

CAVAREV—an open platform for evaluating 3D and 4D cardiac vasculature reconstruction

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Abstract

The 3D reconstruction of cardiac vasculature, e.g. the coronary arteries, using C-arm CT (rotational angiography) is an active and challenging field of research. There are numerous publications on different reconstruction techniques. However, there is still a lack of comparability of achieved results for several reasons: foremost, datasets used in publications are not open to public and thus experiments are not reproducible by other researchers. Further, the results highly depend on the vasculature motion, i.e. cardiac and breathing motion patterns which are also not comparable across publications. We aim to close this gap by providing an open platform, called CAVAREV (CArdiac VAsculature Reconstruction EValuation). It features two simulated dynamic projection datasets based on the 4D XCAT phantom with contrasted coronary arteries which was derived from patient data. In the first dataset, the vasculature undergoes a continuous periodic motion. The second dataset contains aperiodic heart motion by including additional breathing motion. The geometry calibration and acquisition protocol were obtained from a real-world C-arm system. For qualitative evaluation of the reconstruction results, the correlation of the morphology is used. Two segmentation-based quality measures are introduced which allow us to assess the 3D and 4D reconstruction quality. They are based on the spatial overlap of the vasculature reconstruction with the ground truth. The measures enable a comprehensive analysis and comparison of reconstruction results independent from the utilized reconstruction algorithm. An online platform (www.cavarev.com) is provided where the datasets can be downloaded, researchers can manage and publish algorithm results and download a reference C++ and Matlab implementation.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

1.1. Purpose of this work

A promising future development in the field of interventional cardiology is three-dimensional image information before, during and after interventional procedures, e.g. pacemaker implantations or ablation procedures. Especially, the reconstruction of cardiac vasculature, e.g. the coronary arteries or the coronary sinus, has been in the focus of numerous publications, e.g. Shechter *et al* (2003), Blondel *et al* (2006), Schäfer *et al* (2006), Rohkohl *et al* (2008), (2009a), Hansis *et al* (2008a), Keil *et al* (2009a). During the rotational acquisition with a C-arm system, the targeted vasculature is contrasted. Due to the long acquisition time of several seconds at which several heart beats occur, motion related image artifacts e.g. blurring or streaks can be observed. Thus, special care has to be taken in order to obtain enhanced reconstruction results.

This topic is in research and there is still a lack of comparability of achieved results for several reasons. First and foremost, datasets used in publications are not open to public and thus experiments are not reproducible for readers. Further, the acquisition conditions are not the same, i.e. the motion pattern, acquisition time and geometry. Another important aspect is the varying complexity of the cardiac vasculature phantoms used by different authors. In addition, the quality assessment methods vary depending on the selected reconstruction algorithm, e.g. symbolic and segmentation-based approaches use different quality measures than tomographic reconstruction algorithms.

Therefore, we introduce an open platform called CAVAREV which features an online evaluation of 3D reconstructions for two simulated datasets. The projection datasets are obtained from the 4D XCAT (formerly NCAT) phantom (Segars *et al* 1999, Segars 2001) which is based on real patient CT/MR data. The first dataset contains periodic cardiac motion only and the second dataset an aperiodic combination of cardiac and breathing motion. The reconstruction results can be uploaded and automatically evaluated and published at the online platform. Two quality metrics for the 3D and 4D reconstruction quality are introduced which are independent from the utilized reconstruction algorithm and are based on the spatial overlap of the reconstruction image and the ground truth.

1.2. State-of-the-art evaluation strategies

The evaluation and verification of cardiac vasculature reconstruction algorithms are usually done with the help of phantoms where the ground truth is known. In the literature, different methods have been presented. In the following, the different phantoms and evaluation strategies of recent publications will be discussed.

1.2.1. Phantoms. Physical and numerical phantoms have been used to obtain projection datasets containing cardiac vasculature motion. Physical phantoms have the benefit of true data with all physical side-effects. However, the assessment of the quality is difficult and mostly restricted to size measurements. Several examples for physical phantoms (Shechter *et al* 2003, Blondel *et al* 2004, Rohkohl *et al* 2009a) and numerical phantoms can be found in the literature (Schäfer *et al* 2006, Hansis *et al* 2008a, 2007, 2009, Rohkohl *et al* 2009b). They allow an easy quality evaluation but often the synthetic data generation is simplified and does not reflect realistic acquisition scenarios. The benefit of our platform lies in the realistic setup and phantom data generation.

