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Research Paper

Denoising MRI Images through Nonlinear Enhancement

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Abstract

A magnetic resonance image is used for medical analysis, and often it is corrupted with Rician noise. Noise removal from this image must be performed such that the image's original information is not compromised. A technique is proposed in this article for denoising magnetic resonance images. Results from an experiment in which this technique is used validates its applicability.

Keywords *MRI; Image denoising*

Introduction

Magnetic Resonance Imaging (MRI) is a non-invasive technique based on the use of magnetic and electromagnetic energies. It is used by the medical community to produce images of internal organs of the body without the need for surgical procedures. These images are used to display pathological and physiological variations experienced by living tissues. It is a very desirable imaging technique which is considered harmless and produces accurate results. The produced images are used for medical analysis and diagnostics; thus, it is very important that such images be noise free.

Quadrature displaced coils are part of the structure of an MRI system. They form a quadrature detector subsystem used to produce images. It has already been demonstrated that such coil physical arrangement can improve the image's signal-to-noise ratio (SNR) by a factor of $\sqrt{2}$ with respect to a non-quadrature coil structure of similar dimensions, [1]. The signals that are measured with the quadrature detector are essentially two- or three-dimensional arrays of complex numbers. Consequently, a pair of images is produced representing real and imaginary parts of a complex image, [2]. The magnitude of the complex image is used for clinical analysis; however, the image is inevitably corrupted by Rician noise [3]. It is vital to remove this noise from Magnetic Resonance (MR) images. Many processes have been used to remove this noise, see [4-8].

For better diagnoses and medical analyses, the structural details of MR images must be preserved while denoising efforts are applied. This requirement is seen to be of two criteria. The first is that the edges' shapes and locations must be preserved and the second is that no spurious details should be generated when denoising is performed. A denoising technique based on such criteria is proposed in this article. It is based on the use of complex diffusion, the two-dimensional Gabor filter, and an enhancement operator, $\mathfrak{M}$. It is noted here that the diffusion coefficient is a function of an angle, θ, at a given threshold, κ. This coefficient is a positive monotonically decreasing weight function. The proposed technique is made optimum by selecting the best θ value, θ_{op}. The value of θ_{op} is produced through the application of the two-dimensional Gabor filter and entropy measurement. A two-dimensional Gabor filter can be thought of as a complex plane wave modulated by a two-dimensional envelope. Two metrics are used to support the validity of the proposed technique, the structural similarity index measure (*SSIM*), the peak signal-to-noise ratio (PSNR), and image histogram distribution.

MRI Denoising Technique

Steps of the proposed MRI denoising technique is shown in Figure 1.

Figure 1: *The Proposed MRI Denoising Technique Block Diagram*

For comparison purposes, the enhancement part of the technique was omitted, and the resulting procedure was applied to denoise the considered noise corrupted images. The corresponding block diagram is shown in Figure 2.

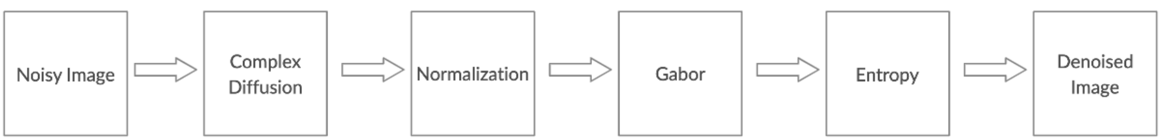


Figure 2: Block Diagram of the Proposed MRI Denoising Technique without Enhancement

Complex Diffusion: Given a Rician noise corrupted MR image, I, the technique is based on the application of the complex diffusion process, [9], to the image. As the complex diffusion process is applied to I it produces two components. A real or active component and an imaginary or reactive component, both related to the original image. This process is presented mathematically as follows,

$$I_t = \nabla \cdot \left[c\big(Im(I)\big)\nabla I\right] \tag{1}$$

Where $(\nabla \cdot)$ represents divergence, (∇) represents gradient, and $Im(I)$ is the imaginary component. The complex diffusion coefficient is given as:

$$c\big(Im(I)\big) = \frac{e^{j\theta}}{1 + \left(\frac{Im(I)}{\kappa\theta}\right)^2} \tag{2}$$

