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Magnetic resonance image enhancement using stochastic resonance in Fourier domain☆,☆☆

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Abstract

Objective: In general, low-field MRI scanners such as the 0.5- and 1-T ones produce images that are poor in quality. The motivation of this study was to lessen the noise and enhance the signal such that the image quality is improved. Here, we propose a new approach using stochastic resonance (SR)-based transform in Fourier space for the enhancement of magnetic resonance images of brain lesions, by utilizing an optimized level of Gaussian fluctuation that maximizes signal-to-noise ratio (SNR).
Materials and Methods: We acquired the T1-weighted MR image of the brain in DICOM format. We processed the original MR image using the proposed SR procedure. We then tested our approach on about 60 patients of different age groups with different lesions, such as arteriovenous malformation, benign lesion and malignant tumor, and illustrated the image enhancement by using just-noticeable difference visually as well as by utilizing the relative enhancement factor quantitatively.
Results: Our method can restore the original image from noisy image and optimally enhance the edges or boundaries of the tissues, clarify indistinct structural brain lesions without producing ringing artifacts, as well as delineate the edematous area, active tumor zone, lesion heterogeneity or morphology, and vascular abnormality. The proposed technique improves the enhancement factor better than the conventional techniques like the Wiener- and wavelet-based procedures.
Conclusions: The proposed method can readily enhance the image fusing a unique constructive interaction of noise and signal, and enables improved diagnosis over conventional methods. The approach well illustrates the novel potential of using a small amount of Gaussian noise to improve the image quality.

Keywords: Stochastic resonance; Noise; Image enhancement; Brownian motion; Brain tumor; MRI; *k*-Space

1. Introduction

Magnetic resonance imaging (MRI), being rich in information content, has always been an important modality in neuroradiological diagnosis. MRI is a tomographic imaging technique that produces images of the internal physical and chemical characteristics of an object from externally measured nuclear magnetic resonance (NMR) signals. MR signals used for image formation come directly from the object itself. In this sense, MRI is a form of emission tomography similar to PET and SPECT. But unlike PET or SPECT, no injection of radioactive agents or radiation into the patient is needed for signal generation in MRI. Also, MRI operates in the radiofrequency range, and hence the imaging process does not involve the use of ionizing radiation nor has the associated potential harmful effects of radiotoxicity or mitogenesis. Nevertheless, for proper enhancement of contrast between lesion and normal tissue, one has to take recourse to invasive procedures in MRI, such as administering contrast agents like chelated gadolinium salts intravenously.

Nevertheless, various imaging algorithms for MRI enhancement have been proposed, but all these image enhancement techniques have been dominated by spatial and frequency filters. For instance, Du et al. [1] proposed a technique for vessel enhancement filtering in three-dimensional MR angiography. Chen et al. [2] developed a technique

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using a Wiener filter and linear prediction to enhance hybrid magnetic resonance (MR) images degraded by T_2 effects and additive measurement noise. Moreover, Crespo et al. [3] and Ishak et al. [4] proposed nonlinear enhancement techniques for enhancing MR images of the brain. Multiple-scale filtering based on the analysis of local intensity structure using the Hessian matrix has been used to effectively enhance vessel structures in MR angiography images [5]. Wu et al. [6] have earlier shown the feasibility of using wavelet-based adaptive algorithm for MR image enhancement in diagnostic and therapeutic radiology. Recently, the wavelet-based approach has been used to explore the possibility of selective image enhancement in functional MRI [7], but the problem is that one has to tune in advance the ab initio or arbitrary scale-specific or scale-dependent parameters. Nevertheless, the majority of enhancement procedures are neither tissue selective nor tissue adaptive, since, in general, the various structures in the image are enhanced evenly together.

