



COSC 6370
FUNDAMENTALS OF MEDICAL IMAGING

PROJECT TITLE

Magnetic Magic
MRI Synthesis Through Variable Field Strength

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Objective:

The objective of this project is to apply MRI physics principles to the OASIS dataset, which includes detailed T1-weighted MRI scans and segmentation maps for brain tissues, to simulate MRI images across varying magnetic field strengths (0.5 to 9 Tesla). By leveraging these simulations, the project aims to analyze how changes in magnetic field strength influence tissue relaxation times, image quality, and noise impacts, thereby providing a practical understanding of the factors affecting MRI image contrast and signal integrity. This study is crucial for enhancing diagnostic techniques, understanding the theoretical aspects of MRI imaging, and developing practical skills in image analysis and noise reduction. The expected outcomes include a comprehensive set of simulated MRI images, quantitative analyses of SNR and contrast variations, and insights into noise management, contributing significantly to academic and practical advancements in medical imaging.

Solution:

Data Preparation:

In the **Data Preparation** section of the project report on MRI image synthesis using the OASIS dataset, the initial steps undertaken to prepare the data are crucial for the success of subsequent image analysis and simulation tasks. Here's a detailed look at how the data was prepared:

Data Loading and Access:

MRI data for two patients was loaded from NIfTI files using the NiBabel library, which is particularly suited for handling neuroimaging data formats. This step is critical as it provides the raw MRI scans needed for the project's analysis and ensures that all subsequent simulations are based on accurate and comprehensive data. The data for each patient was loaded as follows:

```
patient1_mri_data = load_patient_data(patient1_file_path)
patient2_mri_data = load_patient_data(patient2_file_path)
```

Slice Selection:

For a consistent analysis across different patients and to ensure comparability of results, slice number 90 was specifically chosen from the axial plane of each patient's MRI data. This slice was selected due to its relevance in displaying significant anatomical features necessary for the study:

```
# Select slice number 90 in the axial plane
slice_90_1 = patient1_mri_data[:, 90, :]
slice_90_2 = patient2_mri_data[:, 90, :]
```

Data Segmentation:

Segmentation of the MRI data into different tissue types was performed based on voxel values. This step is essential for isolating specific tissues—grey matter (GM), white matter (WM), and cerebrospinal fluid (CSF)—which are crucial for analyzing the MRI properties specific to each tissue type:

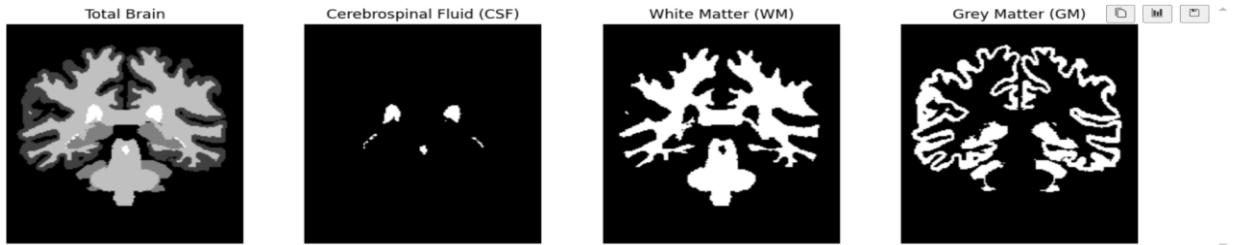
```
# Create a mask for each tissue type based on the voxel values
gm_mask = (slice_90_1 == 1) | (slice_90_1 == 2) # Grey Matter (GM)
wm_mask = slice_90_1 == 3                      # White Matter (WM)
csf_mask = slice_90_1 == 4                      # Cerebrospinal Fluid (CSF)
```

Tools and Libraries:

```
import nibabel as nib # For handling MRI data
import matplotlib.pyplot as plt # For plotting
import pandas as pd # For handling DataFrame
import numpy as np # For numerical operations
from skimage.filters import gaussian # For applying Gaussian filter
from skimage.transform import resize # For resizing images
from scipy.ndimage import gaussian_gradient_magnitude, rotate # For image processing
from scipy.optimize import curve_fit, OptimizeWarning # For optimization functions
import os # For handling file paths
import matplotlib.cm as cm
from scipy.stats import norm
```

Visualization and Validation:

To verify the accuracy of the segmentation and to facilitate a visual check of the anatomical accuracy, the segmented tissues were visualized. This step not only confirmed the segmentation accuracy but also provided a clear visual representation of the spatial distribution of different tissues within the slice, ensuring the data integrity for further simulation:



Signal Acquisition:

The Signal Acquisition phase is a critical component of the MRI image synthesis project. It focuses on simulating T1-weighted and T2*-weighted MRI images using previously prepared data and assessing how various imaging parameters influence the MRI signals of different brain tissues. This phase utilizes calculated relaxation times and Signal-to-Noise Ratio (SNR) under various magnetic field strengths to derive practical insights into optimizing MRI protocols.

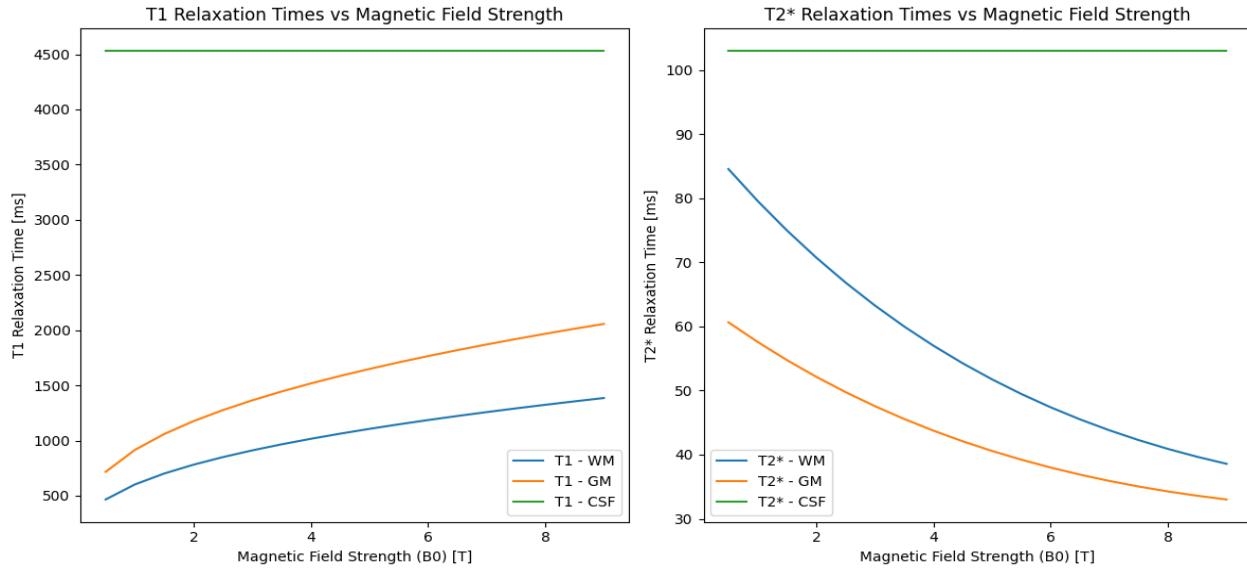
Relaxation Times: The relaxation times T_1 and T_{2^*} are calculated based on their dependence on magnetic field strength, which affects how different tissues appear in MRI images.

T1 Calculation:

```
alpha = params["alpha"]
beta = params["beta"]
delta = params["delta"]
T1 = alpha * (gamma * B0) ** beta + delta
return T1 * 1000 # Convert to ms
```

T2 Calculation:

```
alpha = params["alpha"]
beta = params["beta"]
delta = params["delta"]
T2_star = alpha * np.exp(-beta * B0) + delta
return T2_star * 1000 # Convert to ms
```



T1 Relaxation Times vs Magnetic Field Strength:

- As magnetic field strength increases, the T1 relaxation times for all tissues also increase. This behavior is crucial for MRI because it affects how long tissues take to recover their magnetization state after being excited by the MRI pulse.
- Understanding this relationship helps in optimizing the timing of pulse sequences in T1-weighted imaging. By adjusting the pulse sequence timing to accommodate the longer relaxation times at higher field strengths, clearer and more detailed images can be obtained, which is particularly valuable in distinguishing between different types of tissue in pathological evaluations.

T2 Relaxation Times vs Magnetic Field Strength:

- The decrease in T2 relaxation times with increasing B0 suggests that transverse magnetization decays more rapidly at higher field strengths. This requires adjustments in the echo time (TE) to capture the data before the signal decays significantly.
- For T2-weighted imaging, understanding this decay pattern is critical. The optimal TE needs to be shorter at higher field strengths to avoid loss of signal, ensuring that images retain enough contrast and detail to be diagnostically useful.

Contrast (C_TE) vs Echo Time (TE) for All B0 Values:

Contrast (C_TE) : Contrast (C_TE) is calculated using the difference in signal intensities between WM and GM at various TEs. The formula for the signal intensity for a given tissue at a specific TE, considering its T2* relaxation time, is expressed by the exponential decay equation:

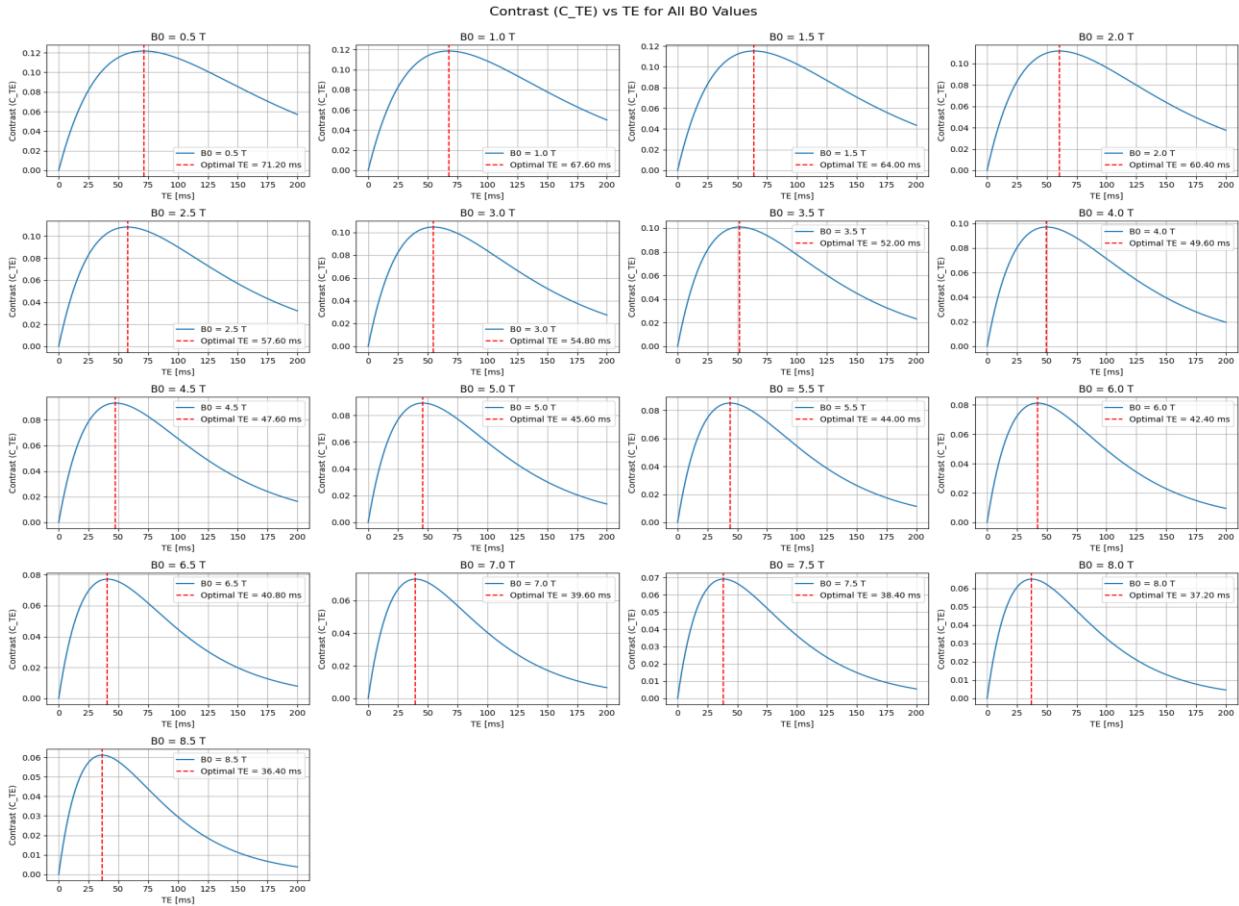
Calculate Contrast

```

def calculate_signal(TE, T2_star):
    return np.exp(-TE / T2_star)

# Function to calculate contrast between WM and GM for T2*-weighted scan
def calculate_contrast(TE, T2_star_WM, T2_star_GM):
    S_WM = calculate_signal(TE, T2_star_WM)
    S_GM = calculate_signal(TE, T2_star_GM)
    return abs(S_WM - S_GM)

```



- The optimal TE for maximum contrast decreases as B_0 increases, indicating that at higher field strengths, the signal behavior changes more rapidly. This information is essential for calibrating the echo time in MRI scans to achieve the best possible image contrast.
- By adjusting TE based on the B_0 used, MRI technicians can enhance the quality of the images obtained, which is especially important in differentiating between similar tissue types and detecting subtle pathological changes.

