Glyph-Based SPECT Visualization for the Diagnosis of Coronary Artery Disease

Jennis Meyer-Spradow, Lars Stegger, Christian Döring, Timo Ropinski, and Klaus Hinrichs

Abstract—Myocardial perfusion imaging with single photon emission computed tomography (SPECT) is an established method for the detection and evaluation of coronary artery disease (CAD). State-of-the-art SPECT scanners yield a large number of regional parameters of the left-ventricular myocardium (e.g., blood supply at rest and during stress, wall thickness, and wall thickening during heart contraction) that all need to be assessed by the physician. Today, the individual parameters of this multivariate data set are displayed as stacks of 2D slices, bull's eye plots, or, more recently, surfaces in 3D, which depict the left-ventricular wall. In all these visualizations, the data sets are displayed side-by-side rather than in an integrated manner, such that the multivariate data have to be examined sequentially and need to be fused mentally. This is time consuming and error-prone. In this paper we present an interactive 3D glyph visualization, which enables an effective integrated visualization of the multivariate data. Results from semiotic theory are used to optimize the mapping of different variables to glyph properties. This facilitates an improved perception of important information and thus an accelerated diagnosis. The 3D glyphs are linked to the established 2D views, which permit a more detailed inspection, and to relevant meta-information such as known stenoses of coronary vessels supplying the myocardial region. Our method has demonstrated its potential for clinical routine use in real application scenarios assessed by nuclear physicians.

Index Terms—Multivariate visualization, glyph techniques, SPECT, myocardial perfusion imaging.

distance/shape/size/color/

1 Introduction

Coronary artery disease (CAD) is one of the most prevalent clinical pathologies in the western world. Atherosclerotic plaques form within the walls of the coronary arteries that supply the heart muscle (myocardium) and narrow the vessel lumen. This may lead to an insufficient blood supply to the myocardial region supplied by this artery. Complete or near-complete obstruction of a coronary artery generally leads to myocardial infarction resulting in death of myocardial cells.

In several clinical application scenarios, visualization techniques are exploited to support the required assessment of cardiac blood supply. For instance, visualization supports exploration of the regional blood supply data of the myocardium (perfusion), obtained during the non-invasive examination of a patient with unclear symptoms that might be caused by CAD. Furthermore, the examination of a patient with known stenoses of coronary vessels as well as the assessment of scarring after a myocardial infarction can be facilitated by using appropriate visualization techniques. Since a multiplicity of variables is required by the physician in order to get insights into the state of a patient's heart, efficient multivariate visualization techniques are essential.

Single photon emission computed tomography (SPECT) and positron emission tomography (PET) are well-suited for myocardial perfusion imaging and have long been among the most important diagnostic techniques in cardiovascular medicine. In contrast to coronary angiography, which depicts the lumen of the larger epicardial conduction vessels, perfusion imaging depicts blood supply right at the level of the myocardial cells. This is achieved by injecting a radiopharmaceutical that is taken up by the myocardial cells in relation to perfusion. By measuring the distribution of the injected radiopharmaceutical it is possible to derive multiple perfusion parameters. In most cases, the perfusion imaging is performed twice, once during physical or pharmacological stress and once under resting conditions. Imaging under stress is necessary, since partial obstruction of a vessel does not lead to inhomogeneous perfusion until the blood flow increases during stress up to a factor of about 5. Additional imaging under resting conditions is required to distinguish a flow deficit under stress caused by partial obstruction of a coronary artery from an uptake inhomogeneity caused by loss of myocardial cells after a myocardial infarction. Perfusion imaging can be performed with ECG-gating to generate multiple image data sets that represent the different positions during cardiac motion. From these data global and regional functional parameters, such as the left-ventricular volume, ejection fraction, wall thickness, wall thickening during contraction, wall movement and others can be derived in order to provide valuable information about the heart function. The physician has to be aware of artifacts in the images, i.e. caused by attenuation. Attenuation occurs since not all gamma particles emitted from the heart reach a detector but are absorbed by tissue on their way. Both an additional transmission scan, if available, and concurrent assessment of perfusion data and functional parameters can help to identify these artifacts. Nowadays all the involved variables are usually visualized by using slices, which are displayed as color-coded images in a 2D checkerboard arrangement (see Figure 1). Other alternatives are bull's eye plots or, more recently, 3D surfaces representing the left-ventricular wall. All these side-by-side visualizations require the physician to analyze the different parameters separately and to fuse the important information mentally.

In this paper we introduce a glyph-based approach for the visualization of SPECT-based myocardial perfusion data. While glyphs have often been used to visualize multimodal and/or multivariate data [2, 3, 5], we focus on the glyph design for a specific application case: SPECT-based diagnosis of CAD. In this case the lower spatial resolution of glyph approaches is adequate, since relevant stenoses of coronary arteries affect a larger area of the myocardium in comparison to voxel size, and SPECT itself has a limited spatial resolution.

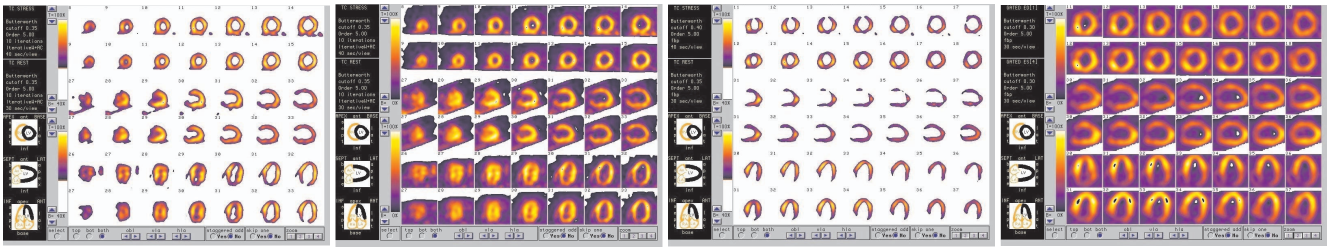
We have analyzed the workflow of the SPECT-based diagnosis of myocardial perfusion data and have identified an hierarchical approach during image interpretation. Initially, an overview of the perfusion during stress and, in case of defects, at rest is needed. Combining this information with the regional wall thickening already allows the physician to draw some conclusions. Based on these results derived pre-attentively from the initial visualization, we provide a visualization with another set of parameters in the next phase, which allows an attentive in-depth analysis. During the sequential inspection of these subsequent visualizations, the physician can always go back to the pre-

- *Jennis Meyer-Spradow, Christian Döring, Timo Ropinski, and Klaus Hinrichs are with the Visualization and Computer Graphics Research Group (VisCG), University of Münster, E-mail: {spradow|c_doer02|ropinski|khh}@math.uni-muenster.de.*
- *Lars Stegger is with the Department of Nuclear Medicine, University Hospital of Münster, E-mail: stegger@uni-muenster.de.*

Manuscript received 31 March 2008; accepted 1 August 2008; posted online 19 October 2008; mailed on 13 October 2008.
For information on obtaining reprints of this article, please send e-mail to: tvcg@computer.org.

