Denoising of highly accelerated real-time cardiac MR images using extended non-local means

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Introduction:

Real-time cardiac MRI may be a powerful technique to assess myocardial function, especially to overcome gating difficulties in patients with arrhythmias, dyspnea or in pediatrics [1]. However, despite improvements in technology and sequences, standard real-time MRI often suffers from compromised spatiotemporal resolution. To achieve high temporal resolution (e.g. compatible with pharmacological stress studies) with a sufficient spatial resolution, highly accelerated TSENSE [2] acquisitions are used. To overcome the signal-to-noise ratio (SNR) limitations of these high acceleration factors, a new method for real-time denoising based on the non-local means algorithm is presented.

Methods:

5 healthy volunteers and 5 patients with coronary artery disease were imaged on a Siemens Trio 3T system using a 6-elements cardiac array coil combined with a 6-element spine coil. 6 short axis view along the heart and 2 long axis views were acquired in every subject with typical imaging parameters: balanced SSFP with TSENSE acceleration factor of 5, 2.2x2.2x8 mm^3 spatial resolution, flip angle 44°, TE/TR 0.9/26 ms, pixel bandwidth 1955 Hz, time resolution (without interpolation) 26 ms. As a gold standard, ECG-gated cine acquisitions were acquired in every subject with typical parameters: balanced SSFP, 1.3x1.3x8 mm^3 spatial resolution, flip angle 50°, TE/TR 1.5/37 ms, pixel bandwidth 930 Hz.

The proposed denoising method is a two-steps process. First, a spline based multi-resolution rigid registration [3] with least square optimization is performed. Then registered images were filtered to enhance SNR. We propose an extension of the NL-means method [4] that uses redundancy between successive frames. This extended non-local means filter (ENL-means) is defined as follow:

$$ENL(s_n)(x_i) = \begin{cases} \sum_{x_j \in V_i} w(x_i, x_j) s_0(x_j) & if \quad n \leq 0 \\ \sum_{k=1}^{T} \sum_{x_j \in V_i} w(x_i, x_j) ENL(s_{n-k})(x_j) & if \quad n > 0 \end{cases}$$

with V_i, the local neighborhood of pixel x_i; s_n, the n^{th} frame of an image sequence; T the number of preceding frames used in the search space; The weight $w(x_i, x_j)$ is defined as in the non-local means optimization (NL-means) of Coupé *et al.*[5].

The denoising method was quantitatively evaluated using a total of 30 sequences (3 short axis slices (base, mid and apex) in every subject). We measure mean point-to-set distances, SNR and relative edge strength for all sequences before and after processing. To quantify the diagnostic usefulness of the technique we compared the inter observer variability in defining end diastolic and end-systolic endocardial ventricular surfaces, before and after processing. The evaluation of the method was performed on a commercial Linux platform with 3.2GHz Intel Pentium IV and 2GB memory. Finally, a blinded analysis was performed by an expert using all acquired images to evaluate the qualitative impact of denoising on the diagnostic of possible contraction deficit.

Results and discussion:

Typical real-time images are shown in figure 1. A comparison study of real-time imaging at 1.5T and 3T (data not shown), shows improved image quality at 3T despite SAR limitations which impose a lower flip angle.

The registration algorithm was very efficient: measured mean point-to-set distances ranges from 0.7 to 1.7 mm after registration (compared to a pixel spacing of 2.2 mm), when it was 3.64±2.17mm before registration.

	Original	ENL-Means	NL-means [5]	Simple averaging filter
Relative edge strength	100%	100±11%	97±9%	63±15%
SNR	13±4.2	22.6±10.6	19.2±8.5	19.2±8.5
Total processing time per frame (registration+denoising)		25 ms	65 ms	

Table 1. Quantitative evaluation of the denoising algorithm

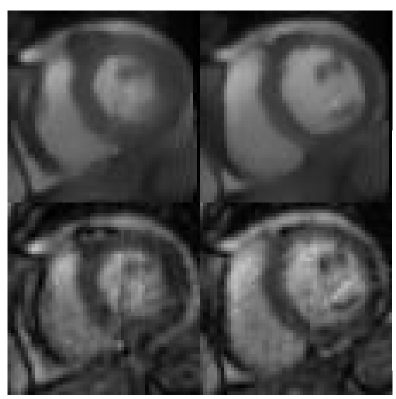

Figure 1.
Real-time images in a patient at end systole (left) and end diastole (right). Processed images (top) are compared with original ones (bottom).

ENL-means improves the denoising performances when compared with standard methods (table 1). In the real time context, ENL-means exhibits short processing times compatible with inline processing of highly accelarated real-time images. We could even improve computational efficiency of ENL-means in future work, as the weight calculation is parallelizable.

The inter observer variability on ventricular surfaces evaluation decreases from 22% before denoising to 11.3% after. No diagnostic discrepancies were found between denoised real-time images and standard cine acquisition, whereas 2 contraction deficits were missed with unprocessed real-time images.

Conclusion:

A method extending non-local means filter has been proposed to process in line real-time cardiac images. The performance of this technique allows more drastic acceleration strategy up to temporal resolution of 26 ms. Our results support that the combination of highly accelerated TSENSE MR acquisitions and ENL-means denoising allows clinical use of real-time cardiac imaging, including stress studies.

References: [1] Nayak, KS *et al.* Cur Cardiol Rep (2005) 7: 45-51; [2] Kellman, P *et al.* MRM (2001) 45(5): 846-852; [3] Thévenaz, P *et al.* IEEE Trans. Imag. Process (1998) 7(1): 27-41; [4] Buades, A *et al.* Multiscale Modeling and Simulation (2005) 4(2), 490-530; [5] Coupé, P *et al.* IEEE Trans Med Imag (2008) 27(4): 425-441.