Localizing Calcifications in Cardiac CT Data Sets Using a New Vessel Segmentation Approach

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The new generation of multislice computed tomography (CT) scanners allows for the acquisition of high-resolution images of the heart. Based on that image data, the heart can be analyzed in a noninvasive way—improving the diagnosis of cardiovascular malfunctions on one hand, and the planning of an eventually necessary intervention on the other. One important parameter for the evaluation of the severeness of a coronary artery disease is the number and localization of calcifications (hard plaques). This work presents a method for localizing these calcifications by employing a newly developed vessel segmentation approach. This extraction technique has been developed for, and tested with, contrast-enhanced CT data sets of the heart. The algorithm provides enough information to compute the vessel diameter along the extracted segment. An approach for automatically detecting calcified regions that combines diameter information and gray value analysis is presented. In addition, specially adapted methods for the visualization of these analysis results are described.

KEY WORDS: Computed tomography, vessel segmentation, coronary arteries, calcification, image analysis, visualization

BACKGROUND

The most frequent cause of death in the developed nations are cardiovascular diseases.* Often, an occlusion of the coronary artery causes severe risks to the patient's health. An early and reliable detection of those areas with a lowered cross-sectional size—the so-called stenoses—is of high importance for a correct diagnosis of a cardiac disease and its severity. The examination of the coronary arteries in a qualitative and

quantitative manner is invaluable for the evaluation of the personal risk for every patient. In addition, such analysis is a prerequisite for the planning of a possibly necessary surgical intervention such as bypass grafting.

An important parameter for the evaluation of the coronary arteries is the number, extent, and localization of stenoses. In most cases, this narrowing of the vessel is caused by sedimentation of several substances at the inner arterial wall.¹ One has to distinguish between so-called soft (mainly lipids) and hard plaques (calcifications). Although in computed tomography (CT) image data soft plaques are in most cases only detectable through a visible decrease of the vessel cross-sectional area, hard plaques appear as bright clusters attached to the inner arterial wall. From the clinical point of view, soft plaques that are prone to rupture seem to represent a higher risk for the patient than stable hard plaques. However, the quantity and quality of hard plaques is an indicator for the severity of a coronary artery disease (CAD).²

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Cardiac CT

In the past, coronary artery calcification has often been detected based on electron beam computed tomography (EBCT) data. Several articles describe methods for quantifying the calcium,^{3,4} whereas others focus on the reproducibility of the calcium scoring.⁵ The reason for the usage of EBCT was the much shorter acquisition time of EBCT compared to present-generation conventional computed tomography. However, with the advent of multislice computed tomography (MSCT) and an increased rotation time of the CT gantry, it became possible to scan the whole heart in a single breathhold.^{6,7}

The potential of MSCT for cardiac imaging was evident from the very beginning. Hence, it evolved very fast from 4- over 16-slice scanners with improved image quality⁸ to the latest development represented by the 64-slice machines recently introduced by all global players on the market.^{9,10} Thus, the acquisition of image data over multiple cardiac cycles in combination with sophisticated reconstruction algorithms^{9,10} delivers a four-dimensional (3D volume + time) cardiac image data with a sufficient temporal and best spatial resolution available.

Consequently, cardiac CT can also be used for investigating issues that have been reserved for other imaging modalities before. For instance, conventional angiography has been the “gold standard” for the examination of vascular structures. However, it is an invasive technique with some negative implications for the patient. Now, it can be replaced by computed tomography angiography (CTA) for inspecting the coronary arteries in a noninvasive way.^{11–14} Their segmentation can enhance data visualization on one hand, and permits an analysis of the vessels on the other. For radiologists and cardiologists, this represents valuable, additional information for diagnosis and planning of a necessary intervention. Most of the approaches described in the literature are limited to the detection of stenoses from 2D image data.^{11,14,15} To the authors’ knowledge, there has not been any published work on true 3D analysis

of coronary arteries based on MSCT coronary angiography yet.