1077-2626/08/$25.00 © 2008 IEEE Published by the IEEE Computer Society

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.



(a) (b) (c) (d)

Fig. 1. SPECT data are often examined by using a multitude of slices (from left to right: (a) with and (b) without thresholding, (c) without attenuation correction, (d) ECG-gated). In (a)-(c) stress (rows 1, 3, 5) and rest (rows 2, 4, 6) are displayed for three different slice orientations (rows 1/2, 3/4, 5/6), and for the ECG-gated display only the two rest images for end-diastole (rows 1, 3, 5) and end-systole (rows 2, 4, 6) are displayed.

vious visualization, revoke his diagnosis, and choose another set of parameters to be visualized. With this approach it becomes possible to reduce the number of differential diagnoses rapidly and to reach a final conclusion after an attentive analysis of all data. By taking into account findings from semiotic theory [15], the used glyph mappings have been designed to guide the physician's focus. Therefore, areas, in which assessed parameters are within the normal range, are depicted using inconspicuous glyphs, whereas pathological parameter combinations are visualized using more noticeable glyphs. For areas with unclear findings, the physician may pick glyphs by using the mouse in order to show supplemental regional information as 2D slices. In addition, tooltips can provide quantitative data and spatially co-registered meta-information such as results of previous coronary angiography.

2 Related Work

For the examination of the myocardium and the coronary arteries several non-invasive imaging techniques are available, e.g., echocardiography, computed tomography (CT), magnetic resonance imaging (MRI), and radionuclide techniques (SPECT, PET) which are all used in clinical routine. Handling the multiplicity of available modalities and derived variables is challenging, and therefore the visualization and processing of these data has been an active research area for several years.

An integrated visualization of MRI-based myocardial perfusion analysis and cardiac and coronary morphology obtained by CT coronary angiography is described by Oeltze et al. [11]. Colored heightfields, interactive lenses, and color icons are used to depict multiple variables derived from MRI data. Furthermore, an extension to the bull's eye plot visualization technique, that is widely used in cardiac diagnosis, is described. Bisecting the segment rings allows to visualize stress and rest state simultaneously. A bi-directional interaction between the bull's eye plot and a 3D view is used. A volumetric extension of the bull's eye plot with overlaid coronary arteries, which gives a global overview of scar tissue (acquired with MRI Late-Enhancement (LE) imaging), was introduced by Termeer et al. [20]. A 3D scan of the entire heart is added to show the scar tissue, combined with context information, in a linked 3D view.

They all used visualisation on on the basis of color coding slices

Nakajo et al. [10] use a semi-automatic reconstruction of the coronary tree and the left ventricle from CT data and register it manually with SPECT data. They visualize the segmented CT-based myocardium with color-coded perfusion data obtained from SPECT and augment it with the coronary tree. Most systems available for the automated SPECT-based analysis and visualization of the myocardium focus on color-coded slices, bull's eye plots, and 3D surface rendering of the perfusion [7].

Scalar and tensor glyph visualization is used by Zhukov et al. [24] to visualize muscle fibers of the heart muscle reconstructed from diffusion tensor MRI data with a moving least squares fiber tracing method. Jung et al. [4] calculate velocity of left ventricle tissue from phase contrast MRI with a fiber tracking algorithm and provide a 3D visualization of the identified acceleration tracks. Wünsche et al. [23] use a biomedical finite element model to extract myocardial strain from MRI data. The resulting heart movement is visualized with different techniques, e.g., color maps, tensor ellipsoids, streamlines, and hyper streamlines. A multi-resolution glyph display was proposed by Oeltze et al. [12] to visualize perfusion parameters extracted from MRI perfusion data sets at different levels of detail. In contrast to our approach, a pure 2D visualization is used, in which the glyphs are embedded into the traditional 2D slice view, and therefore it is more difficult to survey the myocardium quickly. Paasche et al. [13] use size and color of glyphs to depict wall thickening and one of several possible functional parameter of the myocardium derived from MRI data. Scar tissue and the left ventricular wall are shown as context information. Due to the fact that the heart surface is not used for visualizing a parameter, and due to the limitation to two glyph properties only two functional parameters can be visualized simultaneously. The described approaches are examples for the use of glyphs in the visualization of the myocardium. Applications of glyphs in other areas are described by Bürger and Hauser [2] in a state-of-the-art report about visualization of multivariate scientific data.

When using glyphs for visualization, proper mapping of the parameters to glyph properties and proper glyph placing are crucial. The mapping should allow an easy and intuitive perception of the mapped parameters. The placing and the number of glyphs determine the amount of information that can be displayed, and have to be traded off against the occlusion of context information. Ward [21] describes and classifies different placing strategies for multidimensional data visualization. A glyph packing strategy which allows a texture like appearance of glyphs is introduced by Kindlmann and Westin [5]. Furthermore, an isosurface-based placing strategy to visualize multimodal volume data with glyphs [17] as well as a stochastically jittered placing of glyphs to eliminate the possibly distracting effects of a grid placement [6] was proposed.

Ware [22] gives recommendations how data variables should be mapped to different glyph properties in order to make the coded information easily perceivable. Ropinski and Preim [16] presented a glyph taxonomy for medical applications and proposed guidelines for the usage of glyphs in medical visualizations, which have been considered when designing the glyph mapping proposed in this paper.

3 Clinical Workflow

When developing new visualization techniques, a proper integration into the clinical workflow is required. In the following we describe the typical workflow that was used for the clinical examples in this paper, and how our solution fits into it.

3.1 Data Acquisition

A typical one-day protocol of a SPECT stress-rest perfusion examination takes about two hours. First, the radiopharmaceutical is injected during peak exercise or, alternatively, during peak drug-induced widening of the coronary vessels. The radiopharmaceutical is taken up by the cells depending on the regional perfusion and trapped within them. The distribution can then be measured after a short waiting time by scintigraphic techniques. After this a higher dose of the radiopharmaceutical is injected during resting conditions and measured shortly thereafter in a second scan.

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.

Image data were acquired with a two-head gamma camera (Siemens ecam®), and reconstructed with attenuation correction. The image data consists of 32 slices each with 64×64 voxels, having an edge length of 6.3 mm. For functional analysis an ECG-gated data set under resting conditions (8 gates) was acquired.

