NOVEL TECHNIQUES FOR AUTOMATICALLY ENHANCED VISUALIZATION OF CORONARY ARTERIES IN MSCT DATA AND FOR DRAWING DIRECT COMPARISONS TO CONVENTIONAL ANGIOGRAPHY

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Abstract: The new generation of multi-slice computed tomography (MSCT) scanners enables the radiologist to assess the coronary arteries in a non-invasive way. The question of particular interest is whether the quality of the findings based on MSCT data can compete with the *gold standard* - the coronary angiography. In this work we present novel automated methods for a reliable visualization of coronary arteries and for drawing direct visual side-by-side comparisons to conventional angiograms. Our approach comprises a new method for automatically extracting the heart from cardiac CT data and an advanced masking method for eliminating large cardiac cavities to obtain a better visibility of the coronary arteries in the rendered CT data. For drawing direct side-by-side comparisons we present a novel approach for simulating the conventional coronary angiography in an easy-to-handle manner. The new methods have been developed for and tested with contrast-enhanced cardiac CT datasets.

1 INTRODUCTION

In this work we present novel techniques for direct volume rendering of the coronary arteries from cardiac MSCT data and for drawing side-by-side comparisons to conventional angiography in an automated manner.

Coronary artery disease (CAD) and its complications such as myocardial infarction are among the main causes of death in the western world. CAD most often results from a decrease of the cross-sectional area of the coronary arteries. Therefore, a reliable detection of those narrowed areas – the so-called stenoses – is of high importance for diagnosis and in order to plan a possible treatment.

For years, the coronary angiography was the *gold standard* for the assessment of the coronary artery tree – in spite of the fact that it is an invasive modality and therefore associated with potential negative implications for the patient. The new generation of MSCT scanners allows the analysis of the coronary arteries in a non-invasive way. The question of particular interest is whether the quality of the findings based on these image data can compete with the conventional coronary angiography. To answer this question a reliable representation of the coronary arteries that is comparable to the representation in conventional angiograms is required. Further on, registration and matching of these representations allow transfering positions of potential pathologies (stenoses, calcification) detected in CT data to angiograms and vice versa.
Typically, cardiac CT data also includes non-cardiac structures such as ribs or the sternum which partially block the view at the heart and at the coronary arteries (see Figure 2 (a)). In this work we present an automated approach for extracting the heart from cardiac CT data for a better visibility of the coronary arteries. However, drawing direct visual comparisons between corresponding pathologies remains difficult. This is because on one hand, only parts of the coronary arteries are visible. On the other hand, manually achieving a viewing direction adequate to that in conventional angiography is very inaccurate. We present an additional method, that automatically generates so called *digitally reconstructed radiographies* (DRRs) from the CT data by simulating the conventional coronary angiography. Representations of the coronary ar-

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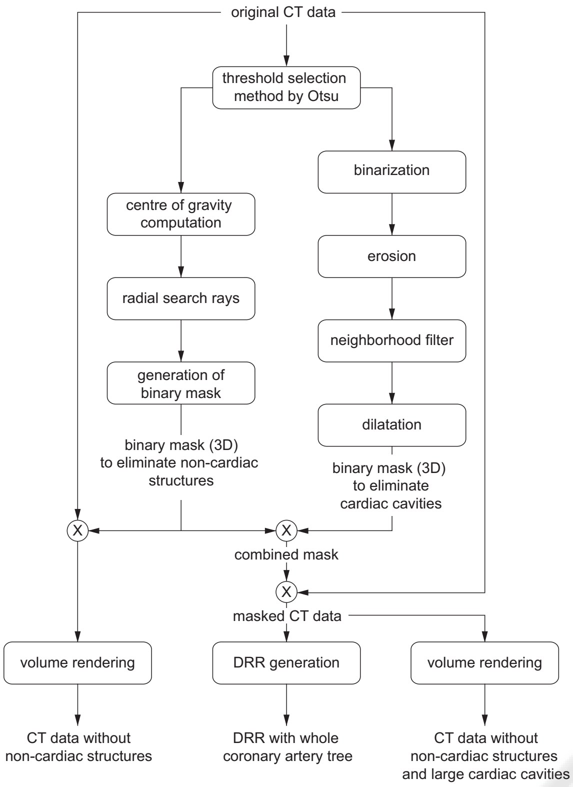


Figure 1: Our three possibilities for the visualization of coronary arteries from CT data. Left: Volume rendered CT data without displaying spurious non-cardiac structures (see Figure 2 (b)). Middle: Generated DRR from masked CT data. Both, non-cardiac structures and large cardiac cavities are eliminated (see Figure 6 (b)). Right: Volume rendered CT data without displaying non-cardiac structures and large cardiac cavities (see Figure 5 (b)).

teries generated this way, can easily be compared with conventional angiograms.