In the past, many approaches for the extraction of vascular structures have been reported. In,¹⁶ several of those algorithms were reviewed and classified. Lately, special efforts have been made to develop segmentation techniques focusing on the extraction of the coronary arteries. One simple approach is the usage of a region-growing¹⁷ technique for extracting the whole coronary artery tree and the adjacent part of the aorta. As stated by Hennemuth et al.,¹⁸ this is only the first step for the analysis of the coronary arteries that must be followed by some kind of skeletonization¹⁹ to extract the vessel centerline.

Better-adapted algorithms for a subsequent analysis of the extracted vessel are tracking-based approaches,²⁰ as these techniques simultaneously extract the vessel centerline and its border. Our study deals with the methods for localizing calcifications in coronary arteries by employing a tracking-based vessel segmentation technique. This algorithm has been developed for the purpose of coronary artery extraction from contrast-enhanced cardiac CT data. Based on that semiautomatic segmentation algorithm, the coronary arteries are analyzed focusing on the vessel diameter and the detection of hard plaques. Furthermore, special visualization techniques developed for the purpose of vessel analysis are presented.

METHODS

Contrast-enhanced cardiac CT data was retrospectively evaluated by employing the “corkscrew algorithm”²¹ for the extraction of the coronary arteries from the data sets. This vessel segmentation was followed by an automatic analysis step for the computation of the diameter and hard plaque detection. All included patients had clinical indication for cardiac CT examination.

Image Acquisition

The MSCT data acquisition was performed on a 16-slice spiral CT (Sensation 16, Siemens, Inc., Germany). All patients were scanned at their original heart rate, which means that no beta-blockers were administered. Their mean heart rate amounted to approx. 70 beats per minute (bpm). Scanning parameters were 120 kV voltage and 400 mA s tube current, 420 ms rotation time, 16×0.75 mm collimation, and 2.8 mm table feed per rotation. Each patient received 120 mL nonionic contrast medium at a flow rate of 3.5 mL/s (Ultravist 370

*Siemens: Somatom Sensation 64.

**GE: LightSpeed VCT.

***Toshiba: Aquilion 64.

†Philips: Brilliance CT 64-channel.

mg/mL; Schering, Inc., Germany) infused through an 18-gauge intravenous antecubital catheter.²² Start delay was calculated using the CareBolus technique, placing an ROI in the ascending aorta. Image reconstruction was performed in all patients by using retrospective ECG gating, a technique that allows continuous image reconstruction from volume data sets during any phase of the cardiac cycle. The reconstruction parameters were 220 mm FOV, kernel B35 (a medium soft tissue kernel), 1.0 mm effective slice thickness, and 0.5 mm increment. The adaptive cardiac volume (ACV) technique, which is regularly provided with the Sensation 16 cardiac software package, served as reconstruction algorithm. Heart rates of up to <72 bpm ACV allow for single-segmental reconstruction, and heart rates >72 bpm for two-segment reconstruction of each 1.00 mm slice.²³ Although the temporal resolution for single-segment reconstruction was 210 ms, two-segment reconstruction had a temporal resolution between 210 and 105 ms, subject to the heart rate.

Segmentation of Coronary Arteries

The proposed analysis is based on a tracking-based vessel extraction technique. Vessels containing contrast agent are relatively homogeneous and have a high contrast with respect to the surrounding tissue. This allows for a segmentation based on the “corkscrew algorithm.” Thus, a connection between the user-defined start and end point following a helical- or corkscrew-shaped path is searched. A cost function, taking into account the voxel values that are obtained by applying common imaging filters to the original data, is used for “guiding” the path search. It provides in the first step an estimation for the centerline, which is afterwards corrected iteratively by detecting the voxels belonging to the vessel border (Fig 1). The user-defined start and end point for the

segmentation as well as an additional point for defining the initial direction must all lie inside the vessel. The algorithm’s output is a set of points defining the centerline and another one representing the border (Fig 1). For more details on the segmentation algorithm itself, see the work of Wesarg and Firle.²¹

Analysis Based on Segmentation Result

The output of the vessel segmentation presented in the preceding section allows for subsequent analysis of the extracted coronary artery. Each computed point of the centerline has a corresponding set of points representing the vessel border perpendicular to that centerline segment. Hence, the diameter of the coronary artery, with its mean value for each centerline position, can easily be computed.

