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Complex Prostate MRI Image Analysis Using Phase Unwrapping and Water-Fat Separation Under Noise Influence

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Abstract
This study aims to analyze complex prostate MRI images using phase unwrapping and Water-Fat Separation (WFS) methods while considering the effect of noise. The steps include complex image formation, phase unwrapping, testing sensitivity to noise, and separating water and fat components using a dual echo time approach (Dixon method). The unwrapping results show that noise significantly affects the accuracy of phase estimation. At a Noise Parameter of 0.3, the Mean Squared Error (MSE) was 39.62, while increasing the Noise Parameter to 0.7 raised the MSE to 168.89. The separation of water and fat signals was successfully achieved, where the water signal followed the original prostate structure, and the fat signal appeared as a distinct spatial gradient. This study demonstrates that complex MRI image processing of the prostate has strong potential to improve diagnostic accuracy through phase analysis and tissue distribution mapping.

Keywords : *Prostate MRI, phase unwrapping, Water-Fat Separation.*

INTRODUCTION

A digital image is a two-dimensional mapping of signals that has undergone spatial discretization and intensity digitization. Typically, image intensity is represented as real numbers. However, in this study, we introduce complex images which contain intensities in the form of complex numbers (with real and imaginary components), carrying both amplitude and phase information simultaneously.

In medical imaging, Magnetic Resonance Imaging (MRI) produces complex signals. Biological tissues contain nuclear spins that, when excited by an RF pulse (B1) in a magnetic field (B0), begin to precess and emit signals V(t), which are detected as two quadrature sinusoidal channels representing the real and imaginary components through a *phase-sensitive detection* technique. This enables the reconstruction of images containing phase data, which can be used to analyze tissue properties such as magnetic susceptibility, temperature, and flow velocity [1].

However, MRI phase is confined within the range $[-\pi, \pi]$, leading to a phenomenon called *phase wrapping*, where discontinuities occur in otherwise smooth phase transitions. This necessitates a correction process known as phase unwrapping, which is crucial before proceeding to further image analysis. Unfortunately, unwrapping algorithms are highly sensitive to noise; interference in the signal can misrepresent these phase changes, resulting in artifacts in the final image. Recent studies have addressed these limitations. For instance, Zhou (2021) introduced PHU-NET, a deep learning-based approach that demonstrated superior robustness in unwrapping noisy MRI phase data compared to traditional algorithms [2].

In prostate MRI, complex images are also used in Water-Fat Separation (WFS) techniques [3]. One widely used method is the Dixon technique, which utilizes phase differences between two or more *echo times (TE)* to separate water and fat components. The accuracy of this method is significantly influenced by the success of the prior phase unwrapping process.

Specifically in prostate imaging, various advanced applications of complex images have been reported. For example, complex averaging in diffusion-weighted imaging (DWI) has been shown to improve lesion detection and reduce artifacts in prostate DWI [4]. WFS has also been applied to characterize prostate and periprostatic tissues, such as distinguishing lipid compositions in tumor regions. These studies confirm the critical role of both accurate phase unwrapping and complex signal processing in enabling high-fidelity water-fat separation for prostate MRI.

METHODS

This study was conducted using a single prostate MRI image in TIFF format with a resolution of 384×384 pixels, obtained from a publicly available dataset on Kaggle. The image is a grayscale medical image that represents a cross-sectional view of the prostate region. The platform used for this research is Google Colaboratory, which supports cloud-based Python programming for efficient image processing. In this study, a complex image processing approach was applied to analyze the MRI data. The research steps include :

1. Complex Image

A digital image consists of a matrix of pixels, each having a specific intensity value. If the intensity values of the pixels are complex numbers, the image is referred to as a complex image. Mathematically, a complex Z number can be expressed as : $Z = I + iQ = A \cdot e^{i\emptyset_u}$.

