Enhanced Cardio Vascular Image Analysis by Combined Representation of Results from Dynamic MRI and Anatomic CTA

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ABSTRACT

The diagnosis support in the field of coronary artery disease (CAD) is very complex due to the numerous symptoms and performed studies leading to the final diagnosis. CTA and MRI are on their way to replace invasive catheter angiography. Thus, there is a need for sophisticated software tools that present the different analysis results, and correlate the anatomical and dynamic image information. We introduce a new software assistant for the combined result visualization of CTA and MR images, in which a dedicated concept for the structured presentation of original data, segmentation results, and individual findings is realized. Therefore, we define a comprehensive class hierarchy and assign suitable interaction functions. User guidance is coupled as closely as possible with available data, supporting a straightforward workflow design. The analysis results are extracted from two previously developed software assistants, providing coronary artery analysis and measurements, function analysis as well as late enhancement data investigation. As an extension we introduce a finding concept directly relating suspicious positions to the underlying data. An affine registration of CT and MR data in combination with the AHA 17-segment model enables the coupling of local findings to positions in all data sets. Furthermore, sophisticated visualization in 2D and 3D and interactive bull's eye plots facilitate a correlation of coronary stenoses and physiology. The software has been evaluated on 20 patient data sets.

Keywords: Cardiac Procedures, Diagnosis, Visualization

1. INTRODUCTION

Although the mortality of Coronary Artery Disease (CAD) has been decreasing during the last years due to enhanced diagnosis and therapy, the morbidity rate is still the highest in western countries.[1] Catheter angiography is the gold standard of imaging techniques for CAD, although it is an invasive method and does not deliver information on the state of dependent tissue. However, especially in case of a mid-grade stenosis the myocardium has to be examined to decide which therapy is most promising. Therefore, perfusion under rest and stress is analyzed to show if the tissue supplied by the diseased coronary branch is still provided with enough oxygenated blood or if there even is a scar. Thus, information about the prospective benefit of a revascularization therapy (e.g., stenting, bypass) for the hypoperfused tissue can be derived. In recent years, CT and MRI have gained importance for the diagnosis of CAD. CT is especially suited for coronary tree imaging because of the good spatial resolution (64-slice CT, $0.4mm$ isotropic). Furthermore, an acquisition time of about $83ms$ per slice for 64-slice CT ensures an artifact-free imaging.[2] One of the major disadvantages of CT is the exposure of the patient to ionizing radiation. This excludes it as acquisition method for examinations over time, e.g., for perfusion, and clearly defers to MRI regarding that aspect. The diagnostic power of MRT nowadays is comparable to SPECT and PET – the gold standards for perfusion imaging and late enhancement analysis.[3] The imaging of the coronary arteries is still challenging with MR. A spatial resolution of $0.7mm$ or above in whole heart images is not sufficient.[4] Thus, today neither CT nor MRT offer full diagnosis support without additional information from a second technique.

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Nevertheless, technical enhancements paved the way for CT and MRT to replace the invasive imaging techniques.[5] Special algorithms for segmentation, registration, and the quantification of cardiac parameters from CTA and MRI are currently being developed. To process the amount of information, a structured representation is required. Thus, similar to the technical fusion of different images in the device itself, e.g., PET-CT, a combination of analysis results from anatomical CTA and dynamic MRI is desirable. Regarding the therapy planning process, both anatomical information from CTA and physiological information from MRI are of upmost importance. A first taxonomy to relate coronary tree segments and myocardial areas was established by the AHA 17-segment model, which offers a rough segmentation scheme of the coronary tree and the myocardium of the left ventricle (LV). Based on this scheme, correspondences with respect to the blood supply are defined.[6] Due to its appearance, the model is also called bull's eye plot (BEP). Pereztol-Valds et al.[7] show that this AHA-conform correspondence is limited due to the fact that 8 of 17 segments corresponded to varying supplying coronary tree segments. This means that a single examination of the left ventricle is not sufficient for the final diagnosis of the vessel disease. Regarding multimodal imaging, the 17-segments model gives an overview of the quantitative myocardial parameters but must be accomplished by a more detailed examination of both the anatomy and the physiology.