Contrast (C_TE) vs Flip Angle (θ) for All B0 Values:

Flip Angle:

The flip angle is typically optimized to provide the best contrast between two types of tissues (e.g., white matter and gray matter) based on their specific T1/T2* relaxation times and the computed repetition time (TR). This optimization is computed using the formula:

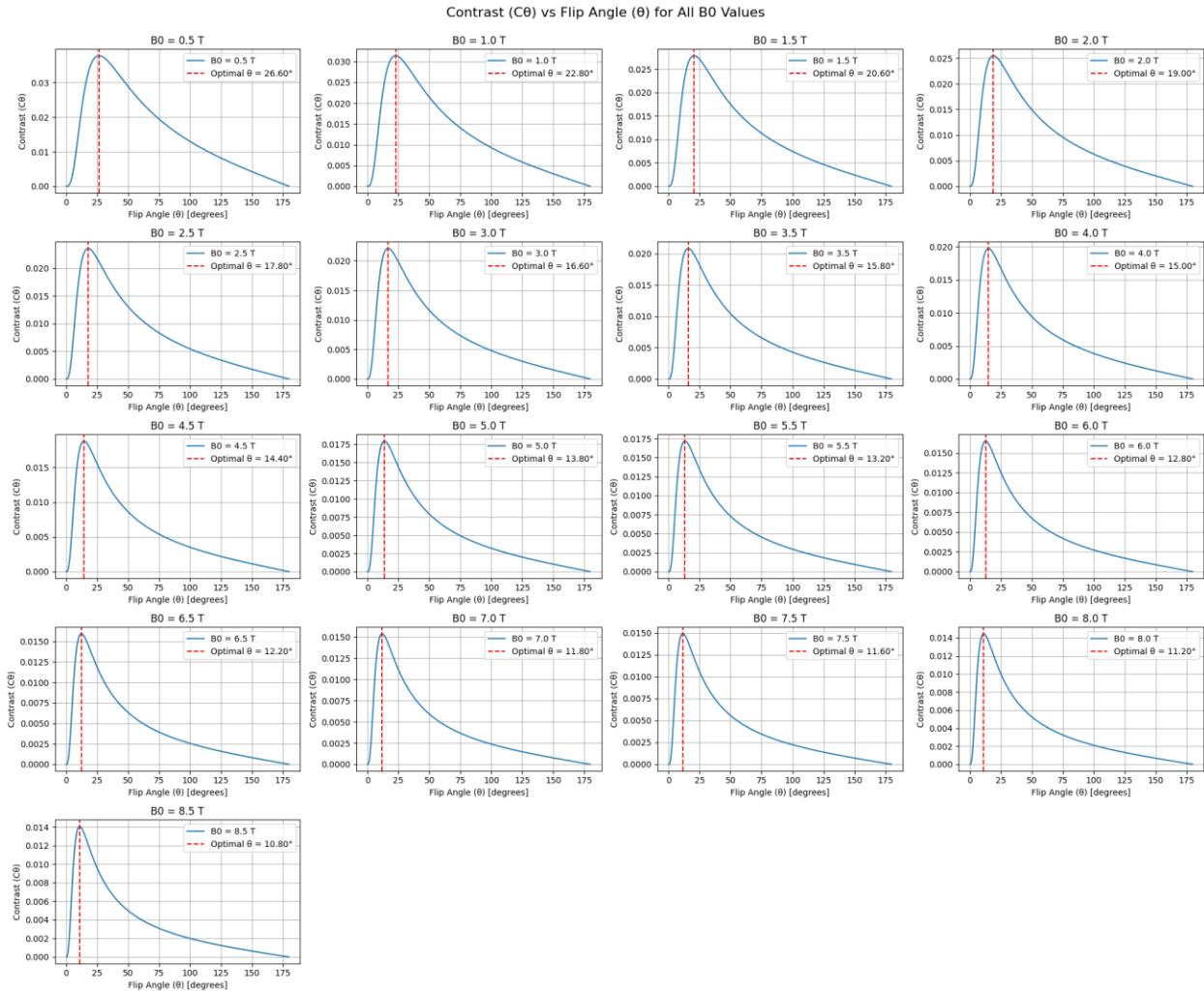
Calculate Flip Angle (θ)

```
def find_optimal_flip_angle_t1(TR, T1_WM, T1_GM):
    theta_values = np.arange(0, 180, 0.2) # Flip angles from 0 to 180 degrees
    contrast_values = [calculate_contrast_theta(theta, TR, T1_WM, T1_GM) for theta in theta_values]
    optimal_theta = theta_values[np.argmax(contrast_values)]
    return optimal_theta, theta_values, contrast_values
```

Calculate Contrast:

```
def calculate_signal_t1(theta, TR, T1):
    theta_rad = np.radians(theta) # Convert angle to radians
    numerator = (1 - np.exp(-TR / T1)) * np.sin(theta_rad)
    denominator = 1 - np.cos(theta_rad) * np.exp(-TR / T1)
    return numerator / denominator

# Function to calculate contrast Cθ for T1-weighted scan
def calculate_contrast_theta(theta, TR, T1_WM, T1_GM):
    S_WM = calculate_signal_t1(theta, TR, T1_WM)
    S_GM = calculate_signal_t1(theta, TR, T1_GM)
    return abs(S_WM - S_GM)
```



- The optimal flip angle for maximum contrast decreases as B_0 increases. This trend suggests that at higher magnetic field strengths, the angle needed to achieve maximum magnetization alignment—and thus, maximum contrast—is lower. Adjusting the flip angle according to the field strength is crucial for optimizing the efficacy of T1-weighted imaging sequences.
- By fine-tuning the flip angle based on the magnetic field strength used, MRI technicians can significantly enhance the differentiation between tissue types. This is particularly valuable in clinical settings where subtle differences in tissue response can be critical for accurate diagnosis.

Ernst Angle vs Magnetic Field Strength (B0) for WM Tissue:

Ernst Angle:

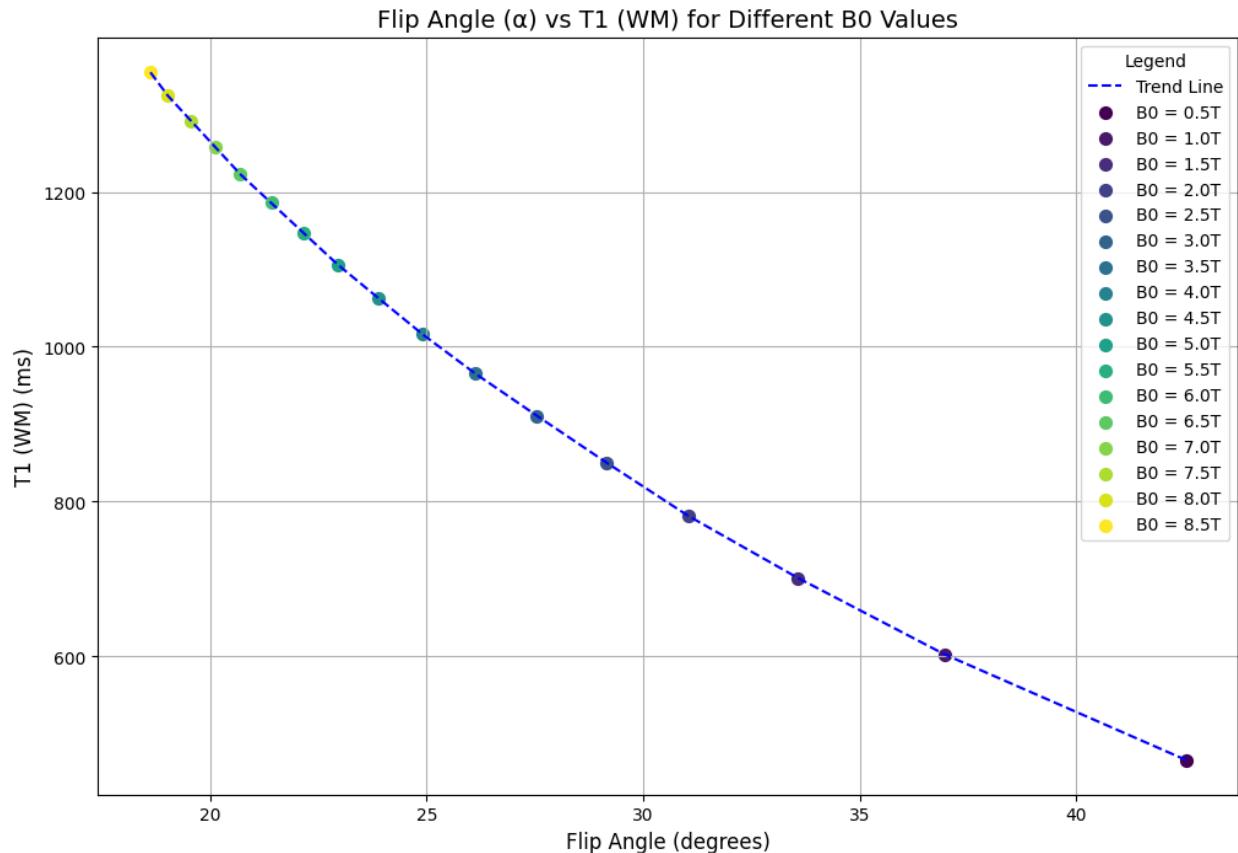
The calculation formula for the Ernst angle in MRI is designed to determine the optimal flip angle that maximizes signal intensity given the specific properties of the tissue being imaged, specifically its T1 relaxation time.

Calculate Ernst Angle:

```
def calculate_ernst_angle(TR, T1):
    """
    Calculate the Ernst angle for T2*-weighted imaging.

    Parameters:
    - TR: Repetition time (in ms)
    - T1: T1 relaxation time (in ms)

    Returns:
    - Ernst angle (in degrees)
    """
    ernst_angle_rad = np.arccos(np.exp(-TR / T1))
    ernst_angle_deg = np.degrees(ernst_angle_rad)
    return ernst_angle_deg
```



- The graph displaying the relationship between the Ernst angle (flip angle, α) and T1 relaxation time for White Matter (WM) across different magnetic field strengths (B0 values) serves multiple purposes in the context of Magnetic Resonance Imaging (MRI).
- The graph demonstrates that as the flip angle increases, the T1 relaxation times for white matter decrease, suggesting that proper adjustment of the flip angle can significantly enhance the effectiveness of MRI imaging by optimizing signal recovery and contrast in T1-weighted images.
- Variation in colors representing different magnetic field strengths (B0 values) shows that higher field strengths generally correspond to lower T1 values at the same flip angles. This insight is crucial for calibrating MRI protocols across different scanners, ensuring consistent image quality regardless of the inherent B0 strength of the equipment used.

Signal-to-Noise Ratio (SNR) Calculation:

SNR measures the level of the desired signal to the level of background noise. It is a ratio of signal power to noise power, expressing the magnitude of the desired signal relative to the level of background noise.

The objective of the SNR Map Generation task is to utilize the SNR equation to generate SNR maps for each tissue type (WM, GM, CSF) across various magnetic field strengths (B_0) from 0.5 T to 9 T. The task involves processing two patients' MRI data and plotting the SNR values for slice number 90, as well as SNR versus B_0 for all tissue types.

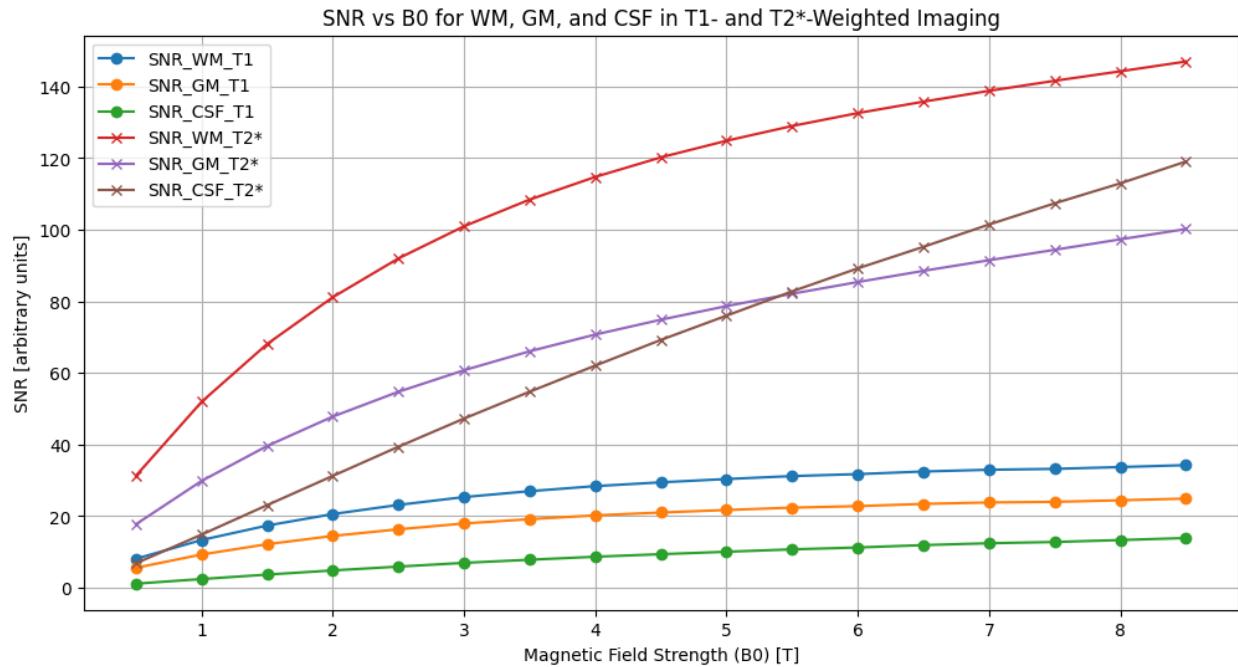
Calculate SNR:

```
def calculate_snr(B0, TR, TE, T1, T2_star, BW, alpha):
    # Calculate each component of the SNR formula
    alpha_rad = np.radians(alpha) # Convert alpha to radians
    numerator = B0 * 1e3 * np.sin(alpha_rad) * np.exp(-TE / T2_star) * (1 - np.exp(-TR / T1))
    denominator = np.sqrt(BW) * (1 - np.cos(alpha_rad)) * np.exp(-TR / T1)

    # Compute SNR
    snr = numerator / denominator
    return snr
```

SNR vs B_0 for WM, GM, and CSF in T1- and T2*-Weighted Imaging:

This graph presents the Signal-to-Noise Ratio (SNR) for White Matter (WM), Gray Matter (GM), and Cerebrospinal Fluid (CSF) across different magnetic field strengths (B_0), distinguishing between T1-weighted and T2*-weighted imaging. The SNR values for each tissue type in T1-weighted imaging are represented by solid lines, whereas T2*-weighted imaging SNR values are marked by crosses.