The relationship between the real and imaginary components to the magnitude and phase is given by :

$$A = |Z| = \sqrt{I^2 + Q^2}$$

$$\emptyset_u = tan^{-1}\left(\frac{Q}{I}\right)$$

In practice, complex images are generally represented in two separate forms : either as a pair of real and imaginary images, or as a combination of magnitude and phase images. This type of decomposition allows for a variety of advanced analyses, such as phase processing, magnetic field mapping, and tissue component separation in medical imaging, such as MRI.

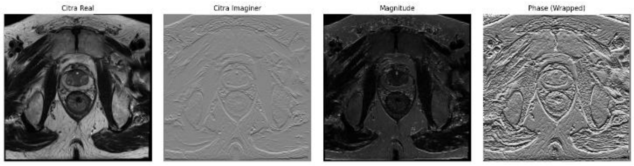

Figure 1. Complex image of Prostate MRI

2. Phase Unwrapping

Phase unwrapping (PU) is a fundamental problem in complex image processing. The primary goal of PU is to extract a phase map that accurately reflects the true phase variations of a system, allowing for further analysis such as magnetic field mapping, surface modeling, or medical image reconstruction. In general, PU can be defined as a computational method used to reconstruct the absolute phase from its wrapped version, which is limited to a principal value range of either $[-\pi, \pi]$ or $[0, 2\pi]$. Mathematically, the concept of absolute phase reconstruction from wrapped phase can be expressed as follows :

$$\emptyset_u(x, y) = \emptyset_w(x, y) + 2\pi \cdot k(x, y)$$

Phase wrapping occurs due to the periodic nature of trigonometric functions (such as arctangent), which restrict phase values to a limited interval. To obtain a physically meaningful and continuous representation, an unwrapping process is needed to correctly determine the value of $k(x, y)$ at each pixel in the image.

Figure 2. Phase Unwrapping

3. Effect of Noise on the unwrapping phase

Noise can significantly interfere with the phase unwrapping process. When complex phase data is affected by noise, the phase values become irregular, making it difficult for unwrapping algorithms to distinguish between actual phase changes and those caused by interference. This may lead to errors in estimating the absolute phase, such as phase jumps or artifacts, which degrade the quality of the reconstructed image. Therefore, the presence of noise often results in an increase in Mean Squared Error (MSE) between the unwrapped phase and the original noise-free phase.

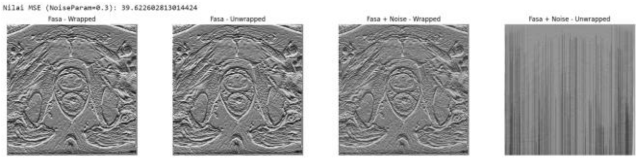

Figure 3. Noise Parameter 0.3

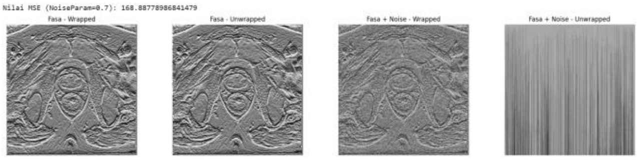

Figure 4. Noise Parameter 0.7

4. Water-Fat Separation

Water-Fat Separation (WFS) is an MRI image processing technique that aims to separate signals from water and fat components based on their phase differences at different echo times (TE). One of the most widely used methods is the Dixon technique, which utilizes the chemical shift between water and fat molecules to generate water-only and fat-only images.

In principle, when MRI signals are acquired at two different echo times (TE_1 and TE_2), water and fat components will exhibit different phase behaviors. By using this phase difference—after accurate phase unwrapping the complex signal can be separated into water and fat components using the following equations :

$$Water = \frac{1}{2}\left(S_1 + S_2 . e^{-j\emptyset_{u/2}}\right)$$

$$Fat = \frac{1}{2}\left(S_1 - S_2 . e^{-j\emptyset_{u/2}}\right)$$

This method is particularly useful, where conventional chemical fat suppression using selective RF pulses is not feasible due to limited spectral resolution. If the phase is not properly unwrapped, the resulting water and fat separation will be inaccurate due to phase wraps, leading to signal contamination. In prostate MRI, WFS plays a crucial role in enhancing tissue contrast and identifying pathological changes.