The employed vessel extraction approach excludes calcifications from the segmentation result.²¹ Calcified regions are expected to lower the mean diameter, as the corresponding border points lie “in front” of them. Consequently, a simple approach for detecting those calcium-induced stenoses could be computed from the diameter followed by an extraction of all positions along the vessel with a corresponding diameter below a certain threshold. However, this simple minimum detection has one weakness: The detected minimum may be related to stenoses that are not caused by a calcification.

Therefore, we extended the analysis to overcome this weakness. An additional three-step analysis based on the diameter function and the image data was performed (see Fig 2):

1. From the diameter function, calcification candidates are extracted by selecting those centerline points with a corresponding diameter below a certain threshold (for instance, the mean value of that function).

Fig 1. The corkscrew algorithm: The search direction is cycling the axes (x , y , z) generating a set of initial sample points. The search is stopped when the path enters a dened region (cube at the top) around the end point (left). The centers-of-gravity for each three subsequent sample points are calculated. This operation generates a list of control points (dark) with positions deeper inside the vessel than the previous sample points (bright) (right). A B-spline interpolation between these control points computes the first estimation for the centerline. Afterwards, it is corrected iteratively by detecting the border points perpendicular to the corresponding centerline segment. The segmentation’s output consists of one point set representing the border and a second one defining the centerline.

Fig 2. The refined analysis for localizing calcifications in coronary arteries: A set of candidate points is selected based on an automatically computed threshold. These points are further analyzed whether bright gray values are in their neighborhood. Finally, the remaining points are decimated again for assuring that only one of them belonging to the same single calcification is stored.

2. Next, the candidate points neighborhoods are searched to see whether voxels with high gray values are present. Our investigations show that for the presented data (see “Image Acquisition”), calcifications are 20–30% brighter than the vessel lumen that is filled with a contrast agent. Only those candidate points having a neighborhood that fulfills the brightness criteria are kept.
3. In a last step, it is analyzed whether several candidate points form a group sharing the same calcification. In such a case, only the middle position between the first and the last points of the group is stored. This ensure that a single calcification is recorded only once.

The result of this refined analysis is a set of points with a position related to a relatively low diameter of the coronary artery on one hand and a neighborhood containing voxels with a high gray value on the other. These two conditions are expected to reliably localize calcifications.

Data Visualization

Results of the vessel analysis can be presented in different ways. In this section, we describe the methods that we have developed. All visualization tasks in this work are carried out using the freely available toolkit VTK.*

The visualization mode for the segmentation results can be selected by the user. The two point sets that are generated during the vessel extraction step can be independently visualized from each other—as a line in case of the centerline points, or as a 3D surface of the vessel border if the volume is displayed using a volume rendering technique (VRT). This

polygonal representation is added to the direct volume-rendered data in one single view (see Fig 3).

The usual way of presenting the computed diameter function is an x–y plot (see left part of Fig 2). This plot allows, in most cases, for visual detection of stenotic areas. However, it is not always obvious how this plotted curve should be mapped to the segmented artery that is shown using a VRT. To avoid the therewith related difficulties, we developed a method to directly visualize the diameter function in the volume-rendered view. For that, we created a tube around the generated centerline. The cross-sectional dimension of the tube varies in the same way as the diameter function. In addition, it is colored based on the diameter values. A red color signifies a low diameter, whereas blue color stands for a large one. The values in-between are represented by a rainbow-based transition from red to blue (see Fig 3). Thus, possibly stenotic areas, represented by a red color, can be easily perceived and located by inspecting the 3D representation of the data set.

A typical way of visualizing vascular structures is the usage of the so-called multiplanar reformations (MPR) of the image data. In fact, this is some kind of a 2D projection of the three-dimensional structure. We use the approach where the coronary artery is not only projected, but also “straightened.” This is achieved through the generation of a virtual cylinder with the vessel’s centerline as its medial axis and a radius that can be set by the user. This virtual cylinder is again a 3D representation of the image data—here restricted to the artery and nearby adjacent areas (see Fig 4). Arbitrarily 2D cuts along the cylinder’s medial axis as well as perpendicular to it can be generated “on the fly,” and are displayed on a rectangular resp. a polar grid. This allows for an easy navigation along the vessel and an in-depth examination of its morphology (see Fig 5).