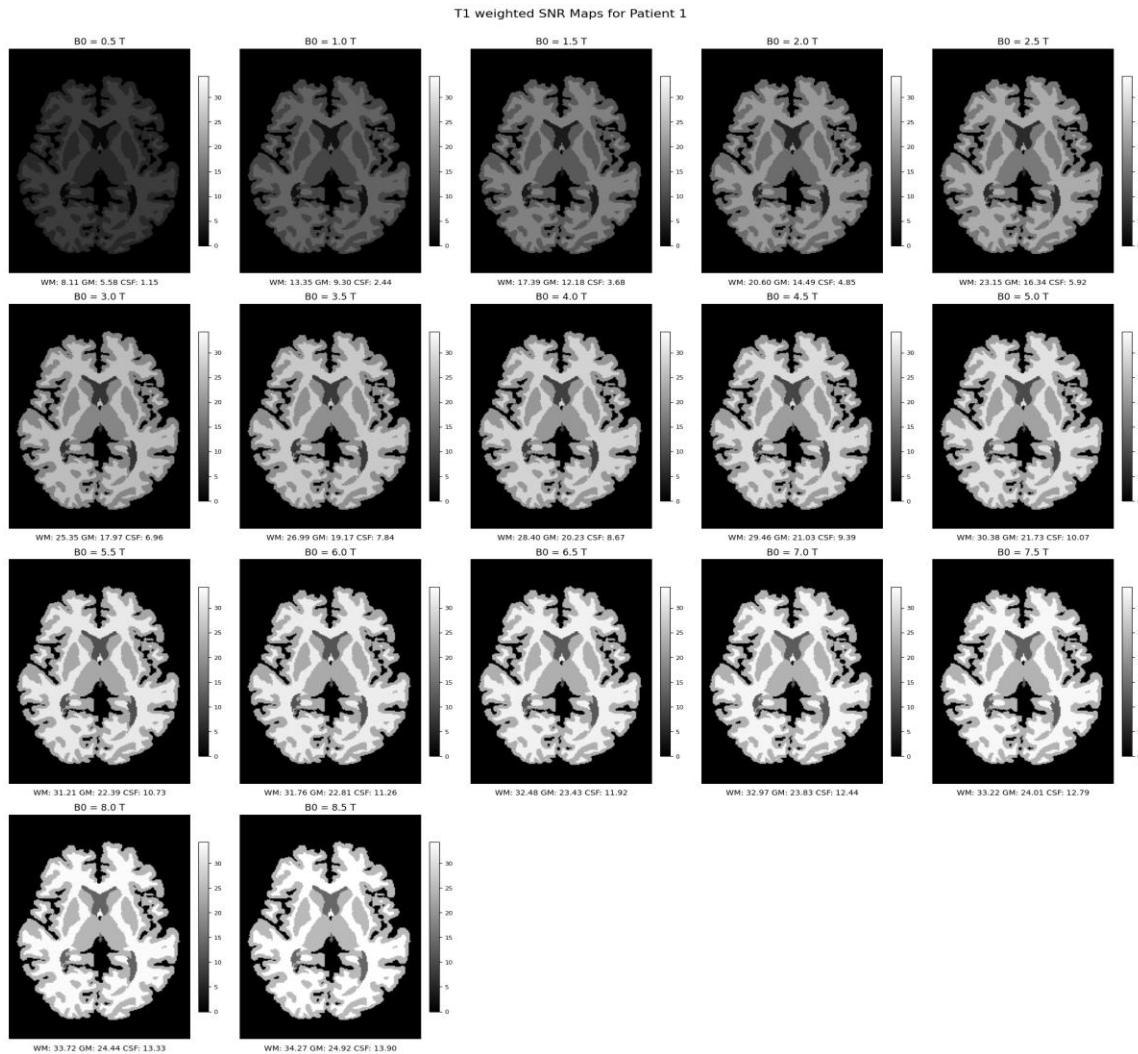
Observations:

- For both T1-weighted and T2*-weighted imaging, SNR increases as the magnetic field strength (B0) increases. This trend is more pronounced in T2*-weighted imaging for all tissue types, indicating that higher magnetic fields significantly enhance signal clarity, especially in T2*-weighted scans.
- SNR disparities among different tissues are evident. White matter consistently shows higher SNR across both imaging types compared to gray matter and cerebrospinal fluid. This suggests that white matter inherently yields better signal clarity under MRI, which is crucial for neurological diagnostics.
- The difference in how SNR scales with B0 between T1- and T2*-weighted imaging is notable. T2*-weighted imaging exhibits a steeper SNR increase with rising B0 levels, highlighting its greater sensitivity to changes in magnetic field strength and its potential for providing clearer images at higher B0 values.

SNR Maps:

T1-Weighted SNR Maps for Patient 1:

The T1-weighted SNR maps for Patient 1 display the Signal-to-Noise Ratio at various magnetic field strengths from 0.5 Tesla (T) to 7.5 Tesla (T). These images illustrate the SNR across different brain tissues—White Matter (WM), Gray Matter (GM), and Cerebrospinal Fluid (CSF). Each image includes annotated SNR values below it, providing a quantitative measure of the image quality and noise levels at each field strength.



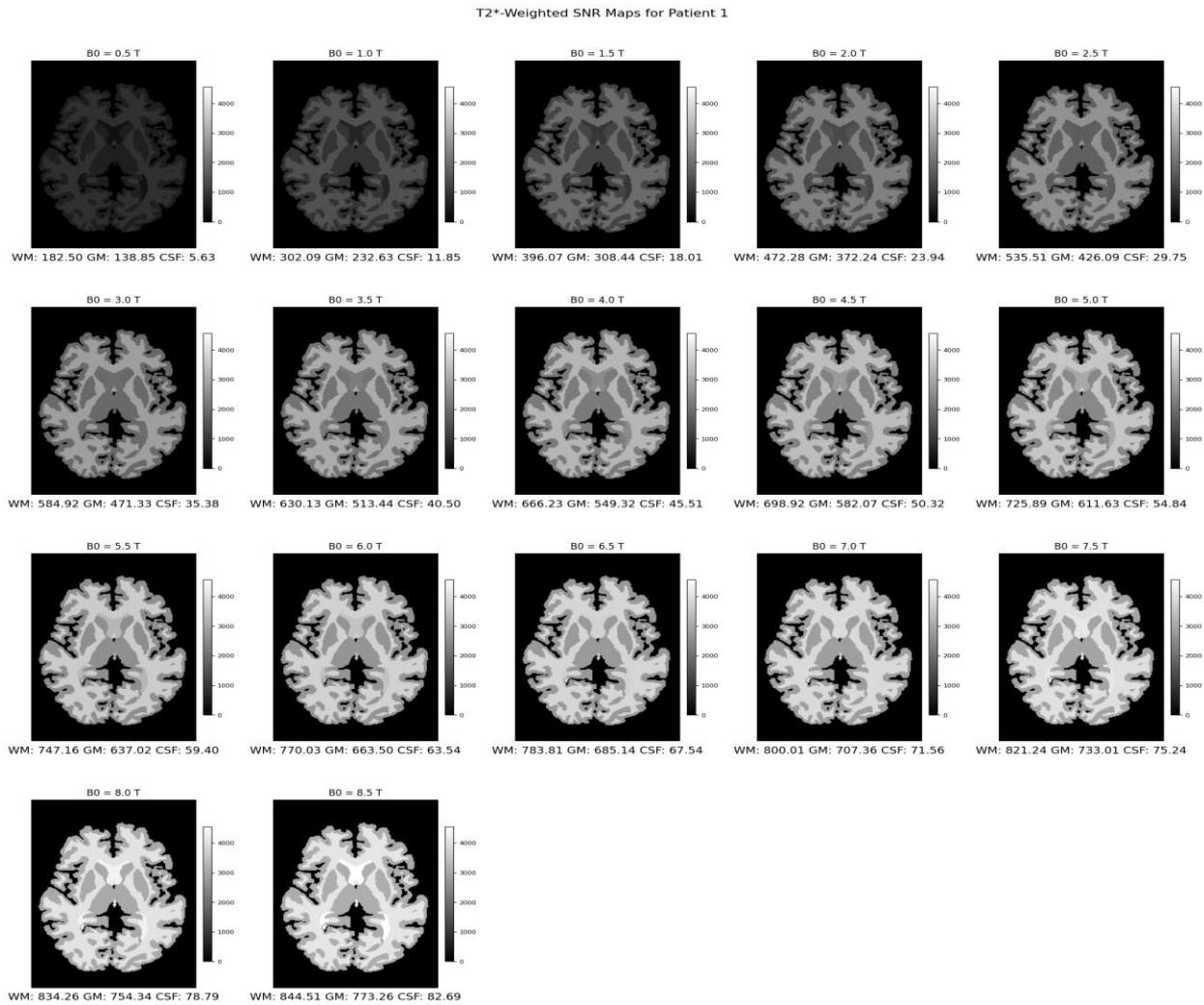
Observations:

- There is a clear trend of increasing SNR with higher magnetic field strengths across all tissue types. This enhancement is indicative of the improved clarity and reduced noise in MRI images obtained at higher field strengths, facilitating better diagnostic capabilities.

- The SNR maps reveal that different tissues respond variably to increases in magnetic field strength. WM consistently shows higher SNR compared to GM and CSF, which is crucial for diagnosing conditions affecting white matter such as demyelinating diseases.
- The detailed SNR values for each tissue type at various B0 levels allow for precise adjustments in MRI settings to optimize imaging protocols for specific diagnostic requirements, enhancing the utility of MRI in clinical practice.

T2*-Weighted SNR Maps for Patient 1:

The T2*-weighted SNR maps for Patient 1 cover the same range of magnetic field strengths as the T1-weighted maps and similarly illustrate the SNR across WM, GM, and CSF. These maps are specifically valuable for their sensitivity to magnetic susceptibility effects and typically offer higher SNR at higher B0 values

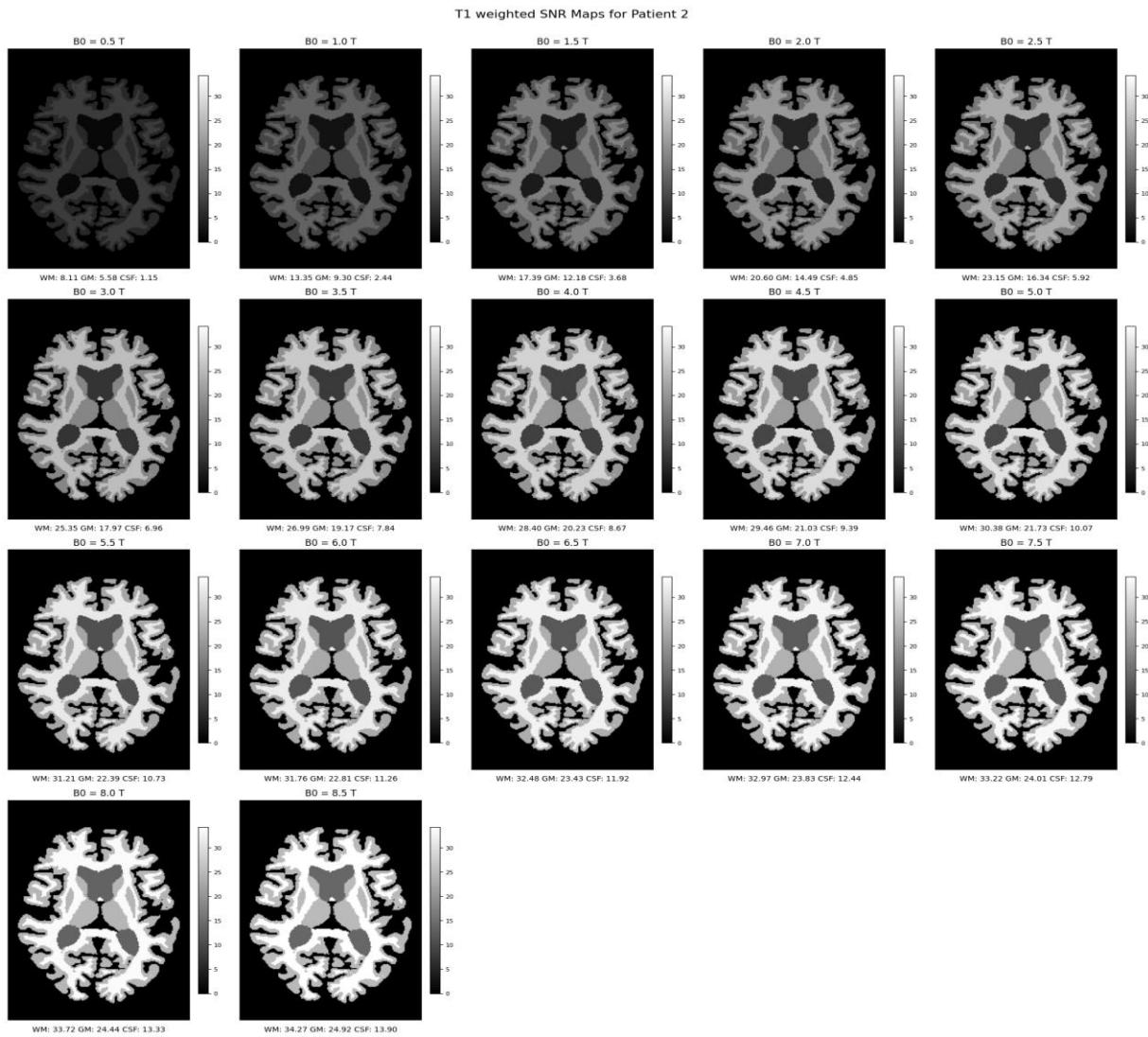


Observations:

- The SNR increases more noticeably in T2*-weighted imaging compared to T1-weighted, especially at higher magnetic field strengths. This suggests that T2*-weighted imaging may be more effective for certain applications, such as detecting hemorrhagic lesions or microbleeds, which are better visualized with T2*-weighting.
- T2*-weighted imaging provides a greater differentiation between tissue types, particularly distinguishing between GM and WM. This differentiation is vital for assessing pathologies that specifically alter the magnetic properties of tissues.
- Given the high sensitivity of T2*-Weighted to variations in tissue composition and the enhanced visibility at higher field strengths, these SNR maps can guide the selection of optimal imaging parameters for detailed assessment of various brain pathologies, enhancing diagnostic accuracy and treatment planning.

T1-Weighted SNR Maps for Patient 2:

These T1-weighted SNR maps for Patient 2 display the Signal-to-Noise Ratio across different brain tissues—White Matter (WM), Gray Matter (GM), and Cerebrospinal Fluid (CSF)—at magnetic field strengths ranging from 0.5 Tesla (T) to 7.5 Tesla (T). Each map highlights the SNR at specific field strengths, providing a visual representation of how SNR levels differ within various brain tissues as the magnetic field strength increases.