1.2.2. Quality metrics. Given the reconstruction of a numerical or physical phantom, the quality of the reconstruction needs to be assessed. For that the similarity of the ground truth and a reconstruction is measured using an evaluation metric.

Blondel *et al* (2004) measured the error of the vessel diameter in the cross-sections of the reconstructions. Hansis *et al* (2008a), (2008b) proposed to measure the error of the mean vessel radius at a number of centerline points. They also proposed to measure the object contrast by calculating the fraction of the image energy (intensity) located inside the volume of the coronary artery phantom. A higher fraction indicates better contrast of the arteries compared to the background. Schäfer *et al* (2006) measured a spatially dependent reconstruction error in 3D. Therefore, the error of the reconstructed absorption coefficients was calculated for neighborhoods of different radii centered at certain vessel centerlines in 3D. Hansis *et al* (2007), (2008a) measured the difference of the absorption coefficient in the complete volume and in a certain neighborhood around the region of interest, i.e. the vessels.

The definition of a proper quality metric is a crucial and difficult part of any evaluation. For our platform, a set of new evaluation measures is proposed which focus on assessing the morphological accuracy.

1.3. Outline

This paper is organized as follows. An overview of the new approach is presented in section 2.1. In section 2.2, the dataset creation and acquisition protocols based on the XCAT phantom are presented. The data formats and coordinate systems are specified in section 2.3. Section 2.4 contains the description of two threshold-dependent 3D and 4D reconstruction quality measures. The online evaluation platform and ranking are introduced in section 2.5. We conclude with a summary and outlook in section 3.

2. Methods and materials

2.1. Overview of the new approach

From a simulated projection dataset, we require the following.

- *Anatomical correctness and completeness* of the vasculature and its embedding. This includes realistic attenuation values and structure dimensions.
- *Physiological correctness* of the cardiac vasculature motion and of its surroundings. This includes a correct model for joint cardiac and breathing motion, also of the thorax and other organs in the field of view, e.g. the diaphragm.
- *Acquisition scenario and geometry* calibration should correspond to a real-world C-arm system. This includes the acquisition time, framerate, projection matrices, projection image size and an axial and trans-axial truncation of the projection data.

In order to obtain those properties, we decided to use the 4D XCAT (formerly known as NCAT) phantom (Segars *et al* 1999, Segars 2001). Its anatomy and motion are based on 4D tagged magnetic resonance imaging (MRI) data and 4D high-resolution respiratory-gated CT data of human subjects. Further, it includes motion models for cardiac and respiratory motion. It allows the simulation of realistic datasets for cardiac vasculature C-arm CT. The XCAT software is used to generate a temporal series of 3D volumes which are used to generate projection images in order to obtain projection data for a C-arm acquisition protocol. Two of such datasets are generated, one with cardiac motion only, and one with joint cardiac and respiratory motion. The corresponding temporal series of 3D volumes are used as ground truth for measuring the reconstruction quality.

Concerning the reconstruction quality, our main interest lies in assessing the accuracy of the reconstructed morphology. In order to obtain morphology information from a user-supplied reconstruction, the vasculature of the 3D image is segmented optimally. The segmentation is obtained by applying a simple and automatic threshold-dependent binarization. Binary representation is sufficient, as we are concerned with high-contrast structures. The quality is assessed by computation of a measure of spatial overlap with the vasculature of each volume from the temporal series of ground truth volumes. As a spatial overlap measure, the Dice similarity coefficient (DSC) is utilized which is a commonly used evaluation metric for the comparison of segmentations of sparse objects (Zou *et al* 2004). In order to find the optimal segmentation, the quality assessment is performed for all possible thresholds and the maximum quality value is selected. This procedure is intuitive and simple but yet powerful enough to obtain a proper segmentation of the cardiac vasculature.

