Avoiding additional hardware and recovering cardiac information from k-space

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Abstract

MRI is considered the gold standard for the imaging of cardiac function and anatomy. In regular cardiac MRI, an external ECG monitor is required in order to synchronize the data acquisition with the motion of the heart. However, this additional hardware increases the examination, preparation and acquisition times. The aim of this proposal is to avoid the necessity of this additional hardware in cardiac MRI examinations by developing an automatic method to recover the cardiac cycle information directly from the MRI data both in breath-hold and free breathing situations. Some different scenarios have been considered and some methods have been proposed with good performances, obtaining errors between 1-4%.

1. Introduction

Cardiovascular diseases represent nowadays the most common cause of death worldwide [1]. Therefore, the urge to update and improve the existing solutions has been increasing in order to detect cardiovascular diseases earlier and more accurately [2].

Cardiac cine MRI is considered the gold standard for the evaluation of cardiac function and anatomy [3]. However, it is a relatively slow technique that involves long examination times and elaborated setups. Specifically, additional hardware, such as ECG and respiratory bellows, is required. The ECG is used to synchronize the acquisition of MRI data with the cardiac beating and bellows are used as respiration sensors to avoid artifacts produced by respiratory motion when the long time required for the procedure prevents breath-hold acquisitions. However, these external devices increase the examination, preparation and acquisition times [4-5]. Moreover, the ECG in high field MRI systems can be severely corrupted by induced electromagnetic signals and the magnetohydrodynamic effect [6]. One way to reduce scan time is to change the usual manner to sample the k-space. This is, indeed, a very active field of research nowadays [7-8], in which the use of Golden radial trajectories [6] has shown to enable high acceleration factors in 2D MRI (see Figure 1). When using radial trajectories, the center point of the k-space, which corresponds with the DC component of the image, is acquired at every *spoke* or acquisition line, a fact that will be exploited as described in the following sections.

The aim of this proposal is to avoid the need of additional hardware in cardiac MRI examinations and develop an automatic method to recover the cardiac synchronization signal directly from the MRI data afterwards. The procedure has been tested via numerical simulation and with real data both in breath hold and free breathing acquisitions.

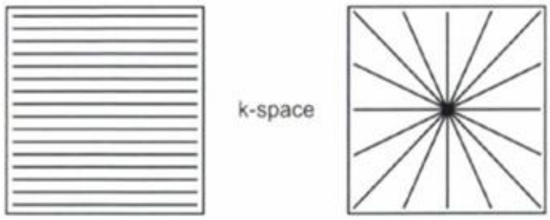

Figure 1. *Cartesian (left) and radial (right) trajectories for the acquisition of k-space data. In the radial case, the center of the k-space (DC component) is acquired at every single shot.*

2. Theory

2.1. Cardiac signal detection

In cardiac cine MRI a set of images along the cardiac cycle are obtained enabling the visualization of the motion of the heart. In these images, blood typically appears bright, surrounded by darker regions (mainly myocardium, lungs, and liver). Therefore, we hypothesize that cardiac contraction will translate into a decrease on the average intensity value of each image (DC component) along the cardiac cycle (Figure 2). Since the k-space data is related to the final images via the Fourier transform, the evolution of DC component of the images along time is contained in the central position of the k-space, which is more frequently sampled when radial trajectories are used. Consequently, the proposed method for the recovery of the cardiac synchronization information is based on the processing of the signal formed by the central samples of the k-space along time. In free breathing scenarios, the change of volume of the lungs will also affect the DC value of the images. Therefore, breathing dynamics will be present in the signal as well. As a preprocessing step, this signal is band-pass filtered between 0.1 Hz and 1.5 Hz, where most of the cardiac and respiratory activities are contained. A peak detection algorithm is then applied to identify cardiac cycles.