Observations:

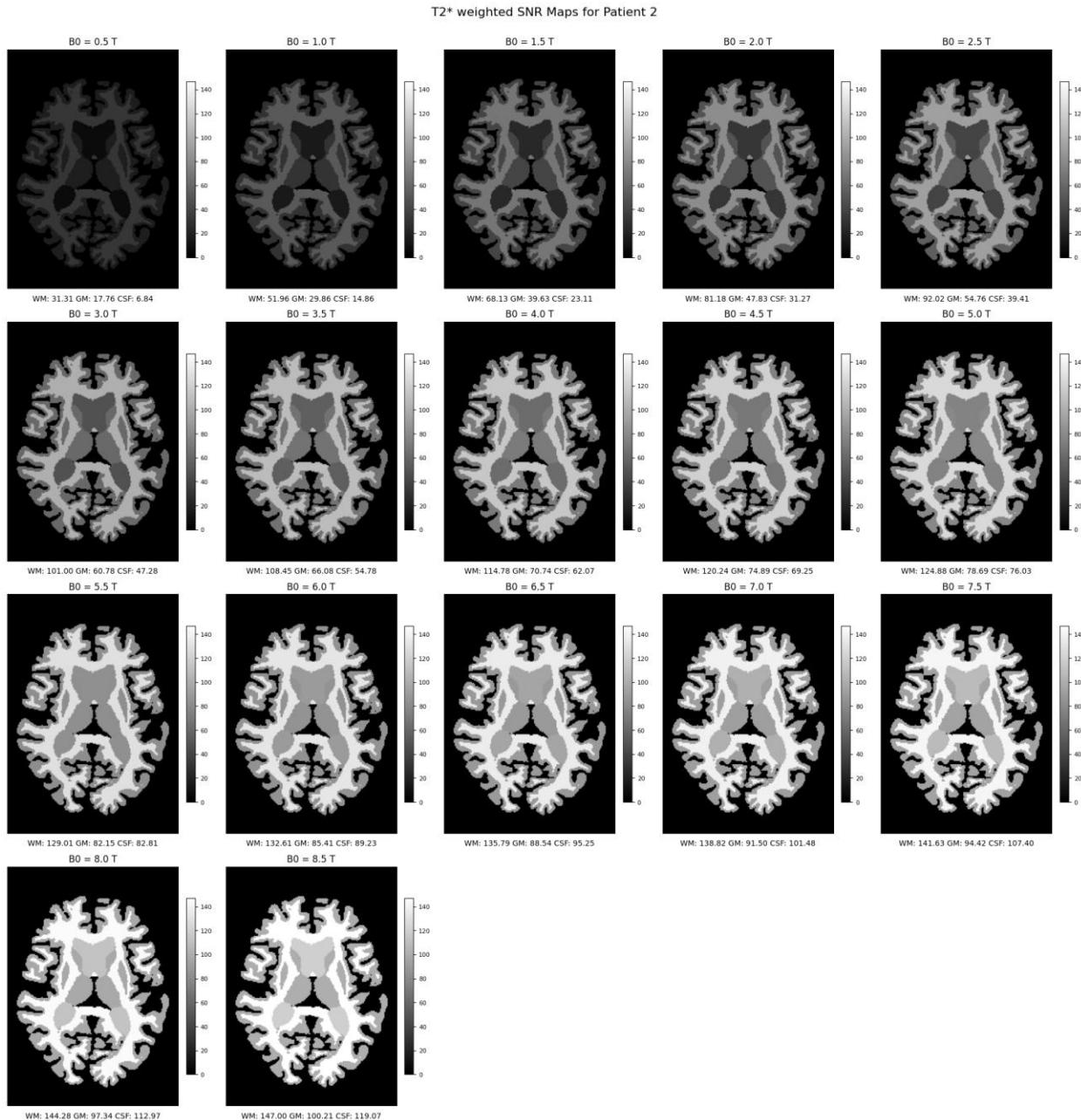
- Consistent with observations from Patient 1, these maps for Patient 2 also demonstrate an increase in SNR with higher magnetic fields across all tissue types. This indicates an

enhanced image quality and reduction in noise, crucial for detailed and accurate medical imaging.

- The SNR maps offer clear visual differentiation between tissue types at varying field strengths. White Matter consistently shows higher SNR values compared to Gray Matter and Cerebrospinal Fluid, which is significant for neurological assessments where detailed imaging of White Matter is essential.
- These maps can be used to tailor MRI scanning protocols based on specific diagnostic needs. Higher B0 levels might be preferred when high-resolution images are crucial, such as in the detection and monitoring of neurodegenerative diseases.

T2*-Weighted SNR Maps for Patient 2:

The T2*-weighted SNR maps for Patient 2 illustrate the Signal-to-Noise Ratio at the same range of magnetic field strengths (0.5T to 7.5T) as the T1-weighted maps. These images are particularly useful for evaluating tissue responses to T2*-weighted imaging, which is sensitive to magnetic susceptibility and offers higher SNR at increased field strengths.



Observations:

- Similar to the findings for Patient 1, the T2*-weighted SNR maps for Patient 2 show more significant increases in SNR with rising magnetic field strengths. This enhancement is most noticeable in White Matter, highlighting its utility in detecting subtle changes within this tissue.
- T2*-weighted imaging provides superior contrast between tissues, particularly between White and Gray Matter. This enhanced contrast is vital for detecting and characterizing lesions or abnormalities that may not be as apparent in T1-weighted images.
- The high sensitivity and enhanced contrast in T2*-weighted imaging make these maps highly valuable for clinical settings, especially in the diagnosis and management of

conditions involving minute pathological changes, such as vascular abnormalities or microbleeds.

Noise Addition in MRI Simulations:

In the noise addition process for MRI images, simulated Gaussian noise is introduced to simulate real-world conditions such as electronic noise or patient movement, helping to optimize MRI scanning protocols. This noise is generated using a function that adjusts its intensity based on the magnetic field strength. The generated noise is then added to the precomputed signal intensities of different tissue types (WM, GM, CSF) for each level of magnetic field strength. This addition is specifically targeted to areas where tissues are present, ensuring that noise does not affect the background areas. Following the noise addition, signal intensity values for each tissue type are recalculated, creating a new set of noisy MRI images for each magnetic field strength. These images are then visualized to evaluate the effects of noise under various conditions, aiding in the assessment of the robustness of image processing algorithms and the effectiveness of noise reduction techniques in clinical environments.

Calculate and normalize signal intensity with noise applied to tissue regions:

```
np.random.seed(123)
def add_noise(signal, sigma_n):
    noise = np.random.normal(-sigma_n, sigma_n, signal.shape)
    noisy_signal = np.where(signal != 0, signal + noise, signal)
    return noisy_signal
```

```
noise_si_data = {}

for index, row in snr_df.iterrows():
    B0 = row['B0']
    noise = 40 * (1 + np.log(B0)) # Calculate noise based on B0

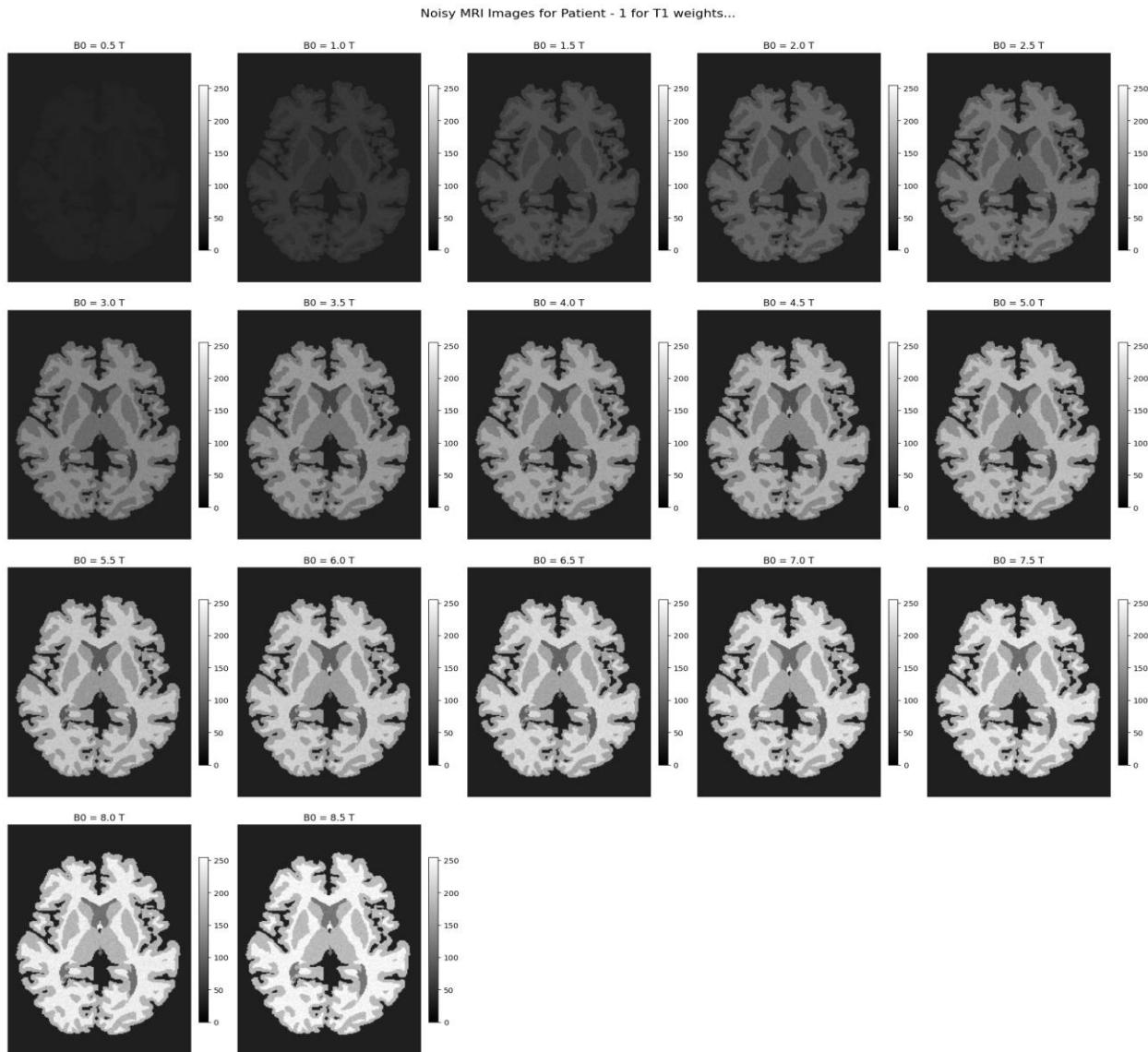
    # Calculate signal intensity for all tissues
    si_values = {}
    for tissue in ['SNR_WM_T1', 'SNR_GM_T1', 'SNR_CSF_T1', 'SNR_WM_T2*', 'SNR_GM_T2*', 'SNR_CSF_T2*']:
        snr_value = row[tissue]
        si_values[tissue] = round(snr_value * noise, 4) # Calculate signal intensity for each tissue

    # Store the data in a structured format
    noise_si_data[B0] = {
        'SNR_T1': {tissue: row[tissue] for tissue in ['SNR_WM_T1', 'SNR_GM_T1', 'SNR_CSF_T1']}, # Store original SNR_T1 values
        'SNR_T2*': {tissue: row[tissue] for tissue in ['SNR_WM_T2*', 'SNR_GM_T2*', 'SNR_CSF_T2*']}, # Store original SNR_T2* values
        'Noise': round(noise, 4), # Store calculated noise
        'SI_T1': {tissue: si_values[tissue] for tissue in ['SNR_WM_T1', 'SNR_GM_T1', 'SNR_CSF_T1']}, # Store SI_T1 values
        'SI_T2*': {tissue: si_values[tissue] for tissue in ['SNR_WM_T2*', 'SNR_GM_T2*', 'SNR_CSF_T2*']}, # Store SI_T2* values
    }

# Convert the structured dictionary to a DataFrame
noise_si_df = pd.DataFrame.from_dict(noise_si_data, orient='index')
noise_si_df
```

Noisy T1-Weighted MRI Images (TE_T1, TR_T1) for Patient-1:

The T1-weighted noisy MRI images for Patient 1 demonstrate the effect of added Gaussian noise across varying magnetic field strengths (B_0), from 0.5T to 8.5T. The images highlight how noise impacts the visualization of anatomical structures in the brain, particularly the grey matter (GM), white matter (WM), and cerebrospinal fluid (CSF). This simulation provides insight into the challenges faced in real clinical environments where noise can degrade image quality, crucial for accurate diagnostics and treatment planning.