2.2. XCAT-based phantom datasets

The acquisition scenario and geometry calibration were obtained from a real-world clinical angiographic C-arm system (Artis Zee, Siemens AG, Healthcare Sector, Forchheim, Germany). A standard protocol for rotational angiography was chosen. The acquisition time is $T = 5.3$ s with $N = 133$ projection images covering an equiangular range of 200° . The projection images have a height of $S_y = 960$ and width of $S_x = 960$ pixels with an isotropic resolution of 0.32 mm/pixel. The isocenter–source and the source–detector distances of the imaging system are about 80 cm and 120 cm, respectively. The total fan angle is 20° and the cone angle measures approximately 7° . The projection matrices $\mathbf{A}_i \in \mathbb{R}^{3 \times 4}$, $i \in \{1, \dots, N\}$, were obtained from an offline calibration (Faugeras 1993, Wiesent *et al* 2000).

2.2.1. Dataset \mathcal{D}_C : periodic cardiac motion. The XCAT software is configured to create a series of 3D volumes for N uniformly distributed points in time at a heart rate of 80 bpm for the acquisition time span of T . For each point in time i , the software generates two volumes f_i^{body} and f_i^{vasc} . The first XCAT volume f_i^{body} contains all anatomical structures except the contrast enhanced cardiac vasculature, which in turn is given by the second volume f_i^{vasc} with a contrast of 4000 HU (see figure 2). The ground truth binary morphology information f_i^{morph} , that is used for later evaluations, is derived from the XCAT volume f_i^{vasc} by simple binarization.

Finally, a projection dataset $\mathcal{D}_C = \{\mathbf{I}_i \in \mathbb{R}^{S_y \times S_x} | i \in \{1, \dots, N\}\}$ with periodic cardiac vasculature motion is obtained by ray-driven forward projection (Weinlich *et al* 2008) of the fusion ($f_i^{\text{body}} + f_i^{\text{vasc}}$) of both volumes using the projection matrices \mathbf{A}_i (see figure 2). The heart phase signal of the dataset is depicted in figure 1. Phase zero corresponds to an R-peak in the ECG. As in real-world scenarios, for no two projection images exactly the same heart phase is observed in the projection images due to the temporal sampling.

2.2.2. Dataset \mathcal{D}_{BC} : aperiodic combination of respiratory and cardiac motion. The projection dataset $\mathcal{D}_{BC} = \{\mathbf{I}_i \in \mathbb{R}^{S_y \times S_x} | i \in \{1, \dots, N\}\}$ with an aperiodic combination of cardiac and breathing motion is created analogously to the dataset \mathcal{D}_C . In addition to the same cardiac motion pattern, the XCAT software is configured to simulate a breathing motion with a cycle time of 4 s. The motion phase signal for the respiratory motion is depicted in figure 1. Phase zero corresponds to full exhale.

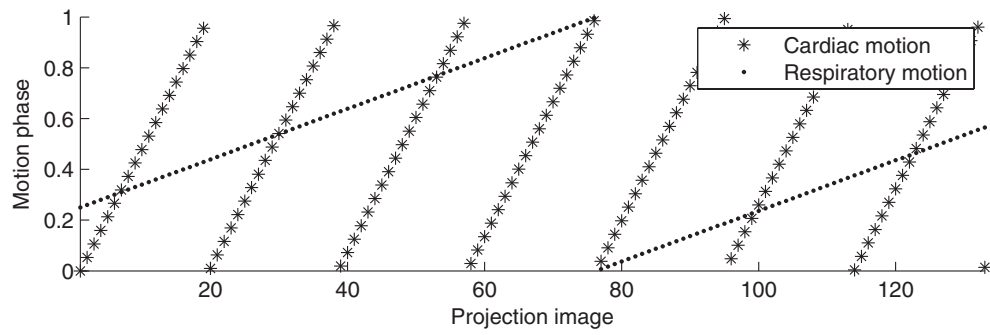


Figure 1. Respiratory and cardiac motion phases of the XCAT phantom used for generating the projection images.