3.2 Data Analysis

For a structured analysis of all data from the myocardial perfusion study, the analyzing imaging physician has to follow a defined protocol. These protocols may vary from imaging center to imaging center and depend on the available imaging equipment. Especially attenuation correction and ECG-gated acquisition are not available everywhere. Given a myocardial perfusion study with attenuation correction and ECG-gating, a typical protocol is the following:

1. Analyze the attenuation-corrected static images from the perfusion study under stress conditions.
2. In the case of regional defects of tracer distribution analyze also the corresponding images acquired under resting conditions.
3. Decide whether the defects remain under resting conditions (fixed defects) or are resolved (reversible defects); there can also be a combination of both.
4. In the case of fixed defects look at wall thickening in order to distinguish between "real" defects and attenuation artifacts.
5. Inspect global and regional function as well as heart size and wall thickness to identify cardiac diseases without regional perfusion defects.

To be able to visualize derived variables such as the wall thickness, we have integrated an automatic segmentation of the left ventricular wall, which is based on a validated contour-finding algorithm [18, 19]. It first computes the initial surface lying midway between the inner and outer contour of the left-ventricular wall by using the distribution of tracer activity within the SPECT image data as a force field that locally attracts the surface towards the center of the myocardium. The regional thickness of the myocardium is calculated similarly with the difference that the field of force now emanates from the activity gradient in relation to the already determined surface. Finally, the inner and outer contours are computed. After executing the algorithm for every gate, the wall thickness at end-diastole and end-systole as well as the wall thickening are calculated.

The segmentation process follows the preprocessing of the acquired SPECT data. The preprocessing is done by a technician and consists of the interactive adjustment of the orientation of the heart to a heart-centered coordinate system and the approximation of the valve plane.

Parameter values derived from SPECT data, e.g. wall thickness, have to be compared to "normal values" during interpretation. These values were obtained from experience with patients without known cardiac disease and with a normal perfusion (i.e. patients with routine examination before cardiotoxic chemotherapy).

4 Glyph-Based Visualization Setup

For the visualization of the various variables we propose to use two views. In the main view the myocardium is rendered as a 3D surface and glyphs are added to depict further parameters. A second view allows the inspection of blood supply under stress and rest in a 2D slice view physicians are familiar with. Both views are linked together in such a way that when double-clicking on a particular position in one view, this position is highlighted in the other view resp. an appropriate viewing position is selected in the 3D view.

4.1 Two-Phase Information Processing

Efficiency as well as accuracy of information processing play a crucial role in clinical practice, and therefore an intuitive association between the visualization of data and their meaning is important. Semiotic theory concentrates on signs and how they convey meaning. According to semiotic theory stimuli are processed in two phases [15]. The first phase is the pre-attentive one, where impulses are perceived in parallel and instantly (within 250 ms) as one entity. Within this phase facts that can be easily perceived are extracted, for example the overall structure of a visualization, differences in shape, and differences in color [22]. Hence these properties are well suited to visualize information which should be perceived immediately or which gives a general overview.

In the second phase stimuli are analyzed sequentially, parts and objects are identified and viewed in more detail one after another, and comparisons can be made to identify minor differences, e.g. in the size or shape of objects. Hence these properties are appropriate to depict information needed for a closer examination.

We have taken into account this two-phase approach to information processing when designing our glyph visualization. In the first pre-attentive phase, we display the most important parameters. Based on this visualization the physician might perform a more detailed inspection of the presented data or consult another glyph setup. The used visualization setups are described in Subsections 4.5.2 and 4.5.3.

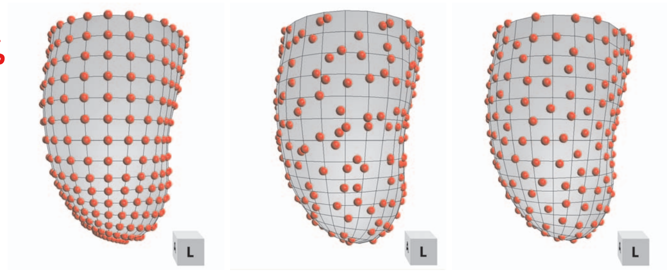


Fig. 2. Glyph placing based on a regular grid (left), a random distribution (middle), and a random distribution with relaxation (right).

4.2 Glyph Characteristics

Glyphs, as geometric objects with properties such as color, size, and orientation, are well-suited for the visualization of multivariate data. To visualize the information contained in a certain variable using glyphs, the variable is associated with a glyph property and its data values determine the values of the property and thus influence the appearance of the shown glyph. By mapping different variables to different glyph properties, multiple parameters can be visualized simultaneously.

experiment

Depending on their shape glyph prototypes have different sets of properties: glyphs with a few, well distinguishable properties are easy to perceive but can depict only a small number of variables, those with more properties are hard to perceive but can handle a larger number of parameters. Hence a tradeoff between complexity of a glyph prototype and the number of visualized variables has to be made.

We use a supertorus prototype and the following subset of its properties: color, opacity, size, and roundness. The latter can be derived by properly transforming the equation of the supertorus [17]. We prefer the supertorus over a supersphere, since due to its hole, the supertorus occludes less of the contextual information displayed on the heart surface. Some properties are particularly suited to depict special data types, e.g. for a variable containing size information the size property should be used. Other properties like hue are more universal.

Glyph mapping. The association between a variable and the desired corresponding glyph property is established using a mapping scheme which defines the relationship between data values and property values. For the mapping a piecewise linear function is used which can have discontinuities. This allows the accentuation of certain ranges. If possible, a mapping should emphasize anomalies and attenuate inconspicuous values.

Glyph placing. The placing of glyphs indicates the position of the data they depict, and their layout is perceived pre-attentively. Hence unwanted accumulations or gaps have to be avoided. Furthermore, glyphs are often combined with the rendering of a volume or a surface,

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.

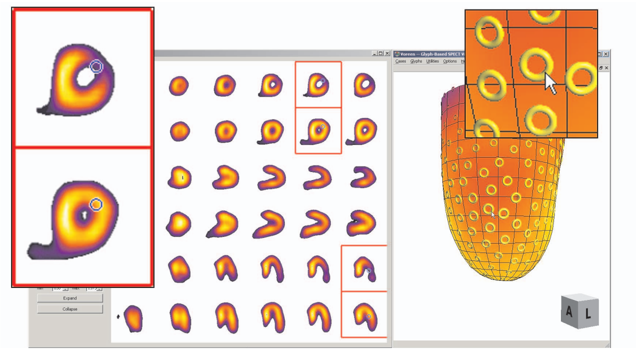


Fig. 3. Glyphs in the 3D visualization are dynamically linked to corresponding slice views.

