PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

ACCELERATING DUAL CARDIAC PHASE IMAGES USING UNDERSAMPLED RADIAL PHASE ENCODING TRAJECTORIES

KARIS DEL PILAR LETELIER FARÍAS

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisors:

SERGIO URIBE A.

CLAUDIA PRIETO

Santiago de Chile, December, 2013

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Dedicado a mis seres queridos por su apoyo incondicional.

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ABSTRACT

Purpose: A 3D Dual-Cardiac-Phase (3D-DCP) scan was proposed to obtain end-systolic and end-diastolic whole-heart images. This work propose to accelerate the acquisition and reconstruction time of the 3D-DCP approach by sharing information from the outer k-space of both cardiac phases using modified Radial Phase Encoding (RPE) trajectories and gridding reconstruction with uniform coil combination.

Methods: Fully-sampled data were retrospectively undersampled and different percentages of the outer k-space were shared to determine the percentage of redundant information between both cardiac phases. Thereafter, prospective undersampled data was reconstructed based on the percentage of redundant information found. Gold standard images were obtained using iterative SENSE reconstruction. We performed image quality assessments and cardiac volume analysis to validate results.

Results: Prospective undersampled data reconstructed with 50% combination produced high quality images while accelerating acquisition time by a factor of 4.There were not statistically significant differences in the image quality and in the cardiac volume analysis between our method and gold standard for the same undersampling factors. In addition, the proposed approach reduced the reconstruction time from 40 minutes to 1 minute.

Conclusion: Our method reduces the acquisition time maintaining an image quality similar to the gold standard and within a clinically acceptable reconstruction time.

Key words: whole-heart MRI; Dual Phase; radial phase encoding**.**

RESUMEN

Un examen de *3D Dual Cardiac Phase* (3D-DCP) se ha propuesto para obtener imágenes completas de corazón a final de sístole y a final de diástole. En este trabajo proponemos acelerar el tiempo de adquisición y reconstrucción del método *3D-DCP* al compartir información del exterior del espacio-K de ambas fases cardíacas usando una trayectoria modificada de *Radial Phase Encoding* y reconstrucción *Gridding* con combinación uniforme de bobinas.

Datos totalmente muestreados fueron submuestreadas retrospectivamente y diferentes porcentajes del exterior del espacio-K fueron mezclados para determinar el porcentaje de información redundante existente entre ambas fases cardíacas. Posteriormente, datos submuestreadas prospectivamente fueron reconstruidos basados en el porcentaje de información redundante encontrado. Las imágenes usadas como *gold standard* fueron datos submuestreados y reconstruidos usando *iterative SENSE*. Se realizó una prueba de calidad de imagen y análisis del volumen cardíaco para validar los resultados.

Los datos submuestreadas prospectivamente reconstruidos combinando un 50% produjeron imágenes con excelente calidad. No se encontraron diferencias estadísticamente significativas en los análisis de calidad de imagen o en de volumen cardíaco entre nuestro método y el *gold standard* para los mismos factores de submuestreo. Además, el método propuesto reduce el tiempo de reconstrucción de 40 minutos a 1 minuto.

Nuestro método reduce al menos cuatro veces el tiempo de adquisición con una calidad de imagen similar al *gold standard* y con un tiempo de reconstrucción clínicamente aceptable.

1. INTRODUCTION

Different whole heart imaging techniques has been proposed to facilitate the acquisition of cardiac MR images and to study anatomy (Razavi et al, 2003; Beerbaum et al, 2004, Sakuma et al, 2006; Botnar et al, 2000), function (Uribe et al, 2007; Barkhausen et al, 2004) and flow (Uribe et al, 2009) of the whole heart and great vessels. Among these sequences, the so called 3D Dual Cardiac Phase (3D-DCP) presents an important advantage since it allows the acquisition of two whole-cardiac phases in one scan with similar image quality compared to the 3D single cardiac phase acquisition (Uribe et al, 2008). 3D-DCP sequence allows us to assess the anatomy (Uribe et al, 2008; Hussain et al, 2012) and to obtain functional parameters. The 3D-DCP images are usually acquired using a 3D balanced steady state free precession sequence (b-SSFP) with Cartesian sampling and SENSE algorithms allowing acceleration factors of 2 or 3. Despite its advantages, the acquisition time of the 3D-DCP scan still remains long.

Radial Phase Encoding (RPE) has been proposed to speed up the acquisition of single cardiac phase whole heart images (Boubertakh et al, 2009). RPE is an acquisition trajectory that combines Cartesian read outs and radial phase encoding steps. Images obtained with RPE trajectories can be undersampled, and they are usually reconstructed using iterative SENSE (Pruessman et al, 2001).Iterative SENSE technique uses additional information from coil sensitivity maps to remove artifacts due to undersampling. The final image is an optimized reconstruction obtained after several time-consuming iterations. One advantage of RPE trajectories are their flexibility to perform different undersampling patterns, especially suitable for dynamic MR imaging (Prieto et al, 2010).

