Quantitative Angiography Using Mean Field Annealing

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Abstract

The vessels in the cineangiogram are degraded by non-uniform point spread function (PSF) and non-stationary noise from the imaging system. In this paper, we present a new method for vessel size measurement which does deblurring, edge-preserving smoothing and edge enhancement in one process.

The presented method is an extended version of an adaptive edge-preserving smoothing technique, Adaptive Mean Field Annealing(AMFA), to the blur problem. AMFA with deblurring technique is an iterative image restoration technique for the restoration of noisy blurred images. With the progress of annealing, the restored image evolves from the maximum likelihood (ML) solution to annealed maximum a posteriori (MAP) solution and the restored edges are enhanced.

This method performs well in images with PSF of large region of support and low signal-to-noise ratio (SNR). The efficacy of the proposed method is demonstrated with the results of the synthetic images, phantom images and real cineangiographic images.

1. Introduction

Accurate and reliable measurement of luminal dimensions from angiography is important for assessment and treatment of coronary stenotic lesions. Vessel boundary detection or edge detection is essential in the measurement of vessel diameters. However, the vessel images in the cineangiogram are degraded by non-uniform blur and non-stationary noise [1]. The blur in coronary angiogram is mainly due to the finite dimension of X-ray focal spot size, light diffusion in the image intensifier and others. Noise in the angiogram includes quantum noise, electronic noise and digitization error. The blur and noise in the angiogram are usually non-homogeneous.

Thus, for accurate measurement of vessel size, especially the vessels in the stenotic lesions, we need *deblurring* without distorting the vessel shape or dimension, non-stationary noise smoothing without losing spatial resolution and detection of vessel boundaries. If these operations can be done in two dimensional processing, we can eliminate the preprocessing procedures which may cause distortion or inaccuracy in the measurement.

Various kind of techniques are developed to solve this problem, however, there are some shortcomings in those techniques. When the blurring effect is not considered in the vessel size estimation with various kinds of boundary detection techniques [2], the results may be an overestimation of the vessel size. Conventional gradient type edge detectors usually overestimate the small vessel diameters because of blur [3]. Thus, we need deblurring.

With filtering techniques such as adaptive Wiener filtering, which is for deblurring and smoothing, the deblurring effect is limited when there is significant amount of noise in the image, because there is trade-off between deblurring and noise smoothing [4]. Also, once smoothing is performed in the Fourier domain, usually the edge locations are not preserved since smoothing with filtering techniques becomes an additional source of blurring. Furthermore, thus, filtering technique is inadequate for the spatially variant blur problem.

There are some techniques which do profile fitting (1-D) [5] or model fitting (2-D) [6] using iterative deconvolution. These techniques are heavily dependent on the assumptions that the vessel has elliptical 1-D cross-sections and the background image can be modeled by 2-D low-order polynomial. These techniques may not work well in general, especially when there is a bifurcation or an occlusion of vessels.

Hence, we propose a new method which does deblurring, noise smoothing, edge detection and edge enhancement in a single process without any specific assumptions on the geometry of vessel or background images. The proposed method is an extention of the Adaptive Mean Field Annealing technique to the blur problem.

2. Adaptive Mean Field Annealing with deblurring

Annealing refers to the process of heating carbon steel to very high temperature and allowing it cool down slowly to room temperature. By doing so, the steel will possess the lowest level of internal energy. This concept of annealing is used in an iterative image optimization in the form

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of minimization of an energy or cost function of an image in the mean field while decreasing the temperature. This so-called Mean Field Annealing (MFA) image restoration technique, does edge-preserving smoothing based on maximum *a posteriori* (MAP) estimation of an image [7].

The Adaptive Mean Field Annealing (AMFA) [8] is an adaptive version of MFA, which does signal-dependent/non-stationary noise smoothing while adaptively preserving the edge locations by taking advantage of the local nature of the Markov random field and the fact that non-stationary or signal-dependent noise can be approximated by locally stationary additive Gaussian noise. In AMFA, the *a priori* information about the noise is not necessary. During annealing, and the restored edges are enhanced. AMFA technique can be viewed as an adaptively annealed MAP restoration technique.

This technique can be extended to solve the problems of blur and noise in the quantitative angiography. When an image is degraded by non-uniform blur and signal-dependent or non-stationary noise, the image can be modelled as

$$g_i = (h_i \otimes f)_i \oplus n_i \qquad (1)$$

where g: observed image
f: unknown true image
n: noise process
i: pixel index
h: space-variant point spread function (PSF)
$\otimes$: convolution
$\oplus$: noise operation

We maximize the posterior probability of an estimation f given observed image g and PSF h. Then, by the Bayes' rule,

$$p(f|g,h) = \frac{p(g|f,h)\,p(f)}{p(g)} \qquad (2)$$

Equation 2 includes the prior probability $p(f)$ which represents our prior information about the true image in the MAP restoration problem. In this paper, we adopt the locally uniform or locally smooth prior model. Also, we assume the PSF is uniform over all the image.