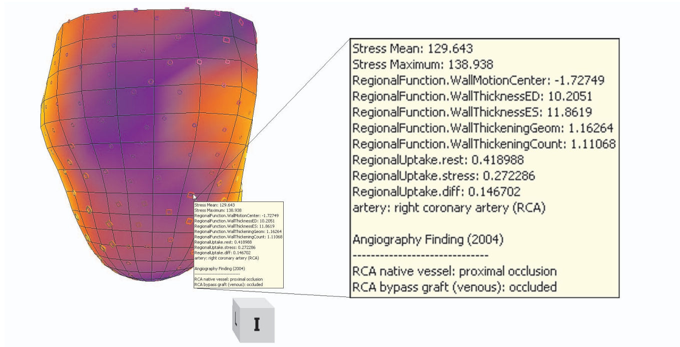


Fig. 4. Tooltips provide access to quantitative data, likely supplying artery, and previous imaging results.

which is used to visualize contextual information and therefore should be occluded as little as possible. Hence a proper placing is crucial for several reasons. There should be enough glyphs, and they should be evenly distributed to characterize the depicted data, but on the other hand, there should not be too many glyphs because the occlusion of the context area has to be minimized.

For myocardial perfusion imaging the glyphs should be placed on the surface of the myocardium in order to depict information about the state of the underlying tissue. Due to the reconstruction of the left ventricular wall a mesh representation of the surface already exists and can be used for the placing. Placing glyphs at the grid points of this underlying mesh has two disadvantages: It restricts the number of glyphs and leads to a non-balanced distribution because the grid converges at the lower part of the surface where it has a hemisphere-like shape (see Figure 2 (left)).

Hence we use an alternative placing method, which achieves an even distribution of an arbitrary number of glyphs across the whole surface. It uses a relaxation method [5, 8], which we adapted to our specific needs. If n glyphs have to be placed on the myocardium the first step is to distribute n points randomly on the surface (see Figure 2 (middle)). A repulsive force is defined which pushes adjacent points away. The force decreases quadratically with the distance. Now in the relaxation step for each point the distances to points in the surrounding area are calculated, and the points are moved according to their distance and the repulsive force. This is repeated iteratively until an even distribution is achieved (see Figure 2 (right)). The number of needed iterations depends on the homogeneity of the initial distribution. For the small number of points needed for the glyph placing, spreading them just randomly results in a poor distribution with some dense point clusters. Therefore another method is used. Each quad of the grid is identified with a subinterval of the unit interval, where the area of the quad corresponds to the length of the subinterval and the area of the whole surface corresponds to the length one of the unit interval. The subintervals are arranged consecutively in random order so that they constitute a unit interval. Then the n points are spread evenly over the unit interval and each point is randomly placed on the quad which corresponds to the hit subinterval.

4.3 Linked Slice View

After identifying pathological areas of the myocardium using the glyph visualization, physicians sometimes would like to inspect selectively the original measurement results of these areas. Hence we provide an additional view presenting these parameters in a visualization the physicians are familiar with (see Figure 3). Rows 1, 3, and 5 display uptake under stress, and rows 2, 4, and 6 uptake at rest. The orientation of the slices are selected on the basis of the underlying heart coordinate system.

To allow physicians to work intuitively with the glyph view and the slice view, they are shown simultaneously (e.g. by using two monitors) and a link between both views is established. When double-clicking onto a region of interest, the selected area is highlighted in the 2D view resp. an appropriate viewing position is selected in the glyph view.

The windowing widget on the left side of the slice view is used for the initial calibration of the upper threshold of the blood uptake to adapt it to the maximum value occurring in the myocardium instead of the overall maximum value which is often reached in the liver. The found threshold is then used for all visualizations.

4.4 Tooltips

Sometimes the graphical representation of various parameters is not sufficient, and additional detail information for certain positions is needed, e.g. the actual data values represented by a glyph. This is supported by the use of tooltips, which can be displayed by clicking on a glyph. Then a small tooltip window appears in the vicinity of the glyph, showing all currently available parameters (see Figure 4). Furthermore, the artery, which most likely supplies the current area, and, if available, the findings of former examinations are displayed.

Displaying the additional information with tooltips has the advantage that they appear in the current focus area of the physician. This outweighs the disadvantage of occluding other glyphs—which are irrelevant while reading the tooltip contents anyway.

4.5 Design of the Glyph Visualizations

To reduce the complexity of the user interface, we have constrained the performable interactions. The user can only perform rotations in the 3D glyph view as well as the interactions described in Subsections 4.3 and 4.4. The glyph mapping cannot be altered by the physicians. It is defined by the normal values, described in section 3.2.

It should be stated, that an inherent problem of a multi-variate glyph visualization is the parameter coverage. When mapping one parameter onto a surface and another one to a glyph, the impression may arise that the former has been acquired continuously, while the latter has only been measured at the discrete glyph locations. This is a general drawback of such combined glyph-based visualization techniques, which also cannot be avoided by our proposed visualization. Most glyph mapping strategies do not consider the positions where measured values exist and, due to the size of the glyphs, only a subset of the measured data can be visualized. Therefore data values for the glyphs have to computed by interpolation or integration. Due to the relatively low resolution of SPECT data a linear interpolation between the measured data values is sufficient for glyph visualization.

In a good mapping scheme, parameters that belong together should be presented in one visualization. Examinations of the myocardium most often start with the basic parameters "blood supply under stress" and "blood supply under resting conditions". In addition, the difference between the two is often considered. Regional wall thickening is a valuable accessory parameter that depicts function. The combination of these parameters gives a good overview over the state of the muscle tissue of the myocardium. Therefore these parameters form the first glyph visualization with the following priorities for the parameters to visualize: blood supply under stress, blood supply under resting con-

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.

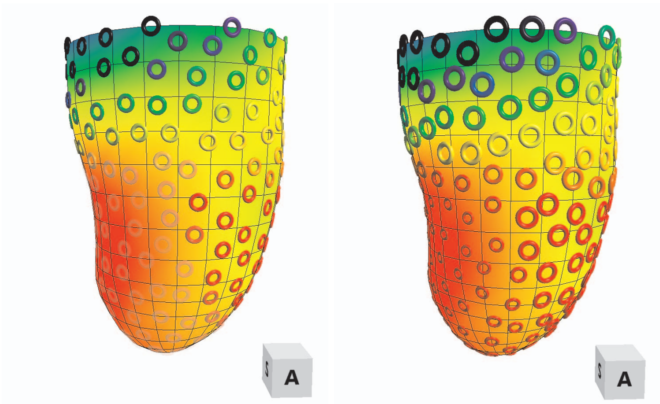


Fig. 5. Mapping of the conspicuousness of glyphs to opacity (left) and size (right).