Dynamic images usually share considerable amount of information between frames. The information redundancy has been used to speed up image acquisition of MR images (Jones et al, 1993; Van Vaals et al, 1993; Lethmate et al, 2003). For instance, the keyhole method combines k-space data between images acquired at different time points (Van Vaals et al, 1993, Lethmate et al, 2003). This method continuously collects low frequencies from k-space and acquires high k-space frequencies only once (reference frame). The assumption is that the not acquired high frequencies do not change significantly between neighbor frames. Thus the high frequencies from the reference frame are then used to fill the high frequencies that were not acquired during the other time points. This approach however, can create problems such as low contrast in small regions, blurring or Gibbs artifacts. To prevent such problems, it is important to know the amount of k-space information that can be shared between different time points (Bishop et al, 1999). A different approach based on a golden ratio RPE trajectory has been recently proposed to speed up the acquisition of dynamic contrast-enhanced MRI (Prieto et al, 2010). RPE trajectories oversample the center of k-space such as in key-hole. However, in contrast to key-hole, undersampled higher frequencies are also acquired at each time frame.

In this work, we propose to use undersampled RPE trajectories to accelerate the acquisition of the 3D dual cardiac phase sequence. The undersampling factor is proportionally to the acquisition time. Our main hypothesis is that the outer k-space information can be shared between both cardiac phases, which allows for an increased undersampling factor without affecting the image quality. The proposed methodology also allows the use of a simple multiple-coil gridding reconstruction to obtain images with similar quality as the images provided by iterative SENSE for the same undersampling factor, but with a clinical suitable reconstruction time.

2. METHODS

Acquisition scheme

Radial Phase Encoding (RPE) trajectories were implemented to acquire 3D-DCP images. End-systolic and end-diastolic images were both acquired using RPE trajectories with the only difference being that the acquisition scheme for the end-diastolic phase was shifted with respect to the end-systolic phase in the angular direction (Figure 1). The angular shifting was equal to half of the angular step used in the RPE trajectory.

To speed-up the acquisition, RPE trajectories were undersampled in angular and radial directions using the methodology proposed by Boubertakh et al (2009). The undersampling factor reduces the acquisition time proportionally. Angular undersampling (R_α undersampling factor) was performed by skipping complete radial profiles along the angular direction. Radial undersampling (R_r undersampling factor) was carried out by leaving out phase encoding profiles along a radial profile. The undersampling along the phase encoding direction was performed using an interleaved undersampling scheme such that the sampled locations were shifted by one position from one angular direction to the next one. When radial and angular undersampling are combined, the total acceleration was the product of both factors: $R=R_\alpha*R_r$.

The acquisition scheme was implemented on a 1.5T Achieva Clinical MR scanner (Philips Healthcare, Best, NL). Data were acquired with a 5-element cardiac coil.

Reconstruction methods

Since RPE trajectories for systole and diastole were angularly shifted with respect to each other, it was straightforward to share k-space data between both cardiac phases.

The amount of shared samples was quantified as a percentage. If 60% of the data is shared, it means that 60% of the outer k-space points from one cardiac phase are added to the other cardiac phase and vice versa as shown schematically in Figure 1.

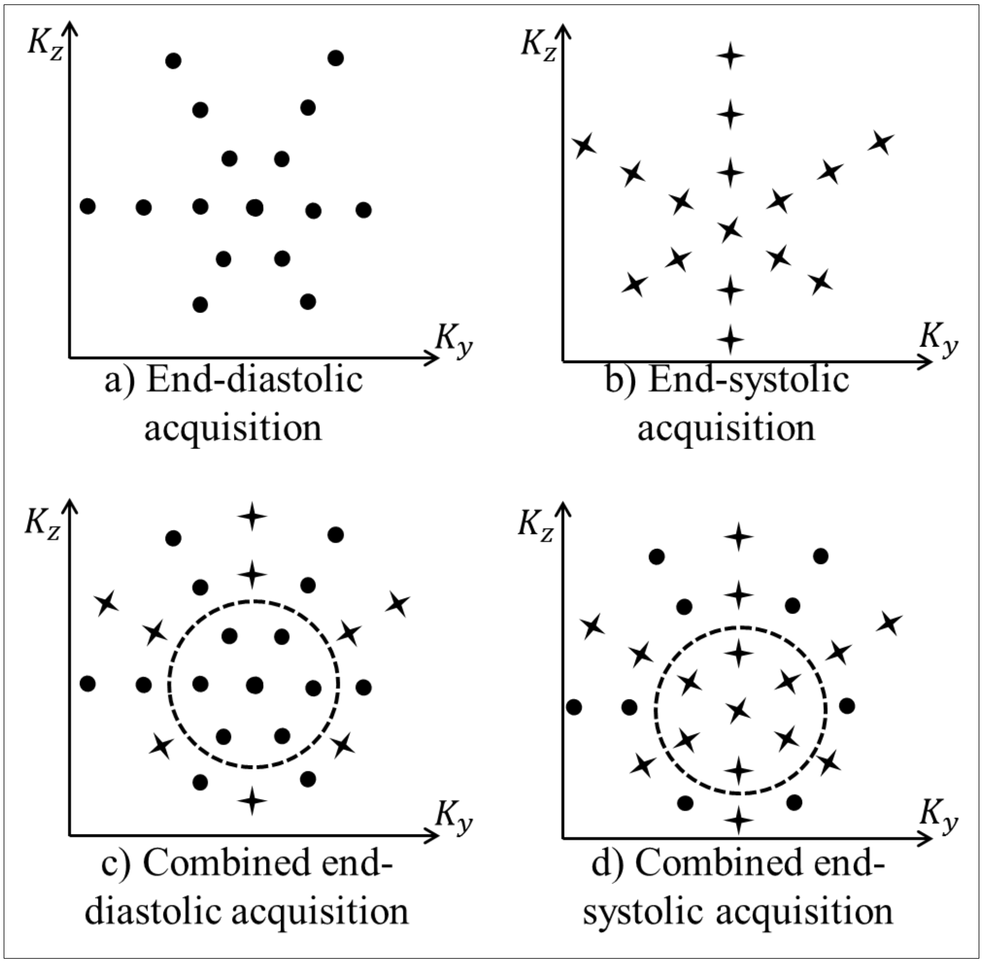

Figure 1 Trajectories scheme for each coil. a) and b) show the acquisition scheme for a projection in the phase-encoding plane (ky-kz) of each cardiac phase, systole (black points) and diastole (crosses). c) and d) show the combined acquisition schemes for diastole and systole where the circle correspond to Kr, the limit between those points which are shared / not shared between different cardiac phases.