Most of the signal-dependent noise can be decomposed into signal and equivalent additive noise. The equivalent additive noise can be approximated by locally additive Gaussian noise provided that the equivalent additive noise is locally zero-mean [8].

Since the equation 2 is known to possess many local maxima, in order to find global maxima we apply mean field theory [7]. Then, the resulting energy function to be minimized while decreasing the system temperature becomes

$$H = \sum_i \left(\frac{((h \otimes f)_i - g_i)^2}{2\sigma_i^2} - \frac{p}{T_i} \sum_{j \in \aleph_i} exp\left(-\frac{(f_i - f_j)^2}{2T_i^2} \right) \right) \qquad (3)$$

where j: pixel index
$\aleph_i$: neighbor pixel set of pixel i
p: prior factor
σ_i: local variance of the image (3x3 window)
T_i: local temperature - local soft threshold to determine the existence of the edge

The energy function is composed of two terms: the noise or negative likelihood term and the prior or edge-preserving smoothing term. The likelihood term, the first term in the right hand side of equation 3, tends to keep the blurred image of the estimation f similar to the observed image during annealing (annealing denotes minimization and decreasing temperature). The smoothing term does edge-preserving smoothing.

When temperature T_i is very high, we can ignore the prior term, and, thus, the minimization of equation 3 becomes maximum likelihood (ML) restoration. The result corresponds to that of inverse filtering. When the temperature decrease, the prior term becomes important, and, thus, the edges are detected and smoothing occurs.

Hence, the annealing algorithm can be divided into two steps:

ML step: 1. initialize f = constant, set σ_i = constant (T_i = infinity)
2. Minimize $H(f)$
MAP step: 1. initialize $f = f_{ML}$, calculate σ_i from f_{ML}, set $T_i = \sigma_i$
2. Minimize $H(f)$
3. Reduce T_i
4. If $T_i \approx 0$ stop, else go to step 2

The resultant image from the ML step is deblurred but noisy. This noise is smoothed end edges are detected and enhanced during annealing in the MAP step.

3. Results

Figure 1 shows results of the synthetic vessel image which has stenotic area. The largest diameter of the vessel is 35 pixel width and smallest diameter is 20 pixel width. This synthetic vessel image is blurred by a uniform PSF (shown in the middle of Figure 1), which is the convolution result of uniform PSF (diameter 20 pixel width) and Gaussian PSF (σ=3). Gaussian noise was added to the blurred image. The resulting noisy blurred image is shown in top right of Figure 1. The image shown in lower left of Figure 1 is the resulting image from ML step, where we can see the vessel is deblurred but noisy and observe Gibbs artifacts around the vessel. Lower right image shows the annealed map result from MAP step. We can see that the vessel is deblurred, the noise is smoothed, Gibbs artifacts are removed and the edges are enhanced. Since we use the locally uniform prior model, it is inevitable to have multiple edges. However, this can be controlled by allowing quick temperature decreasing at the expense of sharpness of restored edge or can be cured by using locally linear prior model.

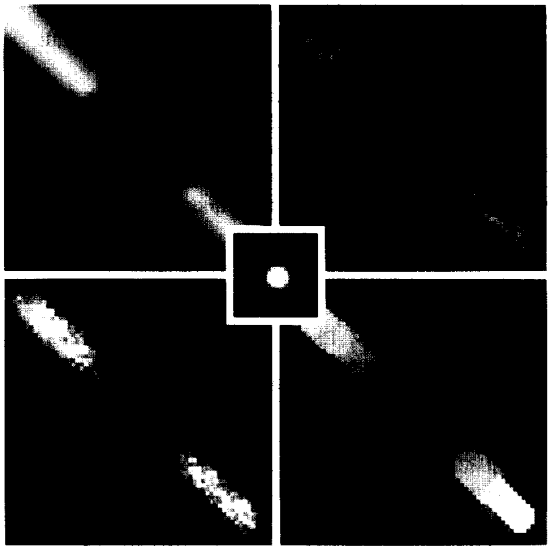

Figure 1. Results of synthetic vessel image

FIgure 2 shows the profiles taken from the center of vessel images shown in Figure 1.

Figure 3 shows the result of real phantom image whose diameter is 0.73 mm (13.7 pixel width). The PSF was estimated from the step wedge in the phantom. The diameter found from the annealed MAP result was 14 pixel width on average.