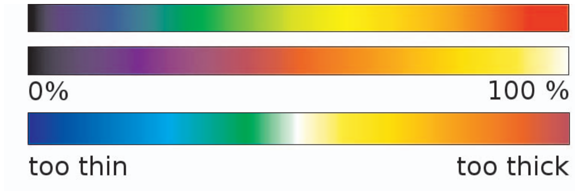


Fig. 6. Different color lookup tables are used for the color-coded visualization of SPECT values on surface and glyphs. The tables at top (CLUT 1) and in the middle (CLUT 2) are used for blood supply. Since SPECT is not quantifiable the values are relative to the maximal tracer uptake. The lower table (CLUT 3) is used for visualizing wall thickness, where blue depicts “too thin”, white “normal thickness”, and red “too thick”.

ditions, difference of the two, and wall thickening (see Table 1 (row 1)).

The second visualization depicts motion- and shape-oriented parameters, specifically wall thickness at end-diastole and end-systole, and wall thickening (see Table 1 (row 2)). These parameters can be used to further confirm the diagnosis of CAD in certain situations, e.g. a severe CAD of all coronary vessels with homogeneously reduced perfusion and hence without regional defects.

4.5.1 Glyph Visibility

To support the physician in doing a fast, efficient, but also reliable assessment and interpretation of the examination, the visualization should direct the physician’s focus to the possibly abnormal parts of the myocardium. This is done by emphasizing glyphs in probably pathological tissue, and attenuating glyphs in probably healthy tissue. It has to be ensured that abnormal values are highlighted. Wrongly emphasizing healthy tissue is tolerable, but attenuating abnormal areas has to be avoided. In either case the physician should be able to examine all glyphs. Therefore glyphs can be emphasized and attenuated, but should never disappear.

We tested two different ways to combine the visualization of the glyphs with the assumed medical importance. The first is the use of semi-transparency, i.e. the opacity increases with increasing conspicuousness (see Figure 5 (left)). The opacity cannot go below a predefined value to ensure a minimal visibility which eases the orientation and allows the validation of areas rendered using unobtrusive glyphs. The second property we used to emphasize glyphs is their size (see Figure 5 (right)). Conspicuous values are depicted using larger glyphs, normal values using smaller ones. A predefined minimum size ensures that all glyphs remain visible and thus enable the physician to consider also probably normal values.

Whether a glyph could be interesting and therefore should be emphasized is determined by considering all parameters mapped to the glyph. Based on the normal values we have defined for each parameter a range of values considered as definitely inconspicuous, which are mapped to minimal conspicuity, and a range containing pathological values which are mapped to maximal conspicuity. Between these ranges a linear interpolation for the parameter mapped to the conspicuity is done. The parameter having the highest conspicuity should determine the perceptibility of the glyph, and hence for a glyph the maximum of all calculated values is used.

4.5.2 Glyph Design for Perfusion Scenario

The visualization in the perfusion scenario depicts the most common parameters for the examination of the myocardium, i.e., blood supply under stress and resting conditions, difference between the two, and wall thickening. The first two are primary parameters because they give a general overview of the perfusion of the heart and therefore should be visualized using properties which can be perceived immediately. The use of color to depict perfusion and functional parameters is problematic since no obvious intrinsic connection exists between color and these parameters. Additionally, no unambiguous mapping between a color space and a single variable is possible, so that the choice and order of colors is not clear when using multi-color lookup tables (CLUTs) [1, 14]. We used these CLUTs anyway for the following reason. Physicians are accustomed to examine blood supply using 2D slice views with different CLUTs and therefore they can decode the mapping immediately—no familiarization is necessary. We have decided to choose the CLUTs the physicians are already familiar with when analyzing SPECT data. For the described application scenarios, these CLUTs are shown in Figure 6.

The values of myocardial perfusion under stress, considered to be the most important parameter, are used to colorize the visualized surface which gives a good overview of this variable at all positions of the surface and not only at the glyph positions. The blood supply under resting conditions is mapped to the color of glyphs using the same coding scheme. Due to this selection glyphs which depict similar intensity levels as the surface in their vicinity have similar color and are therefore less noticeable. This behavior is intended.

The difference of perfusion at rest and during stress is mapped to a further property—even though this parameter could be deducted from them—because the mental calculation of the difference of two color coded variables is challenging. It represents the correlation of two primary variables and thus should be depicted by an easily perceivable property such as the size property.

Wall thickening is used by physicians as a secondary parameter to further examine areas, which are still ambiguous with respect to the color-coding, and to highlight the rarer cases of non-ischemic cardiac illnesses. Therefore roundness as a less dominant property of the glyphs is selected for this parameter.

For the accentuation of glyphs which are probably important for the diagnosis we tested the mappings to semi-transparency and to size explained in section 4.5.1. Finally we decided to use the former for the following reason. The mapping to semi-transparency works well for most cases but has disadvantages in the specific disease pattern of non-ischemic cardiomyopathies or balanced perfusion defects. Symptomatic for these diseases is a homogeneous tracer distribution with only small differences between the stress and resting conditions which result in relatively small glyphs. The wall thickening is abnormal but poorly visible because it is mapped to roundness which is hard to perceive with the small glyphs. Mapping the accentuation to the size property solves the problem and was considered to be better (in this case the difference of blood supply was mapped to opacity). However, using the size property introduces a glyph mapping problem (see section 4.5.3). Therefore we have decided to use the opacity mapping.

4.5.3 Glyph Design for Motion Scenario

Subsequently the motion scenario can be used as an additional source of information if the variables presented in the first scenario are not sufficient for a reliable diagnosis. It consists primarily of the wall thickness in end-diastole (thickness ED) and end-systole (thick-

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.

Table 1. Mapping of the imaging parameters to surface color and glyph properties in the different scenarios.

Scenario	Surface color	Glyph color	Glyph size	Glyph roundness	Glyph opacity
Perfusion scenario	Uptake stress	Uptake rest	Difference of uptakes	Thickening	Conspicuousness
Motion scenario	Uptake rest	Thickness ED	Thickness ES	Thickening	Conspicuousness

ness ES) which are enriched with blood supply under resting conditions and wall thickening to have these parameters simultaneously visible. This scenario is especially useful for diseases without stress-induced ischemia such as non-ischemic cardiomyopathies, either leading to a dilated ventricle with a thinned wall (dilated cardiomyopathy) or to a ventricle with abnormally thick walls (hypertrophic cardiomyopathy). Another important role of the motion scenario is to assess regional tracer accumulation deficits (i.e. attenuation artifact vs. real abnormality). Therefore resting perfusion is a suitable parameter to map on the surface.