Observations:

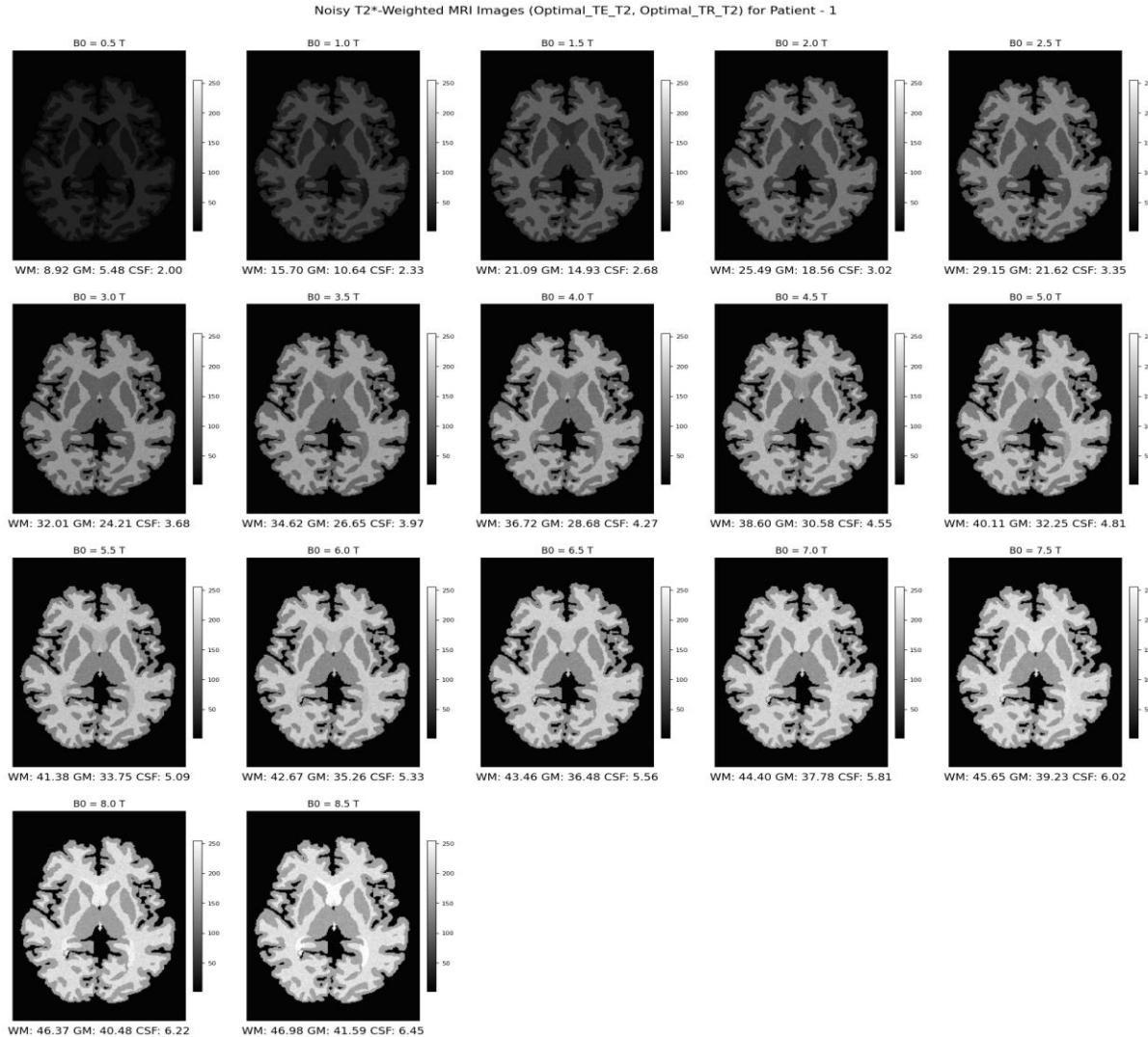
- As the magnetic field strength increases, the noise level also increases, evident from the progressively grayer and less distinct images. Higher field strengths, while typically

providing better SNR, show significant noise impact, which could obscure fine details in tissues.

- The noise affects different brain tissues variably; for instance, white matter (WM) retains more definition than grey matter (GM) at lower noise levels, but both lose clarity as noise increases.
- Understanding the noise behavior at different field strengths is vital for optimizing MRI scan settings to balance clarity and the amount of time a patient must remain still, minimizing potential movement-induced artifacts.

Noisy T2-Weighted MRI Images (Optimal_TE_T2, Optimal_TR_T2) for Patient 1:

The T2-weighted noisy MRI images show the degradation effects of simulated noise under different magnetic field conditions for Patient 1. These images are crucial for understanding how noise influences the differentiation between various tissues in the brain, like WM, GM, and CSF, under T2-weighted imaging conditions, which are sensitive to fluid in the brain and can be critically important in detecting lesions or other abnormalities.

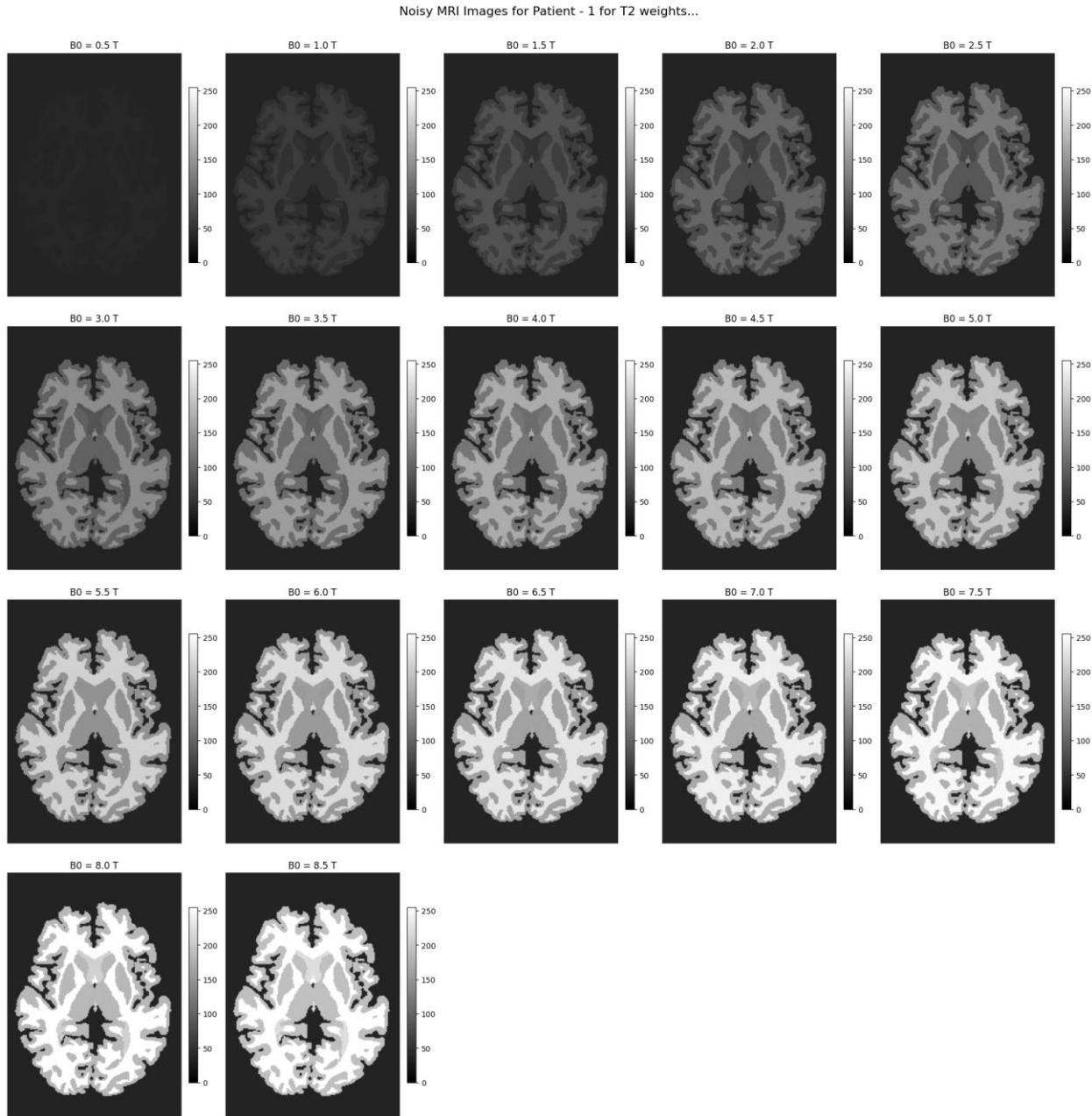


Observations:

- Noise addition distinctly affects the ability to differentiate between tissue types. As B0 increases, the noise not only intensifies but also affects the contrast between tissues, complicating the identification of pathological changes.
- The images reflect a clear trend of increasing noise with higher B0 values, demonstrating the challenge of maintaining image quality without advanced noise-reduction techniques in higher-field MRI systems.
- These simulations are instrumental for researchers and clinicians to develop and test new noise-reduction algorithms, enhancing MRI's diagnostic capabilities even under suboptimal conditions.

Noisy T1-Weighted MRI Images (TE, TR, T1) for Patient 2:

The T1-weighted maps distinctly show the degradation in image quality as the intensity of the noise increases with the magnetic field strength. This effect is evident from the visible distortions in the anatomical structures of the brain, particularly in high contrast areas between tissues. As the field strength increases, the noise impacts finer details more significantly, potentially complicating the diagnosis and analysis of smaller brain structures.

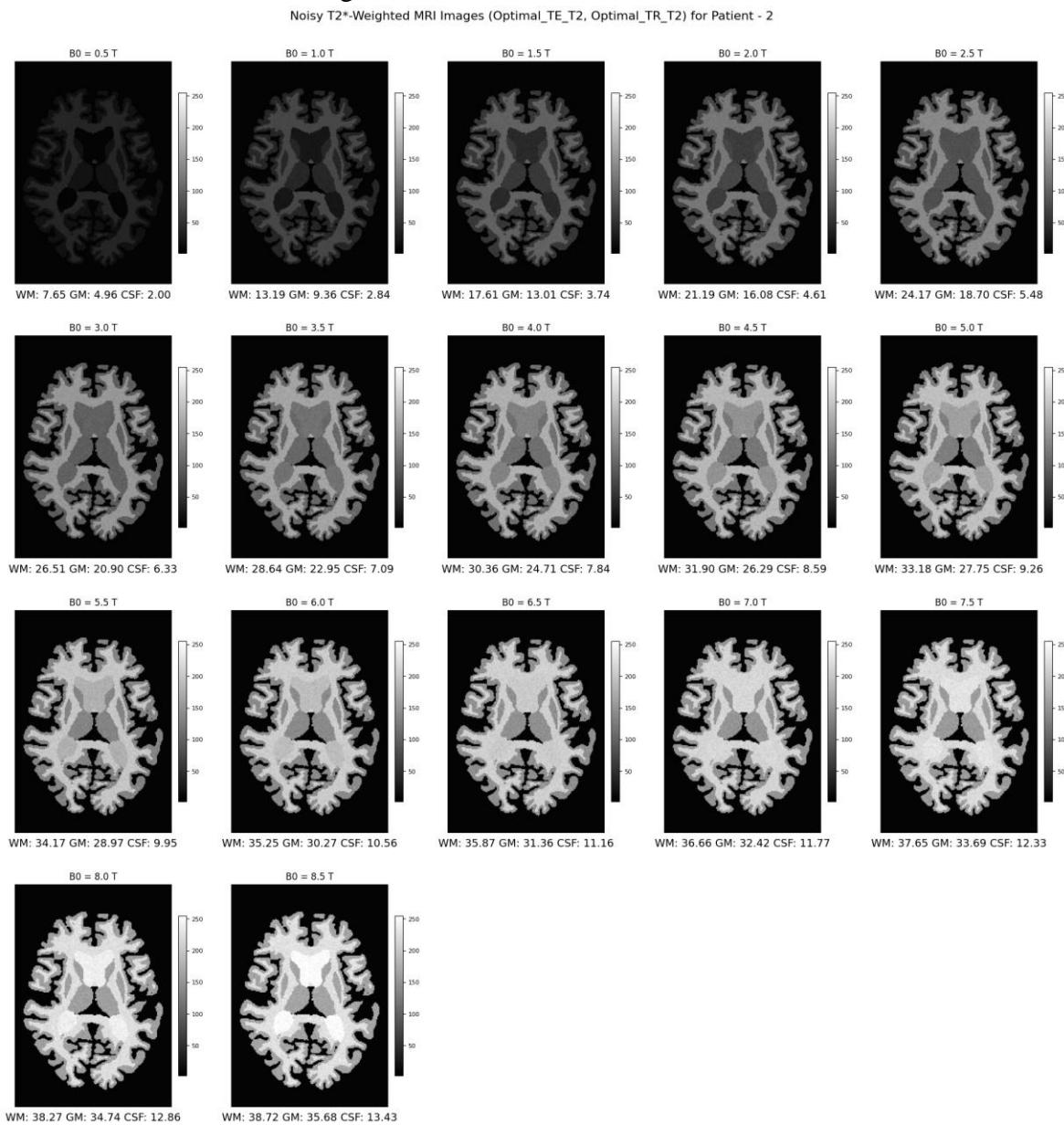


Observations:

- Higher noise levels at increased magnetic field strengths could potentially mask subtle pathological features or mimic the appearance of anomalies, necessitating advanced noise-reduction techniques.
- The effect of noise varies across different tissues, with white matter showing more resilience compared to gray matter and CSF, where the noise more prominently obscures structural details.
- These maps are ideal for testing and developing image processing algorithms aimed at noise reduction, providing a benchmark to improve the robustness of diagnostic tools against varying noise levels.

Noisy T2-Weighted MRI Images (Optimal_TE, Optimal_TR, T2) for Patient-2:

In the T2*-weighted noisy MRI maps, noise introduces a substantial challenge in maintaining the clarity and contrast of images. The noise more drastically affects the differentiation between different brain tissues, making it difficult to discern boundaries and internal structures clearly.



Observations:

- T2*-weighted images are inherently more sensitive to noise, which could interfere more significantly with clinical assessments, particularly in detecting lesions or small vascular abnormalities.
- Noise affects tissues differently; for instance, the CSF spaces appear to be more susceptible to noise, leading to a greater loss of definition in ventricular and sulcal spaces.
- The variability in noise impact suggests that radiologists must be especially cautious when interpreting higher B0 images, as misinterpretation risks are heightened without proper noise management strategies.

MRI Resolution:

MRI resolution determines the clarity and level of detail visible in MRI images, which is essential for accurately identifying and delineating anatomical structures. High resolution is crucial in medical imaging as it enhances diagnostic accuracy, allowing for more precise treatment planning. Resolution in MRI is generally defined by slice thickness and in-plane resolution, where finer resolutions enable better visualization of small anatomical features, critical in detecting subtle pathologies or small anatomical structures. Optimizing MRI resolution can significantly impact the quality of medical diagnostics by providing clearer, more detailed images that aid in accurate diagnosis and effective treatment planning.

