Linköping University Post Print

An interactive software module for visualizing coronary arteries in CT angiography

Chunliang Wang, Hans Frimmel, Anders Persson and Örjan Smedby

N.B.: When citing this work, cite the original article.

The original publication is available at www.springerlink.com:

Chunliang Wang, Hans Frimmel, Anders Persson and Örjan Smedby, An interactive software module for visualizing coronary arteries in CT angiography, 2008, International Journal of Computer Assisted Radiology and Surgery, (3), 1-2, 11-18.

<http://dx.doi.org/10.1007/s11548-008-0160-6>

Copyright: Springer Science Business Media

<http://www.springerlink.com/>

Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-17817>

"CARS 2008 Submission" --Title Page:

An interactive software module for visualizing coronary arteries in CT angiography

CHUNLIANG WANG, HANS FRIMMEL, ANDERS PERSSON, ÖRJAN SMEDBY

Chunliang Wang, MD, Linköping University Hospital, CMIV, Linköping University Hospital, CMIV, Linköping, SE-58185, Sweden

Han Frimmel, PhD, Department of Information Technology, Uppsala University, Department of Information Technology, Uppsala University, Uppsala, SE-75105 , Sweden

Anders Persson, MD, PhD, Linköping University Hospital, CMIV, Linköping University Hospital, CMIV, Linköping, SE-58185, Sweden

Örjan Smedby, Prof., MD, PhD, Linköping University Hospital, CMIV, Linköping University Hospital, CMIV, Linköping, SE-58185, Sweden

Communicating Author: Chunliang wang, chunliang.wang@imv.liu.se, TEL: +46-13 22 8998, Fax: +46-13 22 7020

Word count of abstract: 193

Word count of text: 3988

6 figures, 2 tables and 18 references

An interactive software module for visualizing coronary arteries in CT angiography

Abstract:

Object: A new software module for coronary artery segmentation and visualization in CT Angiography (CTA) datasets is presented, which aims to interactively segment coronary arteries and visualize them in 3D with Maximum intensity projection (MIP) and volume rendering (VRT).

Materials and Methods: The software was built as a plugin for an advanced open-source PACS workstation - OsiriX. The main segmentation function is based on an optimized “virtual contrast injection” algorithm, which uses fuzzy connectedness of the vessel lumen to separate the contrast-filled structures from each other. The software was evaluated in 42 clinical coronary CTA datasets acquired with 64-slice CT using isotropic voxels of 0.3-0.5 mm.

Results: The median processing time was 6.4min, and 100% of main branches (right coronary artery, left circumflex artery and left anterior descending artery) and 86.9% (219/252) of visible minor branches were intact. Visually correct centerlines were obtained automatically in 94.7% (321/339) of the intact branches.

Conclusion: The new software is a promising tool for coronary CTA post-processing providing good overviews of the coronary artery with limited user interaction on low-end hardware, and the coronary CTA diagnosis procedure could potentially be more time-efficient than using thin-slab technique.

Keywords: Coronary Vessels [A07.231.114.269]; Tomography, Spiral Computed [E01.370.350.700.810.810.800]; Algorithms [H01.770.035]; Radiographic Image Interpretation, Computer-Assisted [L01.700.508.100.158.600.680]

1. Introduction

During the last decade, the technique for coronary CT Angiography (CTA) has undergone a rapid development, thanks to the improvement of CT scanners. In particular, the introduction of 64-

slice CT technique has enabled physicians to visualize the coronary arteries with superior spatial and temporal resolution. The coronary CTA technique has proved to be highly accurate for the exclusion of significant coronary artery stenosis, and it is changing the current management of patients with suspected or confirmed coronary artery disease [1]. However, compared to conventional catheter coronary angiography, evaluating the coronary artery in a large stack of time-resolved transverse images is time-consuming. Taking into account the increasing number of examinations per day, it is an important goal for medical image science to find effective and accurate ways of viewing large volumes of images.

In general, volume rendering (VRT) and maximum intensity projection (MIP), which have been used widely in medical image visualization, are believed to be more time-efficient than 2D transversal or oblique multiplanar reformat (MPR) images, as they include all information in one volume and show it as one object. The application of those techniques to CTA or MR Angiography (MRA), e.g. of the carotid and abdominal arteries, has been very successful [2,3]. However, when applied to coronary CTA, they tend to be less useful. As the ventricles are also filled with contrast, using MIP directly on the whole volume will usually result in the ventricles obscuring the arteries. VRT gives some depth information, which may help to visually separate ventricles and arteries, but visualizing the surface of the vessel facing the ventricles is often impossible.