The thickness ES is mapped to the easily perceivable property size. The thickness ED is mapped to the glyphs' color. However, not thickness ED and thickness ES themselves but rather their absolute deviation from the normal value were mapped, so that "abnormal" is easily distinguishable from "normal". Tooltips or 2D slices must be consulted to distinguish between "too thin" or "too thick" for thickness ES, since this information is lost. A split color map (see Figure 6 (CLUT 3)) is used for thickness ED which depicts the different information and ranged from blue for "too thin" via white for "normal" to red for "too thick". Wall thickening is mapped to roundness to preserve consistency with the first visualization. The remaining visualization properties were chosen as in the perfusion scenario.

5 Results

The described visualization techniques have been implemented and used for the examinations of various patients. Below some example cases are presented which represent different classes of disease patterns. During the first examinations the exploring physicians made valuable comments about different aspects of the visualizations which helped to improve them. These results are summarized in the next section.

5.1 Adjustments to the Visualization

Originally it was intended to start the visualization by showing a computed view of the myocardium that depicts the area of the highest conspicuousness [9]. But this feature was not wanted by the physicians because an examination always covers a survey of the whole myocardium, and therefore physicians perceived this preselected view as disturbing, since usually they stick to a fixed exploration pattern.

The emphasis of glyphs using semi-transparency only was not sufficient in some cases. Especially small differences between uptake under stress and rest result in small glyphs making the perception of the roundness-property difficult. Alternatively using the size property for the mapping of conspicuousness was an improvement in this case, but was considered a disadvantage in the perception of the stress-rest perfusion difference that had to be mapped to the glyph thickness property, which visually interferes with the size property. As a compromise, semi-transparency was used for emphasis and a certain minimal size for the glyphs was defined to retain visibility.

For the placing of the glyphs the even distribution was highly preferred over the grid placing. On the one hand it is visually pleasing, and on the other hand it prevents occlusions in the area of the cardiac apex. The visualization of mesh lines enhances the three-dimensional impression which was appreciated.

In the motion scenario it was preferred not to map ED and ES thickness directly but to map the deviation from the mean normal values. A suitable split color lookup table was appreciated as a good way to visualize both increased and decreased thickness ED.

5.2 Clinical Cases

To demonstrate our visualization technique we selected four patients, one of them was without perfusion abnormality, and the others were representatives for three classes of different widespread disease patterns. On the basis of the visualizations it is explained how a physician performs a diagnosis for each class.

5.2.1 Case 1: Normal Myocardial Perfusion

To evaluate the cardiovascular status of a patient before a non-cardiac surgery (kidney transplantation), he was referred for myocardial perfusion imaging under stress and resting conditions.

Findings. Regional tracer distribution under stress conditions, color-coded on the surface, is almost uniform without significant regional defects in tracer distribution (see Figure 7 (case 1)). The same is true for the tracer distribution under resting conditions (coded as the color of the glyphs). The difference between tracer distribution under stress and resting conditions, coded as glyph size, is negligible, wall thickening, coded as glyph roundness, is within normal limits. Therefore glyphs are nearly transparent signifying normal values of the glyph-mapped parameters.

Interpretation. The myocardial perfusion examination was reported as normal. Kidney transplantation is considered safe.

5.2.2 Case 2: Stress-Induced Ischemia

A patient with known three-vessel CAD and recurring symptoms of inadequate blood supply during physical exercise was referred for myocardial perfusion imaging under stress and resting conditions.

Findings. Tracer distribution under stress conditions shows decreased uptake within the lateral and anterolateral wall (see Figure 7 (case 2)). Glyph color and size, depicting uptake under resting conditions and uptake difference, respectively, show a reversible defect. Glyph roundness, depicting wall thickening under resting conditions, is normal. In the relevant region glyphs are opaque showing abnormal values for at least one of the glyph-mapped parameters (in this case: uptake difference between stress and rest).

Interpretation. Stress-induced ischemia due to insufficient blood flow. There was no indication of myocardial scarring or impaired function at rest.

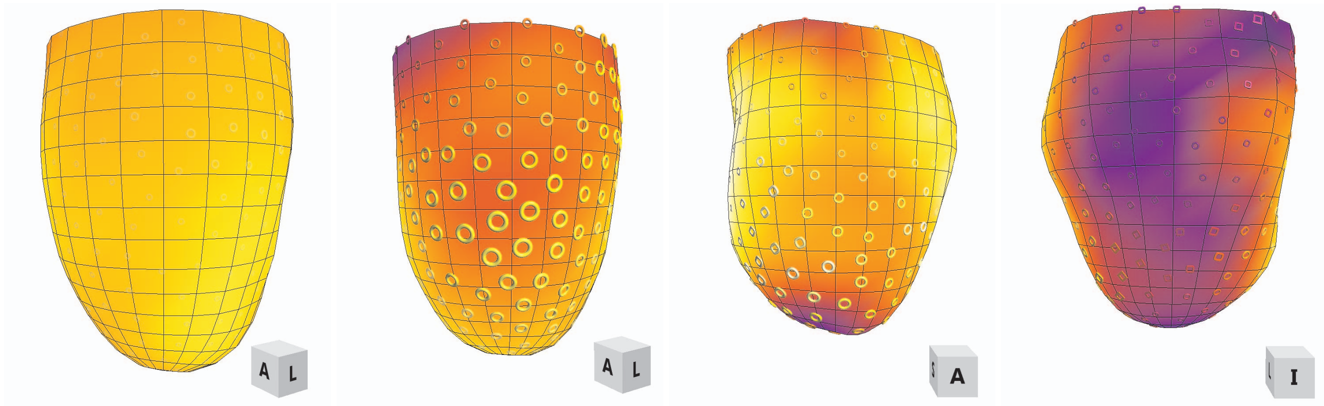
5.2.3 Case 3: Scar and Stress-Induced Ischemia

A patient with known three-vessel CAD, prior bypass surgery, was referred for myocardial perfusion imaging because of chest pain during exercise.

Findings. The tracer distribution under stress conditions shows severe defects in the inferior, inferolateral wall and the apex and additionally moderately decreased uptake in the anterior wall (see Figure 7 (case 3)). The defects inferiorly are fixed (small glyph size). The defect anteriorly is reversible (large glyph size). Wall thickening at rest is abnormal inferiorly and normal anteriorly. These differences are clearly visible in the visualization.

