REAL-TIME NAVIGATOR PROCESSING USING KALMAN FILTERING

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INTRODUCTION

In recent years, free breathing self-gated CINE acquisitions that correct motion artifacts by detecting motion from the data itself, have mostly used retrospective gating [1-4]. Unwanted noise and cardiac motion induced disturbance are filtered out using low pass filters. Retrospective gating is simple to implement but may not eliminate motion completely at the k-space center. Prospective or real-time data acquisition gating, on the other hand, can ensure that all data is acquired within a narrow gating window [5], offering higher effectiveness of motion suppression and efficiency. The response delay of a low pass filter makes it unsuitable for real time filtering. The purpose of this work was to develop a real time filtering algorithm based on the well-known Kalman filter [6], which adaptively estimates motion and suppresses measurement noise using Bayesian statistics and a motion model. Its ability to reduce noise and separate cardiac and respiratory components is studied using simulated data, in-vivo data and in a free-breathing prospectively self-gated CINE SSFP acquisition of the heart.

THEORY

The robust and effective Kalman filter is widely used in aerospace engineering, navigation, robotics, and optimal control theory. It requires a measurement model for the observed data and an evolution model for the underlying process using state vectors. At each time step, the state vector undergoes an evolution described by a transition matrix. The noise in the measurement and evolution models are assumed to be additive Gaussian with known covariance matrices. For each point in time, the Kalman filtering step consists of a prediction (using the evolution model) and a correction (using the measurement model) of the underlying state, that is in essence a Bayesian optimal estimation problem. For cardiac imaging, we propose to use the double periodic motion (DPM) model with frequencies ω_f ("fast" or heart rate) and ω_s ("slow" or respiratory rate). The transition matrix for each independent periodic component [x, v] (position and speed) is [[1, Δt], [$-\omega^2\Delta t$, 1]]. For the filter output, only the low frequency component from the state vector was retained.

MATERIALS AND METHODS

Simulations A ten second numerical waveform (sampling rate 200Hz) was generated as a superposition of a 1.2 Hz sinusoid with amplitude of 0.2 and a 0.2 Hz sinusoid with amplitude of 1.0 – simulating a heart rate of 72 beats per minutes and respiratory rate of 12 breaths per minute. To study the robustness of Kalman filtering against changes of the underlying waveform, five additional waveforms were constructed where the low frequency component was altered (different shape, a sudden jump in frequency/amplitude and a gradual change in frequency/amplitude). To each waveform, Gaussian noise ($\sigma = 0.1$) was added. Performance of the Kalman filter was measured using the root mean square difference (RMSE) with the original 0.2 Hz sinusoid. The "fast" and "slow" frequencies used for the DPM model were 1.2 Hz and 0.2 Hz in all cases.

Experiments Center-of-k-space signal (DC) was continuously acquired at the end of every TR [4,7], in an ungated free breathing cardiac short axis SSFP acquisition in five healthy volunteers. For Kalman filtering, the model frequencies at each time step were adjusted to the instantaneous heart and respiratory as monitored by the scanner during the acquisition. Performance of the Kalman filter was measured against low pass filtering by calculated the RMSE. In a second experiment, an initial implementation of a prospectively selfgated free-breathing SSFP CINE sequence was performed on two healthy volunteers. Two additional calibration scans were obtained before imaging to determine the optimal coil and scaling factor for the self-gating signal and the optimal Kalman filter parameters. Data acquisition of each cardiac phase (segment) was gated independently using the apparent displacement measured by the center-of-k-space signal by the PAWS gating algorithm [8] that was modified to satisfy the smooth view order constraints necessary for SSFP imaging.