2 STATE OF THE ART

2004 Lorenz et al. developed a method for the extraction of the heart from cardiac CT datasets (Lorenz et al., 2004). They locate the chest wall and the descending aorta in all slices of the CT data in order to roughly estimate the location of the heart. Afterwards they use active contours to delineate the border of the heart in a slice-by-slice manner.

A reliable visual comparison between cardiac structures represented in 3D CT data and in 2D angiograms respectively, requires similar representations of those structures. In general, there are two possibilities to meet this requirement. Either, 3D reconstruction of the coronary arteries from a series of 2D angiograms or the opposite way around, projecting the CT data to a 2D image plane and compare these 2D images with conventional angiograms. In (Sang et al., 2006), (Großkopf and Hildebrand, 1997) and (Blondel et al., 2006) a 3D model of the coronary artery tree is reconstructed by segmenting the coronary artery tree. This 3D representation can be compared with the coronary tree extracted from the CT data. In (Schnapauff et al., 2007) emulation of conventional angiography is performed by segmenting the coronary arteries in the CT data and displaying the results by volume rendering techniques.

3 MATERIAL AND METHODS

In the following section, we describe our set of new approaches for an enhanced visualization of the coronary arteries in cardiac CT data (see Figure 1 for an overview). First, we present a new method for extracting the heart, followed by an advanced masking of large cardiac cavities to clearly visualize the whole coronary artery tree in a volume rendering of the CT data. The latter serves as a basis for the generation of DRRs to simulate conventional coronary angiography.

3.1 Image Acquisition

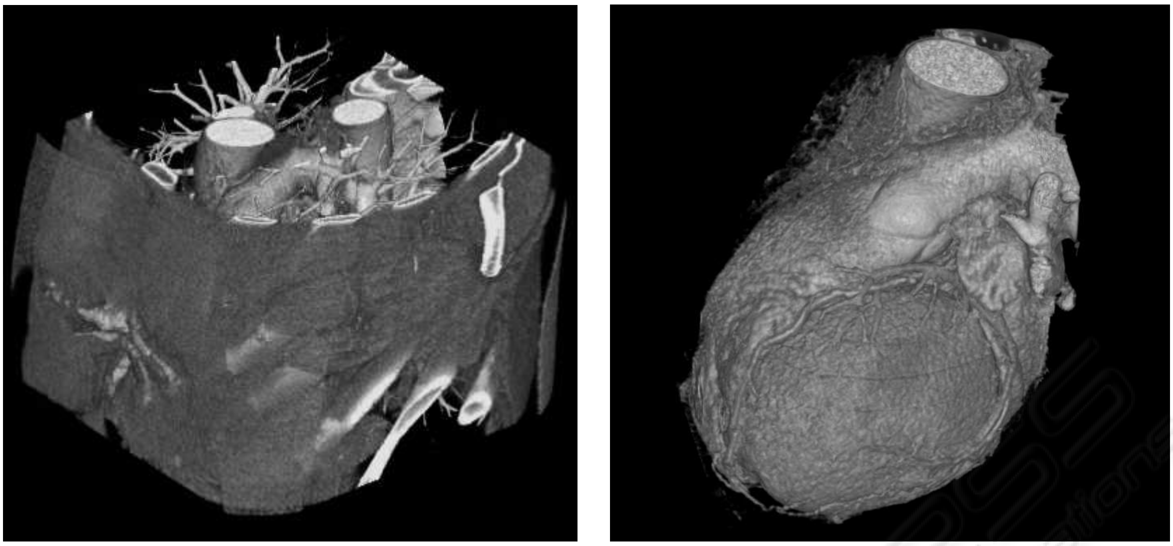
A total of 25 contrast-enhanced CT datasets were acquired by 16-slice[1] and 64-slice[2] CT scanners. The number of voxels in *x*- and *y*-direction constantly amounts 512×512 voxels and varies in *z*-direction from 176 to 441. The size of one voxel in *x*- and *y*-direction is identically, varying from 0.41 to 0.54 mm, and averages 0.5 mm along the *z*-axis. The gray level values of the CT data are normalized values of the computed X-ray attenuation coefficients, expressed in Hounsfield Units (HU) (Hounsfield, 1992). Typically, the CT data includes 4096 gray level values (12 bit).