There already exists a multitude of image processing tools for the coronary tree, the left ventricular function, or the physiology of the left ventricle. Nevertheless, only few approaches commonly represent the results of various cardiac examinations. A merging of molecular information from SPECT, PET, or MRI with anatomical information from CT is described by Slomka et al.[8] However, the authors only consider the registration of the data. A concept for the enhancement of the information content is not presented. The comprehensive evaluation of MR function and late enhancement images is proposed by Noble et al.[9] They apply rigid registration using normalized mutual information to compensate for patient and breath motion. A special function combines the parameters wall thickness and transmurality of the scar. Thus, areas that can still benefit from revascularization were accentuated in the BEP as well as on the 3D ventricle mappings. An approach related to our own work is proposed by O'Donnell et al.[10] Here, CTA and MR function as well as perfusion images are correlated, focusing on the registration task to comprehensively show anatomical and physiological information. Although this approach is promising, the data representation is not workflow-oriented and the analysis within the fused images is not provided. Similarly, Termeer et al.[11] represent a comprehensive medical visualization framework for MRI whole body and late enhancement images named CoViCad. They propose a diagnosis-oriented visualization software with many interaction possibilities to explore the combined 2D and 3D data representation of anatomical data and late enhancement analysis results. A schematic view via a special volumetric BEP relates the 17-segments partitioning to the individual anatomy. Special interaction schemes offer the combination of 3D visualization and the BEP. Clip planes in long or short axis direction allow the incorporation of original data into the 3D visualization and thus provide a suitable comprehensive presentation. A quantitative analysis of a certain stenosis is not possible because MR coronary tree imaging is still not sufficient due to the low spatial resolution. For the analysis process, Termeer et al. use several independent methods. An automatic segmentation is applied to the whole heart image to extract the heart chambers, the valves, the pulmonary artery, and the aorta.[12] Furthermore, a prototypical software facilitates the extraction of the coronary centerline.[13] After manual myocardium segmentation the scar tissue is classified in the late enhancement images by a user-guided threshold. In a clinical study Higashino et al.[14] proposed a combination of CT angiography and function, showing the importance of image and information fusion for the cardio-vascular diagnosis support. However, the generation of the fusion images is often too time consuming because several software tools are needed to perform the analysis. Furthermore, common data handling and the comprehensive evaluation within one software are missing.

We propose a unified concept of patient-based data handling in order to simplify and speed up the diagnosis and therapy planning process. Comprehensive visualization strategies of the analysis results from different image modalities are developed within a dedicated workflow. We have previously developed two specialized software assistants that perform quantitative measurements with respect to the coronary tree and the left ventricular dynamics (function, perfusion, late enhancement).[15] A new class concept allows the common treatment of several result files from these software assistants. Due to the common data handling, unnecessary and time consuming data shifting or conversion are avoided. Furthermore, we investigate advanced visualization and interaction techniques to accentuate the information content from combined data.

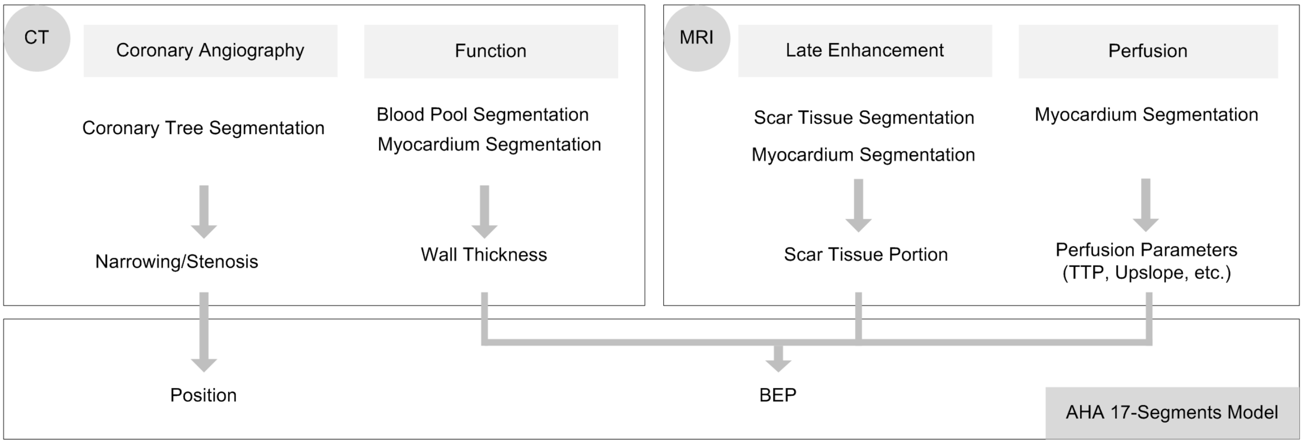

Figure 1. Representation of the available data and processing results. According to the results of our software assistants, coronary tree segmentation and left ventricular function estimation are assigned to CT, whereas the late enhancement and perfusion analysis results are shown on the right beyond MR. To demonstrate the connection to the AHA 17-segments model, we put the result positions in a certain coronary tree segment and segment-based ventricular values into a third group.

2. METHODS

The proposed software assistant has been developed for the structured presentation of analysis results including images and result masks as well as special positions and measurements. Therefore, we developed a dedicated class hierarchy and interaction concept that supports data-driven user guidance. The image analysis results are derived from two advanced software assistants, processing CT angiographic and function images on the one hand, and late enhancement (LE) and perfusion images from MRI on the other hand. Both software assistants contain a wide range of adequate image processing methods. In the following sections, we give an overview of the underlying software concept, the visualization and interaction methods, and the applied image processing algorithms.