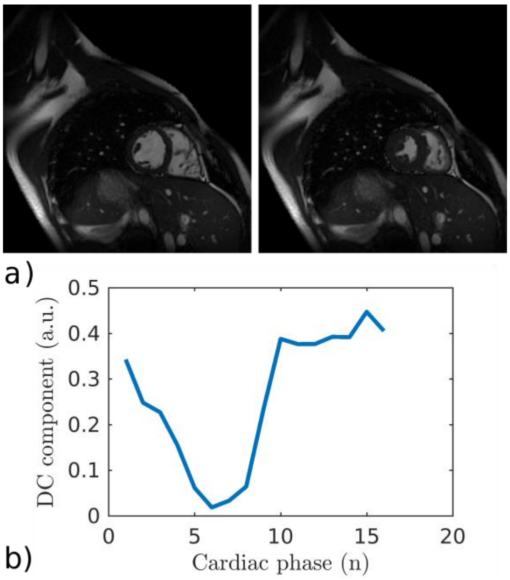

Figure 2. *a) Diastolic (left) and systolic (right) cardiac phases in a cardiac cine exam. b) Evolution of the average intensity value along the cardiac cycle. Minimum corresponds to the systolic phase shown.*

2.2. Coil selection

In modern MRI systems, k-space signal is acquired simultaneously with several coils or antennas (parallel imaging), shortening acquisition time. The data captured by each coil is affected by the radiation pattern or *sensitivity* of that antenna. Given the spatial distribution of the antennas, some of them will provide more useful information for the recovery of the cardiac signal than others (Figure 3).

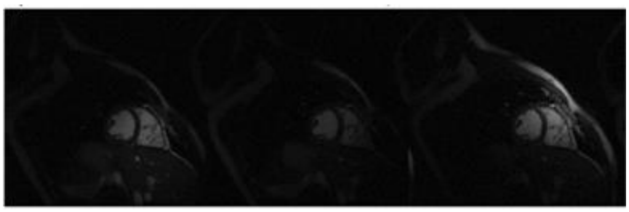

Figure 3. *Coil selection. The images obtained from three different coils are represented. The image in the center is discarded because of its low brightness. The coil on the right side is more focused on the external area than the coil on the left which is more focused on the heart. Therefore, the coil on the left will be preferred.*

A method to automatically select the best coil is a key component of the developed method. Two approaches are presented:

- Automatic selection based on spectral analysis: calculate the ratio between the average of the spectrum of the signal in the [0.5-1.5 Hz] and [0.1-0.5 Hz] bands, which correspond with the frequencies of the cardiac cycle signal and respiratory cycle signal, respectively. The selected coil was the one that provided a higher value of these ratios. In this approach, only the information from one coil is used for signal recovery.
- Principal component analysis (PCA) approach: We hypothesize that, by means of PCA, most of the common dynamic cardiac information that is *distributed* among the different coils can be concentrated in the firsts principal components of the multicoil DC signal.

3. Materials and Methods

Four healthy volunteers with ages ranging 24-29 were scanned with a 32-elements cardiac coil on a 1.5T Philips scanner and a balance steady state free precession (bSSFP) sequence. The acquisitions where performed in three different scenarios:

3.1. Cartesian, breath-hold acquisition

A standard Cartesian acquisition in breath-hold was performed. Relevant acquisition parameters include TR/TE = 2.9 ms/1.44 ms, flip angle of 60°, field of view (FOV) = 320×320 mm^2, spatial resolution = 2×2 mm^2. 20 cardiac phases where reconstructed.

In this approach, a single cardiac cycle is reconstructed. In order to simulate a continuous acquisition along several cardiac cycles the DC signal was periodically extended. The signal obtained has been used as a first stage validation of the proposed approach in a simplistic scenario.

3.2. Golden-radial breath-hold acquisition

A golden-radial acquisition [6] was performed in breath-hold with similar parameters than in the Cartesian case. Total acquisition time was ~12 seconds and a total number of 4000 projections were acquired. The first 400 projections were discarded in order to guarantee that the stationary state was reached.

Contrary to Cartesian, in a radial acquisition each line passes through the center of the k-space. The three central samples along each line were averaged in order to correct possible misalignment with the center of the k-space due to gradient errors and eddy currents and taken as the DC component.

3.3. Golden-radial free-breathing acquisition

An additional golden-radial acquisition was performed with similar parameters in free-breathing to analyze the influence of the respiration in the recovery of the cardiac signal.

