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A novel noise removal using homomorphic normalization for multi-echo knee MRI

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Abstract: This paper presents a novel approach for removing noise from multi-echo knee magnetic resonance images using global intensity normalization and the averaging operation along the echo-time. Firstly, the global mean and standard deviation at the zero echo-time are estimated by applying the mono-exponential spin echo model to the means and standard deviations of multi-echo images. Secondly, the signal and noise levels at multi-echo images are normalized to the estimated mean and standard deviation at the zero echo-time. Then, the normalized multi-echo images are averaged along the echo-time into a noise-removed zero echo-time image. Finally, the multi-echo MR images are reconstructed from the noise-removed zero echo-time image by the inverse normalization. The experiments demonstrate that the proposed method effectively removes not only the noises of each multi-echo image but also noises of the Quantitative T2 image.

Keywords: flow-artifact, multi-echo, denoising, global enhancement, knee MRI

Classification: Science and engineering for electronics

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1 Introduction

Despite of high cost, the usage of MRI (Magnetic Resonance Image) systems has been increasing gradually in medical imaging services because they can characterize and discriminate among human body's tissues using their physical and biochemical properties. MRI systems produce high resolution and high contrast images and have no radiation exposures which are from CT (Computed Tomography). The joint MR imaging with multi-echo pulse sequence has been introduced to access biochemical changes in cartilage degeneration and osteoarthritis [1, 2, 3]. However, multi-echo MR images needs longer acquisition time compared to CT and exhibits flow-artifacts near the joint regions and motion-artifacts in the digestive systems of the human body.

A lot of research works have been made for removing the noise in the knee MR image acquisition stage. However, the real MR images still possess certain types of noise such as Gaussian noise from devices and flow-artifact noise due to strong blood stream in the artery near the joint region. The blood flow occasionally produces intravascular high signal intensities due to flow related enhancement, even echo rephrasing and diastolic pseudogating. The pulsatile laminar flow within vessels often produces a complex multilayered band that usually propagates outside the vessel in the phase encoded direction. Blood flow artifacts should be considered as a special subgroup of motion artifacts.

Recently, most of the studies have focused on removing the random noise only. In most cases, the low-pass filtering such as Gaussian is utilized to remove the random noise, with the cost of blurring edges due to the smoothing operation [4]. Garnier [5] has proposed a denoising method for noisy MR images caused by short TR (Time of Repetition). When the MR im-

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age is acquired with long TR, the SNR (Signal to Noise Ratio) of the image is enhanced. Therefore, there exists a trade-off between TR and SNR. Manjón [6] has presented a denoising method in simulated MR images such as T1 weighted, T2 weighted, proton density, etc. This method proposed an approach to find optimal parameters in the Non-local mean (NLM) filter which is based on a single image. Hence, NLM filter is not comparable with the proposed noise removal method for multi-echo images. Bydder [7] proposed an SVD (Singular Value Decomposition) filter for removing the random noise from the multi-echo MR images. Even though this SVD approach is able to remove the noise effectively, it focuses only on the random noise and it cannot remove the noise in the quantitative T2 image because it cannot change the echo pattern of the signal to the mono-exponentially decaying model. Furthermore, none of the conventional approaches has been able to remove the flow-artifacts in knee MR images.

This paper proposes a denoising filtering process to remove both random noise and flow-artifacts simultaneously. In this paper, the proposed method called HNF (Homomorpic Normalization Filter) utilizes the global information of the multi-echo MR images. After the global intensity normalization, the multi-echo MR images are retrieved by an inverse transformation so that it retains fidelity to the signal, preserves step edges, and suppresses general and flow artifact noises.

2 Multi-echo based noise removing method

In this paper, the number of echoes of MRI is eight, and it is assumed that every multi-echo signal from different tissues (bone, fat, muscle, etc.) satisfies the mono-exponentially decaying model. Fig. 1 shows the overall flowchart of the proposed HNF method. As a pre-processing step, the segmentation of background and foreground is performed by an automatic thresholding using Otsu method [10], and followed by a series of morphological operations for removing the spot noises and filling in the holes in the foreground region.