Resampling to adjust resolution of MRI Resolution:

MRI resolution is simulated by adjusting the slice thickness and in-plane resolution parameters, which directly influence the signal intensity (SI) maps for T1 and T2* weighted images. This implementation uses resampling techniques—bilinear interpolation for adjusting slice thickness and cubic interpolation for in-plane resolution adjustments—to model how variations in MRI acquisition parameters affect image quality. Gaussian noise is also introduced to the SI maps to simulate realistic noisy conditions encountered during MRI scans. The effects of these resolution modifications are quantitatively evaluated using metrics such as Contrast, PSNR, RMSE, and NCC, allowing for a detailed analysis of how different resolutions impact image clarity, anatomical accuracy, and the overall effectiveness of MRI protocols. This approach provides a comprehensive framework for visualizing and assessing the impact of resolution changes on MRI image quality, supporting clinical decisions on optimal scanning parameters.

```
def resample_data(data, in_plane_factor, slice_thickness_factor):
    slice_thickness_shape = (data.shape[0], int(data.shape[1] * slice_thickness_factor), data.shape[2])
    data_resampled_slice_thickness = resize(data,
                                             slice_thickness_shape,
                                             order=1, # Using Bilinear interpolation
                                             mode='reflect',
                                             anti_aliasing=True,
                                             preserve_range=True)

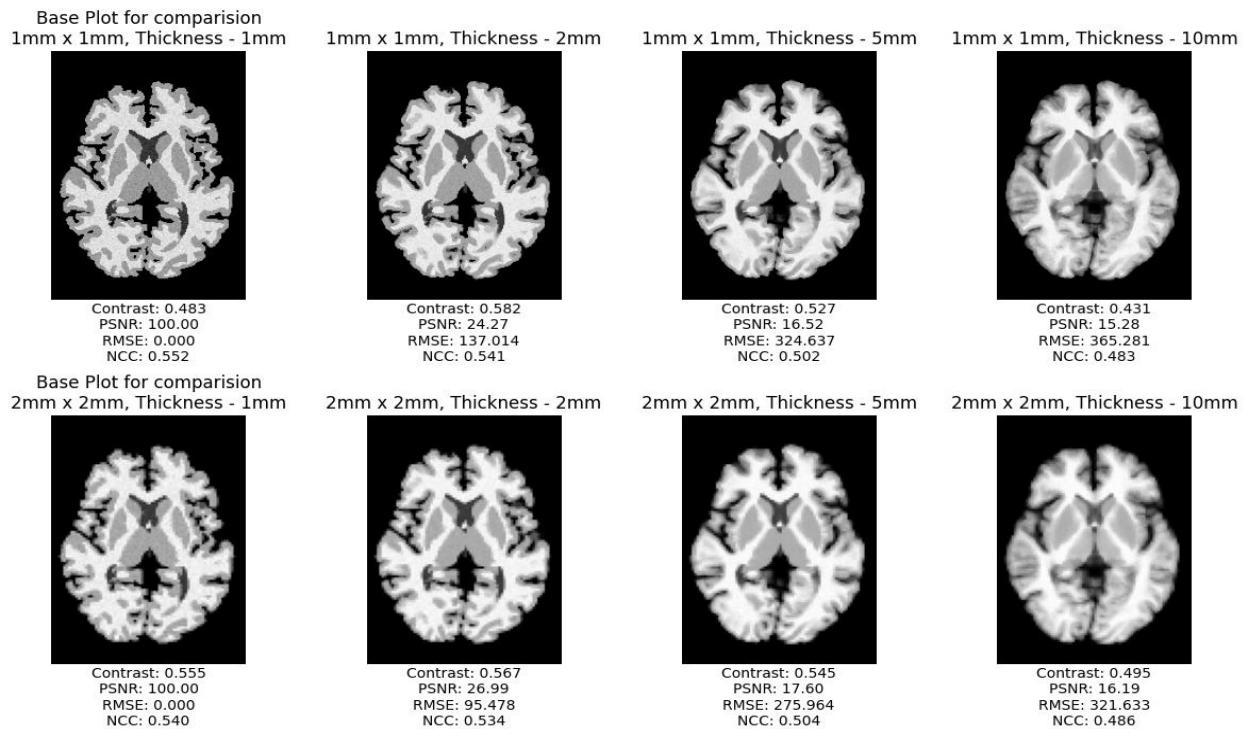
    in_plane_shape = (int(data_resampled_slice_thickness.shape[0] * in_plane_factor),
                      data_resampled_slice_thickness.shape[1],
                      int(data_resampled_slice_thickness.shape[2] * in_plane_factor))
    data_resampled_in_plane = resize(data_resampled_slice_thickness,
                                      in_plane_shape,
                                      order=2, # Using Cubic interpolation
                                      mode='reflect',
                                      anti_aliasing=True,
                                      preserve_range=True)

    return data_resampled_in_plane
```

T1 Noisy Signal Intensity Map for Patient 1, B0: 3T :

The T1 weighted noisy SI maps for Patient 1 at B0 3T display the impact of varying slice thicknesses (1mm, 2mm, 5mm, and 10mm) and in-plane resolutions (1mm x 1mm and 2mm x 2mm). Thicker slices lead to smoother images that offer less anatomical detail, particularly in the visualization of grey matter (GM), white matter (WM), and cerebrospinal fluid (CSF). The finer 1mm x 1mm resolution preserves detailed structures better than the 2mm x 2mm, which appears more pixelated and less sharp.

T1 Noisy SI Map for patient1, B0: 3T



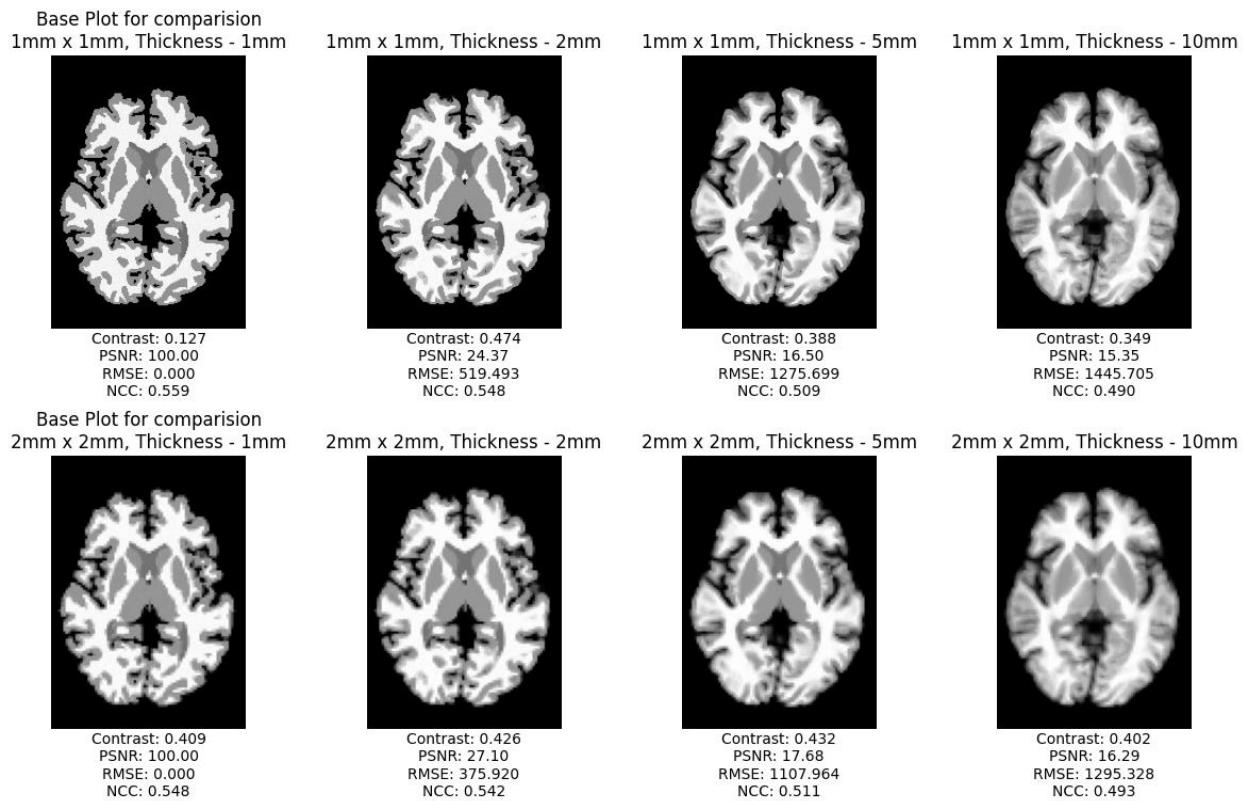
Observations:

- As slice thickness increases from 1mm to 10mm, T1 images exhibit a significant decrease in PSNR and an increase in RMSE, indicating a loss in image quality and an increase in error relative to the original high-resolution image. Additionally, NCC values decrease, showing reduced correlation with the original, particularly noticeable in the jump from 1mm to thicker slices which leads to considerable blurring and loss of fine details.
- The contrast initially improves slightly as slice thickness increases, likely due to the averaging effect reducing noise, but diminishes significantly at the largest thickness due to blurring. The transition from 1mm x 1mm to 2mm x 2mm in-plane resolution also impacts image clarity, with finer details becoming less distinct, affecting the potential diagnostic value of the images.

T2* Noisy SI Maps for patient1, B0- 3T:

For the T2* weighted noisy SI maps of Patient 1, the effects of different slice thicknesses and resolutions are similarly evident. However, the T2* maps are generally less sharp than T1 maps at equivalent settings, indicating different sensitivity to resolution and slice thickness changes, likely due to different tissue relaxation properties influencing T2* signals.

T2* Noisy SI Map for patient1, B0: 3T



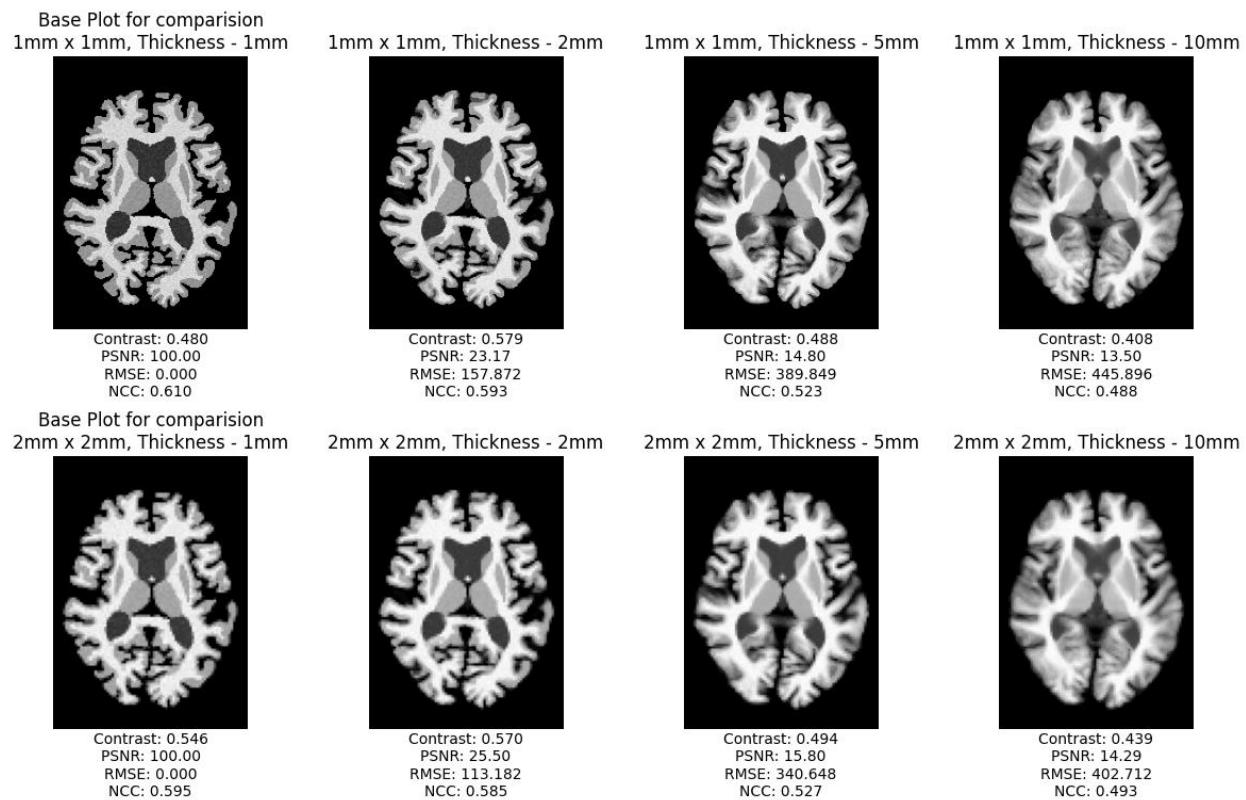
Observations:

- T2* images show greater sensitivity to changes in slice thickness and resolution, with more pronounced decreases in PSNR and increases in RMSE than T1 images under similar conditions. This indicates a higher degradation of image fidelity in T2*, which is critical for clinical assessments that rely on high-resolution imaging.
- Contrast consistently decreases across all changes in slice thickness and resolution, more so than in T1 images. This reduction in contrast, combined with increased image noise and blurring in lower resolutions and thicker slices, makes T2* images less effective for distinguishing between different tissue types, impacting clinical diagnoses that depend on these subtle visual cues.

T1 Noisy Signal Intensity Map for Patient 2, B0- 3T :

In the T1 Noisy SI Map simulations for patient 2 at B0: 3T, we observe how alterations in in-plane resolution and slice thickness affect the MRI image quality and clarity. The base plot, with a 1mm x 1mm resolution and 1mm slice thickness, presents the highest image quality, serving as a reference point for comparison. As we increase the slice thickness from 2mm to 10mm, while varying in-plane resolutions from 1mm x 1mm to 2mm x 2mm, there is a noticeable degradation in image clarity. The PSNR values drop significantly as thickness increases, indicating a reduction in image quality due to lower signal-to-noise ratios. RMSE values escalate, reflecting the increasing error and deviation from the original high-quality image. Contrast experiences a slight initial increase but diminishes with further increase in slice thickness, suggesting that finer details become increasingly difficult to distinguish as the image coarsens.