The reconstructions steps were as follows: the first step was to apply a Fourier transform along the read out direction (K_x) on the data set of each coil. Then, data sets from the two cardiac phases were combined as shown in Figure 1 c) and d). Data sets were treated as a collection of slices with non-Cartesian samples. A 2D non-Cartesian Fourier transform was applied to each slice. Two reconstruction methods were implemented for each slice. Non-Cartesian gridding reconstruction produces the image acquired for each coil, and the images are combined with uniform coil combination as proposed by Roemer et al (1990). The images reconstructed with this method have shared information between the cardiac phases in k-space. For comparison purposes, the second reconstruction method was non-Cartesian iterative SENSE without sharing information between cardiac phases. The stopping criterion for the iterative method was set to a residual smaller than 10^{-3} or a maximum of eight iterations.

Density compensation function

For radial trajectories, an analytical Density Compensation Function (DCF) (Eq.1) is employed for both gridding and iterative SENSE reconstructions.

$$DCF(K_y, K_z) = \left(\sqrt{{K_y}^2 + {K_z}^2}\right)^{-1}, \qquad \text{Eq. 1}$$

where K_y and K_z correspond to both phase encoding directions. In the proposed approach, the DCP changes in areas where k-space samples from the other cardiac phase are added. In the area where the samples are combined, there are twice as many points, which results in doubling of the DCF, so the new DCF is:

$$DCF(K_y, K_z) = \begin{cases} \left(\sqrt{{K_y}^2 + {K_z}^2}\right)^{-1} & < K_r \\ 2\left(\sqrt{{K_y}^2 + {K_z}^2}\right)^{-1} & \geq K_r \end{cases} \quad \text{Eq. 2}$$

where K_r is the radio of k-space that limits the areas of shared and not shared samples.

Experiments

After imaging localizers and a SENSE reference scan, a b-SSFP cine image with high temporal resolution was acquired to determine the quiescent period of the heart at end-systole and end-diastole. Subsequently, end-systolic and end-diastolic cardiac phase images using the dual phase scan were acquired in fourteen healthy volunteers using a 5-element coil. In five of the fourteen volunteers, fully sampled data sets were acquired using the shifted RPE trajectories. This data were retrospectively undersampled to determine the amount of outer k-space information that can be shared between both cardiac phases. The other nine volunteers were scanned with the proposed shifted and undersampled RPE scheme. The acquisition parameters for the 3D-DCP were: b-SSFP sequence, flip angle= 90°, TR/TE= 4.1ms/2.0ms, FOV of 384 x 288 x 288 mm^3. In addition, a fat-saturation and a T2-preparation pulse were employed to null fat signal and to improve myocardial to blood pool contrast (Brittain et al, 1995). All images were reconstructed using a matrix size equal to 192 x 144 x 144 leading to an isotropic reconstruction voxel size of 2 x 2 x 2 mm^3. The local ethic committee approved the study and all volunteers signed a consent form.

Retrospective undersampled acquisition

Retrospectively undersampled data were generated to find out which percentage of outer k-space data can be shared between both cardiac phases. The undersampling factors were R_r =2, and R_α= 2 and 4, resulting in final undersampling factors of R = 4 and 8. For each undersampling factor, end-systolic and end-diastolic images were reconstructed by sharing outer k-space data for different percentages between 0 to 100%, in 10% increments. All of these data sets were reconstructed using gridding with uniform coil combination. The gold standard images were fully sampled RPE data reconstructed using iterative SENSE.

The reconstructed images were compared by calculating the Root Mean Square (RMS) error between the gold standard and the retrospective undersampled shared data reconstructed with the proposed approach. The percentage of k-space shared between both phases was determined from this analysis and used in a prospective undersampled acquisition. The RMS error was calculated in a Region of Interest (ROI) that included the entire heart and the great vessels.

Prospective undersampled acquisition

Prospective undersampled k-space data were acquired with undersampling factors of R_r=2 and R_α=1, 2 and 4, resulting in final undersampling factors of R=2, 4 and 8 with a reduction in the acquisition time of the same factor. The k-space data was then combined using a specific percentage of k-space determined from the fully sampled RPE acquisitions. These data sets were reconstructed using the proposed approach. For comparison, the purely undersampled images (i.e. without sharing k-space information between cardiac phases) were reconstructed using iterative SENSE.

Image quality assessment and statistical analysis

For prospective undersampled acquisition, the image quality and clinical usefulness of the images obtained with the proposed approach was assessed with three tests: a) image quality evaluation for each reconstruction method independently, b) image quality comparison between reconstruction methods for the same undersampling factor, and c) cardiac volume assessment. The first evaluation was performed by two different observers (S.U. and M.A.) with 8 and 5 years of experience in cardiac MRI, respectively. The evaluated features considered were edge definition and amount of artifacts. The image scores were determined as 1 (edges not defined), 2 (edges almost defined), 3 (edges defined) and 4 (excellent edge definition). A similar score was used to define artifact level. The final score for each observer was calculated as the mean between the score of each feature. The final score of each image was then obtained by averaging the score between both observers.