Firstly in the main processing, the global mean, $m(i)$, and the standard deviation, $\sigma(i)$, of foreground are computed for each multi-echo MR image (blue curves in Fig. 1). Then, $m(0)$ and $\sigma(0)$ at the zero echo time are estimated by the mono-exponential model [8, 9] (red curves in Fig. 1). Each multi-echo image is transformed to have the same global mean and standard deviation as the estimated $m(0)$ and $\sigma(0)$ (green curves in Fig. 1). This global intensity normalization process equalizes the signal levels by compensating the difference in echo time.

Secondly, the averaging is applied to the set of normalized multi-echo MR images in order to remove the noise. Then, multi-echo images are reconstructed from the average image, the original global mean and standard deviation of each multi-echo image.

The global mean and the standard deviation at the zero echo time, $m(0)$ and $\sigma(0)$, are estimated using the method proposed by Koff et al. [8]. Since the multi-echo signal at each pixel is assumed to satisfy the mono-

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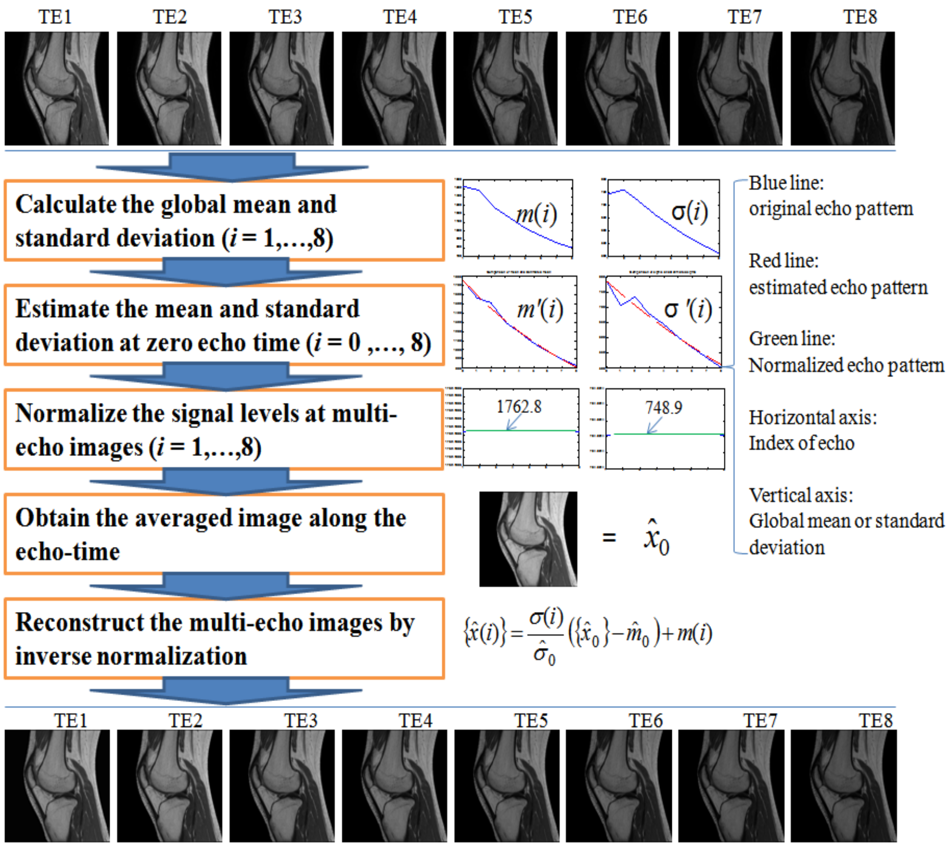

Fig. 1. Flowchart of homomorphic normalization filtering.

exponentially decaying model, $m(0)$, $\sigma(0)$, $T_2^{m(0)}$ and $T_2^{\sigma(0)}$ can be estimated by the model expressed in Eq. (1):

$$S(TE_i) = S_0 e^{(-TE_i/T_2)} \tag{1}$$

where $S(\cdot)$ represents either $m(\cdot)$ and $\sigma(\cdot)$, TE_i is the echo time at the i^{th} echo (i=1,…,8), S_0 is either $m(0)$ or $\sigma(0)$, and T2 is either $T_2^{m(0)}$ or $T_2^{\sigma(0)}$.

