Noise Reduction in Real-Time Phase Velocity Images via the Karhunen-Loeve Transform

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Introduction: Clinical applications such as exercise stress cardiac MRI require the use of accelerated scan techniques to minimize acquisition time while maintaining image quality. In this context, maintaining sufficient signal-to-noise ratio (SNR) is crucial in order to preserve clinically relevant information. While the combination of echo planar readout and parallel reconstruction successfully reduces acquisition time and enables real-time phase-velocity imaging, these techniques increase image noise, potentially reducing their usefulness. Temporal averaging can only be practically applied with ECG synchronization and respiratory suspension or respiratory-gating, but these are often not possible in real-time stress imaging applications. Spatial averaging is another common noise reduction strategy, but can significantly affect image resolution and smooth out relevant image features. Therefore, we investigated the use of an automated post-processing technique for reduction of noise that does not adversely affect relevant information, such as peak velocity, in real-time phase velocity imaging.

The Karhunev-Loeve Transform (KLT) (1) is an adaptive unitary linear transform that applied retrospectively to an image sequence results in a set of eigenimages with the signal energy concentrated within a discrete subset of eigenimages and the remaining eigenimages consisting only of noise. Such a transform is optimal in the least-squares sense and exploits data redundancy found in cardiac cine and velocity images. Filtering of real-time cine images may be carried out by zero-filling noise-only eigenimages in the KLT domain and inverting the transform. Determination of noise-only eigenimages is carried out by performing a search over subsets of eigenvalues in the KLT domain. For frames containing purely independent and identically distributed noise, the corresponding eigenvalues in the KLT domain fit the Marcenko-Pastur distribution (2), and examination of the statistical goodness-of-fit between eigenvalue subsets from the data matrix and the theoretical distribution allow the determination of the largest subset containing noise-only eigenimages. KLT filtering by zero-filling this subset results in an SNR gain determined by the cutoff level of the number of eigenimages identified as containing only noise.

KLT filtering may be regarded as a form of smart adaptive weighted averaging that may be applied automatically to real-time velocity images. The automated application of KLT filtering bears advantages over temporal averaging, which without breath-hold and ECG-synchronization requires registration post-acquisition to produce meaningful results. Additionally, KLT filtering provides advantages over spatial averaging which, while robust to varied levels of noise, tends to significantly affect clinically relevant features.

We apply KLT filtering to real-time phase velocity images in the presence of added noise and demonstrate that the KLT filtering process achieves a significant SNR gain without affecting peak velocity measurements. We then compare our results with those obtained using spatial averaging.

Methods: Through-plane real-time aortic valve phase-contrast data was acquired at 3T (Siemens, Tim Trio) using EPI (TR=10ms, TE=2ms, Echo Train Length=11, Rate 4 Acceleration, Temporal Resolution 40ms, FOV=360, Matrix 92x128, VENC = 150 cm/s) from one healthy volunteer. Five cardiac cycles were acquired (95 frames). All post-processing was performed in the MATLAB environment (Version 7, Release 2010a). Magnitude and phase image data were combined to form complex data, and image noise level was estimated statistically by fitting to the Marcenko-Pastur distribution. Taking the original data as the base case, noise levels within the data were increased in a controlled manner by adding zero mean Gaussian noise to the real and imaginary components of the data. The resultant noisy data was filtered using KLT, and peak velocity measurements were compared with the original data without added noise. The noisy data was also filtered spatially using four- and eight-neighbor averaging, and effect on peak velocity was compared with the KLT-filtered results.

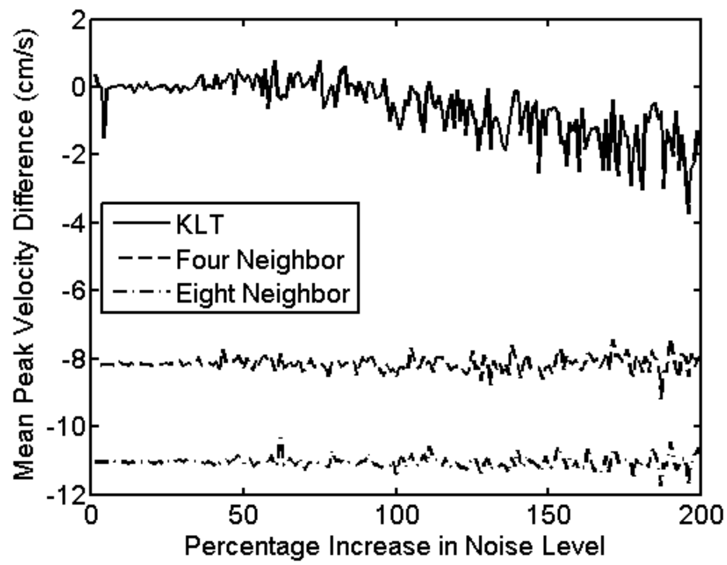

Figure 1: Mean difference in peak velocity averaged over five cardiac cycles for varying levels of noise.

Results: KLT filtering of all five cardiac cycles without additional noise results in an SNR gain of 64.1%. Figure 1 presents the differences in peak velocity measurement before and after filtering over the entire range of added noise levels. The peak velocities for all five cardiac cycles were averaged to obtain these results. Spatial averaging demonstrates a consistent, but significant effect on the peak velocity measurement across levels of added noise. The difference of approximately 8 cm/s in peak velocity induced by 4-pixel averaging would result in an error of 256 mmHg in pressure gradient estimated by the commonly used modified Bernoulli Equation. KLT filtering demonstrates a much less significant effect on peak velocity than spatial averaging, although the effect did increase with noise level.

Conclusions: Application of KLT filtering to real-time cine images for peak velocity measurement is an effective way of reducing noise while not affecting peak velocity measurements and provides the additional benefits of not requiring image registration or ECG-triggering.

References:

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