The second evaluation was performed by two observers (S.U. and C.P.) with 8 years of experience in cardiac MRI. For this evaluation, two images acquired with the same undersampling factor were presented simultaneously. One image was reconstructed with the proposed approach and the other with the gold standard. The observers were asked to answer which image had better image quality.

For test one and two, the compared images were acquired with undersampling factors of 2, 4 and 8, and reconstructed with our approach and with iterative SENSE using no shared k-space samples. In the first test, the Wilcoxon signed rank test was used to detect any statistically significant differences between our approach and iterative SENSE. For both tests, the selected images represent a transversal slice taken from the left ventricle of each volunteer

Cardiac volume assessment was performed in images acquired with an undersampling factor of R=4 and reconstructed with both the proposed and iterative SENSE methods. Images reconstructed with iterative SENSE for an undersampling factor of 2 were considered as the gold standard. In each case, end-systolic, end-diastolic and stroke volumes were calculated on images reformatted along the short axis view, which was obtained using Osirix (Osirix v.5.7.1). A paired t-test was performed to check for any statistical significant difference between the volumes obtained from our method and the gold standard technique. Additionally, an ANOVA test was used to compare the volumes obtained from our approach and iterative SENSE. Finally, Bland Altman plots were performed for comparing both our method and iterative SENSE with a gold standard (Iterative SENSE with R=2).

3. RESULTS

Retrospective undersampled acquisition

End-systolic and end-diastolic images reconstructed with the proposed approach for different percentage of k-space data combinations are depicted in Figure 2. It can be seen that image quality improved as the percentage of combination increased until a certain percentage was reached. Figure 3 shows the RMS error curve between the fully sampled RPE data reconstructed with iterative SENSE and the proposed method for different percentages of combination of k-space data. For the undersampling factor R=4, the RMS error decreased until a 40-60% of shared data between systole and diastole. For percentages of phase combination higher than 60%, the RMS error increased. A similar behavior was observed for an undersampling factor of R=8, with the minimum RMS error value occurring for ~ 70% combination.

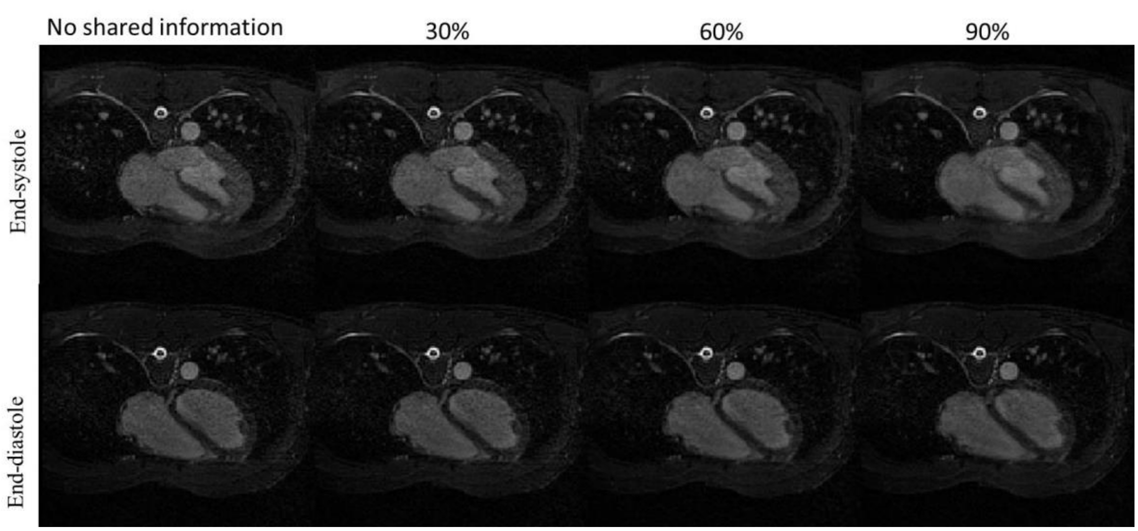

Figure 2. End-systolic and end-diastolic images reconstructed with the proposed approach for different percentage of k-space data combinations with undersampling factor R=4. In the image with 60% shared k-space samples, noise level and artifacts are minimized.