In 8 out of 25 cases X-ray coronary angiography was performed[3] in addition to the CT data acquisition. The resolution of the angiograms amounts 512×512 pixels and they were digitized with 8 bit, thus the gray level values lie in between 0 and 255.

3.2 Enhanced Direct Volume Rendering of the Heart

When displaying the original CT data by volume rendering techniques non-cardiac structures such as ribs

[1]SIEMENS Somatom Session 16
[2]GE Light Speed VCT
[3]SIEMENS HICOR/ACOM-TOP, PHILIPS Integris H



(a) (b)

Figure 2: Volume rendered cardiac CT data. (a) Non-cardiac structures such as ribs or the sternum block the view at the heart and at the coronary arteries. (b) After applying the mask generated in 3.2 the heart and single branches of the coronary arteries are clearly visible.

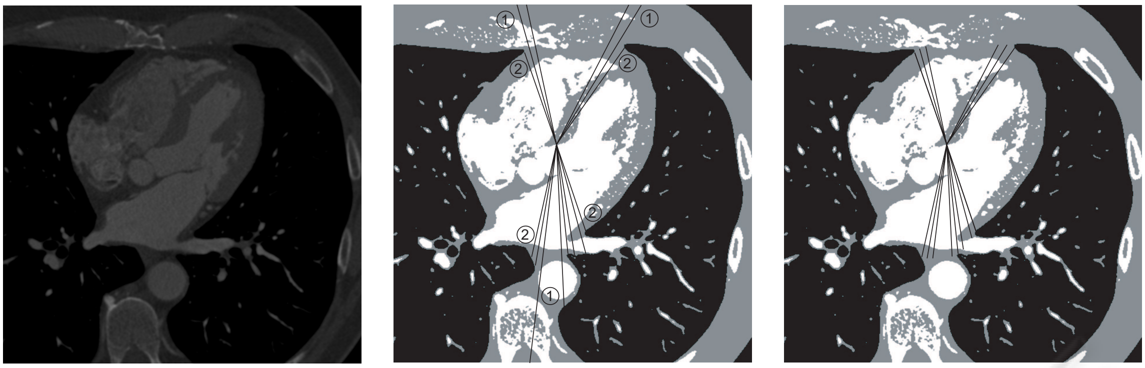
or the sternum block the view at the heart and at the coronary arteries (see Figure 2 (a)). Here, we present our new approach for eliminating those structures in order to obtain a clear view at the heart and at parts of the coronary artery tree in the volume rendered CT data.

Our approach for automatically extracting the heart from cardiac CT data consists of the following two steps. First, we use a statistical method to compute a point in the middle of the heart in all axial slices of the CT data. From this point we send out a search ray pattern to detect the outer boundary of the heart.

The gray level values of the CT data expressed in HU represent a linear transformation of the measured X-ray attenuation coefficients. Thus, the gray level values correlate with the different anatomical structures (air -1000 HU, water 0 HU, bone +1000 up to +3000 HU). In order to obtain a clear partition of the anatomical structures, we use Otsu's method of automatic threshold selection from gray level histogram for image segmentation (Otsu, 1979). An optimal set of thresholds is selected by the discriminant criterion; namely by maximizing the measure of separability of the resultant classes in gray levels. With two thresholds the voxels of the original CT data are dichotomized into three gray level classes. The darkest gray level corresponds to air, the middle one corresponds to fat and muscle tissue and the brightest gray level corresponds to bones and the contrast-enhanced cardiac structures (see Figure 3 (b)). As the result of the computation of the center of gravitiy of the two brightest gray levels we obtain a point in the middle of the heart.