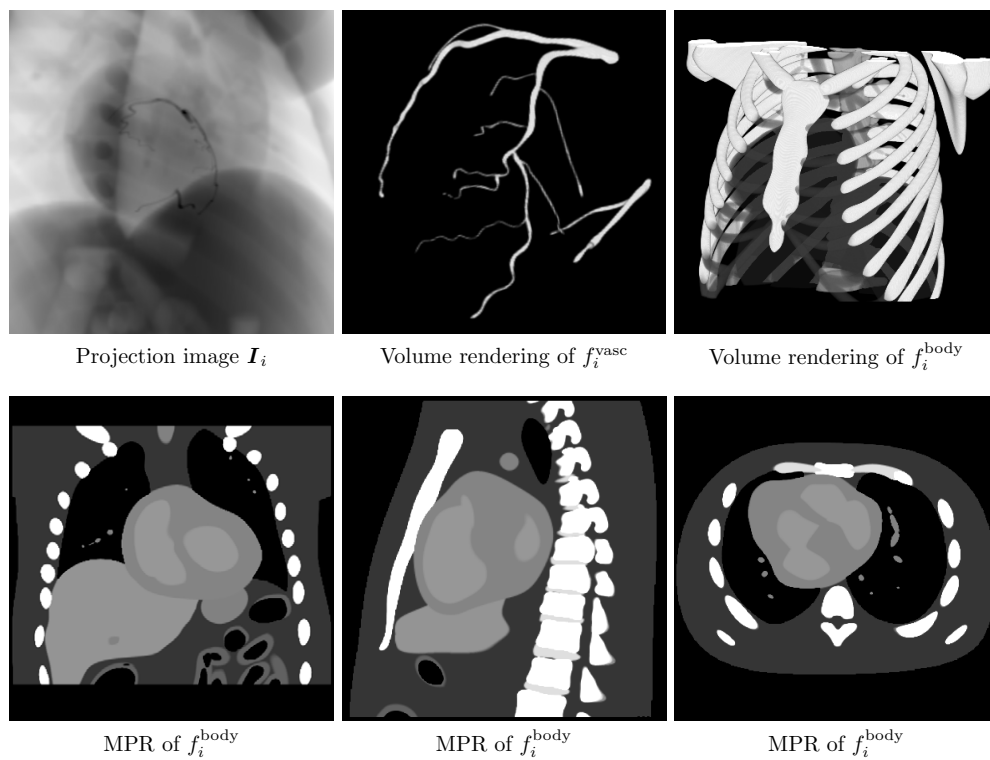


Figure 2. Overview of the XCAT phantom data. Top row: a projection image (left) and the volume rendering of the vasculature (middle) and the remaining body (right) image, that were used for its creation. The data are drawn from the dataset using cardiac motion only. Bottom row: three orthogonal MPR planes through the XCAT volume f_i^{body} in the coronal (left), sagittal (middle) and axial (right) direction.

2.3. Coordinate systems and transforms

The origin of our 3D world-coordinate system is set to the C-arm iso-center. The space unit is set to millimeter. The basic geometrical relationship of a voxel $\mathbf{x} \in \mathbb{R}^3$ in the world-coordinate

system and a pixel $\mathbf{u}_i \in \mathbb{R}^2$ of the i th projection image is described by the 3×4 projection matrix A_i as follows:

$$A_i \cdot \begin{pmatrix} \mathbf{x} \\ 1 \end{pmatrix} \cong \begin{pmatrix} k_{i,0} \\ k_{i,1} \\ k_{i,2} \end{pmatrix} \quad \text{with} \quad \mathbf{u}_i = \begin{pmatrix} k_{i,0}/k_{i,2} \\ k_{i,1}/k_{i,2} \end{pmatrix}. \quad (1)$$

All further system properties are encoded in the projection matrices (Hartley and Zisserman 2004). They can be used to e.g. compute the redundancy weighting.

2.4. Quality metrics

The main goal of C-arm CT imaging of highly contrasted cardiac vasculature is to find the size and location of vessels. Thus, for our benchmark, we are mainly interested in the accuracy of the reconstructed cardiac vasculature morphology. Information about attenuation coefficients for finding plaques is beyond our scope. Furthermore, the goal is to define an evaluation measure which is independent from the reconstruction algorithm. It should be applicable to tomographic and non-tomographic reconstruction methods, e.g. symbolic or segmentation-based algorithms (Lorenz *et al* 2003, Keil *et al* 2009a, 2009b) for which no attenuation values are available.