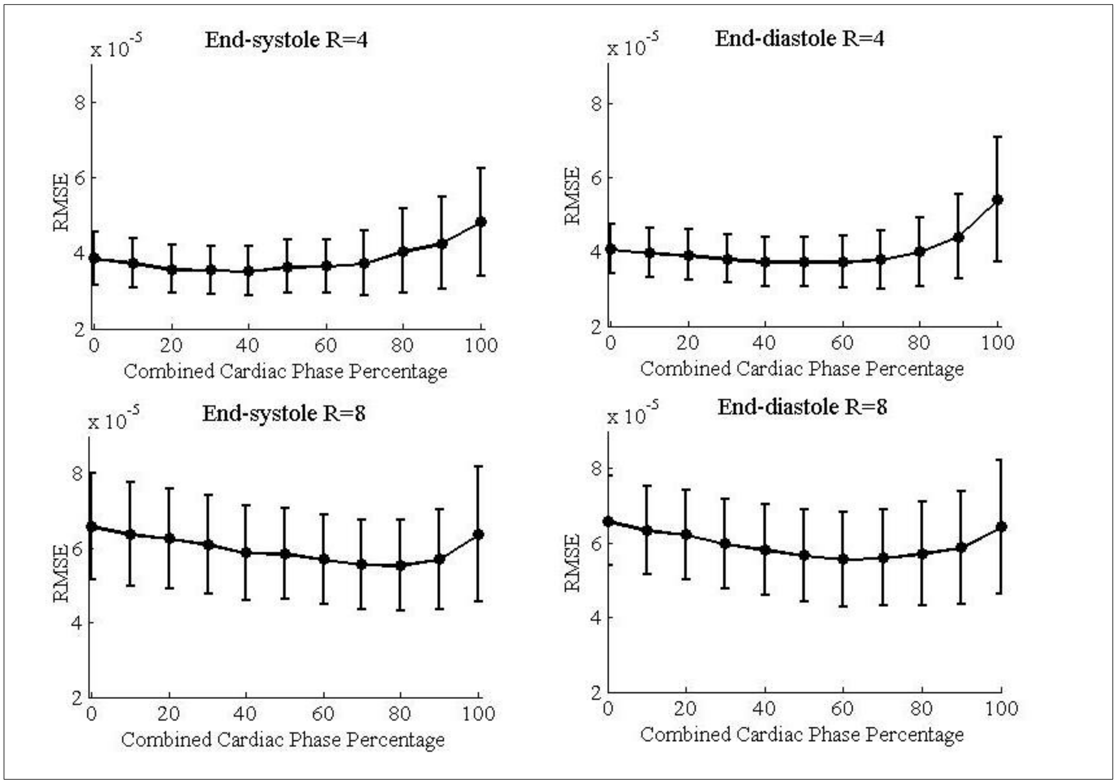

Figure 3. RMS error between the proposed approach and iterative SENSE reconstructions for total undersampling factors (R) of 4 and 8. A fully sampled image (R=1) no shared, reconstructed using iterative SENSE was considered as gold standard.

Prospective undersampled acquisition

Undersampled data sets reconstructed using the proposed approach and the gold standard (iterative SENSE, no shared) are shown in Figure 4 and Figure 5 for undersampling factors (R) of 4 and 8, respectively. For R=4, the images were in general free of artifacts and there was no visual difference between the proposed approach and the gold standard. For R=8, the proposed approach shows a better edge definition but iterative SENSE reconstruction seems to have a lower noise level.

The mean reconstruction time for the two volumes with R=4 was 40 minutes for non-Cartesian iterative SENSE, and 1 minute for the proposed approach. (Intel Core i7, CPU 3.40 GHz and RAM 32 GB)