2.1 Analysis Software

Before we describe the concepts of our visualization software in more detail, we give a short overview of the analysis software used to derive the data. Within the last four years, we developed two software assistants. The first software is dedicated to the analysis of angiographic and functional CT data. In such data, the coronary tree is commonly segmented on an image acquired during the diastolic phase to avoid motion artifacts. We use an advanced progressive region growing algorithm, which has been evaluated on a wide range of data.[16] Furthermore, the left ventricular blood pool is segmented by a similar region growing based approach and quantitative parameters, e.g., the ejection fraction, are determined.[15] A live-wire supported manual segmentation for the left ventricular myocardium extraction is offered to derive the left ventricular wall thickness.
The second software assistant operates on MR data performing a perfusion analysis with affine and B-spline registration methods for motion correction. Different perfusion parameters are determined, e.g., time-to-peak (TTP), upslope, area-under-curve, and peak-enhancement. Additionally, a segmentation within these parameter images is supported. After a life-wire guided segmentation of the myocardium in the LE images, the scar tissue portion is determined by fitting a mixture model to the histogram of the myocardial region.[17] The perfusion and late enhancement images are aligned by affine and elastic image registration using the normalized mutual information similarity measure.
To combine the information of the whole set of images, the CT and the MRI data have to be transformed into a common coordinate system. Therefore, we choose the anatomic data in the diastolic phase and the late enhancement image, and align them using an affine transformation with respect to the center of gravities of the left ventricular segmentation masks. Additional manual correction is supported, yielding the fusion of both images. An overview of the analyzed data and the derived results is given in Figure 1.

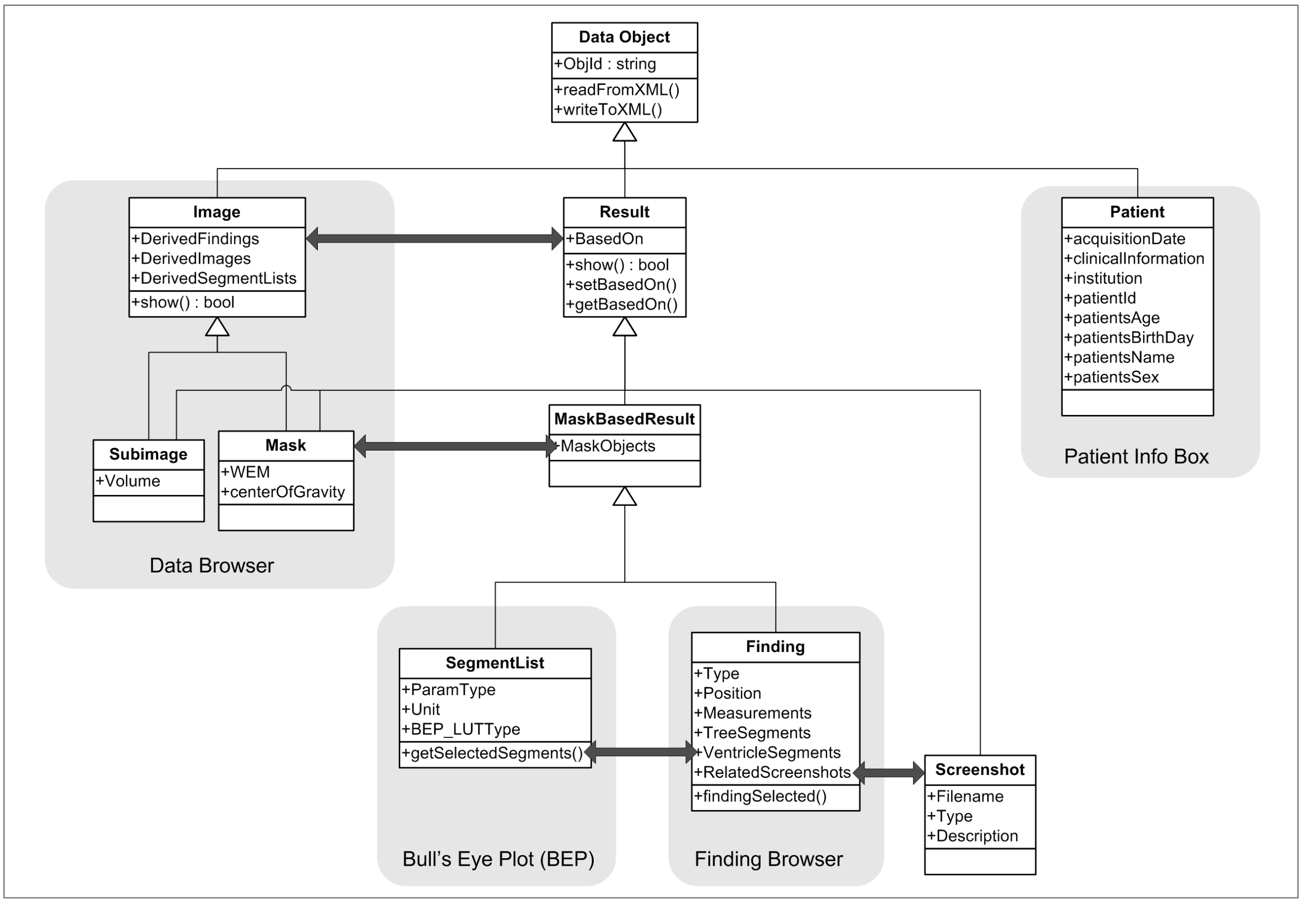

Figure 2. Overview of the main classes and the correlation between objects (dark arrows). Furthermore, GUI elements are marked that represent objects of a certain class.