In the axial slices of the labeled CT data the outline of the heart can be approximated by a circle or an ellipse. Therefore, from the computed center of gravity in the middle of the heart a radial search ray pattern (von Berg, 2005) is send out in order to detect the outer boundary of the heart. Clear bright-to-dark transitions from the heart to the surrounding tissue are found. At locations with overlaying structures, like the aorta and the sternum, the search rays are too long (see Figure 3 (b)) and need to be cut in a subsequent step. On each side of the aorta and the sternum the last rays which hit on lung tissue and therefore have the correct length are automatically detected . The length of the rays which lie between these rays is corrected by interpolating their new length from the length of the detected rays (see Figure 3 (c)). Afterwards the endpoints of the search rays are stored and then connected to get the outline of the heart in every axial slice. We obtain the binary mask by filling up the inner of the 2D outer boundary of the heart.

By applying the generated mask to the original CT data and by rendering these data, the heart and single branches of the coronary artery tree are clearly visible (see Figure 2 (b)).



(a) (b) (c)

Figure 3: Detection of the outer boundary of the heart using the example of a single axial slice. (a) Original CT data. (b) Labeled CT data after performing Otsu's method. The gray labels 0 to 2 correspond to the anatomical structures air, fat and muscle tissues, bone and contrast-enhanced cardiac structures. At locations with overlaying structures (sternum, aorta) the search rays are too long (1). On each side the last rays which hit on the lung tissue, and therefore have the correct length, are automatically detected (2). (c) The length of the rays (1) is corrected by interpolating their new length from the rays (2).

3.3 Drawing Side-by-Side Comparisons

The generation of DRRs from the original CT data leads to insufficient results concerning the visibility of the coronary artery tree in the projected images. On one hand non-cardiac structures such as ribs block the view at the heart. This problem can be fixed by eliminating those structures (see 3.2). On the other hand large cardiac cavities like ventricles and atria are in addition to the coronary arteries contrast-enhanced and occlude the coronary arteries in the projected images. The latter is because in the case of MSCT the contrast medium is applied systemically and is not injected directly into the coronary artery branches like in conventional coronary angiography. We present an advanced masking of spurious cardiac cavities for better visibility of the whole coronary artery tree. The masked CT data serves as input for generating DRRs in order to draw direct side-by-side comparisons to conventional angiography.

3.3.1 Advanced Masking

Our approach for masking out spurious cardiac cavities is based on morphological image processing techniques and neighborhood filters. First, we perform a thresholding operation on the labeled CT data. The highest label correlates with both, the contrast-enhanced cardiac cavities and the contrast-enhanced coronary arteries (see Figure 4 (a)). Thus, the resulting binary mask eliminates large structures correlating with the cardiac cavities as well as small structures correlating with the coronary arteries (see Figure 4 (b)). To avoid the masking of the coronary arteries, we perform an erosion operation on the thresholded data. This allows a clear seperation of coronary arteries and cardiac cavities, even when they are in close proximity to each other. Small areas of connected pixels can be assigned to the coronary arteries in the eroded data. We then apply a neighborhood filter along each of the three orthogonal axes of the dataset to remove those areas. As the size of the cardiac cavities was reduced by eroding the data, we perform a dilatation operation for resizing purpose.

By applying the generated mask to the CT data after extracting the heart, the data can be rendered that way that the whole coronary artery tree is clearly visible (see Figure 5 (b)).

3.3.2 DRR Generation

Simulating conventional coronary angiography requires an appropriate projection model as well as information about the X-ray attenuation coefficients of the different anatomical structures. In our approach, a perspective projection model forms the geometrical basis for the calculation of the DRRs. Obtaining comparable views to those of conventional angiograms, requires general knowledge of the projection parameters such as the origin of the CT data, the position of the center of the detector, or the position of the virtual X-ray source. In our model we assume that the central ray starting from the virtual X-ray source passes directly through the virtual iso-center - that is the center of the CT data - and the center of the detector. This mimics the rigid geometry of the X-Ray C-arm. The transformation to project one voxel of the CT data to the detector plane can be expressed in terms of a translation $\boldsymbol{t}$, followed by a rotation $\boldsymbol{R} = \boldsymbol{R}_{\phi_x} \cdot \boldsymbol{R}_{\phi_z}$ around the transversal and longitudinal axes of the volume, respectively, and a perspective projection matrix $\boldsymbol{P}_{\text{perspective}}$. The angiograms are pre-