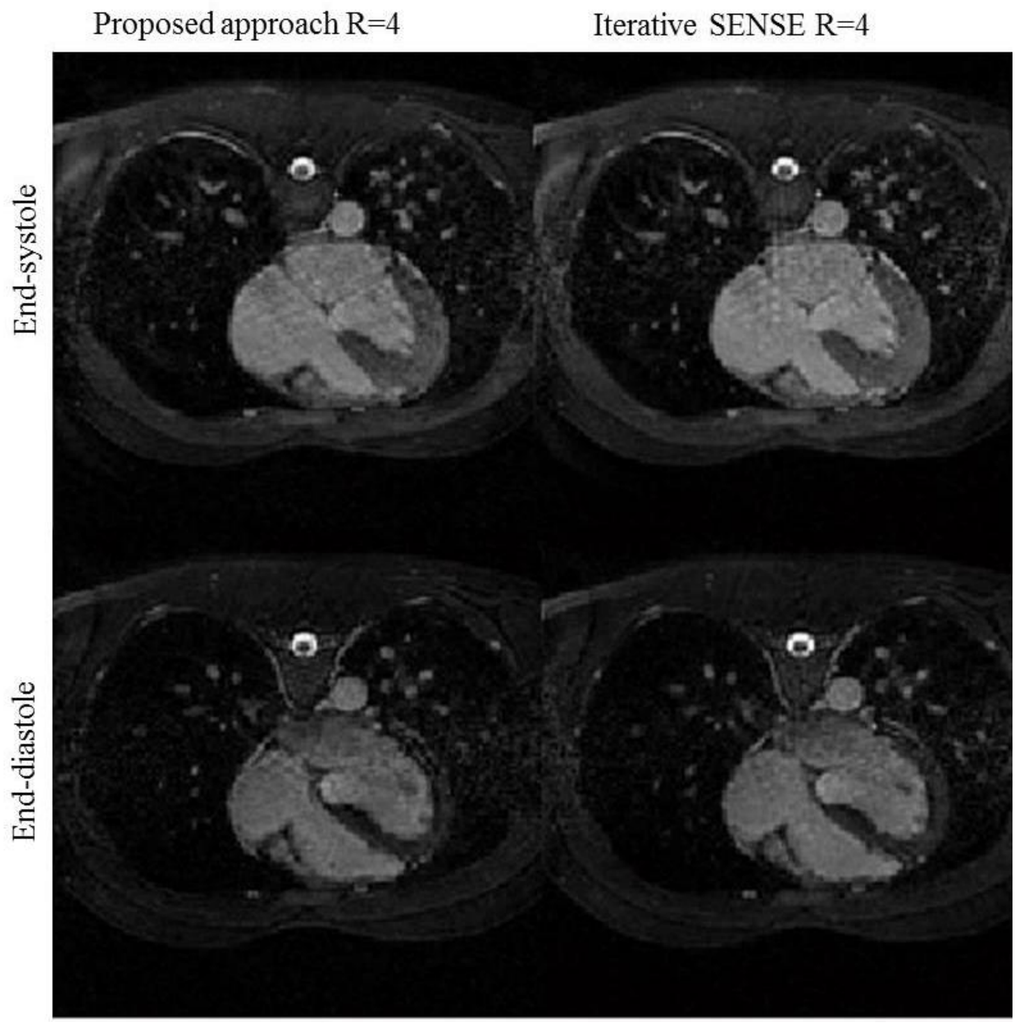

Figure 4. End-systolic and end-diastolic images obtained with an undersampling factor of 4. The first column shows the combined images reconstructed with Gridding and uniform coil combination. The second column shows the undersampled images reconstructed with non-Cartesian iterative SENSE and no shared information. Systolic and diastolic images are shown in the superior and bottom rows respectively. Minor differences can be appreciated between the proposed method and iterative SENSE for both cardiac phases.

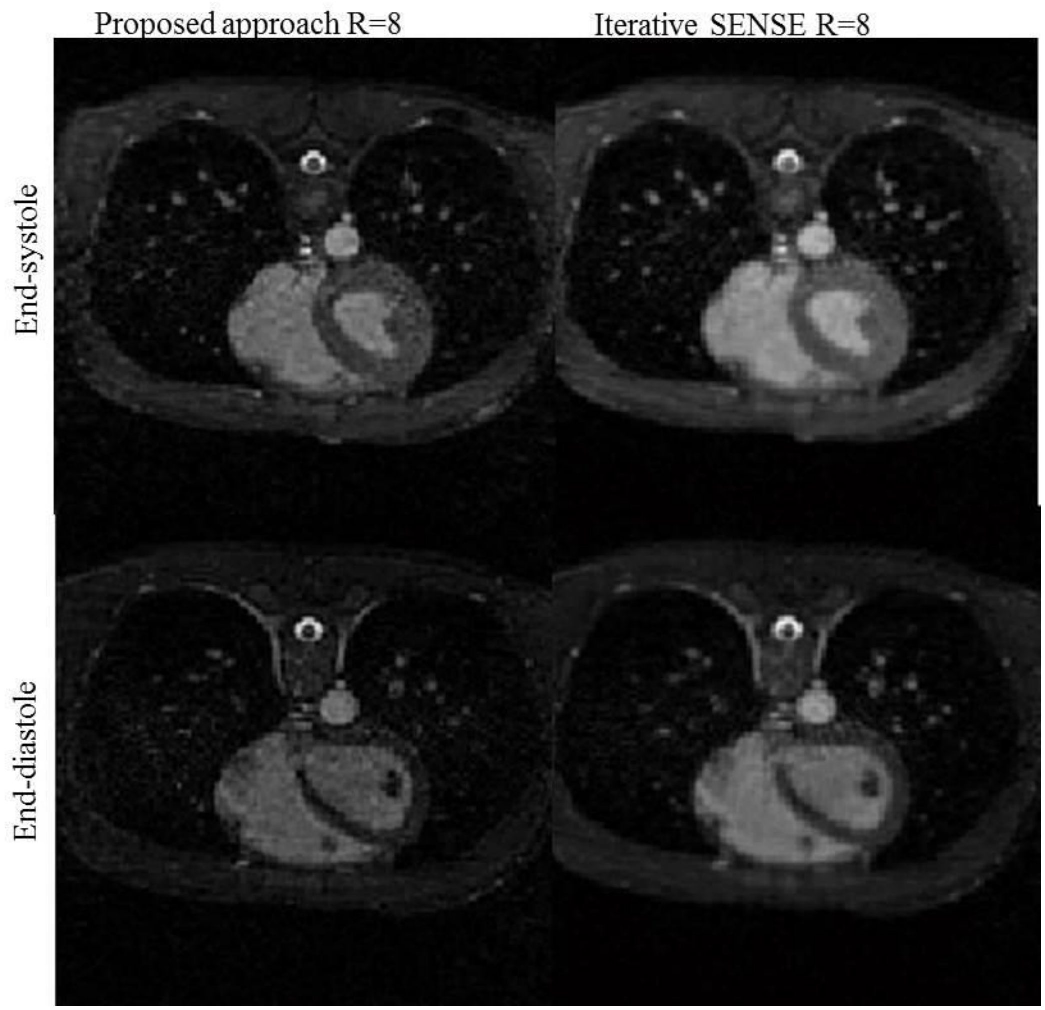

Figure 5. End-systolic and end-diastolic images obtained with an undersampling factor of 8. The first column shows the combined images reconstructed with Gridding and uniform coil combination. The second column shows the undersampled images reconstructed with non-Cartesian iterative SENSE. Systolic and diastolic images are shown in the top and bottom rows, respectively. The proposed approach shows a better edge definition but iterative SENSE reconstruction seems to have a lower noise level.

Image quality assessment and statistical analysis

The results of the first image quality analysis (i.e. each image was scored individually) are shown in Figure 6. As expected, the highest scores were obtained for the iterative SENSE reconstruction image acquired with an undersampling factor of 2, which was considered as the gold standard. We found that for an undersampling factor of 4, 66.7% of the images had an image quality over or equal to 3 using iterative SENSE and 77.8% using the proposed approach. For an undersampling factor of 8, 33% had an image quality equal or over 3 for both reconstruction methods.