A compromise may be to use MIP or VRT of a thin slab to exclude irrelevant structures and view the coronary arteries segment by segment [4]. However, this approach does not give an overview of the coronary tree. It would therefore be attractive to remove the contrast-filled heart chambers and other high-intensity structures from the volume and only show the coronary arteries in 3D. Our group has previously proposed a “virtual contrast injection” algorithm based on fuzzy connectedness theory to separate arteries from veins in MRA datasets [5]. The algorithm has been extended to separating coronary arteries from ventricles in CTA volumes, achieving promising results with limited user interaction in preliminary experiments [6,7]. In this paper, we describe a dedicated software module for intuitive user interaction and coronary visualization. The module has been implemented as a plug-in for the OsiriX Viewer [8], an open-source PACS workstation.

2. Theory

In this section we will give a brief review of fuzzy connectedness theory and the “Virtual contrast injection” algorithm. More details can be found in our earlier reports [5,7].

2.1 Fuzzy connectedness

Just as the coronary arteries can be bluntly separated from the heart during surgery because of the varying connectivity of the wall structures, they can be separated in 3D CTA images based on the connectivity of the contrast agent in the vessel lumen, using fuzzy connectedness theory (cf. Fig. 1 A).

In a 3D image, we define a path p joining two voxels, u and v , as a sequence of distinct voxels $u = w_0, w_1, \dots, w_{n-1}, w_n = v$, such that for each i , $0 \leq i \leq n$, w_{i+1} is a 26-neighbor of w_i . Let $g(w_i)$ be the strength that the voxel w_i contributes to the path. The strength of connectedness of p is determined by the weakest voxel along the path:

$$S(p) = \min_{w_i \in p} (g(w_i)) \quad (1)$$

Although more sophisticated concepts, such as the Fuzzy Affinity function [9], can be used to calculate the contribution function $g(w_i)$ of each voxel, we have here chosen, for simplicity, to use the gray-scale function $f(w_i)$ directly, i.e. $g(w_i) = f(w_i)$.

The connectedness between u and v is the strength of the strongest of all paths joining u and v :

$$C(u, v) = \max_{p(u, v)} (S(p)) \quad (2)$$

Given a seed region A , the connectivity between u and A is defined by

$$C(u, A) = \max_{a \in A} (C(u, a)) \quad (3)$$

2.2 Virtual contrast injection algorithm

Using fuzzy connectedness theory, we can calculate a connectedness map relative to an arbitrary seed region within the image. When thresholding is used to segment objects of high intensity from the background, the phenomenon of leaking often makes it impossible to find an ideal threshold, separating the objects from each other. Applying the fuzzy connectedness concept defined by (3), nearby objects of high intensity will also have higher connectedness to the seeds if two structures are too close to each other [5]. Thus, thresholding in the connectivity maps will not satisfactorily separate coronary arteries from ventricles. In the virtual contrast injection algorithm, this problem is overcome by carrying out the fuzzy connectedness computation in a competitive fashion among multiple seeds.

Two or more seed regions, representing different vascular structures, are specified by the user, and the connectedness map from each seed region is calculated. At this stage, the membership of

every voxel can be calculated by comparing its connectedness value to different seeds, assigning the voxel to the seed yielding the highest connectivity. Fig. 1B shows an example with two seed regions, A and B , representing different vascular structures. Once the degree of connectedness of a voxel u to each seed has been calculated, it can easily be decided to which structure u should belong by comparing $C(u, A)$ and $C(u, B)$. Applying this strategy to all voxels in the image, a natural segmentation by “virtual contrast injection” is achieved [5].

Fig 1. A: The basic principle of Virtual Contrast Injection. B: Deciding a voxel's membership by comparing the connectivity strengths. The dashed curve indicates the strongest path between voxels and seeds. C: Tree structure created in the virtual contrast injection algorithm

In addition to seeds representing vascular structures, a new kind of seed, the stopping seed, has been introduced to separate the coronary artery from the root of the aorta. A stopping seed is a region that will never propagate but terminate the propagation of other seeds.