T1 Noisy SI Map for patient2, B0: 3T



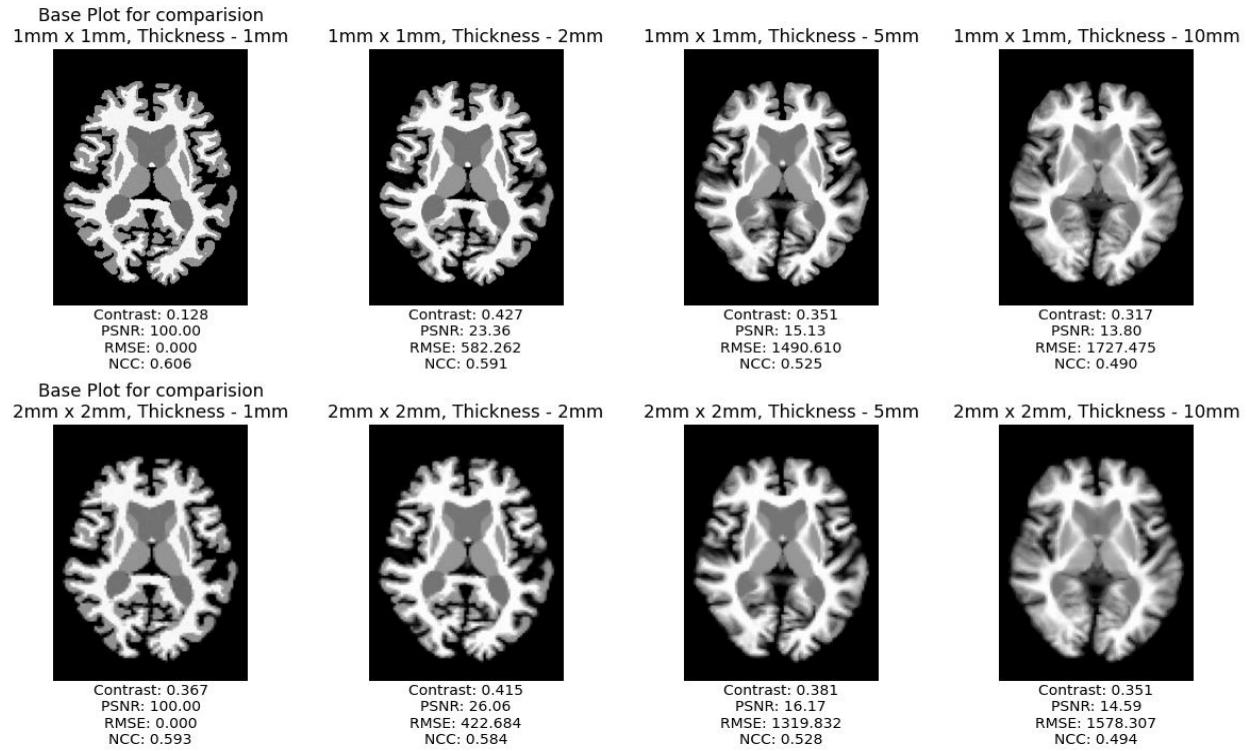
Observations:

- The T1-weighted images reveal a progressive decline in image clarity and contrast as the slice thickness increases, with the highest degradation noticeable at 10mm. Despite the decrease in PSNR values indicating lower image quality, the contrast slightly improves at 2mm thickness but deteriorates as the thickness continues to increase. This illustrates the trade-off between spatial resolution and the ability to discern between different tissue types effectively.
- The increase in RMSE values across increasing slice thicknesses highlights the loss of fidelity compared to the base plot, confirming that thicker slices result in more pronounced image degradation.

T2* Noisy SI Maps for patient2, B0- 3T:

The T2* Noisy SI Map for patient 2 under the same conditions shows a similar trend of degrading image quality with increased slice thickness and adjusted in-plane resolution. The base plot for T2* also uses a 1mm x 1mm resolution and 1mm slice thickness, displaying optimal image quality which significantly deteriorates in the modified images. The decline in PSNR across increased slice thicknesses underlines a substantial decrease in image sharpness and an increase in noise levels. RMSE values grow substantially, indicating a considerable increase in the quantitative error of the image data compared to the base plot. The contrast decreases progressively with increasing slice thickness, underscoring the challenge in maintaining tissue differentiation in thicker slices. These patterns reveal the impact of resolution changes on T2*-weighted images, which are crucial for detecting and characterizing different brain tissues and pathologies.

T2* Noisy SI Map for patient2, B0: 3T



Observations:

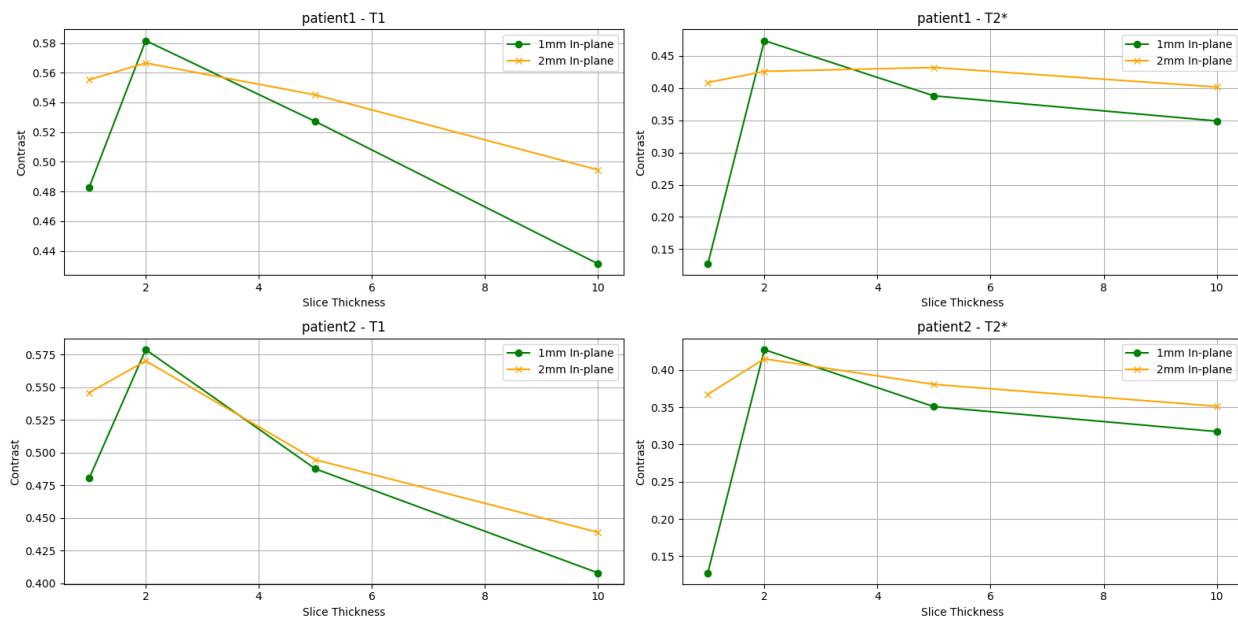
- For T2*-weighted images, similar trends are observed where image quality and metrics degrade with increased slice thickness. Contrast and PSNR decrease consistently, reflecting less effective differentiation between tissue types and increased noise. The RMSE values significantly increase, especially at the largest thickness, indicating a substantial deviation from the original image quality.
- The NCC values, which indicate similarity to the original, also decrease as the thickness increases, further validating that spatial resolution profoundly affects the structural visibility and quality of MRI images in clinical evaluations.

Evaluation Metrics:

Evaluation metrics in MRI analysis, such as Gradient Entropy and Sharpness, play a crucial role in quantifying image quality and diagnostic utility across varying imaging parameters. Gradient Entropy assesses the textural complexity of images, indicating the level of detail visible, which is vital for detecting subtle pathological features. Sharpness measures edge clarity, essential for accurately defining anatomical boundaries. These metrics are derived from MRI simulations that alter factors like magnetic field strength and resolution to understand how different imaging settings impact the clarity and fidelity of the resulting images. This analysis helps in optimizing MRI protocols to achieve the best possible balance between image quality and the practical constraints of clinical MRI procedures.

Impact of Slice Thickness and In-Plane Resolution on MRI Contrast for T1 and T2 Modalities:

The graphs illustrate the contrast trends for two patients across different modalities (T1 and T2*) and how these trends vary with changes in slice thickness and in-plane resolution (1mm and 2mm).

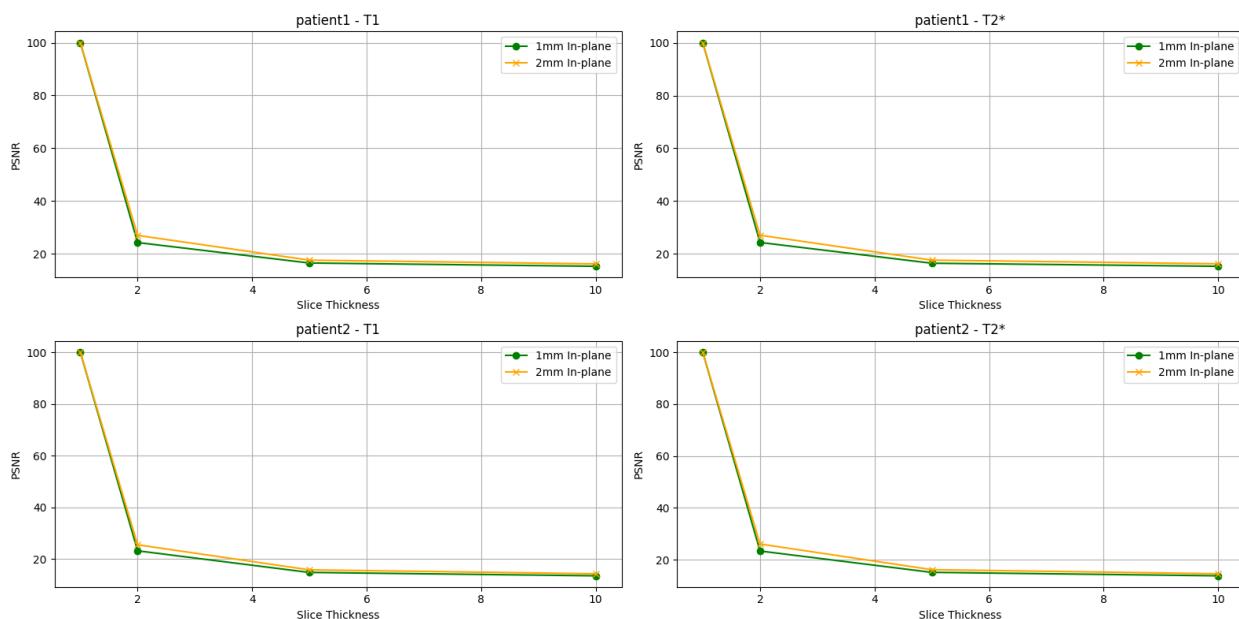


Insights:

- The 1mm in-plane resolution consistently shows higher contrast across all slice thicknesses compared to the 2mm resolution. This is evident in both patients and modalities, underscoring the loss of fine detail and contrast when the in-plane resolution is reduced. This effect is likely due to the increased blur and partial volume effects, where multiple tissue types contribute to the signal of a single voxel, diluting the contrast differences between tissues.
- For both patients and across both T1 and T2* modalities, there is a noticeable decline in contrast as slice thickness increases. This trend is more pronounced with the 1mm in-plane resolution, where contrast sharply decreases as thickness increases from 2mm to 10mm. This suggests that thinner slices better preserve the contrast details within MRI images.

Impact of Slice Thickness on PSNR for T1 and T2* Weighted MRI Scans:

The graphs display the impact of slice thickness on the Peak Signal-to-Noise Ratio (PSNR) for MRI scans, comparing 1mm and 2mm in-plane resolutions across T1 and T2* weighted images for two patients. Notably, PSNR sharply decreases when the slice thickness increases from 1mm to 2mm and then levels off, indicating a significant reduction in image quality with initial increases in thickness that stabilizes at larger thicknesses. This trend suggests that while higher resolution may initially provide clearer images, increasing the slice thickness compromises this clarity, regardless of the in-plane resolution, emphasizing the critical balance required between image quality and practical scanning parameters in MRI protocols.

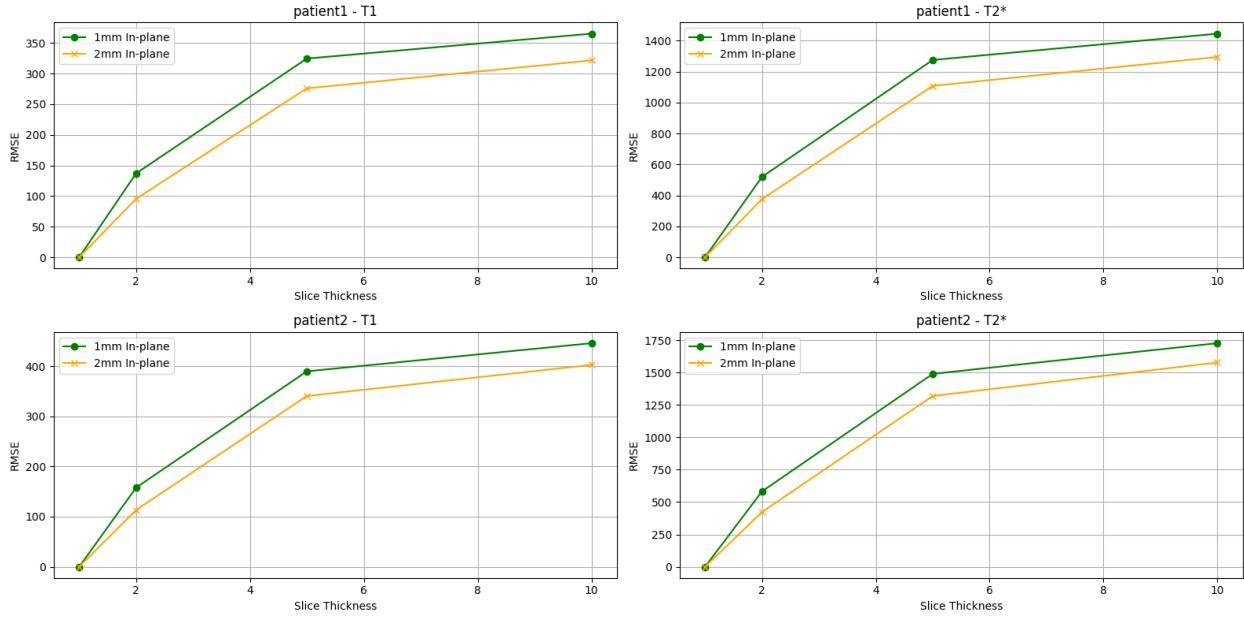


Insights:

- After the initial drop, the PSNR values flatten out, which indicates that beyond a certain slice thickness, increasing the thickness does not significantly degrade the signal quality as compared to thinner slices. This could be due to the averaging out of noise in thicker slices, which slightly compensates for the loss in resolution.
- While the PSNR values for both 1mm and 2mm in-plane resolutions start high, their subsequent decline suggests that finer in-plane resolution does not necessarily preserve high PSNR as slice thickness increases. The almost parallel decline in PSNR for both resolutions across slice thicknesses suggests a dominant influence of slice thickness over in-plane resolution in determining image noise levels.