(a) (b) (c)

Figure 4: Advanced masking. (a) The highest gray level value in labeled CT data correlates with both, cardiac cavities and coronary arteries. (b) Binary CT data after thresholding. The coronary arteries (arrows) must be excluded from masking. (c) Masked CT data after applying the combined mask obtained in previous steps to the original CT data. Both, non-cardiac structures and cardiac cavities are eliminated, whereas the coronary arteries (arrows) are still visible. The masked CT data serves as input for the generation of DRRs.

sented in DICOM[4] format. Typically, its header file contains acquisition specific information. By parsing the DICOM header we obtain the relevant projection parameters.
The transmitted intensity I of X-ray s, is given by,

$$I = I_0 \cdot e^{-\sum \mu_i s_i}, \tag{1}$$

whereas I_0 is the incident X-ray intensity and μ_i are the linear attenuation coefficients. The intensity of one pixel of the DRR is computed by analysing the exponent in Equation 1, i.e. by accumulating the gray values of the CT data along each of the virtual X-rays passing through the CT data. This procedure conforms to a classical ray-casting approach as implemented in (Schroeder et al., 2002).

4 RESULTS

We tested our approach for extracting the heart and the advanced masking of large cardiac cavities with all 25 CT datasets. In all cases we obtained clinical useful results at a single press of a button (see Figure 2 (b) and Figure 5 (b)). The generation of DRR was tested on those 8 CT datasets for which corresponding conventional angiograms existed. In 5 out of 8 cases spurious cardiac cavities could successfully masked, while the run of the coronary arteries was clearly visible (see Figure 6 (b)). In the other 3 cases the quality of the original CT data was reduced, e.g. the contrast medium was not equally distributed. Therefore, the coronary arteries were not sufficiently enhanced.

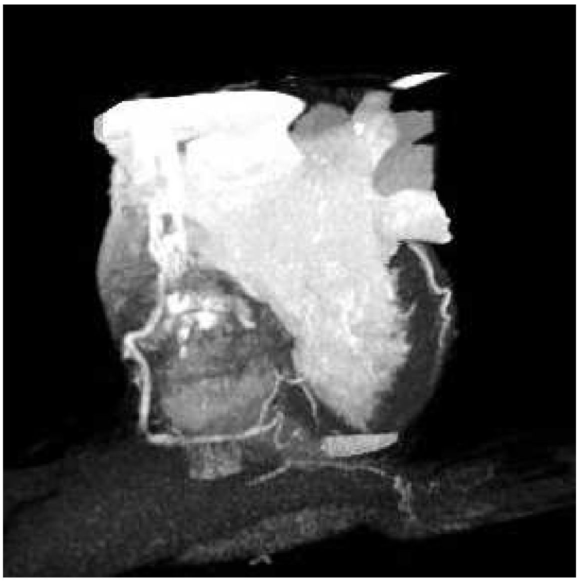
By generating the DRRs the radiologist obtains a representation of the coronary tree that is morphologically equivalent to conventional angiograms (see Figure 6 (a)-(b)). Right and left branches of the coronary artery tree are visible in the projected images because in the case of MSCT the contrast medium is applied intravenously. For more similar representations we clip the volume along the axial direction, projecting only the relevant part of the CT data (see Figure 6 (c)).