We propose to define a discretized volumetric data format for storing reconstruction results. This can be easily obtained from most reconstruction algorithms. The vasculature of the reconstruction result is then segmented in order to obtain morphology information. For segmentation, a simple threshold-dependent binarization is performed and an overlap measure using the ground truth is calculated. The segmentation and quality assessment is performed for all possible thresholds to ensure the best segmentation quality. This methodology is intuitive and simple but yet powerful enough to obtain a proper segmentation of the cardiac vasculature. The quality assessment is performed using the Dice similarity coefficient (DSC), a measure of spatial overlap. Generally speaking, the DSC represents the size of the union of two sets divided by the average size of the two sets. This normalized evaluation measure is a proven method in the segmentation literature for assessing the quality of a binary segmentation given a ground truth. It is also utilized in online evaluation platforms for segmentation algorithms, e.g. Shattuck *et al* (2009), Schaap *et al* (2009).

2.4.1. Motion phase-dependent reconstruction quality. Due to temporal sampling, each projection image shows the cardiac vasculature in a different motion state. Correspondingly, the reconstruction quality of a given reconstruction f needs to be determined for each of the N binary ground truth phantom volumes f_i^{morph} .

Formally, the quality measure $Q_i(f)$ for a reconstruction f at the projection image i is given by

$$Q_i(f) = \max_{x \in f} \text{dsc}(f_i^{\text{morph}}, T(f, f(x))), \quad (2)$$

with $T(f, a)$ being a threshold function which returns a binary volume with all elements of f being one if they are larger than or equal to the scalar a . In (2), we set $a = f(x)$. The DSC value is given by

$$\text{dsc}(f_1, f_2) = 2 \frac{\sum_{\mathbf{x}} f_1(\mathbf{x}) \cdot f_2(\mathbf{x})}{\sum_{\mathbf{x}} f_1(\mathbf{x}) + f_2(\mathbf{x})} \in [0, 1]. \quad (3)$$

The DSC ranges from 0, for no spatial overlap, to 1, for a perfect match. In figure 3, the threshold-dependent DSC for a 8-bit reconstruction is shown. The threshold a varies between

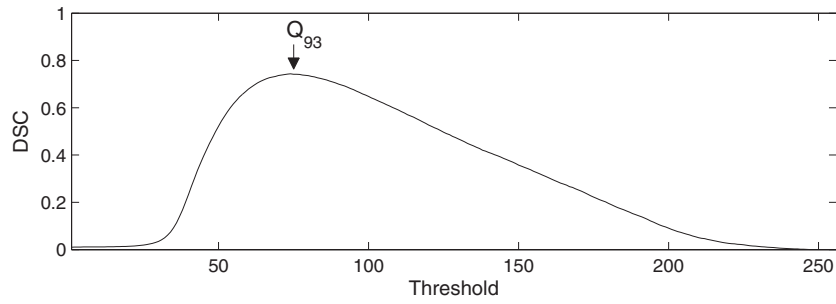


Figure 3. Threshold-dependent DSC for the 93rd image frame (cardiac phase 88.8%) of an ECG-gated FDK reconstruction (gating phase 90%, width 25%) for the dataset with cardiac motion only. The corresponding motion phase-dependent reconstruction quality is depicted in figure 4.

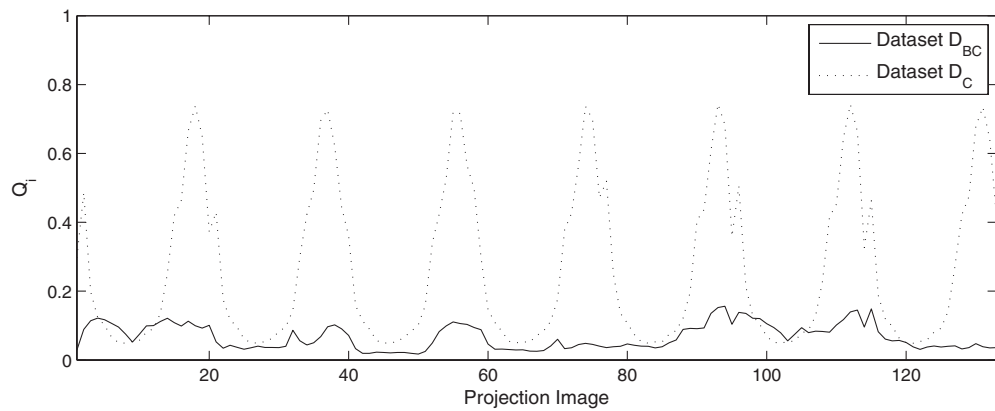


Figure 4. Motion phase-dependent reconstruction quality for an ECG-gated FDK reconstruction (gating phase 90%, width 25%) for both datasets.