Stochastic resonance (SR) is one of the most notable and relatively simple examples of this type of nontrivial behavior of nonlinear systems for improving the physical or chemical signals under the influence of noise [8]. The notion of SR determines a group of phenomena wherein the response of a nonlinear system to a weak input signal can significantly increase the signal-to-noise ratio (SNR) or enhance the degree of order in a system with appropriate tuning of the noise intensity [9,10]. At the same time, the integral characteristics of the process at the output of the system, such as the spectral power amplification, SNR or input/output cross-correlation measures, have a well-marked maximum at a certain optimal noise level [11]. Mitaim and Kosko [12] elucidated that SR can be viewed as a noise-induced enhancement of the response of a nonlinear system to a weak input signal. Owing to the noticeable advantage of SR to enhance a weak signal, the SR approach transpires to play a growing role in many diverse fields. Marks et al. [13] have shown the SR of a threshold detector in image visualization, whereby an optimal noise level produces a better visual representation than when other noise levels are used. Hongler et al. [14] found that the ubiquitous presence of random perturbations of noise in vision systems can advantageously be used for edge detection. It is traditionally considered that the presence of noise is paradoxical to the system or makes the image display worse. The conventional presumption is that image noise is an unwanted feature, which either corrupts the NMR radiofrequency signal during acquisition or is added by the imaging process. Here, we are interested in using *stochastic fluctuation* (also called ‘noise’ in popular parlance) to enhance the 2-D signal or an image.

In contrast to high-field MRI scanners (typically 3 to 7 T), a major concern in enhancing brain images of lower-field scanners up to 1.5 T is the poor quality of the images secondary to a worsening SNR compared with the high-field MRI scanners. The motivation of this study was to lessen the noise and enhance the lower-field MRI scanner image. We intend to approach the problem of adapting and optimizing enhancement of MR images, and hence we explore one of the newer techniques for signal enhancement, namely, the SR phenomena. Here we are motivated to study whether the same signal enhancement process of SR can be applied to enhance MR images. If so, this would furnish pointers towards a new paradigm, for optimal enhancement for an MRI scan. Furthermore, the advantage of the proposed SR technique over conventional image processing ones is that, in the latter, we need to de-noise the image using filters and then enhance the image, whereas the former is a more direct approach that does not need any filter to remove the noise, instead noise is used to counter noise. In other words, for SR enhancement, a small amount of extra noise is administered to ameliorate the intrinsic noise already in the image, the effect is both enhancement of a signal and reduction of its noise. This SR technique works more efficiently for radiological images as these images contain inherent noise. We have also developed a computational parameter, the image enhancement factor, to quantitatively measure the image enhancement performance, and herein the stochastic resonant method surpasses the conventional methods of image enhancement, like the Wiener method, the wavelet method, etc. Furthermore, it is observed that the stochastic resonant algorithm always produces adequate contrast in the processed (output) image, without generating any ringing artifacts even around sharp transition regions. One may remark that such artifacts are occasionally seen in images processed by the conventional enhancement procedures.

It may be mentioned that we have earlier shown the feasibility of using SR for signal enhancement in computed tomography scan (CAT scanning); there we used a stochastic resonator in the Radon space, the basic domain in CT image processing [15]. In the present article, we use the stochastic resonator on MR images, operated in the Fourier space, the intrinsic domain of MR image processing. Here, we approach a specific clinical area and investigate the possibility of utilizing SR to enhance MR images of brain lesions, spanning across a wide spectrum of clinical conditions, ranging from vascular and developmental lesions to benign and malignant pathology. We have tested the proposed method satisfactorily to both aspects of image processing, namely, to image restoration, as well as to image enhancement. Needless to say, the procedure can be applicable to enhance MR images of lesions in other parts of the body.

2. Materials and methods

We have tested the approach on various brain tumors and lesions of different age groups. We accessed MR images of brain lesions from brain images (plain as well as contrast based) of 60 patients, obtained from two 1-T MRI scanners (Siemens Avento and General Electric Signa) in DICOM format of 1024×1024 pixel size. The study was cleared by the Institutional Human Ethics Committee. Three experienced radiologists reported the images under consensus. As a