ADAPTIVE HEART RATE PREDICTION FOR BLACK-BLOOD SYSTOLIC IMAGING

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INTRODUCTION:

Cardiac MRI is still challenging due to the perpetual heart motion. In order to avoid cardiac motion artifacts, acquisitions are synchronized with heart activity, generally by triggering on R-waves of the Electrocardiogram (ECG). Double Inversion Recovery Fast Spin Echo (DIR-FSE) sequences, resulting in black-blood images, require furthermore specific timing. For such acquisitions, inversion time (TI) is needed to cancel blood signals (~500ms) [1], making acquisitions in the first 500ms of the cardiac cycle impossible. Black-blood imaging allows then only diastolic view of the heart. Moreover heart rate (HR) variability has been shown to be important during breath-holds [2] making cardiac synchronization even more complicated.
In this paper, a RR interval prediction method has been implemented, which permits to launch DIR pulses before R waves and thus enables black blood systolic imaging.

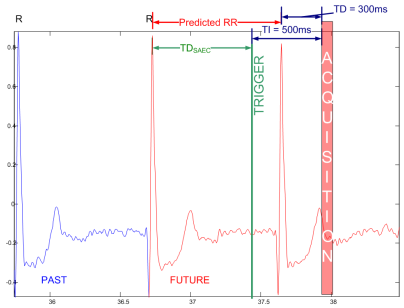

Fig 1: Flowchart of the prediction method and sequence triggering.

MATERIALS AND METHODS:

Five healthy volunteers underwent a cardiac examination on a 1.5T GE Signa Excite HDx MR scanner (GE Healthcare, Milwaukee, WI). DIR FSE images were acquired at end-expiratory breath-hold. (TE=30ms, TI=500ms matrix size 256x256, ETL=16, 20s). ECG and respiratory signals were carried by a custom Maglife (Schiller Médical, Wissembourg, France) patient monitoring system and recorded on the Signal Analyzer and Event Controller (SAEC) homemade dedicated hardware [3].
RR interval was assumed to be a linear combination of the previous RR interval, the respiration and its first derivative [2].
Let $\boldsymbol{RR_n}$ be the length of the nth RR interval, $\boldsymbol{B_n}$ the respiration signal sampled at QRS times, and $\boldsymbol{dB_n}$ the derivative of the respiration sampled at QRS times as well, the model can then be written as:

$$R\hat{R}_n = \sum_{i=1}^{2} a_i RR_{n-i} + \sum_{i=1}^{2} b_i B_{n-i} + \sum_{i=1}^{2} c_i dB_{n-i} \quad \textbf{(1)}.$$

The HR model parameters $\boldsymbol{a_i}$, $\boldsymbol{b_i}$ and $\boldsymbol{c_i}$ were adaptively estimated using Kalman filtering [4], which is commonly used in signal processing for a wide range of application fields. It is based on a set of two equations, the first representing a measurement model for the observed data and the second the evolution model of the process:

$$\begin{cases} y_n = H_n \underline{x}_n + \varepsilon_n \\ \underline{x}_n = G_n \underline{x}_{n-1} + \underline{u}_n \end{cases} \quad \textbf{(2)},$$

where the observation $\boldsymbol{y_n}$ was $\boldsymbol{RR_n}$, the state vector $\boldsymbol{\underline{x}_n}$ the HR model parameters $\boldsymbol{(a_i\ b_i\ c_i)}$, $\boldsymbol{H_n}$ = [$\boldsymbol{RR_{n-1}, RR_{n-2}, B_{n-1}, B_{n-2}, dB_{n-1}, dB_{n-2}}$] and $\boldsymbol{G_n}$ = ***Identity***. We assumed the dynamic and measurement noises (resp. $\boldsymbol{\varepsilon_n}$ and $\boldsymbol{\underline{u}_n}$) were both Gaussian distributed with zero mean and constant covariance.
This Kalman filter modeling enabled to adaptively predict the upcoming RR interval length, and was implemented into the SAEC such that real time MR sequence control was made possible. Once a QRS was detected, estimation of the coming RR was computed. After a Time Delay ($\boldsymbol{TD_{SAEC}}$) DIR pulses were launched so that acquisitions were performed at the desired cardiac phase. $\boldsymbol{TD_{SAEC}}$ was computed with the following equation:

$$TD_{SAEC} = R\hat{R}_n + TD - TI \quad \textbf{(3)},$$

where Trigger Delay (***TD***) was fixed at 300ms and ***TI*** at 500ms.
For systolic imaging, ***TD*** was set at a defined value (300ms) since systole duration has a much lower variation than heart rate. SAEC and MR sequencer were connected by TTL.
The flowchart of the method is illustrated on fig 1.

RESULTS:

If HR were assumed to be constant, no prediction would be needed. $\boldsymbol{TD_{SAEC}}$ could also be computed by simply applying equation 3 and replacing the predicted RR by a constant value, for example the average HR computed during preparation scan. Let call Constant RR this method and compare it with the presented one.
The prediction accuracy has been assessed by computing the mean error of the estimation (*Bias*) and its standard deviation (*Std*), comparison of the results are assembled in table1. The presented method seems to be very efficient for both bias (~5.7ms) and standard deviation (~29.1ms), which outperforms the method based on a constant HR assumption. Moreover the method accuracy is such that systolic black blood acquisitions are possible and exploitable (fig. 2).

	Presented Method		Constant RR	
	Bias (ms)	*Std* (ms)	*Bias* (ms)	*Std* (ms)
Subject 1	3.11	19.33	-234.67	24.73
Subject 2	5.36	38.34	49.57	46.9
Subject 3	4.47	41.36	178.47	92.72
Subject 4	7.75	16.65	-66.42	76.96
Subject 5	7.75	29.73	-31.78	41.64

Table 1: Results comparison.

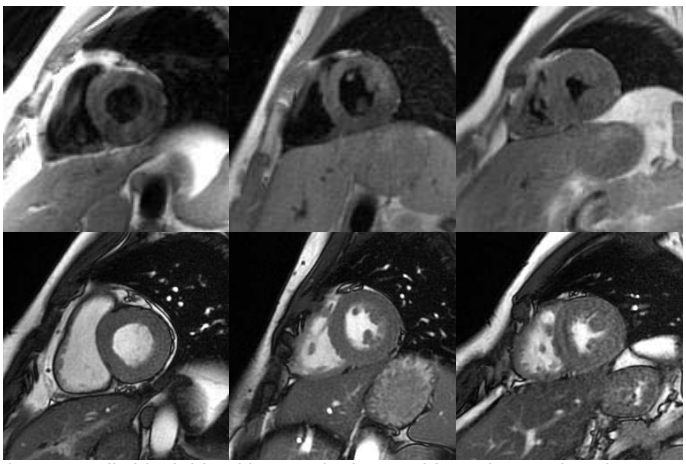

Fig 2: Systolic black-blood images in three subjects (top row) and comparison with CINE acquisitions (bottom row).

DISCUSSION:

This study shows how a simple HR modeling combined with common signal processing can provide an interesting real-time tool that enables black-blood systolic images during breath-hold. However the method is not only applicable for systolic DIR FSE sequences, but could be extended to all kind of cardiac images where acquisitions should occur at the exact same cardiac phase and also extended to free-breathing acquisitions.

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