Spatially Adaptive Temporal Smoothing for Reconstruction of Dynamic PET and Gated SPECT Images

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Abstract

In this paper we propose a method for spatio-temporal reconstruction of dynamic or gated image sequences. In a previous method we proposed, temporal smoothing in a Karhunen-Loève (KL) transform domain was used prior to reconstruction to reduce the effect of noise. Unlike the Bayesian priors that are usually used in image reconstruction, temporal KL smoothing is a data-driven approach that takes advantage of the fact that the desired part of the observations is characterized by strong inter-frame correlations, whereas the noise is entirely uncorrelated.

In this paper we improve on our previous technique by making the temporal smoothing adapt spatially to local image characteristics. This substantially improves the noise performance of the temporal smoothing, while significantly lessening the possibility of signal distortion.

In the proposed method, spatial regions of the projection-data sequence having similar statistical characteristics are identified by an unsupervised *k*-means clustering algorithm. A different Karhunen-Loève (KL) transformation is designed for each image region, adapting the smoothing to the local temporal behavior. Finally, images are reconstructed from the smoothed projections by existing approaches.

Experimental computer simulation results are shown that demonstrate potential improvements in image quality obtained by this technique in dynamic and gated imaging applications in brain and heart.

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I. Introduction

In PET and SPECT, dynamic and gated imaging studies yield useful kinetic and/or motion information, but do so at the cost of lowering the number of counts per image. The noise in each frame of a sequence is, of course, much higher than in a static image acquired over the same time period, thus special image reconstruction and processing methods are called for. In this paper, we propose one such method. Specifically, we describe a spatially adaptive temporal smoothing method designed to alleviate the problem of noise in nuclear medicine image sequences. The temporal smoothing is achieved by separating the desired signal, characterized by strong between-frame correlations, from the noise, which is entirely uncorrelated.

Temporal smoothing of image sequences is an example of the more general problem of multichannel image processing (see, for example [1]). In the field of nuclear medicine, a temporal Wiener filter was proposed in [2]. Principal component analysis was used in [3] to smooth the PET data along their time axis. In [4,5] this idea was expanded to show that temporal noise smoothing was essential for spatial resolution recovery. Fully four-dimensional reconstruction methods have been proposed recently that have temporal smoothing built into the algorithm (for example, [6,7]). The methods in [4,5] are limited by their use of space-invariant statistical descriptions of the temporal correlations in the data. In [8] and [9] methods were proposed, using known tissue properties, in an effort to improve on the methods in [4,5]. In this work we propose an alternative, data-driven approach to overcoming the potential limitation of the methods in [4,5].

II. Methods

In previous work [4,5], we proposed the smoothing of noisy projection data along the time axis prior to reconstruction by using a low-order approximation based on the Karhunen-Loève transform. Specifically, a sequence of K time frames is smoothed by truncating the KL expansion of each time-activity curve $\mathbf{p}$ in the projections, to obtain a smooth version:

$$\hat{\mathbf{p}} = \sum_{i=1}^{K'} c_i \varphi_i \tag{1}$$

where φ_i are the eigenvectors of the temporal covariance matrix of the noise-free projection data (estimated from the observed data), and $K' < K$. In this approach, high-order terms (typically dominated by noise) are omitted from the expansion, resulting in significant noise reduction. This type of smoothing is very effective because it makes use of measured statistics of the desired signal.

The temporal covariance matrix from which the KL basis is computed quantifies the statistics of the desired signal. In our previous implementation, this covariance matrix was estimated from all the projection data collectively by assuming every time activity curve to be drawn from the same probability density function. In this paper, we refine this approach by identifying spatial regions sharing common temporal behavior, then estimating a separate covariance matrix for each region.

We use an unsupervised *k*-means clustering algorithm [10] to identify groups (clusters) of pixels having common temporal statistics. We then compute a different KL transformation matrix for each cluster. These transformations are then used to perform smoothing as described in (1) along each time activity curve in the projection data. Next, the images in the sequence are reconstructed separately by using the expectation maximization (EM) algorithm [11].

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III. RESULTS

Our method for spatial smoothing in the sinogram domain was tested for two possible applications: a kinetic study of the brain and a gated study of the heart.

