal encodings were appreciated, as they show the temporal evolution of all velocities over an entire cardiac cycle and

one "could better conceptualize the temporal relationship of velocity changes" (according to one medical expert). It is effective to quickly detect the abnormal myocardial motion. One possible downside is that the three velocity components had to be visualized separately using side-by-side views, where the comprehension of the correlation among the velocity components is difficult. One possible future direction is to combine the alternative encodings to the color mapping in an integrated view. Another future extension of our system is to support the direct comparison of multiple datasets.

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