Result of the Wilconxon Signed Rank test (significance for systole = 0.386 and significance for diastole = 0.792) indicated that the median of the undersampled acquisitions were different from the iterative SENSE reconstruction (R=2). We also found no statistically significant differences (significance for systole = 0.023 and significance for diastole = 0.027 when R=4 and significance for systole = 0.011 and significance for diastole = 0.070 when R=8) between images acquired with the same undersampling factor (R=4 and R=8), but reconstructed with the proposed approach and iterative SENSE.

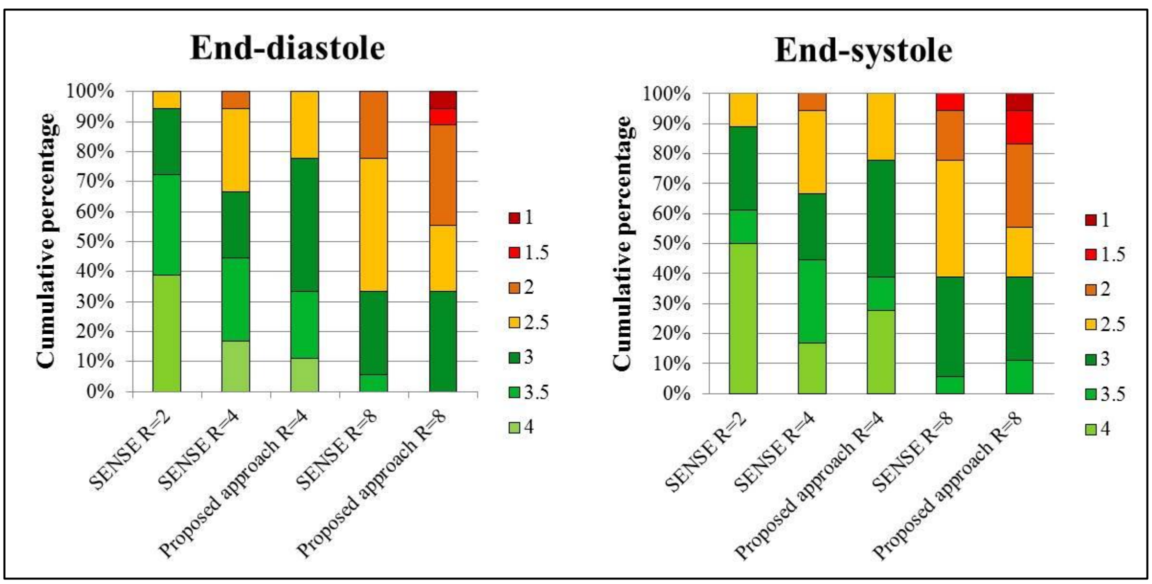

Figure 6. Cumulative percentage for each score obtained by each reconstruction method with different undersampling factors.

	Mean ± standard deviation	Median	Range
Iterative SENSE R=2	3.5 ± 0.5	3.5	2.5 - 4
Iterative SENSE R=4	3.1 ± 0.6	3	2 - 4
Proposed approach R=4	3.1 ± 0.5	3	2.5 - 4
Iterative SENSE R=8	2.5 ± 0.4	2.5	2 - 3.5
Proposed approach R=8	2.3 ± 0.6	2.5	1 - 3

Table 1. Scores for the image quality assessment. Minor differences can be observed between no shared SENSE R=4 and the proposed approach.

Results of the second image quality test showed that for an undersampling factor of 4, the proposed approach had an equal or better image quality than the images obtained with the iterative SENSE algorithm in 83.34% of the cases. For 85.56% of the cases iterative SENSE showed a better performance than the proposed approach when the undersampling factor was 8.

Results of the cardiac volume analysis are shown in Table 3 and Figure 7. Results of the paired t-test for iterative SENSE with undersampling factors of 2 and 4 showed no statistical differences for the EDV (p=0.1526), ESV (p=0.1704) and SV (p=0.2083). The same test applied for iterative SENSE (R=2) and the proposed approach (R=4) also did show no statistically significant differences for any of the functional parameters (EDV, p=0.3490; ESV p=0.6403; and SV p=0.9314). Additionally, results of the one-way ANOVA test between all volumetric data sets showed no statistical differences for all parameters (EDV, p=0.476; ESV p=0.854; and SV p=0.999).

	Iterative SENSE R=2		Iterative SENSE R=4		Proposed approach R=4	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
EDV	135	24.4	134.6	25.2	134.6	24.9
ESV	53.1	12.6	53.4	12.3	53.9	12.9
SV	81.9	20	81.1	18	80.7	20.4

Table 2. Mean and standard deviation (Std. Dev.) of cardiac volumes quantification for the left ventricle. End Diastolic Volume (EDV), End Systolic Volume (ESV), Stroke Volume (SV).