In Eq. (1), S_0 and T_2 are unknown parameters which will be estimated. For estimating these two values, a cost function is defined as

$$\varphi\left\{\ln(S_0), -\frac{1}{T_2}\right\} = \sum_{i=1}^{n}\left\{\ln(S(TE_i)) - \ln(S_0) - \left(-\frac{TE_i}{T_2}\right)\right\}^2 \tag{2}$$

where $n = 8$ is the number of echoes. The partial derivatives of the cost function with respect to $\ln(S_0)$ and $(-1/T_2)$ are obtained and set to zero, and the linear least square technique is used to solve this problem simultaneously. The final solution for $\ln(S_0)$ and $(-1/T_2)$ are obtained by

$$\ln(S_0) = \frac{\sum_{i=1}^{n}(TE_i)^2\sum_{i=1}^{n}\ln(S(TE_i)) - \sum_{i=1}^{n}(TE_i)\sum_{i=1}^{n}(TE_i)\ln(S(TE_i))}{n\sum_{i=1}^{n}(TE_i)^2 - \left(\sum_{i=1}^{n}(TE_i)\right)^2} \tag{3}$$

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$$-\frac{1}{T_2} = \frac{n\sum_{i=1}^{n}(TE_i)\ln(S(TE_i)) - \sum_{i=1}^{n}(TE_i)\sum_{i=1}^{n}\ln(S(TE_i))}{n\sum_{i=1}^{n}(TE_i)^2 - \left(\sum_{i=1}^{n}(TE_i)\right)^2} \tag{4}$$

In Eq. (3) and (4), all the parameters are already known so that the $\ln(S_0)$ and $(-1/T_2)$ can be calculated. Substituting $m(i)$ (or $\sigma(i)$) and TE_i to Eq. (3) and (4), $m(0)$(or $\sigma(0)$), $T_2^{m(0)}$ and $T_2^{\sigma(0)}$ can be also calculated. The estimated $m(0)$, $\sigma(0)$, $T_2^{m(0)}$, and $T_2^{\sigma(0)}$ are substituted to the mono-exponential model to obtain the adaptive $m'(i)$, $\sigma'(i)$ as shown in the following equations:

$$m'(i) = m(0)e^{(-TE_i/T_2^{m(0)})} \tag{5}$$

$$\sigma'(i) = \sigma(0)e^{(-TE_i/T_2^{\sigma(0)})} \tag{6}$$

In this study, a global intensity mapping model is proposed as in Eq. (7), so that the mean and standard deviation of the MR image after the mapping are changed from $m(i)$ and $\sigma(i)$ to $m'(i)$ and $\sigma'(i)$:

$$\{\tilde{x}(i)\} = \frac{\sigma'(i)}{\sigma(i)}(\{x(i)\} - m(i)) + m'(i) \tag{7}$$

where $\{x(i)\}$ and $\{\tilde{x}(i)\}$ $(i = 1, \ldots, 8)$ denote the original and the transformed multi-echo MR images, respectively.

For adjusting the signal level for each multi-echo MR image, the global intensity normalization, Eq. (8), is applied and a new multi-echo image is produced so that the signal level is the same for every multi-echo image:

$$\{\tilde{x}'(i)\} = \frac{\sigma(0)}{\tilde{\sigma}(i)}(\{\tilde{x}(i)\} - \tilde{m}(i)) + m(0) \tag{8}$$

where $\tilde{m}(i)$ and $\tilde{\sigma}(i)$ are the mean and the standard deviation of $\{\tilde{x}(i)\}$ by Eq. (7). Eq. (9) shows an average filter in the multi-echo axes direction for removing flow artifact and general noise in the normalized multi-echo images$\{\tilde{x}'(i)\}$:

$$\{\hat{x}_0\} = \frac{1}{n}\sum_{i=1}^{n}\{\tilde{x}'(i)\} \tag{9}$$

where n= 8 in this study.