In the current implementation, only a single connectedness map needs to be computed since the algorithm is applied to all seeds simultaneously, using an iterative approach. Every voxel is labeled with a color denoting the current membership of the voxel, using a tree structure that allows the colors to propagate from the seeds until the whole volume has been labeled (Fig. 1C). The competing fuzzy connectedness tree (CFCT) structure also serves to solve an ambiguity problem that may arise when propagation from different seeds occurs along the same path [7]. The whole concept can be illustrated by contrast agents of different color being injected in the seed regions and circulating within the cardiovascular system while competing with each other.

The propagation procedure for a seed is similar to Region Growing, but uses a non-local propagation criterion. The algorithm is described in detail in [7].

2.3 Algorithm optimization

The virtual contrast injection algorithm, originally proposed (as the SeparaSeed algorithm) in [5] and later modified to the CFCT algorithm [7], now also includes a marker structure indicating for every voxel whether any of its 26 neighbors has been changed in each iteration. This allows us to exclude voxels whose neighbors' connectedness values have not changed from being checked in the next iteration. Using this strategy has decreased the calculation time of each iteration substantially. However, the initialization of the marker structure increases the execution time of the first iteration. We have solved this problem by using the SeparaSeed algorithm for the first iteration and then switching to the CFCT algorithm.

A second speed improvement is a new principle for treating saturated voxels, where a saturated voxel (with our definition of path strength) is a voxel whose connectedness value equals its gray-value in the input image. According to fuzzy connectedness theory, the connectedness value of these voxels will not change in any subsequent iteration [9]. For example, in Fig. 1A, assuming that voxel w has the lowest grayscale value along the path $sI-u$, all voxels on the segment from sI to w (including w) are likely to become saturated after several iterations, if the intensity decreases along the vessel from the proximal to the distal end. In general, there will be a large number of saturated voxels in a volume. To avoid checking saturated voxels repeatedly, an additional marker is introduced to record all the saturated voxels and exclude them from further checking. Those voxels are then checked once more after the CFCT algorithm has converged.

2.4 Structure of Plugin

The current software module was implemented as a plugin to OsiriX, a workstation program developed using an open architecture built on existing open-source components such as DICOM Toolkit (DCMTK), Insight Segmentation and Registration Toolkit (ITK), Visualization ToolKit (VTK), etc [8]. The plugin is distributed under the General Public License and available together with OsiriX at <http://www.osirix-viewer.com>. Except for the main segmentation function, most functions in the user interface are based on OsiriX classes. Some 3D visualization functions and general image processing algorithms invoke VTK and ITK directly. The QuickTime library is used to create QuickTime Virtual Reality (QTVR) movies (Fig. 2).

Fig. 2. General architecture of the the plugin and OsiriX showing some of the open-source components and libraries that were used.

3. Methods:

3.1 Image acquisition

Forty-four patients (30 male, 14 female) with clinically suspected coronary artery disease were selected from routine coronary CTA examinations. Coronary CTA datasets were acquired using a 64-slice CT scanner (SOMATOM Definition, Siemens Medical Solutions, Erlangen, Germany) with 0.6 mm collimation, 120 kVp, 320 mAs after injection of contrast (70 ml of Ultravist 370, Bayer Schering Pharma, Berlin, Germany). The images were reconstructed with 0.33-0.5 mm isotropic resolution. To reduce the X-ray dose, a modulation technique was used limiting the exposure to the interval 50%-70% of the cardiac cycle (RR interval) resulting in an average dose of 5-12 mSv. For each patient, 10 cardiac phases were reconstructed.

3.2 Image Processing:

The images are transferred to an OsiriX workstation running on an Apple PowerPC Macintosh (CPU: 2.5GHz G5, RAM: 2GB DDR) and processed by a radiologist experienced with the OsiriX platform. The processing of each case includes 4 basic steps: preview and volume of interested (VOI) definition, initial seed planting, interactive segmentation and centerline extraction.

3.2.1 Preview and VOI definition

For each examination, the visually most pleasing among the 10 phases was chosen for processing. The transverse images of the chosen phases were then loaded into memory as a single volume and shown in a graphical interface using MPR for defining the VOI. The user then interactively adjusts the VOI to fit the borders of the heart. Thus, other structures will be excluded from further processing, which shortens the computation time of the algorithm, usually by a factor of at least 2.