In each case, the observed sinogram was simulated by degrading the source sinogram using a distance-independent Gaussian-shaped point spread function and Poisson noise. In temporal smoothing there were two KL components retained followed by EM reconstruction whit resolution recovery.

Three different reconstruction procedures were compared: EM reconstruction, (denoted as EM) sinogram presmoothing by method described in [4, 5] followed by EM reconstruction (denoted as KL); and the spatially adaptive temporal smoothing followed by EM reconstruction (denoted as KL/Clustering).

In the first study, the 4D gated mathematical cardiac-torso gMCAT D1.01 phantom [12] was chosen as a test object for our simulation. In our simulation, we used the upper part of the phantom, containing the heart, with a total of four million counts per frame. Sixteen frames were simulated to represent the gated SPECT study. For each reconstruction we used 150 iterations of the EM algorithm.

The time-activity curves (TACs) for a small region in the left ventricular wall are shown in Figure 1(a). Note the significant corruption of the TAC by noise in the EM reconstruction. Further, the KL smoothing approach as proposed in [5], introduces a significant distortion of the TAC estimate in the region labeled “A.” This distortion results from the use of space-invariant temporal statistics. The new spatially-adaptive approach produces excellent noise reduction without such a distortion. These conclusions are also supported by measurements of the mean square error in estimation of the TACs.

In the second study, a single slice of the Zubal brain phantom [13] was used to simulate a dynamic study of [^{11}C] carfetanil binding to μ-selective opiate receptors. A four-compartment and a three-compartment tracer kinetic model were used to produce TACs for various brain regions. The model used parameters derived from data in [14] and an input function obtained in an actual study. We simulated 23 image frames with a total of four million counts. The results, after 300 EM iterations, are shown for the thalamus (having a high receptor concentration) and occipital cortex (having a low concentration).

In Figure 1(b), the mean square error in estimation of the thalamus and occipital cortex TACs are shown. The occipital cortex is poorly represented by the space-invariant temporal smoothing proposed in [4], leading to a significant distortion of the TAC in the early part of the study (region B of the curve). The EM reconstruction is severely corrupted by noise. In both the thalamus and occipital cortex, the proposed spatially adaptive temporal smoothing produces much better results. By the time of the conference we expect to have conducted more sophisticated evaluation.

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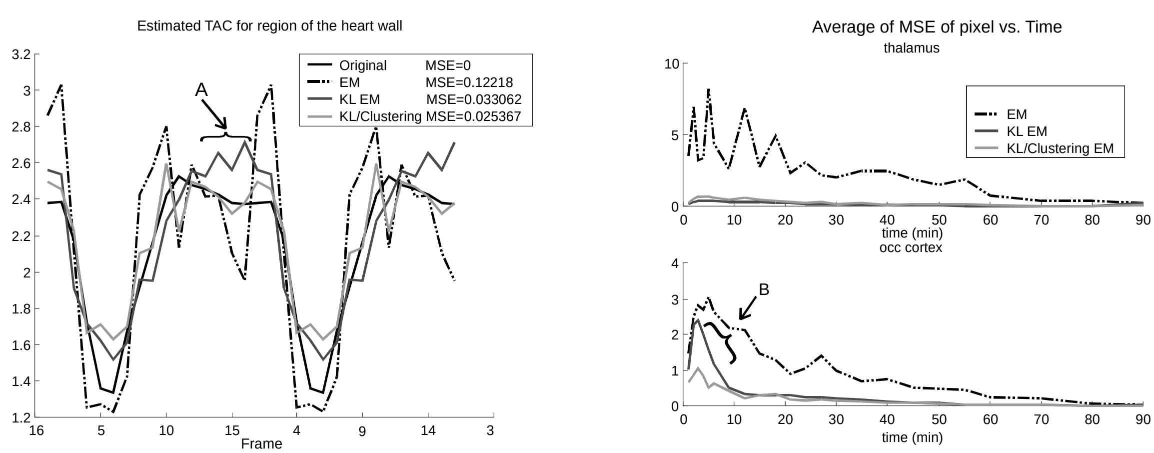

(a) (b)

Figure 1: (a) Time activity curve (TAC) for small region in the left ventricular wall, and (b) the mean square error (MSE) of pixels in thalamus and occipital cortex vs. time.