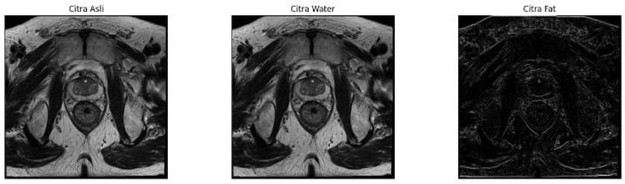

Figure 5. Water-Fat Separation

RESULTS

This study was conducted using a prostate MRI image in TIFF format with a resolution of 384×384 pixels. The image was processed through several computational steps to analyze its phase and signal components. The results for each stage are described as follows :

1. Complex Image

In the first stage, the prostate MRI image was converted into a complex image by combining real and imaginary components. This resulted in four visual representations derived from the complex domain : (a) Prostate Real Image, (b) Prostate Imaginary Image, (c) Prostate Magnitude Image, and (d) Prostate Magnitude Image. Each output was successfully displayed and visually preserved the anatomical structure of the prostate. These representations are essential for the next phase based processing steps.

2. Phase Unwrapping

The phase unwrapping step was applied to the wrapped phase image obtained from the prostate complex data. The unwrapping process generated the following results : (a) Wrapped Phase Image, (b) Unwrapped Phase Image, and (c) Rewrapped Phase Image. Visual comparison between wrapped and unwrapped images showed a smoother phase transition after unwrapping, confirming the method's effectiveness in restoring true phase continuity in the prostate image.

3. Effect of Noise on the unwrapping phase

The third stage evaluated the effect of noise on the unwrapping process. Noise was artificially added to the prostate phase image, and the resulting accuracy was assessed using Mean Squared Error (MSE) :

- At Noise Parameter = 0.3, the MSE between the unwrapped phase (with and without noise) was 39.62
- At Noise Parameter = 0.7, the MSE significantly increased to 168.89

The test results indicate that adding noise to the prostate phase data significantly affects the accuracy of the phase unwrapping process. When the Noise Parameter was set to 0.3, the MSE was recorded at 39.62, and it increased sharply to 168.89 when the noise level was raised to 0.7. This rise suggests that higher noise levels cause greater deviations in the unwrapped phase from the original. This occurs because noise disrupts phase continuity, leading the unwrapping algorithm to misinterpret phase transitions. Therefore, sensitivity to noise is a critical factor to consider in phase-based image processing.

4. Water-Fat Separation

In the final step, Water-Fat Separation (WFS) was performed using the two-echo Dixon method on the prostate MRI complex image. The process exploited the phase shift between water and fat resonance frequencies, producing : (a) Water Component Image and (b) Fat Component Image. In this method, the separation of water and fat components is carried out by utilizing phase differences caused by the shift in their resonance frequencies. By using two complex signals acquired at different echo times, the amounts of water and fat in each pixel are estimated using a linear approach. Simulation results show that the water signal tends to follow the structure of the original image, while the fat signal appears as a distinct gradient that is successfully separated from spatial noise. This separation serves as an important foundation in clinical MRI applications for assessing the distribution of fat and water in biological tissues, such as muscles, the liver, or the prostate.

CONCLUSION

Based on the results obtained, it can be concluded that the analysis of complex prostate MRI images through the stages of complex image formation, phase unwrapping, noise influence testing, and Water-Fat Separation (WFS) was successfully carried out. The phase unwrapping process proved to be sensitive to noise disturbances, where increasing the Noise Parameter from 0.3 to 0.7 caused the Mean Squared Error (MSE) to rise sharply from 39.62 to 168.89. This indicates that the higher the noise level, the greater the error in phase estimation. Meanwhile, the Water-Fat Separation method based on two echo times was able to accurately separate the components, where the water signal reflected the original prostate structure and the fat signal appeared as a distinct spatial gradient. Overall, these stages demonstrate that complex MRI image processing of the prostate holds great potential in supporting non-invasive diagnosis through phase analysis and tissue distribution mapping.

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