0 and 255. The maximum DSC corresponds to Q_i . The motion phase-dependent quality Q_i is different for each i as motivated before. In figure 4, $Q_i(f)$ is depicted for all the image frames for both projection datasets. For the dataset \mathcal{D}_C , it can be seen, how the projection image-dependent quality measure varies with the motion phase of the image frame. However, due to the temporal sampling, the perfect match of the motion phase is not achieved in each motion cycle and thus not each local maximum is equally good. On the other hand, the ECG-gated reconstruction for the dataset \mathcal{D}_{BC} cannot gain any advantage from the heart phase information. Due to the non-periodicity of the breathing motion, no significant maxima can be observed.

The motion phase-dependent reconstruction quality can be used to define objective 3D and 4D reconstruction quality measures. This will be the subject of the upcoming paragraph.

2.4.2. Quality measures for 3D and 4D reconstructions. We propose two different reconstruction quality metrics for assessing the 3D and 4D reconstruction quality. They are based on the motion phase-dependent reconstruction qualities Q_i presented in the previous paragraph.

The first measure Q_{3D} is used if the output of your reconstruction algorithm is a single 3D reconstruction. The quality measure searches the image frame whose motion phase fits best to the reconstruction and returns the corresponding DSC. It is simply given by the maximum of the motion phase-dependent quality, i.e.

$$Q_{3D}(f) = \max_{i \in \{1, \dots, N\}} Q_i(f). \quad (4)$$

The second quality measure Q_{4D} , on the other hand, can be used to assess the 4D performance of a reconstruction algorithm. The output of the reconstruction algorithm is assumed to be a series of M reconstructions f_1, \dots, f_M each encoding a different motion state. The measure is defined to average the best DSC out of the M reconstructions for each of the N motion phases, i.e.

$$Q_{4D}(f_1, \dots, f_M) = \frac{1}{N} \sum_{i=1}^N \max_{m \in \{1, \dots, M\}} Q_i(f_m). \quad (5)$$

2.5. Online platform: download, evaluation and ranking

We offer an online platform (www.cavarev.com) where relevant data can be downloaded and algorithm results can be administered. In the following each relevant part of the online platform will be detailed.

2.5.1. Download of data and examples. In the download section of our website, the two projection datasets \mathcal{D}_C and \mathcal{D}_{BC} and the corresponding acquisition information, i.e. the projection matrices and motion phases, can be downloaded. For each projection dataset, the raw projection images and a pre-processed version for FDK reconstruction (Feldkamp *et al* 1984, Zellerhoff *et al* 2005) are offered. The raw projection data can be used for any algorithm, e.g. iterative reconstruction. The pre-processed version contains redundancy weighting, cosine weighting and filtering of the projection data. It can be used in conjunction with an example FDK-reconstruction implementation which is also offered for download. It can be used to perform a standard or ECG-gated FDK reconstruction (Schäfer *et al* 2006). An example implementation in C++ and Matlab is provided which shows the usage of the data.

2.5.2. Algorithm and result administration. After registration researchers can administer reconstruction algorithms and the corresponding reconstruction results. The author is free to provide detailed algorithm information. The platform is secure and by default all uploaded results are confidential and cannot be seen by other users. However, the author is free to decide to publish the results at any time. For each uploaded result the 3D and 4D qualities are calculated from the motion phase-dependent qualities. The user can export them or view and analyze them in automatically generated graphs.

2.5.3. Ranking. All results and algorithm information are kept private until a participant requests to publish certain reconstruction results in an official ranking table. The table includes all quality measures and contains a volume viewer for a detailed visual inspection. Further, the algorithm authors have the possibility of uploading or referencing additional information, e.g. papers or source code. At the time of writing, the current ranking list includes results and descriptions of three different reconstruction algorithms. A snapshot of the current ranking table can be found in figure 5.