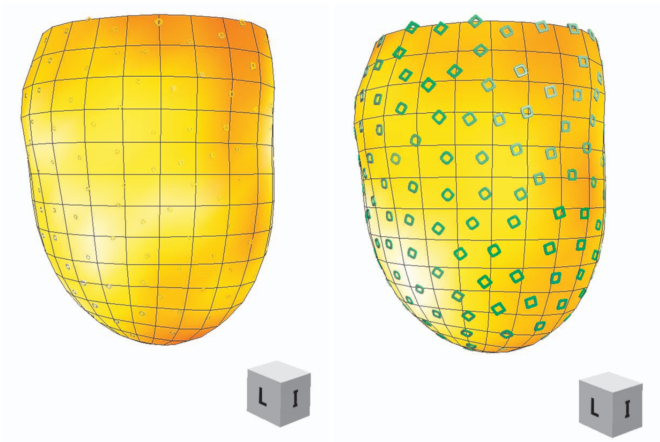
Interpretation. Extended transmural scarring inferiorly was reported but also a moderate stress-induced ischemia anteriorly indicating relevant stenosis of the left anterior descending artery (LAD). Since wall changes of the LAD had already been visible in the prior coronary angiography (information accessible by means of tooltips), the current results strongly suggest a progress.

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.



Case 1: normal Case 2: ischemia Case 3: ischemia Case 3: scar

Fig. 7. Visualization (perfusion scenario) for three clinical cases. From left to right: Case 1: normal perfusion and wall thickening; Case 2: stress-induced ischemia of the anterolateral wall; Case 3: ischemia of the anterior wall and scar of the inferior wall. Color lookup table 2 (CLUT 2) was used in all cases.



Case 4: Perfusion scenario Case 4: Motion scenario

Fig. 8. Visualization (perfusion and motion scenario) for an interesting clinical case with near-normal perfusion but highly abnormal motion parameters globally. CLUT 2 was used for perfusion and CLUT 3 for thickness ED.

5.2.4 Case 4: Heart Failure

A patient with known two-vessel CAD and a recently diagnosed severely reduced global left-ventricular function was referred for myocardial perfusion imaging under stress and resting conditions to test for myocardial scars and stress-induced ischemia.

Findings. Regional tracer distribution under stress and resting conditions is nearly uniform with only minor inhomogeneity in the anterior wall under stress conditions (see Figure 8). The difference between stress and resting images is small. However, the regional wall thickening is extremely abnormal almost everywhere in the left ventricular wall. This is clearly depicted in the glyph visualization. Glyphs are opaque, so that the abnormal wall thickening, coded as glyph roundness, is visible. Further analysis of motion and ED and ES wall thickness revealed thinned walls.

Interpretation. The results were assessed as heart failure, not caused by myocardial infarction. Either microvascular disease or additional non-ischemic cardiomyopathy were suggested as possible causes of the poor heart function.

5.3 Clinical Applicability

In order to test the clinical applicability of the presented visualization approach, we have performed an informal task performance test. Four nuclear medicine physicians with different degrees of experience (one specialist, one in-training with advanced experience and two in-training with intermediate experience) were asked to perform a formal image analysis and interpretation for the four above described cases. The four physicians had not been previously acquainted with the glyph-based visualization nor with the clinical cases. Prior to the experiment a short five-minute introduction into the software was given.

The time needed to interpret all four cases using the glyph-based visualization was 558 seconds on average. The nuclear medicine specialist needed 406 s, the physician in-training with advanced experience needed 437 s and those with lesser experience 588 s and 801 s, respectively.

The time needed to interpret four control cases of similar complexity with the traditional slice-based approach was 627 s on average. The values for the specialist, the physician in-training with advanced experience and those with limited experience were 547 s, 552 s, 476 s, and 933 s, respectively.

The average time with the glyph-based approach was more than 10 percent faster; however, the small number of subjects and the inexperience with the glyph-based approach makes interpretation of these numbers difficult. We believe that the times for the diagnoses using the glyph visualization will further decrease when the physicians are more familiar with it.

All data needed for the visualizations (e.g. the glyph placing) were pre-calculated. Therefore the above times reflect the interactive image interpretation only.

With our technique the physicians perceived a better diagnostic confidence than when using the traditional side-by-side slice view. Especially the proposed combination of a glyph-based representation with an additional linked slice view for in-detail inspection, as well as provision of local meta-information through tooltips, supported their diagnostic confidence. The 3D glyph representation of stress and resting perfusion together with the regional wall thickening (perfusion scenario) provides an easy and nearly complete overview over the myocardial status. With this first view it is hardly possible to miss important lesions. In contrast, side-by-side viewing of the multiparametric data requires more concentration in order to fully interpret the data, important lesions might be overlooked, especially when inexperienced or tired. It is important to note, that the proposed visualization does not decrease the information content of the study since in addition to the 3D view the original 2D slices are also available. The provision of meta-information with a mouse-click is also considered an important feature in order to speed up interpretation and reporting of the study. Traditionally, the reports from previous examinations have to be read and mentally matched with the current image data, requiring more time.

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.

However, a thorough evaluation of time efficiency and accuracy, which eliminates possible stochastic effects, needs a longer-term clinical evaluation with glyph-trained physicians.

6 Conclusion and Future Work

A glyph-based visualization approach for the structured analysis of myocardial perfusion imaging examination is presented. After an analysis of the common medical workflow those parameters which are usually examined together by physicians have been identified and are then visualized simultaneously. A contour-finding algorithm is integrated into the normal workflow for the automatic calculation of wall thickening and wall thickness in order to be able to visualize these important parameters.

Based on suggestions of physicians the main element of our approach is the 3D representation of multiple parameters by a combination of surface rendering and glyphs. The mapping of parameters to glyph properties is based on semiotic theory in order to support an easy and fast perception of the important information and a reliable diagnosis even under time pressure. Furthermore a scheme for emphasizing glyphs representing probably malperfused or malfunctioning tissue and attenuating glyphs representing normal values is introduced to direct the physician to probably abnormal regions.

In addition, for in-depth analysis a traditional 2D slice-based representation of single parameters is always available. By clicking glyphs metadata such as the mapping of a myocardial region to the most likely supplying coronary artery as well as the results of prior examinations such as coronary angiography are also readily accessible. This concept lends itself to a fast, structured analysis of multi-parameter perfusion studies. Hidden additional parameters such as the regional contraction are not ignored.

The four presented classes of clinical cases cover a wide range of relevant clinical questions and show the power of this visualization concept. The different diseases as well as the normal study show a typical, easily recognizable pattern in the 3D glyph-based visualization. The particular choice of the mapping schemes makes it especially easy to distinguish normal from pathological myocardial regions and highly unlikely to report a pathological study as normal.