2.2 Representation of the Data

A common data representation is required, to provide an easy access to the CT and MR data derived by our previously described software assistants in a diagnosis-oriented way, such that, e.g., unnecessary conversion is not needed. We apply the extracted information to a common class hierarchy concept, distinguishing between image data (original as well as analysis results), other types of derived results, and patient information (cf. Fig. 2). This allows a grouping of the data, which forms the basis for the workflow control and for the interface design described below. Moreover, the processed data sets can be reloaded into the result exploration software, even if not the full range of analysis steps is provided. Information about the result images, e.g., subimages or masks, are stored into instances of special classes, which inherit from both the ”Image” and the ”Result” class. The correspondence between a result and the input image is described in the ”BasedOn” attribute. Moreover, the ”Image” class has attributes pointing to the derived results, e.g., masks, subimages, findings, or segment-based parameter lists. Therefore, we relate both object classes by that special information (cf. arrows in Fig. 2). We further introduce findings as certain features of pathological structures, e.g., stenosis, scar tissue or abnormal LV wall thickening. They are characterized by a specific position, the affected coronary tree and LV segments, and corresponding values such as the vessel diameter or the wall thickening. Further information about the underlying data, for instance a coronary tree segmentation mask or an LV segmentation mask, is also stored into an attribute. The adaptation of this scheme in all three software assistants enables a comprehensive analysis of abnormal cardiac measurements from the coronary tree as well as the LV. The underlying image analysis tools are embedded into a common framework that provides efficient and flexible methods to access and store all necessary types of data in an adequate XML structure.[18] The interface between the framework and our class scheme is given by the read and write functions of the parent “Data Object” class.

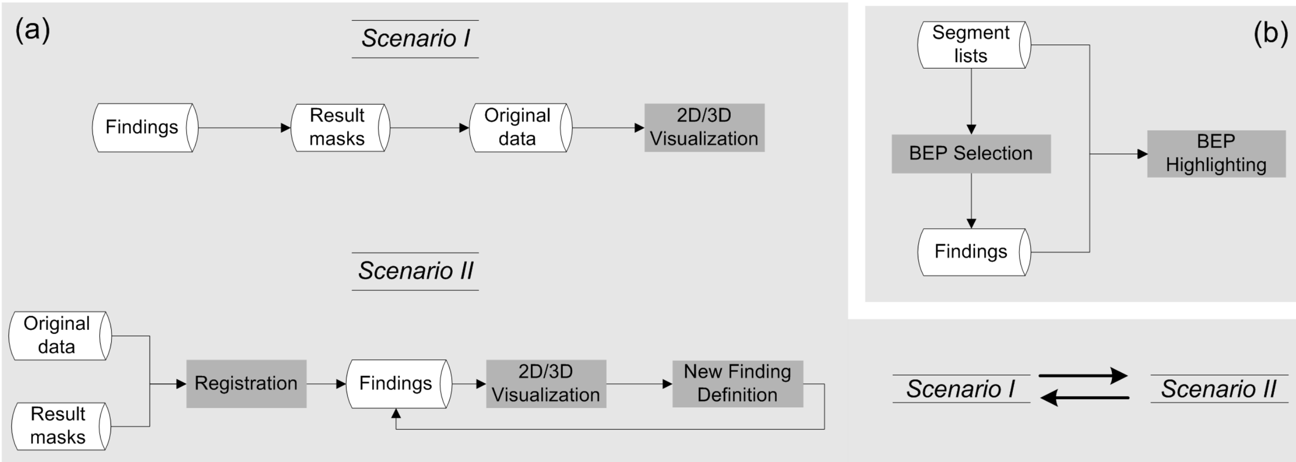

Figure 3. (a) Description of workflow scenarios based on the selection of findings (Scenario I), or on original data and result masks (Scenario II); (b) description of interactive BEP navigation.

2.3 Workflow

For an appropriate diagnosis support we have to provide the radiologist with a wide range of information in a structured fashion. Exploring the data, the physician does not have to follow a single predefined process, but may consider different combinations and scenarios of the images and measurements depending on the individual case. Therefore, workflow-design for our software assistant is a challenging task. We focus on a relation of cause and effect, since we want to support the diagnosis of the CAD. That means, we provide the physician with the anatomical data, e.g., of the coronary arteries, and support the comparability of findings from that special examination with the results from the function and perfusion analysis. Common image combinations are defined and firmly included to simplify and speed up the usage. For example, the comprehensive examination of the CTA and the late enhancement data is a common requirement. We incorporate the data dependencies into the previously described class hierarchy concept (cf. black arrows in Fig. 2) and bind the workflow to object-specific functionality. Thus, the amount of analysis data is structured to fit into the workflow.
Two workflow scenarios are defined: Either a finding is selected in the navigation section, or some image data is chosen (cf. Fig. 3 a). In the first scenario, the user selects a finding and related information from its attributes are derived. The finding position will be highlighted and focused in the 2D and 3D viewers, showing the result masks and the original data on which the finding is based. Moreover, the measurements are loaded into tables in the quantitative information section. In the second scenario, original and mask data are selected. They have attributes describing derived findings, which will be additionally loaded. Furthermore, new findings can be defined and added to the analysis results (cf. Fig. 3 a). The categorization of findings into coronary tree, left ventricular, or combined analysis especially emphasizes the significance of a certain finding.