In all the scenarios, an ECG signal was recorded simultaneously with the data and used as a ground truth. In order to validate the proposed methods in the different scenarios the following error measure has been defined:

$$Error = \frac{RR_{ECG} - RR_{MRI}}{RR_{ECG}}$$

where RR_{ECG} are the RR intervals obtained from the ECG signal of reference and RR_{MRI} are the intervals obtained from the cardiac cycle signal obtained from the MRI data.

4. Results

Figure 4 shows the cardiac cycle signals obtained from Cartesian real data in breath-hold. Only the data from a single coil was manually selected. To select the coil, the images resulting from each coil were represented and visually inspected. The coil that provided an image that showed a better compromise between brightness and direction (that is, the coil that was more focused on the heart region) was selected (Figure 3). In the plotted signal, cardiac dynamics are cleared appreciable, with an abrupt decrease of its value indicating ventricle contraction.

With respect to golden radial acquisitions, Figure 5 shows the cardiac signal obtained from the golden radial data only for the free-breathing case, for conciseness. Data from only one coil was automatically selected applying the automatic method described in the Theory section based on spectral analysis. The peak detection algorithm was adapted to allow RR intervals between 0.5 and 1.2 seconds, corresponding to heartrates between 50 and 120 BPM. Then the obtained RR-intervals were compared with the RR-intervals obtained from the ECG signal of reference.

In the free-breathing scenario, we adapted the band-pass filter to use to mitigate the influence of the respiratory component in the cardiac signal and a higher cutoff frequency to collect additional harmonics of the cardiac cycle signal at higher frequencies. Its original spectrum and the signal obtained after filtering are also represented in Figure 5. We have achieved an error of 2.0589% in breath-hold situation. Before adapting the filter as described, the error in the free-breathing case was as high as 30.8826%. After readjusting the filter and inverting the signal to detect the minimums of the resulting signal instead of the maximums, we obtained an error of 1.6271%.

Finally, the PCA approach was applied to the free-breathing golden-radial data. In this scenario we used all the information provided by the 32 coils from the previous data set by using a PCA approach. In a first step, we used the first PCA component to obtain the cardiac cycle signal. In order to test the hypothesis that the first principal component gathers most of the cardiac information, we applied the automatic coil selection approach based on spectral analysis to all the PCA components.

Results are summarized in Table 1, which shows the error between manual and automatic selection of a single coil and for PCA based approach. The second column shows the error obtained when the coil was selected manually by visual inspection. The number preceded by the '#' symbol means the number of the selected coil. In the third column

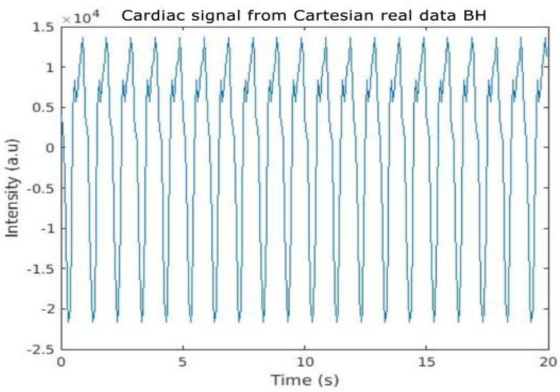

Figure 4. *Cardiac cycle signals obtained from Cartesian real data in a breath-hold situation.*

Subject	Visual inspection	Automatic selection	PCA	PCA after filtering
1	#5: 1.63%	#13: 2.514%	C1: 3.04% C5: 2.34%	2.65%
2	#12: 0.93%	#11: 0.984%	C1: 2.40% C4:1.45%	1.37%
3	#14: 1.40%	#13: 3.103%	C1: 4.39% C8: 1.97%	3.20%
4	#4: 3.56%	#5: 3.731%	C1: 7.57% C2: 3.40%	3.88%

Table 1. *Error comparison (in percentage) between manual and automatic selection and between single or multi-coil methods.*

the results from the method described in section 2.2 are shown. In the fourth column the results obtained from the PCA approach are shown. The number preceded by a 'C' letter means the selected PCA component by the automatic method based on spectral analysis. The results from selecting the first PCA component (C1) are also shown for comparison. Finally, in the fifth column we present the results of the PCA approach with a previous filtering of the data and automatic selection of the PCA component.