Finally, the reconstruction of the MR images is carried out as Eq. (10) for recovering the individual multi-echo images:

$$\{\hat{x}(i)\} = \frac{\sigma(i)}{\hat{\sigma}_0}(\{\hat{x}_0\} - \hat{m}_0) + m(i) \tag{10}$$

where $\hat{m}_0$ and $\hat{\sigma}_0$ are the mean and standard deviation of $\{\hat{x}_0\}$ given by Eq. (9). $\{\hat{x}(i)\}$denotes each reconstructed multi-echo MR image with the mean and standard deviation of $\hat{m}(i)$ and $\hat{\sigma}(i)$. This inverse mapping retains the original mean and standard deviation, while the noise is suppressed by the averaging.

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3 Experiments

MR imaging was obtained by a 3T MR imager (Intera Achieva Philips Medical Systems, Best, The Netherlands), using a commercially available knee coil (SENSE Knee Coil 3.0T, eight channels; In-vivo, Gainesville, Fla., USA). T2 relaxation times were obtained from the T2 maps reconstructed by using a sagittal multi-echo spin-echo acquisition with a repetition time of 1,244 msec and eight echo times (10.5, 21.0, 31.4, 42.0, 52.4, 62.9, 73.3, and 83.8 msec). The field of view (FOV) was 150×150 mm, with a pixel matrix of 512×512 and a slice thickness/gap of 2/1 mm. The pixel bandwidth was 349.21 Hz/pixel and 25 layers were acquired.

When the echo time increases in an MRI, the signal intensity decreases and is easily affected by noise, especially, in the bottom and top parts of the MR images. Fig. 2 (a) shows that the original MR image has noise in the bottom and top parts. However, the noise is removed and the edge information is preserved as seen in Fig. 2 (b) and Fig. 2 (c) after applying the SVD and the proposed method. The Fig. 2 compares the quantitative T2 images calculated by different methods over multi-echo MR images, (d) the original

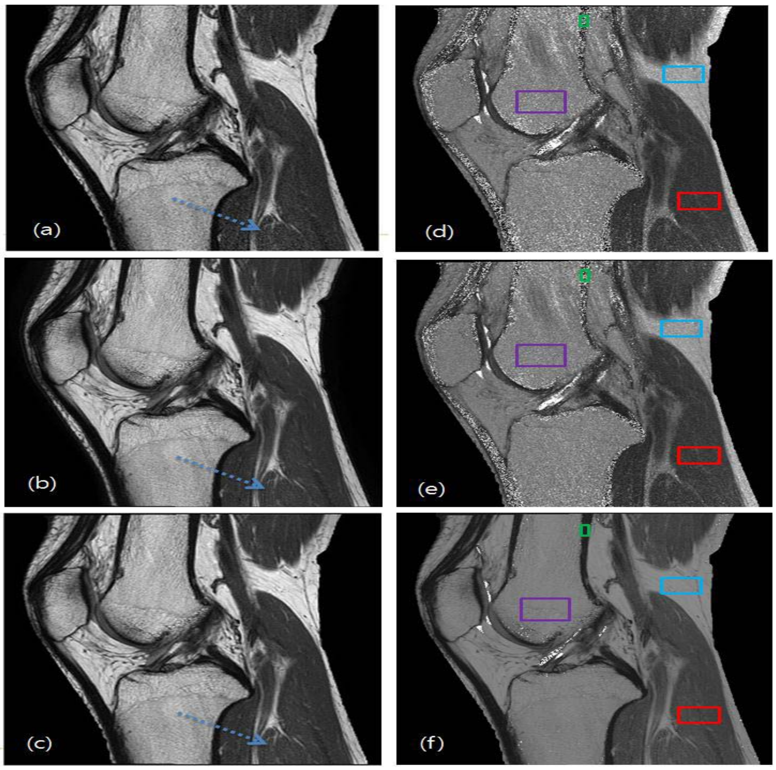

Fig. 2. Comparison of original and reconstructed MR image in 14th layer at 4th echo: (a) original, (b) reconstructed by SVD, (c) reconstructed by proposed HNF, (d) T2 image from the original 14th layer multi-echo images, (e) T2 image from the reconstructed 14th layer multi-echo images by SVD, (f) T2 image from the reconstructed 14th layer multi-echo images by HNF.