Where:

κ is the threshold and θ is an angular value

Enhancement Operator: The contrast of an image is improved using a two-dimensional nonlinear filter developed in [10]. The formulation of this filter is based on the generalization of an algorithm developed in [11] used to calculate the energy of signals employing Teager's algorithm given in [12]. The filter proposed in [10] works like a local-mean weighted bandpass filter; it enhances the contrast of an image by combining an image with its filtered version.

Application of Newton's law of motion equation to the motion of a mass is described with a second- order ordinary differential equation, with the discrete solution for an oscillatory motion given as: $x(n) = A\cos[\Omega n + \varphi]$. In this solution, *A* is the amplitude, Ω is the discrete sampling frequency, and φ is an arbitrary initial phase. It is shown in [12] that energy, *E*, associated with this oscillation is proportional to *A* and Ω as: $E \propto A^2\Omega^2$. To characterize A, Ω, and φ, three equations are used:

$$x(n-1) = A\cos[\Omega(n-1) + \varphi] \quad (3)$$
$$x(n) = A\cos[\Omega(n) + \varphi] \quad (4)$$
$$x(n+1) = A\cos[\Omega(n+1) + \varphi] \quad (5)$$

These equations can be manipulated to produce [11]

$$A^2\sin^2(\Omega) = x(n)^2 - x(n+1)\cdot x(n-1) \quad (6)$$

Small values of Ω result in a formula for the corresponding oscillation as

$$E = A^2\,\Omega^2 \approx x(n)^2 - x(n+1)\cdot x(n-1) \quad (7)$$

A nonlinear filter has been obtained by applying the filtering operation of Equation (7) along both the vertical and horizontal directions resulting in a 2-D version given by:

$$y_1[p,q] = 2x^2[p,q] - x[p-1,q]\cdot x[p+1,q] - x[p,q-1]\cdot x[p,q+1] \quad (8)$$

It is shown in [10] that very high-quality image enhancement is achieved through the application of these filters. The block diagram of the enhancement operator, $\mathfrak{M}$, is shown in Figure 3.

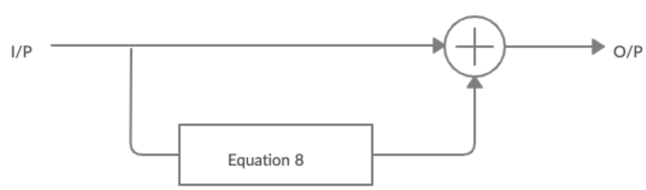


Figure 3: *The Enhancement Operator,* $\mathfrak{M}$

Gabor Filter: The two-dimensional Gabor filter is given as follows [13]:

$$G_{f,\sigma_1,\sigma_2}(x,y,\beta,\psi) = exp\left[-0.5\left(\frac{u^2}{\sigma_1^2} + \frac{v^2}{\sigma_2^2}\right)\right]\cos(2\pi f u + \psi)$$
$$u = x\sin(\beta) + y\cos(\beta) \quad (9)$$
$$v = x\cos(\beta) + y\sin(\beta)$$

To produce θ_{op} the following values are substituted in Gabor filter:

- $\psi = \pi/2$
- $\beta \in \{0, 2\pi\}$

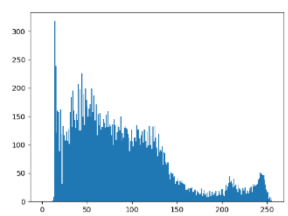
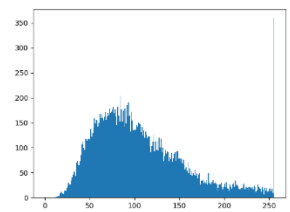
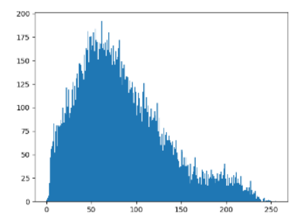
- $f = 1/4$
- $\sigma_1 = \sigma_1 = \sigma = 4$

