Fast Free Breathing 3D Coronary MR Angiography Using Undersampled Radial Imaging

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Abstract
In the present study, 3D radial imaging was used for fast free breathing coronary MR angiography. Double oblique 3D data sets were acquired that include the proximal part of right coronary artery (RCA). Radial imaging was used for in-plane encoding whereas Fourier encoding was applied in the third dimension ('stack of stars'-approach). For comparison, fully Fourier encoded data sets (Cartesian) were obtained. It is shown that angular undersampling can be applied to radial imaging to reduce the scan time by a factor of two while maintaining the in-plane resolution.

Introduction
MR angiography of the human coronary arteries still remains a challenge. Despite advances, such as e.g. thin slab double-oblique 3D acquisition and navigator-based scanning without breathing restrictions, the scanning times may still be too long for clinical routine [1]. Therefore, more efficient ways to sample data in k-space have recently been considered [2, 3]. 3D spiral imaging for coronary MR angiography have been proposed. However, spiral imaging is a very hardware demanding imaging sequence with a high sensitivity to off-resonance effects requiring a good shim. Radial imaging has been shown to be a very robust imaging sequence that is less sensitive to motion [4]. In addition, it has been shown that angular undersampling can be used in radial imaging to reduce significantly the imaging time of abdominal angiography [5]. In the present work, free breathing 3D radial coronary MRA was investigated and compared with a conventional 3D Fourier imaging technique. The effect of angular undersampling was applied in order to investigate the reduction of the scan time and the preservation of image quality.

Methods
Healthy volunteers were studied using a commercial 1.5 T whole body scanner (Gyroscan ACS-NT15, Philips Medical Systems) and two elements of the cardiac phased array coil. In the present study, double oblique 3D data sets were acquired that include the proximal part of right coronary artery (RCA). Coronary MRA was performed using magnetization-prepared (T2-preparation, regional signal pre-saturation, fat suppression) 3D gradient-echo imaging [1]. MR signal was acquired using a Cartesian and a radial sequence. The Cartesian scheme was a segmented linearly ordered k-space acquisition (constant flip angle 30°, partial echo acquisition, TE/TR = 2.4/8.1 ms, 512 x 288 x 10 scan matrix, cardiac acquisition window 70 ms, c.f. ref.[1]) resulting in an image resolution of 0.7 x 1.2 x 3mm^3. For comparison, the radial acquisition was adapted to the Cartesian sequence, i.e. a partial echo acquisition (TE / TR=2.4 / 8.1ms), and 288 radials were used. For the spatial resolution in the third dimension, conventional phase encoding for 10 slices was applied ('stack of stars'). After phase-correction of the radial profiles (absolute and linear phase effects), image reconstruction was performed by gridding and Fourier transform taking the partial echo acquisition into account ('homodyne reconstruction'). From each radial data set, two images were reconstructed. One with using all 288 profiles the other using only 144 profiles to mimic a faster acquisition, i.e. in the latter case, the angular undersampling halves the scan time.
Real-time navigator gating and prospective motion correction [6] using a rigid body motion model was applied in all experiments. Thus, for both scans (Cartesian and Radial Imaging) in-plane and through-plane motion components were corrected. The complete scan duration depends on the breathing pattern of the volunteer and was in the order of 12 minutes using 288 profiles (50% scan efficiency).
In the present study (imaging of the RCA), the signals of front elements of the phased array coil were combined using the approach of sum of squares.

Results
In all the measured individuals and for all of the different imaging techniques, the major parts of the proximal coronaries could be visualized. In Fig. 1, selected reformatted images showing the RCA for the two techniques are shown. In Fig. 1a, an image obtained with the Cartesian scan technique is shown, where the resolution differs along the readout and phase-encoding direction. In the images obtained with the radial imaging technique (Fig.1b, c), the in-plane resolution is isotropic (0.7 x 0.7). However, since k-space is angular undersampled, minor streaking artifacts occur that appear like high frequent noise. In the subsampled radial image (Fig. 1c), the streaking artifacts get slightly stronger, while maintaining the in-plane resolution. As a consequence of using only 144 profiles the SNR drops.

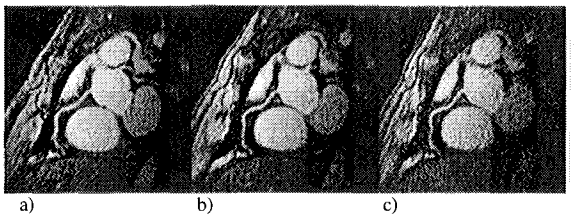

Fig. 1: Reformatted RCA images for the different techniques. a) Cartesian acquisition using 288 phase encoding steps along y-direction, b) Radial acquisition using 288 profiles, c) Radial imaging using 144 profiles

Discussion
The quality and contrast of the images obtained by both techniques is comparable, but the artifact behavior differs. In all experiments, a prospective motion correction for a rigid body motion model was applied. Deviations from this model result in motion artifacts. In the images obtained by the Cartesian scan technique, uncorrected motion resulted in ghosting that could hinder image interpretation. In the images obtained by the radial technique uncorrected motion results in blurring artifacts that are more acceptable [4].
The Cartesian scan technique was optimized in a way that the preparation experiments (fat-suppression, T2-preperation) have their optimums (zero-crossing), when the central profiles in k-space are acquired. One pitfall in the radial technique is the use of an appropriate profile order. Since all acquired profiles traverse through the k-space center, a modulation after the magnetization preparation experiments can occur from relaxation in the fat or cardiac muscle. Therefore, the profile order is fixed to $k_{z,0}$ in radial imaging, i.e. during the cardiac acquisition window the phase-encoding along the third dimension is performed, whereas the radial direction is changed between the cardiac acquisition windows.
So far, the amount of radial undersampling was limited due to SNR-reasons. However, in high-field applications, a higher degree of angular undersampling may be applied. In addition, projection MRA obtained by an add-subtract scheme [7] as well as contrast agent studies can benefit from undersampled radial imaging.

Conclusion
It has been shown that 3D radial imaging can be used to image the proximal parts of the coronaries. Radial imaging is less sensitive to uncorrected motion. Furthermore, angular undersampling can be applied to reduce the scan time significantly while maintaining the in-plane resolution. Undersampled radial imaging can be considered for more sophisticated experiments like projection MRA or contrast agents studies.

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