It still remains to be seen whether the chosen parameter representation is adequate and optimal for image analysis in daily routine on a long term.

Acknowledgements

This work was partly supported by grants from the Deutsche Forschungsgemeinschaft (DFG), SFB 656 MoBil, Germany (projects C2, PM3, PM5, Z1). The presented concepts have been integrated into the Voreen volume rendering engine (`www.voreen.org`). We would like to thank Peter Kies, Peter Lenz, Kambiz Rahbar and Christian Wenning for testing the introduced visualizations.

References

[1] D. Borland and R. M. Taylor II. Rainbow color map (still) considered harmful. *IEEE Computer Graphics and Applications*, 27(2):14–17, March 2007.

[2] R. Bürger and H. Hauser. Visualization of multi-variate scientific data. In *EuroGraphics 2007 State of the Art Reports (STARs)*, pages 117–134, 2007.

[3] D. Ebert, R. M. Rohrer, C. Shaw, P. Panda, J. M. Kukla, and D. Roberts. Procedural shape generation for multi-dimensional data visualization. *Computers & Graphics*, 24(3):375–384, June 2000.

[4] B. A. Jung, B. W. Kreher, M. Markl, and J. Hennig. Visualization of tissue velocity data from cardiac wall motion measurements with myocardial fiber tracking: principles and implications for cardiac fiber structures. *European Journal of Cardio-thoracic Surgery*, 29S1:S158–S164, 2006.

[5] G. Kindlmann and C. Westin. Diffusion tensor visualization with glyph packing. In *IEEE Transactions on Visualization and Computer Graphics*, volume 12, pages 1329–1336, September 2006.

[6] D. H. Laidlaw, E. T. Ahrens, D. Kremers, M. J. Avalos, R. E. Jacobs, and C. Readhead. Visualizing diffusion tensor images of the mouse spinal cord. In *VIS '98: Proceedings of the conference on Visualization '98*, pages 127–134. IEEE Computer Society Press, 1998.

[7] G. Lin, H. H. Hines, G. Grant, K. Taylor, and C. Ryals. Automated quantification of myocardial ischemia and wall motion defects by use of cardiac SPECT polar mapping and 4-dimensional surface rendering. *Journal of Nuclear Medicine Technology*, 34(1):3–17, 2006.

[8] M. Meyer, B. Nelson, R. M. Kirby, and R. Whitaker. Particle systems for efficient and accurate high-order finite element visualization. *IEEE Transactions on Visualization and Computer Graphics*, 13(5):1015–1026, September 2007.

[9] K. Mühler, M. Neugebauer, C. Tietjen, and B. Preim. Viewpoint selection for intervention planning. In *IEEE/Eurographics Symposium on Visualization (EuroVis)*, pages 267–274, 2007.

[10] H. Nakajo, S. Kumita, K. Cho, and T. Kumazaki. Three-dimensional registration of myocardial perfusion SPECT and CT coronary angiography. *Annals of Nuclear Medicine*, 19(3):207–215, 2005.

[11] S. Oeltze, F. Grothues, A. Hennemuth, A. Kuß, and B. Preim. Integrated visualization of morphologic and perfusion data for the analysis of coronary artery disease. In *IEEE/Eurographics Symposium on Visualization*, pages 131–138, 2006.

[12] S. Oeltze, A. Malyszczyk, and B. Preim. Intuitive mapping of perfusion parameters to glyph shape. In *Bildverarbeitung für die Medizin (BVM 2008)*, pages 262–266, 2008.

[13] L. Paasche, S. Oeltze, A. Hennemuth, C. Kühnel, F. Grothues, and B. Preim. Integrierte Visualisierung kardialer MR-Daten zur Beurteilung von Funktion, Perfusion und Vitalität des Myokards. In *Bildverarbeitung für die Medizin*, pages 212–216, 2007.

[14] P. L. Rheingans. Task-based color scale design. In *Proceedings Applied Image and Pattern Recognition '99*, pages 35–43, 2000.

[15] J. F. Rodgrigues Jr., A. J. Traina, M. C. F. de Oliveira, and C. Traina Jr. Reviewing data visualization: an analytical taxonomical study. In *Tenth International Conference on Information Visualisation (IV'06)*, pages 713–720, 2006.

[16] T. Ropinski and B. Preim. Taxonomy and usage guidelines for glyph-based medical visualization. In *Proceedings of the 19th Conference on Simulation and Visualization (SimVis08)*, pages 121–138, 2008.

[17] T. Ropinski, M. Specht, J. Meyer-Spradow, K. H. Hinrichs, and B. Preim. Surface glyphs for visualizing multimodal volume data. In *Proceedings of the 12th International Fall Workshop on Vision, Modeling, and Visualization (VMV07)*, pages 3–12, November 2007.

[18] L. Stegger, S. Biedenstein, K. P. Schäfers, O. Schober, and M. A. Schäfers. Elastic surface contour detection for the measurement of ejection fraction in myocardial perfusion SPET. *Eur J Nucl Med Mol Imaging*, 28(1):48–55, January 2001.

[19] L. Stegger, C. Lipke, P. Kies, B. Nowak, O. Schober, U. Buell, M. A. Schäfers, and W. Schaefer. Quantification of left ventricular volumes and ejection fraction from gated 99mTc-MIBI-SPECT: Validation of the elastic surface model approach in comparison to cardiac magnetic resonance imaging, 4D-MSPECT and QGS. *Eur J Nucl Med Mol Imaging*, 34(6):900–909, June 2007.

[20] M. Termeer, J. O. Bescós, M. Breeuwer, A. Vilanova, F. Gerritsen, and M. E. Gröller. CoViCAD: Comprehensive visualization of coronary artery. *IEEE Transactions on Visualization and Computer Graphics*, 6(13):1632–1639, November 2007.

[21] M. O. Ward. A taxonomy of glyph placement strategies for multidimensional data visualization. In *Information Visualization*, volume 1, pages 194–210. 2002.

[22] C. Ware. *Information Visualization: Perception for Design*. second edition, 2004.

[23] B. C. Wünsche and R. Lobb. The visualization of myocardial strain for the improved analysis of cardiac mechanics. In *GRAPHITE '04: Proceedings of the 2nd international conference on Computer graphics and interactive techniques in Australasia and South East Asia*, pages 90–99, 2004.

[24] L. Zhukov and A. H. Barr. Heart-muscle fiber reconstruction from diffusion tensor MRI. In *Proceedings of the 14th IEEE Visualization 2003*, pages 597–602, 2003.

Authorized licensed use limited to: SWANSEA UNIVERSITY. Downloaded on November 23,2022 at 00:43:08 UTC from IEEE Xplore. Restrictions apply.