Characteristics and Performance of the Karhunen-Loeve Transform Filter in Dynamic Cardiac Magnetic Resonance Imaging

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Introduction: Real-time cine cardiac magnetic resonance imaging (RT-CMR) can achieve high temporal resolution with parallel acquisition techniques such as TSENSE, but at the expense of reduced and spatially dependent SNR [1]. Spatial or temporal low pass filtering can enhance image SNR but may blur sharp boundaries, smear fine structures, and generate artifacts. We propose a new temporal filter for dynamic MR images based on the Karhunen-Loeve Transform (KLT) to remove random noise without compromising either spatial or temporal resolution [2]. A set of p cardiac images are transformed to p eigenimages by KLT. The filtered p images are reconstructed by keeping only m eigenimages ($m < p$) corresponding to largest eigenvalues. In this work, we deduce a simple mathematical formula for the noise reduction effect of the KLT filter, and then verify it in RT-CMR TSENSE images acquired in normal volunteers. To select the optimal number of eigenimages in the KLT filter, a compromise between noise reduction and information content retention is necessary. A filter cutoff selection criterion based on the eigenimage autocorrelation function is proposed.

Theory: The KLT is a linear transform that maps high dimensional data into a lower dimensional representation space with respect to minimizing the mean square error. This is achieved by transforming the original data set into a set of orthogonal eigenmodes by a p x p unitary matrix $\boldsymbol{E}$ such that most of the variance of the original data is contained in the first a few eigenmodes [3]. KLT filtered images are reconstructed by applying the inverse transform to the first m eigenimages. The relative noise level (RNL) of the j^{th} filtered images, measured by the noise standard deviation (SD) ratio after and before KLT filtering, is $\sqrt{\sum_{i=1}^{m} v_{i,j}^2}$, a function of the first m elements of the j^{th} row of the matrix $\boldsymbol{E}$ [2]. We further simplify this complex relation by replacing each matrix element using its mean value $\sqrt{(1/p)}$. Thus, the mean RNL in the filtered images is:

$$\mathrm{RNL} = \sqrt{(m/p)} \qquad (1)$$

Methods: Dynamic RT-CMR images in 6 healthy human volunteers were acquired on a 1.5T clinical MRI system (Avanto, Siemens Medical Solutions Inc., Erlangen, Germany). The study was approved by our institution's Human Subjects Committee and all subjects gave written informed consent to participate. Untriggered, free-breathing, real-time cine series of 256 images each were acquired in short-axis, horizontal long-axis, and vertical long-axis views in each subject. A real-time steady-state free precession (SSFP) cine sequence combined with TSENSE acceleration factor 4 was used. The imaging parameters were: voxel size = 2.08 x 2.08 x 8 mm^3 (192 x 144 matrix), flip angle = 66 degrees, temporal resolution = 60.0 ms, TE = 1.04 ms, pixel bandwidth= 1185 Hz/pixel, scan time = 16 seconds. Each series of images was KLT filtered with eigenimage cutoff ratio ranging from 1/256 to 1, and the mean and SD of the RNL of all image series was plotted to investigate the correspondence of the RNL in *in vivo* images to that predicted by Eq. (1). The noise SD was measured in an air region.

In order to determine the optimal filter cutoff, three reviewers, each with over 7 years experience in CMR, were blinded to the filter cutoff and asked to select the image series that visually had the best SNR without apparent blurring or artifacts caused by filtering. The original and filtered image series with eight different eigenimage cutoffs: 1, 2, 4, 8, 16, 32, 64, and 128, were simultaneously presented in a 9-on-1 format with a random order. Equivalently, the optimal eigenimage cutoff should include all eigenimages containing structured information, eliminating only those eigenimages containing random noise. Shrager et. al. proposed that the FWHM of the autocorrelation function is a good metric to measure the structured pattern in the spectral analysis of chemicals [4]. We plotted the FWHM of the autocorrelation functions of all eigenimages, and determined the eigenimage cutoff from this same criterion.

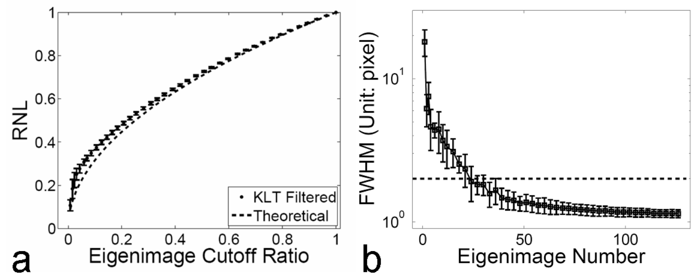

Figure 1 (a) Relative noise level decreases with eigenimage cutoff ratio. Error bars indicate the SD of the RNL across all the images. The dashed line is the theoretical prediction of RNL. (b) The mean FWHM of the first 128 eigenimages of all 18 real-time cardiac MRI cine image series. The error bars indicate the SD of the FWHM, and the dashed line indicates FWHM = 2.0.

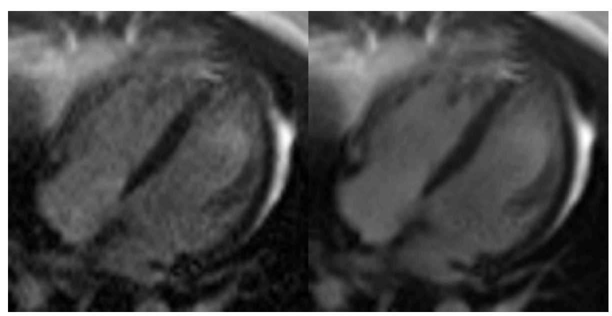

Figure 2 Left: the original unfiltered image; right: the KLT filtered image with eigenimage cutoff ratio = 0.137. Mean gain in SNR is 144% at this eignenimage cutoff selected by quantitative and qualitative evaluation.

Results: Figure 1a shows that the mean noise reduction achieved by KLT filtering was close to that predicted by Eq. (1). Figure 1b shows the FWHM of the autocorrelation function for all eigenimages. A dashed line indicates the FWHM = 2.0 pixels, which yielded an eigenimage cutoff of 35 ± 9, corresponding to a SNR gain of 144%. The mean ± SD optimal eigenimage cutoffs selected by the three reviewers were 32 ± 18, 23 ± 10, and 38 ± 16. Paired student t-test revealed that one reviewer selected a significantly lower cutoff (p-value = 0.001), i.e., more aggressive filtering, while the other reviewers' selections did not show statistically significant deviation (p-value = 0.54 and 0.50, respectively) from the autocorrelation method. Figure 2 shows one example image before and after KLT filtering at a cutoff of 35 eigenimages.

Discussion: We propose a new post-processing filter based on KLT that was shown to substantially increase SNR in dynamic real-time CMR images. Noise reduction in *in-vivo* images followed the theoretical prediction. We found that a subjectively chosen optimal eigenimage cutoff corresponded to eliminating eigenimages with an autocorrelation FWHM < 2.0 pixels. At this filter cutoff, a gain in SNR of 144% was achieved without apparent blurring or other image artifacts, indicating that KLT filtering of dynamic images may permit recovery of a significant amount of SNR lost by parallel acquisition acceleration methods.

References: [1] Pruessmann K, et.al. MRM 1999; 42(5):952-962. [2] Sychra JJ, et.al. Med Phys 1994; 21(2):193-201. [3] Jolliffe IT. Principal Component Analysis: Springer; 2002. [4] Shrager R, et. al. Anal Chem 1982;54:1147 -1152.