[4]Digital Imaging and Communications in Medicine

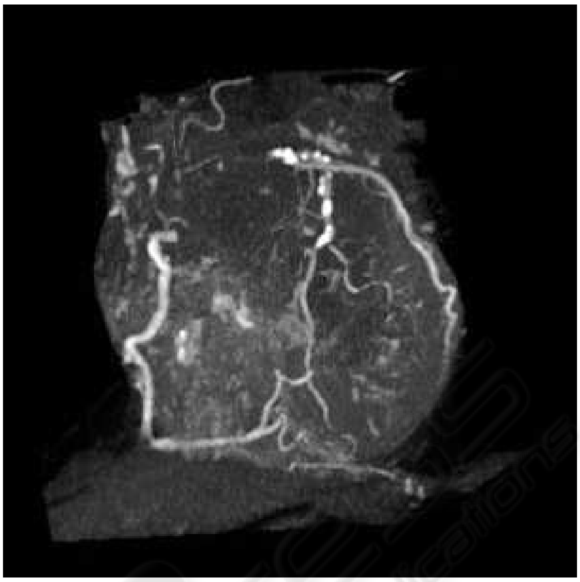
5 CONCLUSIONS AND DISCUSSION

The approaches presented in this work are new and automated techniques for enhanced visualization of coronary arteries in MSCT data. The extraction of the heart and the masking of large cardiac cavities enables the radiologist a clear view at the heart and at the coronary artery tree in volume rendered CT data. For drawing direct visual side-by-side comparisons between representations of the coronary arteries obtained by MSCT with that in conventional angiograms we present a novel automated technique based on the generation of DRRs.

While (Lorenz et al., 2004) delineates the heart from the outside, we extract the heart from within a point in the middle of the heart. Thus, we need less information about the position of the heart in the CT data and therefore our approach is more flexibly applicable (e.g., regarding the portion of the rib cage that is included in the CT data). For simulating the coronary angiography we proposed the generation of DRRs, which is a common technique to obtain radiographical representations from tomographic datasets. The advantage of our approach is that we get along with-



(a)



(b)

Figure 5: Volume rendered cardiac CT data. (a) By eliminating non-cardiac structures only parts of the coronary artery tree are visible. (b) By eliminating also large cardiac cavities the whole coronary artery tree is clearly visible.

out an explicit segmentation of the coronary artery tree, neither in the CT data nor in the conventional angiograms. At a single press of a button the radiologist obtains a representation of the coronary arteries analogous to the representation in conventional angiograms. To our knowledge, no comparable automated approach has been published yet.

Since we opperate on the entire CT data the masking of cardiac cavities and the generation of DRRs depends on the quality of the original CT data. For instance, if the CT dataset was reconstructed at a point in time, where the contrast medium was not optimally distributed, a clear assigment of the contrast-enhanced cardiac cavities to the two brightest gray level values in the labeled CT data is difficult. To circumvent such problems the radiologist has the possibility to adjust some parameters (e.g. the number of thresholds).

Currently, we extend our approach by aligning the generated DRR and the angiogram. By registrating the two modalities it will be possible to highlite positions of potential pathologies (stenoses, calcification) detected by quantitative 3D CT-analysis in the angiograms. This would be a further step in enhancing the trust of the radiologist in the assessment of the coronary arteries by MSCT.

An extended clinical evaluation together with our clinical partners will be conducted in the near future.

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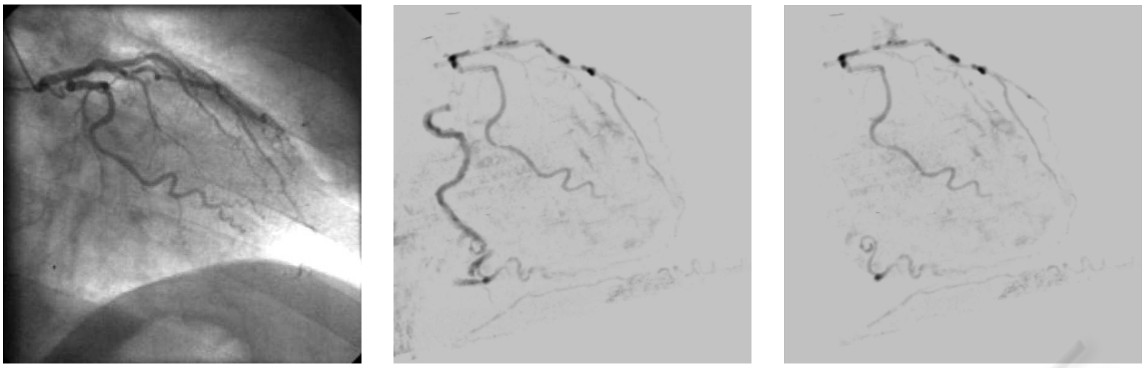

(a) (b) (c)

Figure 6: (a) Conventional angiogram of the left coronary artery branch (RAO 30.9 / CRAN 0.1) (b) Generated DRR from the pre-processed CT data with projection parameters extracted from DICOM header file of (a). Both, left and right coronary artery branches are visible. (c) Generated DRR from clipped pre-processed CT data.

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