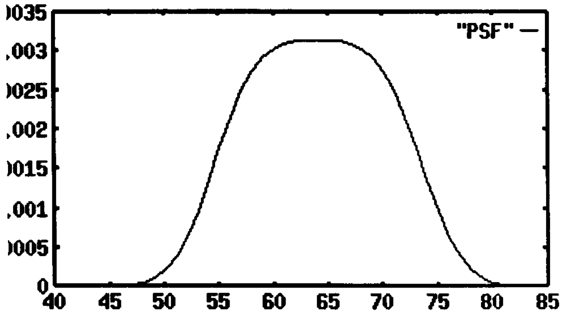

Figure 2. The profiles of the results of the synthetic vessel image

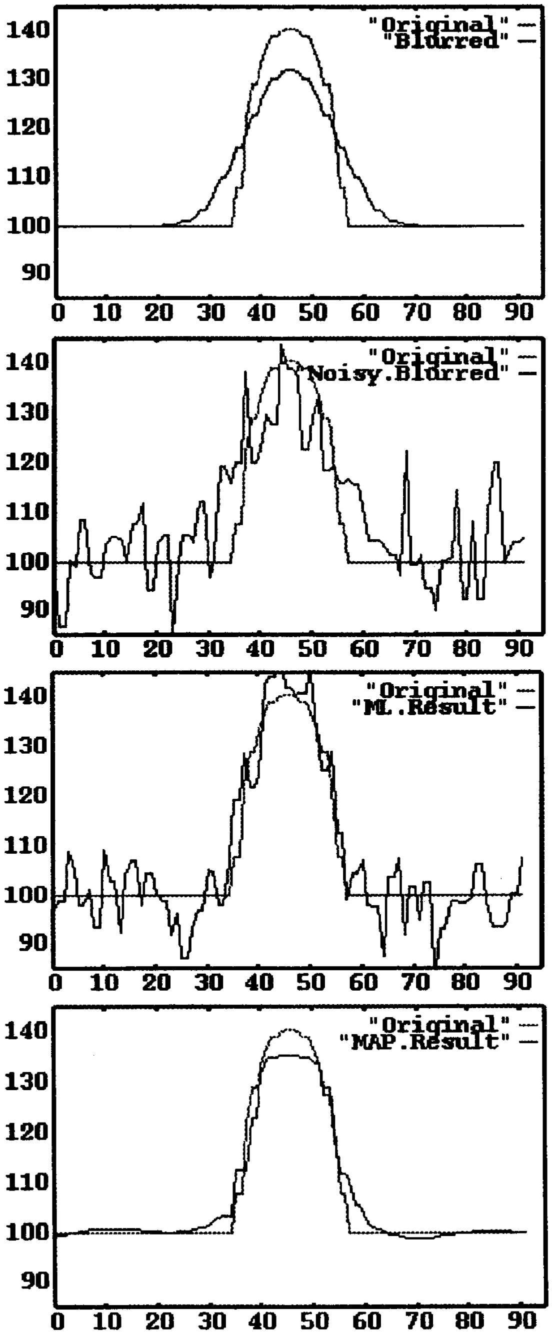

Figure 2. (continued)The profiles of the results of the synthetic vessel image

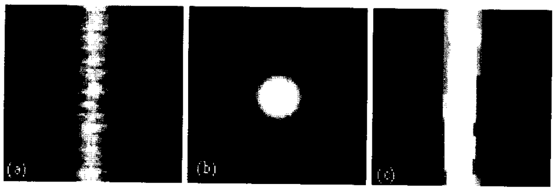

Figure 3. Result of phantom image

Figure 4 shows the results of the real cineangiogram which shows stenotic lesions. The PSF used in this restoration is shown in the top right, bottom left shows the AMFA result without deblurring, and bottom right shows the AMFA result with deblurring.

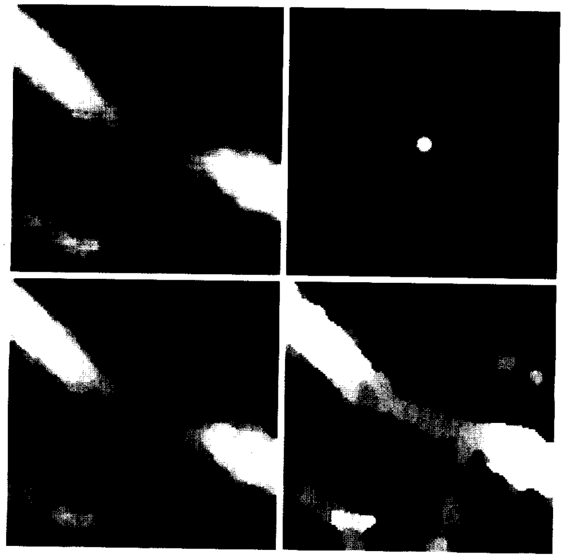

Figure 4. Results of real cineangiogram: (bottom left) result of AMFA without deblurring, (bottom right) result of AMFA with deblurring

4. Further work

Since the proposed method can deal with spatially variant PSFs, it is necessary to estimate the spatial variation in the point spread function of the imaging system experimentally and theoretically. Currently the proposed method adopts the locally uniform prior model. If we use locally linear prior model, where the intensity is changing locally linearly, better results may be expected. However, there may be some limitations in the use of linear prior model, such as the noise sensitivity of second derivative and difficulty in suppressing the Gibbs artifacts.

5. Conclusion

By using the proposed method, deblurring, smoothing, and edge detection enhancement can be performed in one process and there is no need of complex preprocessing, such as artery straightening procedure, which may result in the distortion of vessel geometry.

The proposed method does not employ the assumption about the vessel cross-section shape and background correction is not necessary.The proposed method is expected to work well with large size of blur kernel under the low SNR.This method may be useful for quantitative angiography.

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