2.4 Visualization

The visualization of several parameters, in our case derived from various cardiac CT and MRT examinations, requires adequate methods. Moreover, a fast visualization, even for large data sets (CT: 512x512x300, MR: e.g., 256x192x10 for LE data), must be provided. Hence, efficient and informative visualization is an important task in multimodal image analysis. On the one hand, the objective is to emphasize suspicious regions, and on the other hand to support the user navigation within the data. To show the relation between the original CT and MR data, result masks of the left ventricle are color-coded with parameters such as the wall thickening, and overlaid in 2D. For a better recognition, selected findings are accentuated in 2D and in 3D.
For 3D visualization, we use a winged-edge mesh (WEM) representation, in which measured parameter values can be assigned to each node.[19] A color-coding of the nodes maps the measurements onto the surface by commonly defined cardiac look-up tables. Registered WEMs and volume renderings of the coronary tree and the parameter overlaid LV particularly give an overview of the physiology and the anatomy. The overlay of the coronary tree segmentation mask within the 2D function and late enhancement images gives a direct correspondence between

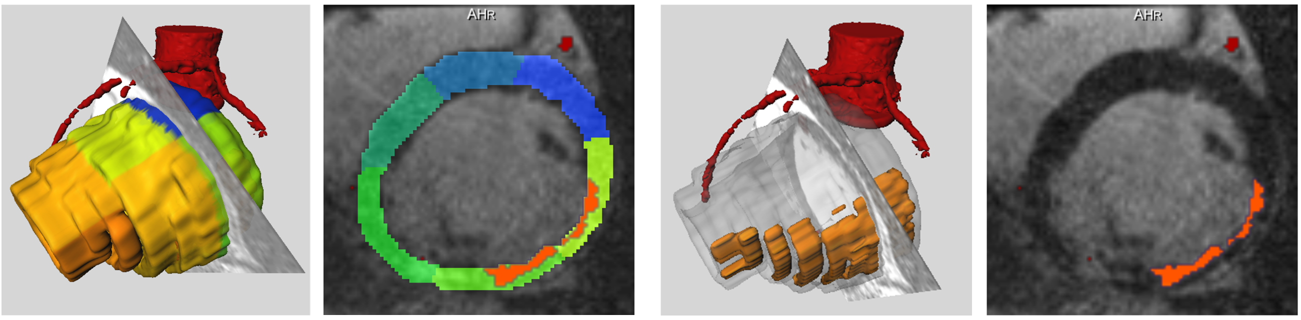

Figure 4. Exemplary 2D and 3D representation of the combined anatomic and dynamic information. In 2D, original late enhancement data is shown with overlays of the coronary tree segmentation mask (red), the segment-division of the left ventricle, and the scar tissue (orange). The selected slice is shown in the 3D image for orientation purpose.

the vessel and the supplied myocardium. Additionally, rendered corresponding 2D slices allow an incorporation of the original data into 3D scenes (cf. Fig. 4). This establishes a reference to the underlying image data. Further 2D multi-planar reformations (MPR) of a certain coronary tree segment give a more detailed impression about possible distortions. Moreover, we developed an interactive bull's eye plot, which supports the AHA 17-segment model-based correlation of coronary tree branches and the supplied LV myocardium segments.[20]

2.5 Interaction

To reduce the required user interaction, our software assistant comprises a structured user interface (cf. Fig. 6). On the left-hand side, it consists of an information and navigation section. On the right-hand side, there is a viewer section including a 2D viewer, a 3D viewer, and an interactive bull's eye plot (BEP). The shown BEP parameter can be chosen via a pull-down menu. As mentioned above, the navigation depends either on the findings or on the image data (original and result masks). Both are listed in two independent browsers with checkable contents to guide through the visualization scenarios, using the dependencies encoded in the class structure. When a finding is selected, the corresponding data is loaded. Furthermore, simultaneous positions and a focus in 2D and 3D give a better orientation within the data. Thus, the corresponding slice is shown in 2D and the camera is continuously moved to focus on the finding position in 3D. Further navigation is possible using the interactive BEP. This tool is selectable and all findings related to this segment are shown corresponding to the selected segment. The same can be done vice versa, selecting a finding and highlighting the affected BEP-segment.[20] For the creation of an MPR a certain coronary tree segment can be selected in 3D and will be shown in a crossed, a curved, or a stretched view.