3.2.2 Initial Seed Planting

As mentioned in Section 2, the software will segment the coronary arteries by growing a vessel tree from several initial regions, the “seeds”. The proper placing of the seeds is crucial for the whole procedure.

Fig. 3. Seed planting interface. The green arrow indicates the direction of the vessel and the green circle represents the cut plane separating the artery from the aorta.

Our seed planting tools are based on an interactive MPR system (Fig. 3), which allows the user to place a cut plane at any location in the volume and view cross-section images from any angle. The most important part in the seed planting step is to define the roots of right coronary artery (RCA) and left coronary artery (LCA). To facilitate this procedure, we have introduced a “vessel cutting” tool (Fig. 3). The user first has to locate the root of the target branch in the MPR View

and then draw an arrow along the vessel, indicating the root of the vessel and the direction to the distal end. The circle in the right top window represents the cross section of the branch and should be adjusted to closely surround the cross section of the branch. It will eventually be converted to a stopping seed, preventing leakage to the aorta, and a small seed on the distal side with the name of the corresponding branch, where the virtual contrast will start to propagate. After the root seeds have been planted, some irrelevant structures, such as heart chambers, aorta, vertebra and sternum, are also marked using a freehand “marker”, forming seeds of a different color.

3.2.3 Interactive Segmentation

Fig.4. Interactive segmentation interface

After CFCT segmentation using the initial seeds, the result is presented as a 2D or MIP image to the user who can decide whether the results are satisfactory (which they are in about 50% in our experience). If this is not the case, e.g. if some branches are missing, more seeds need to be specified. This is done in an MPR image. The CFCT algorithm is then restarted, using the newly planted seeds and the results from the first round as input. Thus the computation time is much shorter than in the initial segmentation. The segmentation results can be visualized in 2D or 3D and compared with MPR images of the input volume (Fig. 4), and the process iterated, if

necessary. The MPR image can be placed through a particular point by clicking in the 3D window.

3.2.4 Centerline Extraction

In addition to segmentation, the CFCT algorithm as a by-product yields centerlines of the vessels studied [7]. Using these centerlines, curved MPR or curved plane reformat (CPR) images can be produced to follow individual vessels or branches. All the results are shown in a list in a special window, and the user can view the curved MPR or straightened CPR image by selecting from the list (Fig. 5.). Centerlines can be renamed and exported into the OsiriX database, and thus saved for the future.

Fig 5. CPR interface

3.2.5 Results Export

All images produced in the software can be saved as DICOM images with simple command buttons. The DICOM images can then be sent to any DICOM workstation for further processing or evaluation. In OsiriX, there is a choice of multiple formats for exporting the 2D and 3D images, including static pictures (JPEG, TIFF etc), rotating movies (mov,MPEG), and QuickTime Virtual Reality (QTVR) object movies. The plugin itself also includes a tagged volume rendering function [10] which allow users to show different segments in the VRT volume in different colors and export the result into a QTVR object movie (cf. Fig. 6D).

4. Results

Two out of 44 CTA datasets were discarded by the radiologist due to severe artifacts and interruption between slices. Thus, 42 of the datasets were processed in our software. Typical size of those datasets is 350-450 slices of 512×512 voxels. The average processing time was 7.4 ± 1.8 min (Table 1). In the final segmentation results, all of the 126 main branches, RCA, left circumflex(LCX and left anterior descending (LAD), were intact (at least one voxel of soft tissue surrounding the contrast-enhanced lumen) (Table 2), and 87% (219/252) of the visible minor branches were intact. Visually correct centerlines were obtained automatically in 94% (345/367) of the intact branches. An example of the segmentation results is shown with various visualization techniques in Fig. 6.

Table 1. Processing times [s] in 42 datasets. Median (min-max).