RESULTS

Fig 1a compares the Kalman filter output (red) with the low pass filter output (orange) on a simulated double periodic noisy input (green). The response of the low pass filter was markedly delayed (group delay here was 2s) versus virtually no delay for the Kalman filter. RMSEs were 0.035 versus 0.034 (after correcting for the delay), respectively. Fig1b demonstrates the robustness of the Kalman filter in removing both noise and the high frequency component when the underlying waveform deviates from the model. Here the low frequency component jumped to 0.3Hz (while the model still assumed 0.2Hz) Fig 2 shows the Kalman filtered output (red) from center-of-k-space data (green) from a cardiac short axis scan. The output correlated very strongly with the simultaneously acquired diaphragm navigator displacements (r^2=0.96, blue, bottom of the graph). The high frequency output compared well with the recorded ECG triggers (top). Fig 3 demonstrates effective motion artifact suppression of the self-gated CINE SSFP sequence, using Kalman filtering.

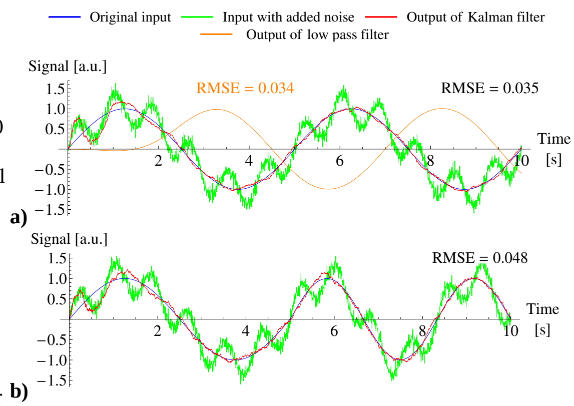

Fig. 1 Kalman filtering on numerical simulation of double periodic motion waveforms a) 0.2Hz and 1.2Hz waveforms b) sudden jump in low frequency component 0.2Hz→0.3Hz

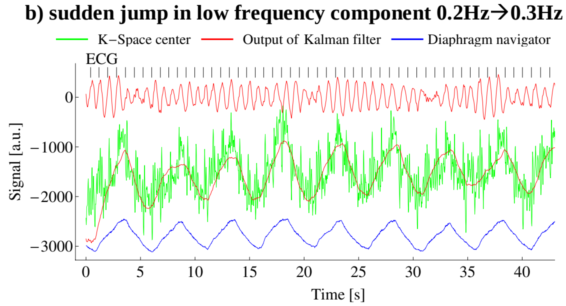

Fig. 2 Kalman filtering on center-of-k-space data from a continuous cardiac short axis scan. Diaphragm displacement (bottom) and ECG triggers (top) are shown for comparison.

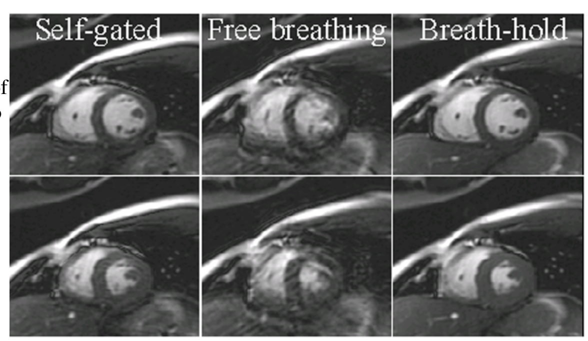

Fig. 3 CINE SSFP images obtained with prospectively self-gating, free breathing without gating, and breath-hold.

DISCUSSION

These preliminary results demonstrate the feasibility of Kalman filtering to remove noise and to separate respiratory and cardiac components from the MRI data in real-time for prospective gating of the data acquisition to suppress motion artifacts. A double periodic motion Kalman filter was able to distinguish between the cardiac and the respiratory component in center-of-k-space data obtained from a continuous SSFP short axis heart scan. Kalman filter is an adaptive recursive filtering algorithm for estimating the true state of the system immediately from noisy measurement. This adaptive filtering without delay makes it very suitable for real-time MRI applications such as prospective respiratory gating. A preliminary implementation of a prospectively self-gated CINE SSFP sequence demonstrated the feasibility of this real-time data filtering in healthy volunteers for reliable self-gating and motion artifact suppression.

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