2.6 MeVisLab

The development of our software assistant is completely based on the rapid prototyping platform MeVisLab.[21] This platform is designed for image processing and visualization with the focus on medical imaging. It is based on a graphical programming approach. A wide range of algorithms is accessible and can be combined as graphical components within networks. A modular description language has been developed, allowing a rapid generation of graphical user interfaces (GUI),and hiding the complexity of a network. Dynamic functionality can be added to the GUI using JavaScript or Python. Furthermore, MeVisLab provides certain concepts, e.g., an application framework for the data handling, which provides a common data structure formulation.[18] This makes the reusability of data and analysis results within different software assistants possible. The available DICOM service allows an integration in the radiological workflow. New features can be easily added to current software solutions.

We constructed a network with MeVisLab, which incorporates the complete visualization modules and data handling functionality. The network structure shows already the clear division of the GUI into different tasks. Beside the design of the GUI-elements, we developed special functions to manage the dynamic behavior, whereas we distinguish between those affecting the GUI (e.g., updating the data browser), those reading the XML data and the classes for the data structuring and handling.

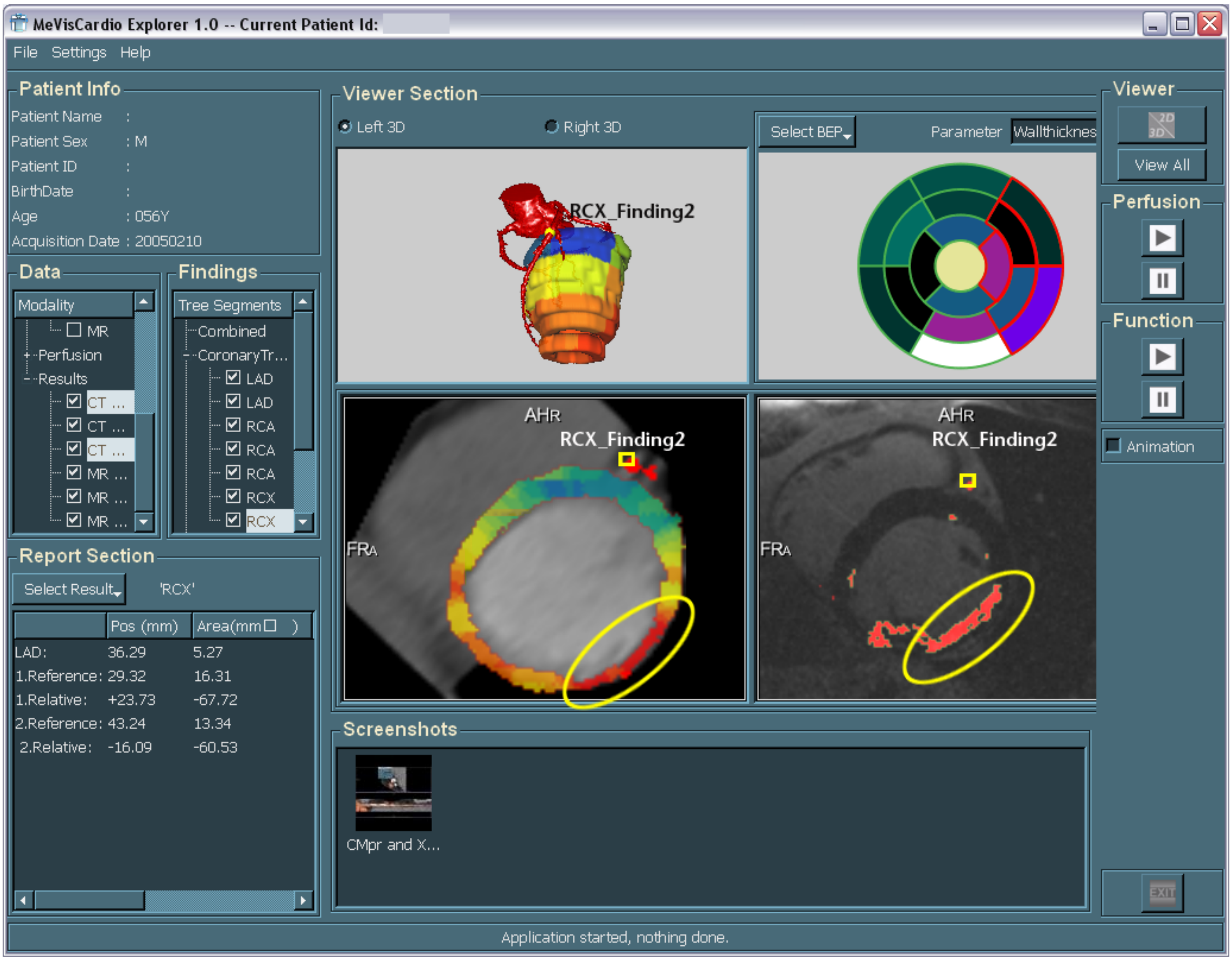

Figure 5. Example case with 3D combined LE and coronary tree examination. One finding is selected and shown in 2D and 3D. The coronary tree mask is overlaid in the CT data and in the LE data as well, which illustrates that the stenosis is not responsible for the myocardial dysfunction and the scar tissue in the lower part (yellow ellipse). Ventricular segments assigned to the coronary branch affected by the selected finding, are highlighted in the BEP.