But, we also go a step further than common MPR-based visualization. In conventional angiography, vessels are displayed as a 2D x-ray projection. A quite similar result can be achieved with CT data when a VRT is used that is based on a maximum intensity projection (MAXIP) of the image data.²⁴

*The Visualization Toolkit by Kitware, Inc. (<http://www.vtk.org>)

Fig 3. Result of the segmentation step: The coronary artery borders have been extracted. It is shown as a polygonal mesh that is overlaid in volume rendering view (left). Visualization of the diameter function directly in 3D; a tube around the computed vessel centerline is shown. It varies in diameter corresponding to the diameter function. In addition, this variation is color-coded using a linear rainbow-based transition from red to blue (right).

However, a simple MAXIP of the whole 3D image data would suffer from a poor visibility of the coronary arteries. Surrounding tissue and the contrast filled left and right ventricles and atria would shadow the small vascular structures and hinder their good perception. Since we have already generated the virtual cylinder for the MPR, we can use this for the definition of a binary mask. Consequently, all image data lying outside the cylinder is masked out, and only the vessel and the closely lying areas are shown in MAXIP mode. An additional advantage of this visualization that we call “vessel region focused (VRF) rendering” is the fact that it is a 3D rendering, allowing for full user interaction with the data such as rotating and zooming. Thus, calcifications and their position relative to the artery can be easily investigated (see Fig 6).

Finally, for visualizing the results of hard plaque detection, multiple cone-shaped pointers are used (see Figs 5 and 6). In

addition, their positions are enumerated in a list box control. Selecting one of them adjusts the common 2D views (axial, coronal, sagittal) and highlights the selected position (see Fig 6). This ensures the connection between the automatic hard plaque detection presented in this article and the traditional way of detecting hard plaques by manually inspecting the axial slices.

RESULTS

The reliability and accuracy of the presented calcification detection approach has been tested with contrast-enhanced CT data from 10 patients. In all these data sets, the left anterior descending

Fig 4. Generation of the multiplanar reformation view: A virtual cylinder around the centerline of the segmented vessel is generated. It consists of circular cuts through the vessel and its close neighborhood that are perpendicular to the corresponding segment of the artery centerline (left). By creating a stack of these circular cuts, the virtual cylinder can be straightened, and arbitrary views can be generated (right).

Fig 5. Analysis of the extracted vessel: Arbitrary multiplanar reformations of the vessel can be generated. Cuts perpendicular to the artery centerline are displayed on a polar grid (upper left). Straightened cuts along its centerline are displayed on a rectangular grid. Automatically detected calcifications and the current position are indicated as pointers above and below the vessel (bottom). The computed diameter is shown as an x-y plot (upper right).

(LAD), the left circumflex (LCX), as well as the right coronary artery (RCA) have been segmented with the aforementioned corkscrew algorithm. The segmentation did not always extract the whole artery because imaging artifacts that interrupted the continuous run of the vessel. In these

cases, only the part that has been segmented could be further analyzed. In data set 5, only the LAD could be segmented, because the image data was of very poor quality. For the 28 vessels that could be extracted, we evaluated the correspondence between the automatic hard plaque detection

Fig 6. A coronary artery shown in VRF rendering mode: The image data outside the vessel has been automatically masked out. The artery is rendered using a MAXIP rendering technique, allowing for a good visibility of hard plaques attached to the vessel's wall. The pointers represent the automatically detected positions of calcifications (left). Selecting one of the listed position coordinates adjusts the corresponding 2D slices and highlights that position (right).

Table 1. Results for the automatic detection of hard plaques in coronary arteries based on their segmentation: data sets of ten patients were used, in whom LAD, LCX, and RCA were inspected

Data set	Hard plaques	LAD	LCX	RCA
1	Visible	0	0	0
	Detected	0	0	0
2	Visible	3	1	1
	Detected	3	1	1
3	Visible	5	2	5
	Detected	6	2	5
4	Visible	1	0	0
	Detected	1	0	0
5	Visible	0	—	—
	Detected	0	—	—
6	Visible	3	0	0
	Detected	3	0	0
7	Visible	6	0	1
	Detected	6	0	1
8	Visible	4	0	2
	Detected	5	0	2
9	Visible	3	6	1
	Detected	3	5	2
10	Visible	6	6	3
	Detected	8	9	3

technique described in the preceding section and a manual inspection of the axial slices.