ROI definition	Seed Planting	Initial Segmentation	Interactive Segmentation	Centerline Extraction	Total
38 (22-57)	62 (42-126)	44 (17-76)	144 (30-415)	53 (16-135)	385 (195-622)

Table 2. Segmentation results of the main branches in 42 patients

Vessel	Intact after initial segmentation	Intact after final segmentation	Visually correct centerlines	Total
RCA	39 (93%)	42 (100%)	41 (98%)	42
LCX	31 (74%)	42 (100%)	40 (95%)	42
LAD	35 (83%)	42 (100%)	40 (95%)	42
Total	105 (83%)	126 (100%)	121(96%)	126

Fig. 6. Samples of results: A: the seeds used for segmentation. B: MIP images of coronary arteries. C: VRT images of coronary arteries. D: tagged VRT images of coronary arteries and heart chambers. E: midlines (skeleton) of the coronary tree. F: curved MPR image of the right coronary artery. In this case, the initial segmentation was sufficient and no improvement needed.

5. Discussion and Conclusion

For coronary artery visualization in CTA, the most popular techniques in clinical routine are oblique MPR, oblique MIP (MIP of an oblique slab containing a vessel segment), curved MPR, curved MIP, and VRT of the entire heart [11]. Oblique MPR and oblique MIP are believed to be more accurate than the others when carried out in an interactive way by the diagnostic physician [11]. However, these methods may be more time-consuming, as only a limited segment of the vessel can be viewed in the same image. The somewhat complicated post-processing is often carried out by a technician on an advanced workstation, so that the physician is only presented with the final result as static images. The goal of our software is to make the whole coronary tree interactively available as MIP or VRT images for a radiologist or cardiologist on a low-end computer.

To make the tool useful in the clinical routine workflow, considerable efforts have been made to reduce the processing time. After optimizing the algorithm as described in section 2.3, the computation now runs 3-4 times faster than with the previous algorithm [6]. To reduce the interaction time, we introduced the interactive MPR seed planting interface. This enables a user familiar with cardiac anatomy to identify the relevant structures very fast. Using the MPR technique, seeds can be planted anywhere in the volume, and oblique planes used whenever needed to avoid adjacent structures. Compared to other seed planting systems [6,12], based on MIP or axial images, our solution seems to allow more accurate placing of seeds in complicated anatomic situations. In our experience, the learning curve of the software is fast, and a new user is soon able to place seeds in such a way that less subsequent interaction is needed.

The automatic centerline extraction is another feature of this software that may save user time. The way the centerlines are obtained from the segmentation algorithm [7], there is no need to define the distal end of branches, in contrast to some other software solutions. The ability to save centerlines, as well as other results as images and dynamic movies, is essential for documentation, reproducibility and integration in a clinically useful system. In particular, saving results as QTVR files is valuable for educational purposes [13,14].

To make the tool available for any radiologist or clinician, a user friendly workflow was designed as a step-by-step “wizard”, which enables a user with basic computer skills to learn the procedure easily. Considering the importance of the 2D images, a function to automatically relate 2D MPR images to points in the 3D images has been added. This strategy may help users to inspect suspected coronary lesions in the 2D images as soon as they are found in the 3D images.

Several other software tools have been developed for coronary artery segmentation [13-15]. Due to the complicated structure of the coronary artery tree, most of them either yield imperfect segmentation results or are computationally too expensive to be clinically useful. Until present, their spread into the clinical routine appears to have been rather limited. In contrast to such tools, our approach does not aim to define the exact border of the vessel, but rather to keep a sufficient amount of myocardial tissue surrounding the vessel in the segmentation result. This may seem to contradict the definition of segmentation, but since the results are shown with MIP or VRT, the exact delimitation of the lumen is left to the eye of the user, who may interactively adjust the window setting or VRT transfer function whenever needed. This approach facilitates preservation of detailed information about the coronary artery tree, e.g. the tips of minor branches, which may otherwise be lost as a result of under-segmentation. Moreover, it prevents the introduction of false stenoses arising from imperfect segmentation, which may be crucial for the diagnostic accuracy.

It should be noted that, although this software was designed to facilitate coronary artery CTA examination, it can also be used to separate vessels or other high-intensity structures from each other in CTA examinations of other organs. We have also successfully tested it for separating arteries and veins in MRA datasets with a blood-pool agent enhancing both vascular trees[18]. In conclusion, a new software module for coronary artery segmentation and visualization in CTA datasets has been presented. It seems to give satisfactory results with limited user interaction on low-end hardware, and the coronary CTA diagnosis procedure could potentially be more time-efficient than using thin-slab technique. Future studies will be needed to evaluate it relative to alternative software and an established reference method such as invasive catheter angiography. Our plans for future work also includes the addition of automatic or semi-automatic quantitative measurement tools for 2D and 3D, using one-click or no-click technique to locate the roots of arteries [16], and extending the method to 4D datasets for studying multiple cardiac phases.