3. RESULTS

To demonstrate the capabilities of our software, we present exemplary patient data that exhibit typical examination tasks from CT and MR. In the first step, the user has to select the directory with the patient data. Subsequently, the XML files are parsed and the data objects are constructed. The example patient case includes CT coronary tree and the left ventricular function examination, the MR late enhancement analysis, and additional tagged MR images for visual function analysis. Figure 5 illustrates the example, therein the set of images is clearly listed in the data browser; furthermore, all findings are listed in an additional browser. Regarding the coronary tree analysis, several findings are marked and selectable. To compare them with the tissue state, the LE data is selected. Both datasets are shown in the short axis view and the coronary tree segmentation mask is overlaid, such that a comprehensive examination is possible. For additional inspection of the heart motion, the user can take a look at the tagged MR images in cine mode as shown in Figures 6. The registration of the data enables an overlay of the segmentation masks and the corresponding short axis representation of the coronary angiography, and thus gives a better comprehensive visualization. It is now possible to supplement the currently selected finding by information from the LE analysis results, whereas the finding is categorized into the combined finding section. Thereby, the diagnosis process is well documented by the finding categorization. The

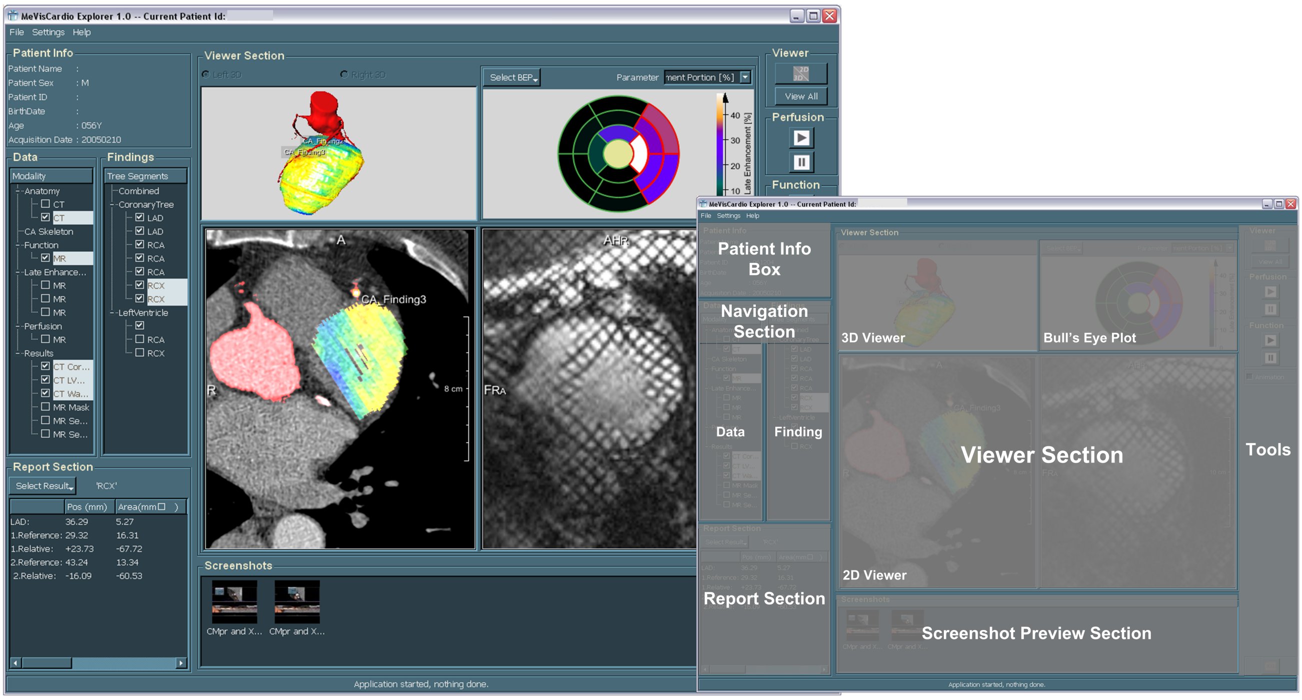

Figure 6. Combination of the coronary tree examination and the tagged image, which can be seen in a cine mode for further visual investigation. The smaller image on the right illustrates the structure of the software assistant's user interface.

3D visualization also serves as an overview and provides a good correlation between the schematic 17-segment division and the patient-specific supply areas.

Positive feedback after first demonstration and discussion with radiologists affirmed the feasibility of our software. Especially the side by side 2D presentation of the CT and MR data from the same perspective, e.g., the short axis view, was found to be most promising for a comprehensive diagnosis. The overlay of the coronary tree segmentation mask in the MR images additionally simplifies the orientation within the data.