Entropy Calculation: In this article, image entropy, $H(X)$, where X is a discrete random variable, is calculated using Shannon's formula:

$$H(X) = -\sum_{i=1}^{n} P(x_i)\ \log_2 P(x_i) \tag{10}$$

In Equation (10) P contains the image's normalized histogram counts. Here entropy is a measure of useful image information. As an example, the histograms of an MRI image, its Rician noise corrupted, and denoised versions are shown in Table 1.

Table 1: *Histograms*

MRI Image	Noise Corrupted Version	Denoised Version
		

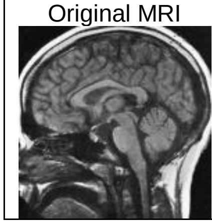
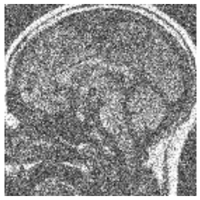
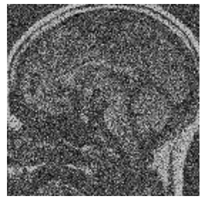
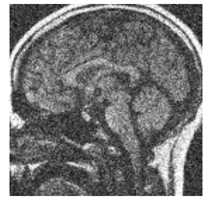
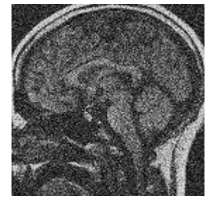
Optimum θ Calculation: At a given threshold value, κ, the process given in Equation (2) is made optimum when a value of θ, θ_{op}, is generated through the application of Gabor filter and entropy computations. The value of θ in Equation (2) is incremented one degree at a time, for every value of θ and the value of β in Equation (9) is incremented one degree at a time for a total of 360 degrees. The value of local entropy is calculated at every increment. Once the sweep through all values of θ and β is complete, the global maximum entropy value is generated, and the value of θ_{op} is identified. This procedure is performed in both cases, with and without the enhancement part. As a result, two denoised images are produced, one due to the process given in Figure 1 and the other from the process given in Figure 2.

Performance Evaluation

The original image was obtained by taking the real and imaginary of the MRI images, squaring the images, adding them and then, taking the square root of the result. Consequently, the resulting image is the magnitude image. To obtain an image with Rician noise, additive white Gaussian noise is added to the real and imaginary at the desired SNR level before finding the magnitude image. To show the impact of the enhancement part on the denoising process, the noise-free image is used as a reference, and the values of SSIM and PSNR are calculated for both cases. The values of SSIM and PSNR are computed right after normalization on Figures 1 and 2 for the denoised image at the global maximum entropy value. Experiment results are shown in Tables 2 and 3. Table 2 shows the data *without enhancement*, and Table 3 shows the data *with enhancement*. The corresponding images are shown in Table 4.

	Table 2: Denoising Data (No Enhancement)					***Table 3:*** Denoising Data (Enhancement)				
SNR	β°	θ_{op}°	Entropy	SSIM	PSNR	β°	θ_{op}°	Entropy	SSIM	PSNR
10	346	205	1.1624	0.0024	7.6648	67	59	4.8184	0.2527	13.8570
15	143	205	0.9694	0.0017	7.6640	31	185	4.7097	0.4315	16.7966

***Table* 4:** Performance Evaluation Images

Original MRI	SNR = 10	Denoised	SNR = 15	Denoised
				

Conclusion

A technique based on complex diffusion and nonlinear enhancement is proposed in this article for denoising MRI images. Results from a performed experiment demonstrate the effectiveness of the technique and support its validity. The technique is effective and machine adaptable.

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