5. Discussion

In the first scenario with Cartesian data, the cardiac cycle signal can be easily obtained by extracting the zero-frequency component along time in a breath-hold situation. The RR-intervals are constant due to the heart rate variability is not included. However, in a free-breathing situation the cardiac cycle signal was affected by the respiratory signal. A band pass filter (cutoff frequencies 1 and 2.5 Hz) was used to remove the respiratory signal. Since the results were not accurate enough, different band-pass filters with different cutoff frequencies were used until we achieved the desired accuracy. In the free breathing situation, the signal is affected by respiratory cycle but it can be removed by filtering.

For breath-hold golden-radial acquisitions, the filtering method is showing good results and allows us to recover the RR intervals with accuracy. When switching to a free-breathing scenario, and after applying the described modifications in the filtering procedure, the error between automatic selection of one coil and filtering before the PCA approach look similar. It can be presumed, that if more subjects had participated, this slight difference may be included in the standard deviation. Concerning the resulting images from coils, it is really difficult to clearly detect differences between the optimal coil and the two other coils selected by an automatic approach. However, it seems that the best choice between these proposed methods is the PCA approach after filtering the data, since the information of all coils is combined. This also makes sense because we remove some noise, which can affect negatively to the resulting PCA directions.

Another important point in this discussion is that the recovered signals are not in the same cardiac phase when

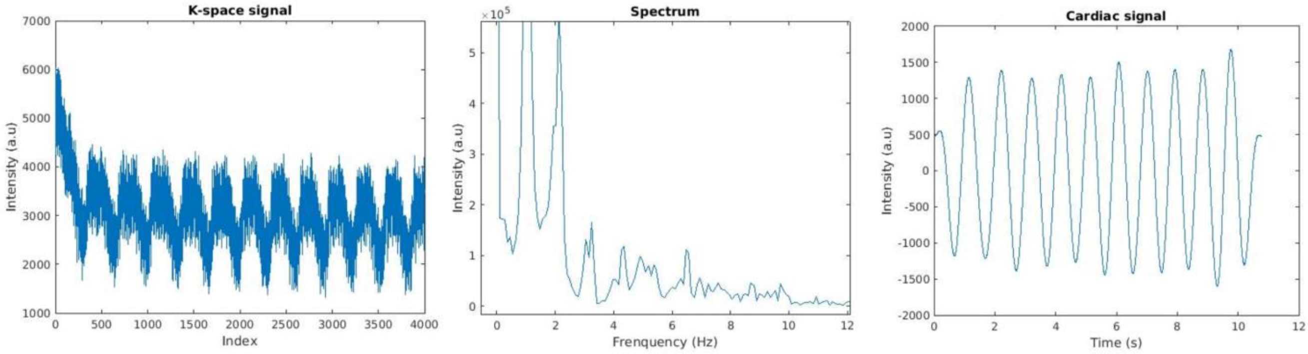

***Figure** 5. Cardiac cycle signals obtained from golden radial real data. On the left is represented the signal (only real part of the complex signal is considered) obtained before filtering; in the center its spectrum is represented; and on the right, the signal after filtering is shown.*

the image is reconstructed, since an offset is introduced between the peaks detected in the real ECG signal and the one recovered from the k-space data. This fact is not such a big problem since the information reside in the RR interval series.

6. Conclusions

An automatic method for recovering the cardiac cycle signal from k-space data with two approaches was proposed. The automatic selection of coil reveals that the selected coil may be not the best one but one with a low error. If a comparison of the results of the automatic coil selection and the filtering plus PCA approach is made, it can be seen that the error are quite similar. Moreover, it is presumed that with a wider data set those differences may be enclosed in the standard deviation and consequently there would be a non-significant difference between these two methods. However, the best choice between these two methods seems to be the PCA approach after filtering the data, since the multi-coil information is combined and provide more accurate results than only one coil.

7. Limitations and future work

One of the major limitations of the current work is the reduced number of dataset available for validation, as mentioned in the Conclusions section. In the automatic selection method based on spectral analysis, the presence of breathing dynamics in the temporal behavior of the DC signal has been pointed out. As a future work, the possibility of recovering a respiratory navigator signal will be studied. This approach would eliminate the use of additional respiratory sensors or navigator sequences in respiratory navigated free-breathing acquisitions.

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