References

1. Hoffmann U, Ferencik M, Cury R C, Pena A J (2006). Coronary CT Angiography. *J Nucl Med* 47: 797-806.
2. Fishman E K, Ney D R, Heath D G, Corl F M, Horton K M, Johnson P T (2006). Volume Rendering versus Maximum Intensity Projection in CT Angiography: What Works Best, When, and Why. *Radiographics* 26: 905-922.
3. Leclerc X, Godefroy O, Lucas C, Benhaim J-F, Michel T S, Leys D, Pruvo J P (1999). Internal Carotid Arterial Stenosis: CT Angiography with Volume Rendering. *Radiology* 210: 673-682.
4. van Ooijen P M A, Ho K Y, Dorgelo J, Oudkerk M (2003). Coronary Artery Imaging with Multidetector CT: Visualization Issues. *Radiographics* 23: e16-.

5. Tizon X, Smedby Ö (2002). Segmentation with gray-scale connectedness can separate arteries and veins in MRA. *J Magn Reson Imaging* 15: 438-445.
6. Löfving A, Tizon X, Persson P, Smedby Ö (2006). Angiographic visualization of the coronary arteries in computed tomography angiography with virtual contrast injection. *The Internet Journal of Radiology* 4.
7. Wang C, Smedby Ö (2007). Coronary artery segmentation and skeletonization based on competing fuzzy connectedness tree. *Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv* 10: 311-318.
8. Rosset A, Spadola L, Ratib O (2004). OsiriX: an open-source software for navigating in multidimensional DICOM images. *J Digit Imaging* 17: 205-216.
9. Udupa J K, Saha P K (2003). Fuzzy connectedness and image segmentation. *Proceedings of the IEEE* 91: 1649-1669.
10. Hadwiger M, Berger C, Hauser H (2003) High-quality two-level volume rendering of segmented data sets on consumer graphics hardware. *Visualization, 2003. VIS 2003. IEEE* pp. 301-308).
11. Ferencik M, Ropers D, Abbara S, Cury R C, Hoffmann U, Nieman K, Brady T J, Moselewski F, Daniel W G, Achenbach S (2007). Diagnostic Accuracy of Image Postprocessing Methods for the Detection of Coronary Artery Stenoses by Using Multidetector CT. *Radiology* 243: 696-702.
12. Lei T, Udupa J K, Odhner D, Nyul L G, Saha P K (2003). 3DVIEWSNIX-AVS: a software package for the separate visualization of arteries and veins in CE-MRA images. *Computerized Medical Imaging and Graphics* 27: 351-362.
13. Silén C, Wirell S, Kvist J, Nylander E, Smedby Ö Advanced 3D visualization in student-centred medical education. *Submitted for publication*.
14. Smedby Ö, Wirell S, Kvist J, Silén C, Petersson G, Fyrenius A, Nylander E (2007). Interactive volume rendering 3D images for anatomy learning on low-end computers. *ECR -European Congress of Radiology*.
15. Florin C, Paragios N, Williams J (2005). Particle filters, a quasi-Monte-Carlo-solution for segmentation of coronaries. *Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv* 8: 246-253.
16. Hennemuth A, Boskamp T, Fritz D, Kuhnel C, Bock S, Rinck D, Scheuering M, Peitgen H O (2005). One-click coronary tree segmentation in CT angiographic images. *International Congress Series* 1281: 317-321.
17. Khan M F, Wesarg S, Gurung J, Dogan S, Maataoui A, Brehmer B, Herzog C, Ackermann H, Aßmus B, Vogl T J (2006). Facilitating coronary artery evaluation in MDCT using a 3D automatic vessel segmentation tool. *Eur Radiol*: 1789-1795.
18. Wang C, Kihlberg J, Persson A, Smedby Ö (2007) Artery-Vein Separation in Vasovist enhanced MR Angiograms with Virtual Contrast Injection. *19th International Workshop on MR Angiography* Istanbul.