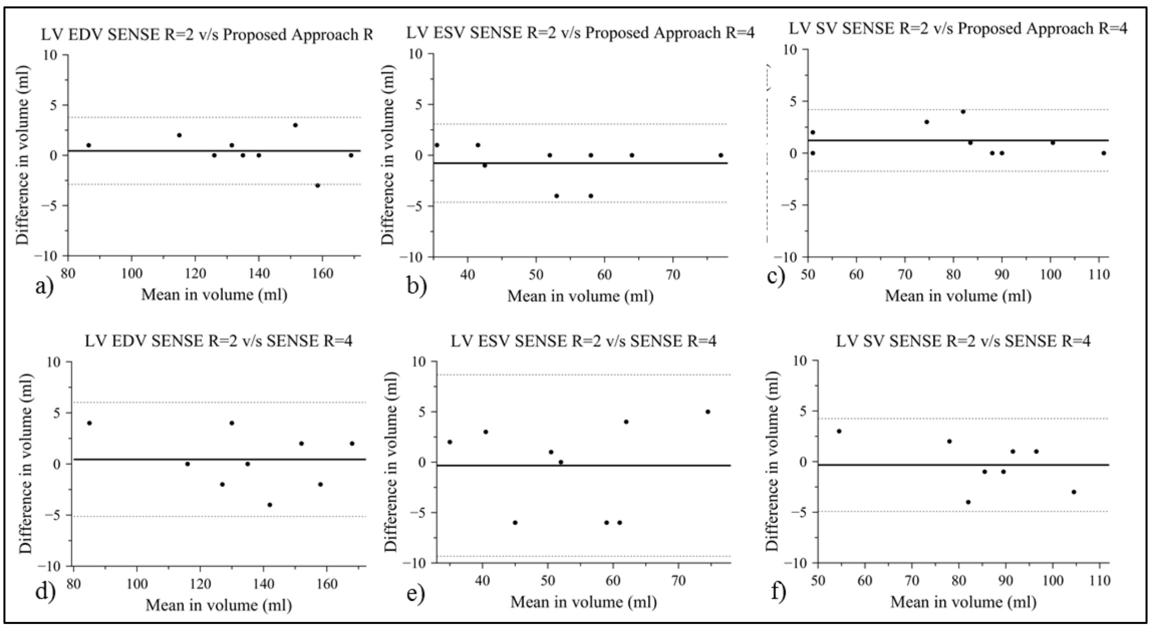

Figure 7. Bland-Altman plots. Image using iterative SENSE reconstruction and R=2 is compared to an image with R=4 obtained with the proposed approach and with iterative SENSE. Middle line: mean, upper and lower lines: two standard deviations. a) Left Ventricle (LV) volume at the End Diastolic Volume (EDV). b) LV volume at the End Systolic Volume (ESV). c) Stroke Volume (SV) of the LV.

4. DISCUSSION

We have proposed an approach that allows images to be obtained from the 3D-DCP scan with excellent image quality using undersampled RPE trajectories. We have shown that combining k-space data from both phases, the acquisition time is reduced by a factor of 4 (from 13:35 minutes to 3:28 minutes) obtaining excellent image quality, and by a factor of 8 (from 13:35 minutes to 1:43 minutes) obtaining images with good quality. Additionally, by using gridding reconstruction and uniform coil combination we reduced the reconstruction time from 40 minutes using the gold standard technique to 1 minute for the two 3D data sets.

The proposed approach is based on exploiting the redundant information between both cardiac phases in a dual cardiac phase scan. A RMS error curve between a fully acquired RPE and undersampled data with different percentage of k-space combination was employed to determine the amount of redundant information between the diastolic and systolic phases. Based on the RMS error analysis, prospective undersampled images were reconstructed with a 50% combination of k-space. This conservative percentage combination was employed in order to compare the proposed approach with iterative SENSE independent of the undersampling factor. However, higher undersampling factors may benefit from higher combination percentages, as suggested from the RMS error analysis for an undersampling factor of 8.

In this work, the RMS error was calculated on retrospectively undersampled images for different combination percentages. In future work, mutual information and cross correlation approaches, based directly on the acquired images, will be investigated to obtain patient-specific combination percentages for different undersampling factors.

We proposed to reconstruct the combined data using gridding with uniform coil combinations since it is a simple and efficient way to reconstruct non-Cartesian k-space coil by coil. One of the limitations of gridding is that this method easily generates artifacts when it is used to reconstruct undersampled k-space data. However, adding information from one cardiac phase to the other resulted in a significant reduction of those artifacts. On the other hand, iterative SENSE takes advantage of the additional information present in the multiple receptor coils. With multiple iterations, SENSE can find an optimized reconstructed image with the knowledge of the coil sensitivity maps, but only after several time consuming iterations.

To acquire and reconstruct the images, we used a 5 element cardiac coil. However it is possible that by using more elements, the iterative SENSE method could achieve higher undersampling factors or better image quality. It has been shown that by using 32 channels the maximum achievable undersampling factor was 8 while maintaining a clinically acceptable image quality (Boubertakh, et al, 2009) We also expect that our method could provide better image quality with increased number of coil elements; however, the acceleration factor achieved by our method does not necessarily depend on the number of coils.

The proposed method was validated using three different tests. The first image quality test showed that the proposed approach achieved similar or better image quality scores than iterative SENSE for the same acceleration factor. The second test showed that images reconstructed with the proposed method achieved better image quality than iterative SENSE for R= 4 but lower image quality than iterative SENSE for R=8. However, from the first test, the mean of the quality score was similar for both cases. For an undersampling factor of 8, the image quality score was 2.3±0.6 for the proposed approach and 2.5±0.4 for iterative SENSE.

Cardiac volume assessment showed that there were not statistically significant differences between cardiac volumes evaluated with any of the methods compared. Bland Altman plots showed a mean difference close to 0 for all of the compared methods; however, the standard deviation was much lower when our method was compared with the gold standard (±0.8925) than when comparing iterative SENSE (R=4) with the gold standard (± 2.4576).

5. CONCLUSION

We have proposed a new method to acquire and reconstruct dual cardiac phase images using RPE trajectories and k-space data sharing. In this paper, a four-fold reduction in acquisition time was achieved by undersampling. Our proposed method achieves excellent image quality based on both a quantitative and qualitative assessment, and it is capable of reconstructing whole heart images in a clinically- acceptable time.

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