The software assistant is applied to 20 patient data sets. Included are 10 cases both with CT angiographic and MR late enhancement images, and data of 10 patients exhibiting CT angiography and function. On the multimodal data from CT and MR we demonstrate that a fused visualization of coronary tree and the parameter mapped LV provides detailed information about coronary artery distortion and the effect on the supplied myocardium. Due to the patient-specific anatomy, a comprehensive representation of available analysis data on anatomy and physiology is more accurate than a correlation with respect to the AHA 17-segment model. Furthermore, relating the workflow to the structured data representation has proved to be feasible for user guidance. It enabled a sophisticated visualization of corresponding information.

We further analyze the CT data of the 10 patients with the coronary tree and the left ventricular function examination and show the applicability of our approach (cf. Fig. 7). New findings can be defined, relying on the user-selected combined visualization of different data. The possibility to save findings within already analyzed cases makes the software assistant a valuable tool for comprehensive information mining from more than one examination or modality. This mainly results from the unified case handling concept common to both the analysis and the visualization software.

4. DISCUSSION & CONCLUSION

We introduce a new software assistant for the dedicated diagnosis support based on the combined representation of results from cardiac CT vessel and function analysis as well as MR late enhancement assessment. Our initial evaluation of 20 clinical cases already showed the feasibility of our integrated analysis and visualization concept. Relying on a common storage scheme, original and result data as well as measured quantitative values can be easily loaded into the visualization software. A common class design for the data enables an appropriate

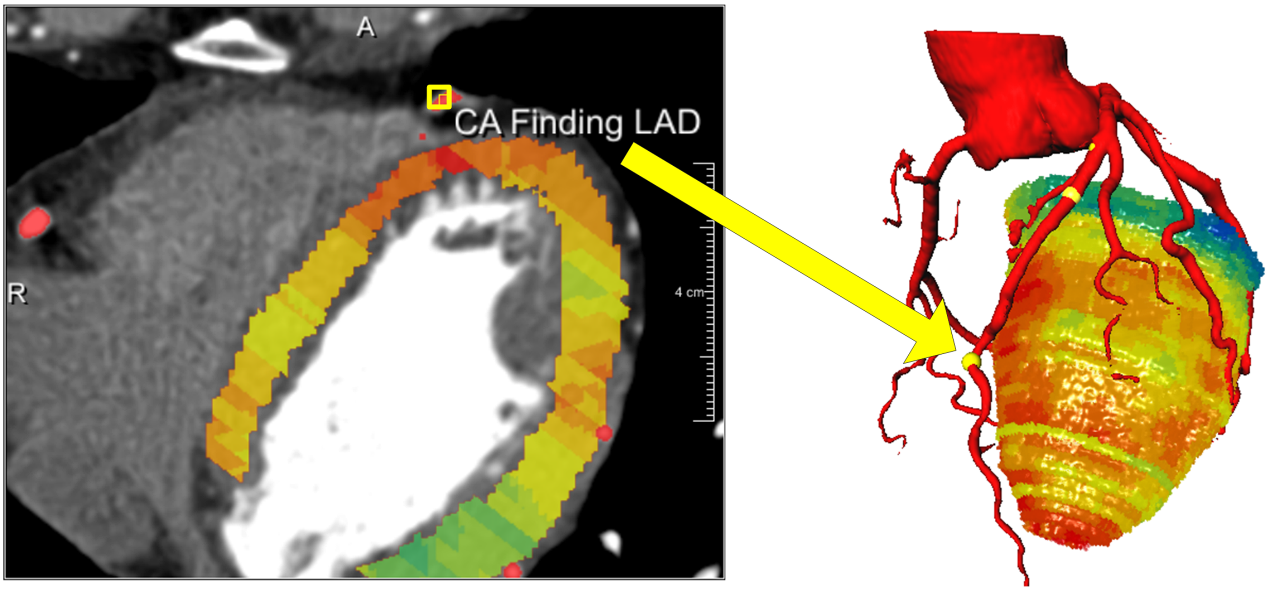

Figure 7. Finding position shown in 2D original data with overlay of wall thickness and vessel segmentation plus corresponding 3D volume rendering.

workflow design. For the first time, the user can define new findings resulting from the consideration of data from both MRI and CT. These can be additionally stored to the patient data and allow a more detailed diagnosis support. In future work, we will focus on more detailed evaluations with our clinical partners. A standardization of the comprehensive utilization of anatomical and physiological data will be shown in more extensive studies. Therefore, the definition of a standardized clinical report for CAD diagnosis based on multimodal images is necessary. It will enable a further integration of patient individual information into the software assistants which makes it feasible for clinical usage. Moreover, we intend to integrate the catheter angiography into the workflow of our assistant, as this modality represents the current gold standard for coronary artery analysis. This will allow to better validate the potential of combined CTA and MRI analysis with respect to a replacement of invasive cardiac imaging techniques.

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