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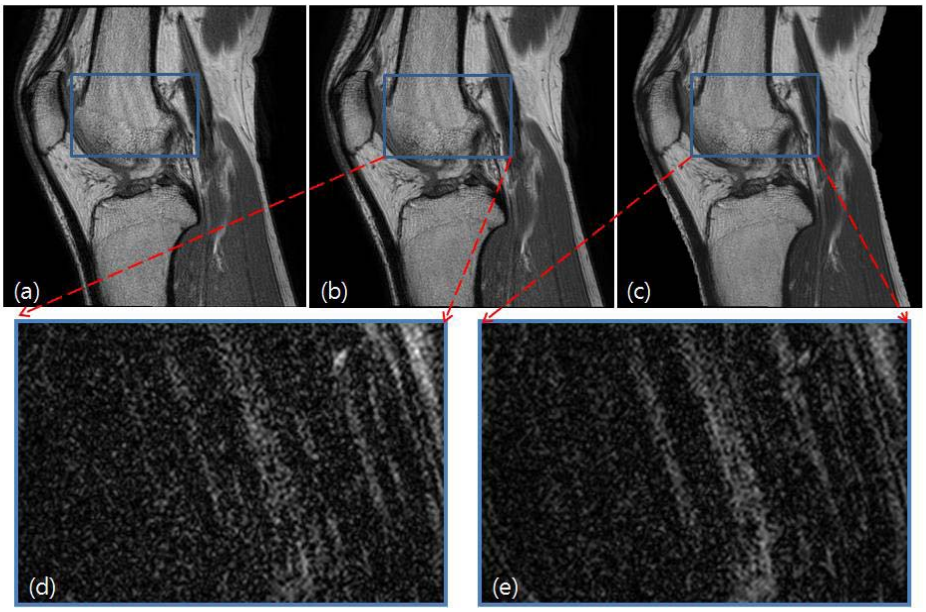

Fig. 3. (a) original MR image, (b) MR image filtered by SVD, (c) MR image filtered by HNF, (d) noise information that computed with original and SVD result in ROI, (e) noise information that computed with original and HNF result in ROI.

images, (e) using SVD, and (f) using the proposed method, respectively.

The means and the standard deviations of various ROI's in Fig. 2 (d)-original, (e)-SVD, and (f)-HNF are (134.15, 17.51), (130.15, 13.78), (125.42, 4.63) for bone marrow; (161.28, 13.87), (145.27, 11.38), (134.68, 2.74) for fat; (57.60, 8.36), (60.87, 7.87), (67.94, 5.54) for muscle; (137.91, 5375), (88.31, 1592), (35.86, 32.64) for cortical bone, respectively (unit: msec). This comparison indicates that the proposed HNF not only removes the noise from the quantitative T2 image but also preserves the inherent T2 values of each tissue such as cortical bone, muscle, bone marrow, fat, etc., and water. In particular, the T2 relaxation times in cortical bones are shorter than those in muscle, while the values in bone marrow and fat are longer than those in muscle. Therefore, the HNF can remove the noise efficiently compared against SVD.

The proposed HNF is based on the averaging and normalization of the multi-echo images, therefore the flow-artifact noise can be removed efficiently because the pulsation and sampling interval are asynchronous. Fig. 3 shows the experimental results of the flow-artifact removal. Fig. 3 (a) shows the original MR image in the 15th layer at the first echo time, where the flow-artifacts seem apparent in ROI. Fig. 3 (b) shows the SVD filtered MR image over the same image, where the flow-artifacts are inefficiently removed. Meanwhile, Fig. 3 (c) shows the results of the proposed HNF filtered MR image, in which the flow-artifacts are effectively removed. Fig. 3 (d) and 3 (e) are the difference images from the original to the SVD result and the HNF result, respectively, for the purpose of highlighting the effectiveness of the

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noise removal.

4 Conclusions

This paper presents a novel noise removal method for multi-echo MR images which is assumed to fit in the mono-exponentially decaying model. The proposed method dramatically removes both the random noise and the flow-artifact noise near the joint area by applying global normalization, averaging, and inverse normalization over multi-echo MR images.

In practice, the histogram of knee MR image has a bi-modal Gaussian distribution. However, this study assumes a uni-modal Gaussian distribution and utilizes global information only. For future works, the HNF filter for a multi-modal Gaussian distribution will be investigated, and the local information will also be integrated to the intensity normalization process.

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