Table 1 shows the results for the newly introduced three-step analysis for the detection of hard plaques. This automatic technique reliably detected the present calcifications in nearly all cases. Four of the hard plaques that have been found during a preceding manual inspection of the axial slices have been indicated more than once as a result of their large size. This led the algorithm to an overestimation of the number of calcifications in these cases (data sets 3, 8, and 10). In one of the cases (data set 9), a visible calcification was not automatically detected. Figure 6 shows an example for the detection of multiple calcifications. In addition, we determined a false-positive value of 0 for the automatic hard plaque detection. The segments not containing any visible hard plaque have been classified by our technique to be calcification-free.

DISCUSSION

The technique presented in this work has the potential for reliably localizing calcifications in

coronary vessels in an automatic manner. The introduced detection scheme, based on a combination of the computed vessel diameter and an analysis of gray values, detected visually determined calcifications in 98% of the cases. One very important fact for the clinical usage in our approach is that the tests had a false positive value of 0.

However, there is one limitation in the results. As only 10 data sets were available for initial tests of our approach, only preliminary results could be presented. A future work will focus on tests with a larger group of patients.

Recent work investigating the usability of automatic vessel detection tools for examination of the cardiovascular system based on multislice CT data states that such a method reduces the time needed for diagnosis by a factor of 2.¹⁴ In contrast to our approach, the analysis was performed using curved multiplanar reformation and orthogonal cross-sections (see also Refs. 14 and 15). To our knowledge, there has been no published work yet about true 3D analysis of coronary vessels. An advantage of our method is that it provides results that are based on the original 3D data and not on (artificially created) 2D data. The latter always represents a reduction of information and, in some cases, also a loss of accuracy due to data interpolation.

In this work, we introduced several intuitive visualization methods for analysis results. We focused on the automated generation of those data representations that allow a convenient interaction with the image data. Thus, our MPR approach is more flexible than other techniques that generate only two orthogonal virtual cuts along the vessel. VRF rendering provides a visualization mode completely focusing on the coronary artery of interest, allowing—in conjunction with 3D interaction possibilities—their detailed inspection.

The localization of calcifications presented here is a two-step process. Based on the result of a 3D segmentation of the vascular structure of interest (step 1), the subsequent analysis is executed (step 2). Our vessel segmentation approach has several limitations regarding the handling of bifurcations and the sensitivity to imaging artifacts producing discontinuities of the coronary vessels (see Ref. 21 for more details). However, problems with the segmentation step could easily be solved by using a more suitable algorithm (as long as the algorithm extracts the vessel border as well as its centerline).

This independence from the segmentation technique is one of the strengths of our approach.

Compared to the current practice of vessel analysis, which is a manual slice-by-slice inspection process, our approach makes much more use of the potential of the latest MSCT scanners. In addition, the proposed automatic analysis reduces the time for the diagnosis. However, the extent of time reduction is currently under investigation. A clinical study with a larger patient group will also determine the accuracy of the proposed approach in a strong quantitative manner by comparing the results with those obtained by conventional coronary angiography.

CONCLUSION

The automatic analysis of coronary arteries based on vessel segmentation technique in 3D with contrast-enhanced MSCT data is feasible, and its reliability is proven on a (still limited) number of data sets. Automatically detected positions of calcifications corresponded to those determined by a manual approach. Further tests for the use of this technique on a larger patient group are under way.

Besides the qualitative analysis presented here, subsequent tests should also include a quantitative analysis of the detected calcifications with an aim of integrating the calcium score introduced by Agatston et al.³ Another extension of our coronary analysis tool could be an automatic detection and quantification of stenoses—not limited to those that are caused by hard plaques as discussed in the present work.

The current “gold standard” for the analysis of coronary arteries is conventional angiography. We are convinced that in the future, MSCT could replace this conventional invasive diagnostic technique. Within the framework of an ongoing cooperation between the Fraunhofer IGD and the University Hospital Frankfurt, we are performing an initial study comparing the results obtained from coronary angiography with those from contrast-enhanced MSCT data. Results are to be published in the near future.

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