CAVAREV CArdiac VAsculature Reconstruction EValuation

WELCOME
CAVAREV is an open platform for evaluating 3-D and 4-D cardiac vasculature reconstruction algorithms using C-arm CT.

Feedback Fully3D/MICCAI 2009: New Image Data

Posted on October 2nd, 2009

During the last weeks two important conferences of the medical imaging community took place (Fully3D, MICCAI). We were lucky to have talks at both conferences and did a first presentation of CAVAREV to the public. The responses were quite good. As a result of discussions novel image data with a much better resolution has been [...]

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★ Evaluation Area

Algorithm authors may decide to publish their algorithm results to the public. In the two listings below all public algorithms are listed sorted by the 3-D reconstruction quality Q_{3D} . The listings are divided by the utilized dataset.

More information on the quality metrics can be found [here](#). The two different datasets are explained [here](#).

Dataset DC: Cardiac motion only

Algorithm	Q_{3D}	Q_{4D}
1. Streak-Reduced ECG-Gated FDK Reconstruction ECG-Gated FDK reconstruction using an additional weighting function for reducing streaks artefacts. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.744	0.618
2. ECG-Gated FDK Reconstruction ECG-Gated FDK reconstruction using a cosine-square based weighting function. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.595	0.501
3. Standard FDK-Reconstruction Non-gated FDK-Reconstruction without Gating, i.e. all projection data is used without any correction. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.431	0.347

Dataset DCB: Cardiac & respiratory motion

Algorithm	Q_{3D}	Q_{4D}
1. Streak-Reduced ECG-Gated FDK Reconstruction ECG-Gated FDK reconstruction using an additional weighting function for reducing streaks artefacts. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.208	0.108
2. Standard FDK-Reconstruction Non-gated FDK-Reconstruction without Gating, i.e. all projection data is used without any correction. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.206	0.105
3. ECG-Gated FDK Reconstruction ECG-Gated FDK reconstruction using a cosine-square based weighting function. <i>C. Rohkohl; University of Erlangen-Nuremberg</i>	0.156	0.097

GENERAL INFORMATION

- The CAVAREV 1-2-3 Guide
- About

EVALUATION AREA

- Public Rankings
- Login
- Register

DOWNLOADS

- Dataset and Calibration Data

TECHNICAL DETAILS

- 3-D/4-D Reconstruction Quality Metrics
- World Coordinate System and Projection Matrices
- 3-D Reconstruction Data Format Specification
- Using the XCAT Phantom for Simulating Realistic Projection Data

IMPLEMENTATIONS

- C++ Code: ECG-Gated FDK-Reconstruction
- Matlab Code: ECG-Gated FDK-Reconstruction

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Figure 5. Website snapshot of the public ranking table on the online platform at http://www.cavarev.com/evaluation_area.

3. Summary and outlook

There is a need for objectively comparing 3D and 4D reconstruction images of cardiac vasculature, e.g. the coronary arteries, from C-arm CT (rotational angiography). CAVAREV aims to provide a solution to this problem by offering an open platform. It provides two realistic C-arm projection datasets that are simulated on a numerical model consisting of anatomical and physiological data from patients. The inherent motion of both datasets can be distinguished into strictly periodic cardiac motion and a non-periodic combination of cardiac and breathing motion. For qualitative evaluation of the reconstruction results, two segmentation-based quality measures are introduced which allow us to assess the 3D and 4D reconstruction quality. They are based on the spatial overlap of the vasculature reconstruction with the ground truth.

The framework is combined into a comprehensive online platform (www.cavarev.com). Using the online platform is straightforward and can be summarized in four steps.

- (i) Download the required projection and calibration data.
- (ii) Write a reconstruction algorithm and perform your desired 3D reconstructions. For a simple start, we provide implementations of an ECG-gated FDK reconstruction in Matlab and C++.
- (iii) Signup for an account or log into the evaluation area. Once logged in, several reconstruction algorithms can be added. For each algorithm, an arbitrary number of reconstructions can be assigned by uploading. For each reconstruction, the quality measures are then calculated.
- (iv) Publish your algorithm results. By default all your algorithms are private and only visible for you. By changing a flag in your algorithm administration, you can make it available to the public. Once the status is changed, your algorithm will be listed on the public ranking page.

We are looking forward to a growing community and await feedback for improving the online platform.

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