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A survey on the magnetic resonance image denoising methods

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A B S T R A C T

Over the past several years, although the resolution, signal-to-noise ratio and acquisition speed of magnetic resonance imaging (MRI) technology have been increased, MR images are still affected by artifacts and noise. A tradeoff between noise reduction and the preservation of actual detail features has to be made in the way that enhances the diagnostically relevant image content. Therefore, noise reduction is still a difficult task. A variety of techniques have been presented in the literature on denoising MR images and each technique has its own assumptions, advantages and limitations. The purpose of this paper is to present a survey of the published literature in dealing with denoising methods in MR images. After a brief introduction about magnetic resonance imaging and the characteristics of noise in MRI, the popular approaches are classified into different groups and an overview of various methods is provided. The denoising method's advantages and limitations are also discussed.

Contents

Abbreviations: ABONLM, adaptive blockwise nonlocal means; AMPT, adaptive multiscale products thresholding; BC, Bhattacharyya coefficient; CNR, contrast to noise ratio; LMMSE, linear minimum mean square error; MRI, magnetic resonance imaging; MSE, mean square error; NLM, nonlocal means; OBNLM, optimized blockwise nonlocal means; ODCT3D, Oracle-based 3D Discrete Cosine Transform; PDF, probability density function; PRI-NLM3D, prefiltered rotationally invariant nonlocal means; PSNR, peak signal-to-noise ratio; RLMMSE, recursive linear minimum mean square error; RMSE, root mean square error; RSNLMMSE, recursive SNR adapted nonlocal linear minimum mean square error; SNLMMSE, SNR adapted nonlocal linear minimum mean square error; SNR, signal-to-noise ratio; SSIM, structural similarity index; UKR, unbiased kernel regression; UNLM, unbiased nonlocal means; WSM, wavelet subband mixing.

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1. Introduction

Magnetic resonance imaging (MRI) is a notable imaging technique to provide highly detailed images of tissues and organs in the human body. MRI is primarily used to demonstrate the pathological or other physiological alterations of living tissues [1,2]. It provides information that differs from other imaging modalities such as ultrasound and computed tomography (CT). Its major technological advantage is that it can characterize and discriminate among tissues using their physical and biochemical properties. MRI produces sectional images of equivalent resolution in any projection without moving the patient. The ability to obtain images in multiple planes adds to its versatility and diagnostic utility and offers special advantages for radiation and/or surgical treatment planning. MRI is limited only by its spatial resolution and long imaging times. The inherent flexibility of MRI also permits its application in many clinical tasks other than imaging static anatomy. Recently, the important applications have been proposed including imaging blood vessels without contrast agents, measuring diffusion in tissue, measuring tissue temperature, cardiac imaging, dynamic imaging of the musculoskeletal system, liver and reticuloendothelial system.

The visual quality of magnetic resonance images plays an important role in accuracy of clinical diagnosis which can be seriously degraded by existing noise during acquisition process. In a single channel signal acquisition, the MR image is commonly reconstructed by computing the inverse discrete Fourier transform of the raw data. The signal component of the measurement is present in both real and imaginary channels. Each of the orthogonal channels is affected by additive white Gaussian noise [3]. Most commonly, the magnitude of the reconstructed MRI image is used for visual inspection and automatic computer analysis. Since the magnitude of the MRI signal is the square root of the sum of the squares of two independent Gaussian variables, it follows Rician distribution [4]. In multichannel signal acquisition, the MR image is reconstructed by combining complex images and the noise distribution can be described by noncentral Chi distribution [5,6]. Moreover, in case of parallel imaging, the noise amplitude varies according to the spatial location of the image and can follow Rician or Chi distribution according to the reconstruction technique [7].

The noise affects both the medical diagnostic tasks and the ability of automatic computerized analysis, such as segmentation of important features, classification, three dimensional image reconstructions and registration. The denoising is an important MRI preprocessing step used for regularization process, such as in voxel-based morphometry (VBM) [8] to reduce anatomical inconsistencies. In order to analyze the functional MRI (fMRI) data, like detecting brain activity from fMRI data, parametric hypotheis-driven methods are used. Statistical parametric mapping (SPM) [9] is one of the most popular approach for this type of analysis. Its main characteristics are the preprocessing of the data by a fixed Gaussian filter and the application of Gaussian random field theory to control the multiple hypothesis testing problem. And later, wavelet based statistical parametric mapping (WSPM) [10] framework was developed for this analysis which combines adaptive denoising of the parametric maps in the wavelet domain with statistical testing at the voxel level. Therefore, denoising techniques are of great interest in MR imaging.

In general, there are two typical ways to reduce the noise in the images. One way is to acquire the data several times and average them. However, it increases the acquisition time. Another way is to denoise the images by using the post processing methods. In the literatures, numerous approaches to denoising MR images have been proposed including the classic spatial and temporal filters [11], approaches based on anisotropic diffusion filter [12–24], the nonlocal means algorithm [25–38], bilateral and trilateral filters [39–44], the wavelet transform [45–67], the curvelet and the contourlet transforms [68–72], maximum likelihood approach [74–82], linear minimum mean square error estimation [83–86], nonparametric neighborhood statistics/estimation [88–94] and singularity function analysis [95,96]. The aim of this paper is to summarize these literatures on MRI denoising.

The rest of this paper is organized as follows: Section 2 describes the magnetic resonance imaging techniques and parallel imaging MRI. Section 3 describes the characteristics of noise in MR images and the estimation of noise. The techniques for denoising MR images are discussed in Section 4. In Section 5, the MRI denoising methods are compared with one another. Finally, the conclusion is presented in Section 6.

2. Magnetic resonance imaging

MRI system is working on the principles of nuclear magnetic resonance (NMR), to map the spatial location and associated properties of specific nuclei or protons in a subject using the interaction between an electromagnetic field and nuclear spin [1,2]. It detects and processes the signals generated when hydrogen atoms are placed in strong magnetic field and excited by a resonant magnetic excitation pulse. The human body is largely composed of fat and water molecules. Each water molecule has two hydrogen nuclei or protons. These hydrogen protons are usually imaged to demonstrate the physiological or pathological alterations of human tissues.

Hydrogen atoms have an inherent magnetic moment as a result of their nuclear spin, when placed in a strong magnetic field, the magnetic moments of these hydrogen nuclei tend to align. The nuclei have a resonant or larmor frequency determined by their localized magnetic field strength. Proper simulation by a resonant magnetic or RF field at the resonant frequency of the hydrogen nuclei can force the magnetic moments of the nuclei to partially, or completely, tip into a plane perpendicular to the applied field. When the applied RF excitation field is removed, the magnetic moments of the nuclei precess in the static field as they realign. This tipping generates an RF signal at a resonant frequency. This signal is detected by the MR imaging system and for image reconstruction, this MR signal's both frequency and phase data are collected in *k*-space. A two dimensional inverse Fourier transform of this *k*-space is computed to produce a gray scale image. Frequently, the main limitation of MRI is the acquisition time [97]. Usually an MR scan takes at least 20 min and can go on for an hour or more sometime. To reduce the acquisition time, the gradient is increased to scan the *k*-space faster. However, in practice these performances are limited. Another idea is to undersample the *k*-space and compensate by using multiple coils.

Parallel imaging is a recently developed family of techniques that takes advantage of the spatially sensitive information inherent