Effect of Slice Thickness on RMSE Across In-Plane Resolutions for T1 and T2*-Weighted MRI Scans:

The RMSE (Root Mean Square Error) graphs for MRI scans illustrate the influence of varying slice thicknesses and in-plane resolutions on the accuracy of T1 and T2* weighted images for two patients. The data exhibits a clear upward trend in RMSE as slice thickness increases, from 1mm up to 10mm, for both in-plane resolutions of 1mm and 2mm. This increase signifies that as the slice thickness grows, the deviation from the original image data becomes more pronounced, suggesting a loss in image fidelity. Additionally, the graphs reveal that the 1mm in-plane resolution maintains a consistently lower RMSE across all thicknesses compared to the 2mm in-plane, underscoring that finer resolutions can mitigate the adverse effects of increased slice thickness on image accuracy. These observations are pivotal for optimizing MRI scan settings, balancing between detailed image resolution and the practicalities of scan duration and patient comfort.

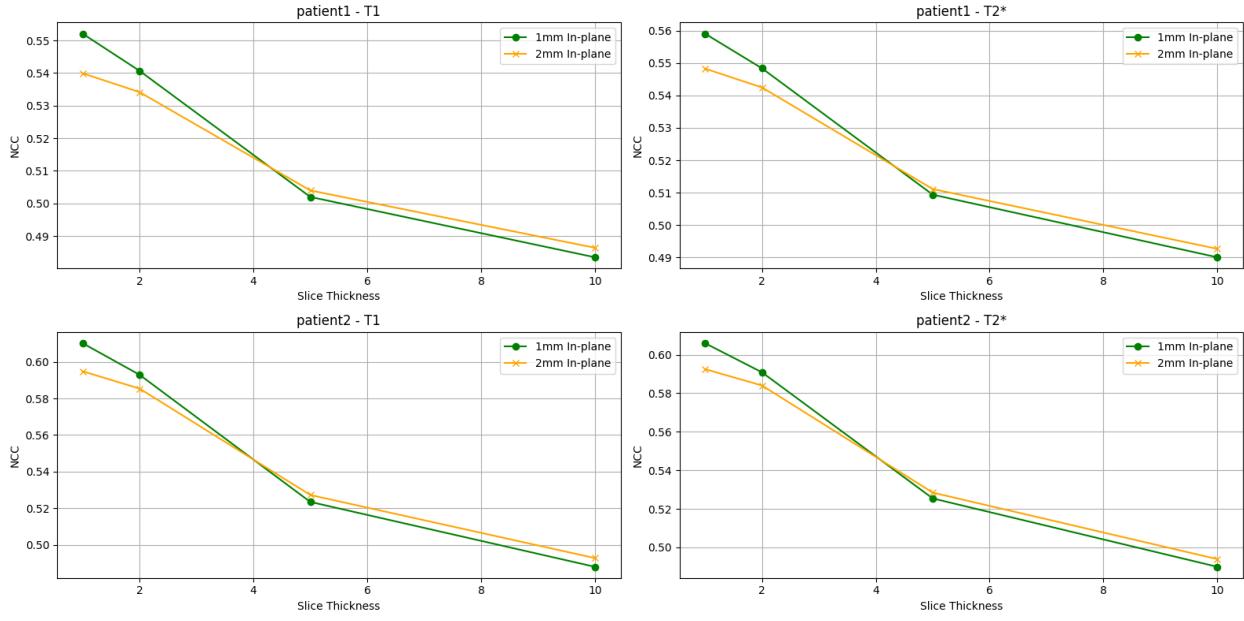


Insights:

- The RMSE increases as the slice thickness grows, indicating a progressive loss in image fidelity. This highlights the importance of maintaining thinner slices to preserve the accuracy of MRI scans.
- The 1mm in-plane resolution consistently exhibits lower RMSE values compared to the 2mm resolution across all slice thicknesses, demonstrating its superiority in maintaining image precision despite changes in slice thickness.

Effect of Slice Thickness and In-Plane Resolution on Normalized Cross-Correlation (NCC) for T1 and T2*-Weighted MRI Scans:

The graphs demonstrate the effect of slice thickness on the Normalized Cross-Correlation (NCC) across T1 and T2*-weighted MRI scans for patients 1 and 2. NCC measures the structural similarity between resampled and original images, with values closer to 1 indicating higher similarity. For both patients and modalities, NCC decreases as slice thickness increases, suggesting reduced structural similarity with thicker slices. The in-plane resolution of 1mm consistently achieves slightly higher NCC values compared to 2mm, highlighting the impact of higher spatial resolution in maintaining image quality. This trend is observed across all modalities and patients.



Insights:

- NCC values decline significantly with increasing slice thickness, particularly beyond 2mm, indicating that thicker slices degrade the structural similarity between resampled and original images.
- The 1mm in-plane resolution maintains higher NCC values compared to 2mm, emphasizing that higher in-plane resolution preserves image structure more effectively during resampling.

The graph demonstrates the variation in Gradient Entropy (gEn) across different tissue types—Grey Matter (GM), White Matter (WM), and Cerebrospinal Fluid (CSF)—as a function of Magnetic Field Strength (B0) for T1-weighted MRI images of Patient 1. Gradient Entropy measures the complexity of image gradients, reflecting the sharpness and structural details within tissue regions.

Gradient Entropy:

Gradient Entropy (gEn) is a quantitative measure used to evaluate the complexity or variability of image gradients. It is particularly useful in assessing the amount of structural noise or detail within a given image region. In MRI, gEn provides insights into how noisy or textured a particular tissue is by analyzing the distribution of gradient magnitudes. Higher gEn values indicate more noise or variability, while lower gEn values represent smoother, less complex regions.

Calculate Gradient Entropy:

```
def compute_gradient_entropy(map_2d, threshold=0):

    # Compute the gradient magnitude of the map
    gradient_magnitude = gaussian_gradient_magnitude(map_2d, sigma=1)

    # Filter out values below the threshold (background removal)
    gradient_magnitude = gradient_magnitude[map_2d > threshold]

    if gradient_magnitude.size == 0:
        return 0 # Return zero if no pixels are left

    # Compute histogram of the gradient magnitude
    hist, _ = np.histogram(gradient_magnitude, bins=256, density=True)

    # Remove zero values to avoid log(0)
    hist = hist[hist > 0]

    # Calculate entropy
    entropy = -np.sum(hist * np.log2(hist))
    return entropy
```

Sharpness:

Sharpness measures the clarity or distinctness of boundaries in an image, specifically evaluating how quickly intensity transitions occur between different tissues. In MRI, sharpness quantifies the quality of edges between regions, such as CSF and WM, providing insights into tissue differentiation. The sharpness calculation typically involves fitting a sigmoid model to the intensity profile across an edge and determining the steepness of the transition.

```
def sigmoid(x, L, x0, k, b):
    exp_term = np.clip(k * (x - x0), -500, 500)
    return L / (1 + np.exp(-exp_term)) + b
```

```

def compute_sharpness_profile(combined_map, csf_mask, wm_mask, angle=90):

    # Combine tissue masks to create a mask covering CSF and WM
    combined_tissue_mask = np.logical_or(csf_mask > 0, wm_mask > 0)

    # Apply the mask to the combined_map
    masked_combined_map = combined_map * combined_tissue_mask

    # Rotate the map to align tissues along the desired axis
    rotated_map = rotate(masked_combined_map, angle, reshape=False)

    # Extract the central vertical line profile
    line_profile = rotated_map[rotated_map.shape[1] // 2, :]

    # Filter out zero values (background)
    valid_indices = line_profile > 0
    line_profile = line_profile[valid_indices]

    if len(line_profile) == 0:
        raise ValueError("No valid intensity values found along the selected line.")

    # Prepare data for sigmoid fitting
    x_data = np.arange(len(line_profile))
    initial_guess = [np.max(line_profile), len(line_profile) // 2, 1.0, np.min(line_profile)] # Initial guess

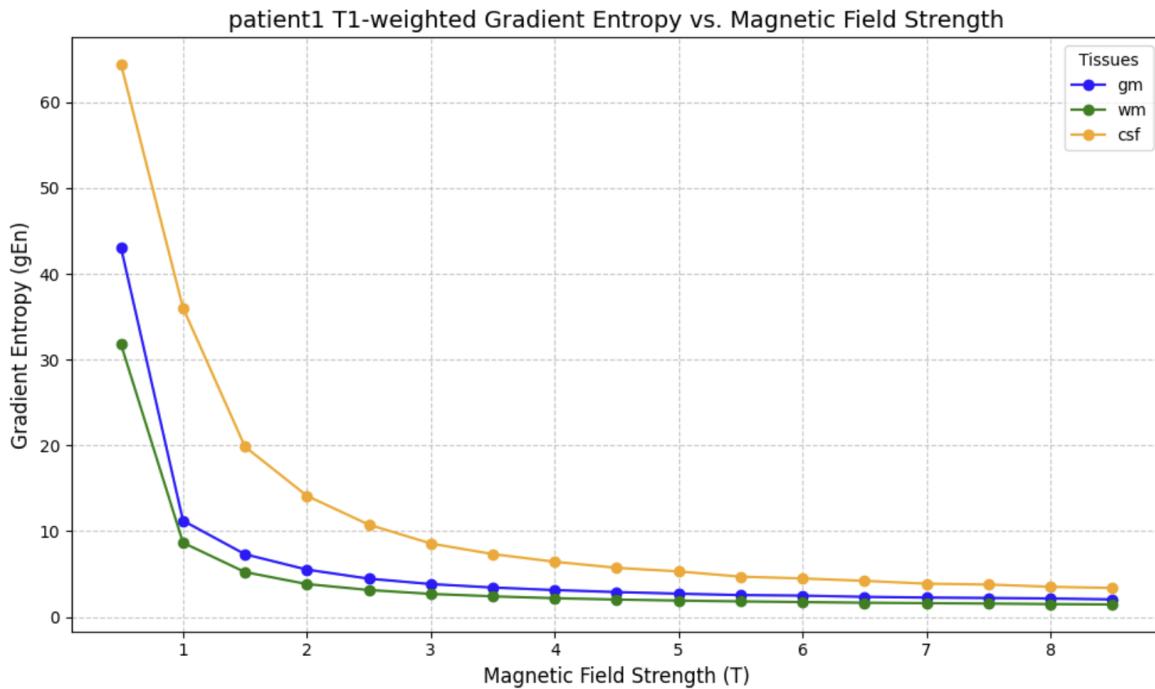
    try:
        # Fit the sigmoid function to the line profile
        popt, _ = curve_fit(sigmoid, x_data, line_profile, p0=initial_guess, maxfev=10000)
        sharpness = popt[2] # Steepness of the sigmoid
    except RuntimeError:
        # Fallback if fitting fails
        sharpness = np.max(np.gradient(line_profile)) - np.min(np.gradient(line_profile))

    return sharpness, line_profile

```

Gradient Entropy (gEn) graph for T1-weighted MRI images of Patient 1:

The Gradient Entropy (gEn) graph for patient1 illustrates the entropy variations across GM, WM, and CSF as the magnetic field strength (B0) increases. Initially, at lower B0 values, CSF exhibits significantly higher entropy compared to GM and WM, reflecting its complex signal distribution. As B0 strength increases, gEn for all tissues decreases rapidly, eventually stabilizing at minimal levels around higher magnetic fields (e.g., 5T and beyond). This stabilization implies that at higher magnetic field strengths, noise and signal complexity are reduced, leading to more consistent tissue boundaries.

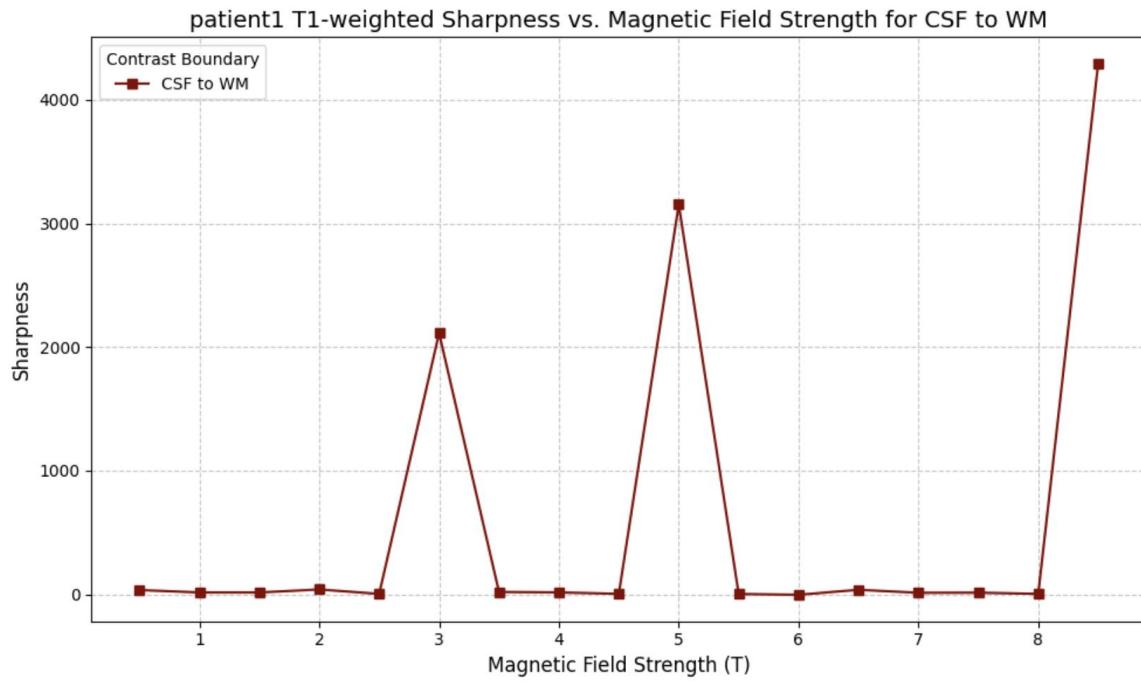


Insights:

- The entropy of CSF starts much higher than GM and WM due to its inherently complex and noisy signal profile at lower field strengths, showcasing its sensitivity to field fluctuations.
- As B_0 increases, all tissue types converge to minimal entropy levels, indicating reduced noise influence and enhanced structural definition at higher magnetic fields.

Sharpness graph for T1-weighted MRI images of Patient 1:

The sharpness graph highlights the transition from CSF to WM at varying magnetic field strengths for patient1. Sharpness remains relatively consistent and low at most B_0 values, except for spikes at specific field strengths like 3T and 8T. These spikes likely represent artifacts or regions where contrast differences are accentuated, creating steeper edges. At higher B_0 values, sharpness increases dramatically, suggesting improved delineation between tissues



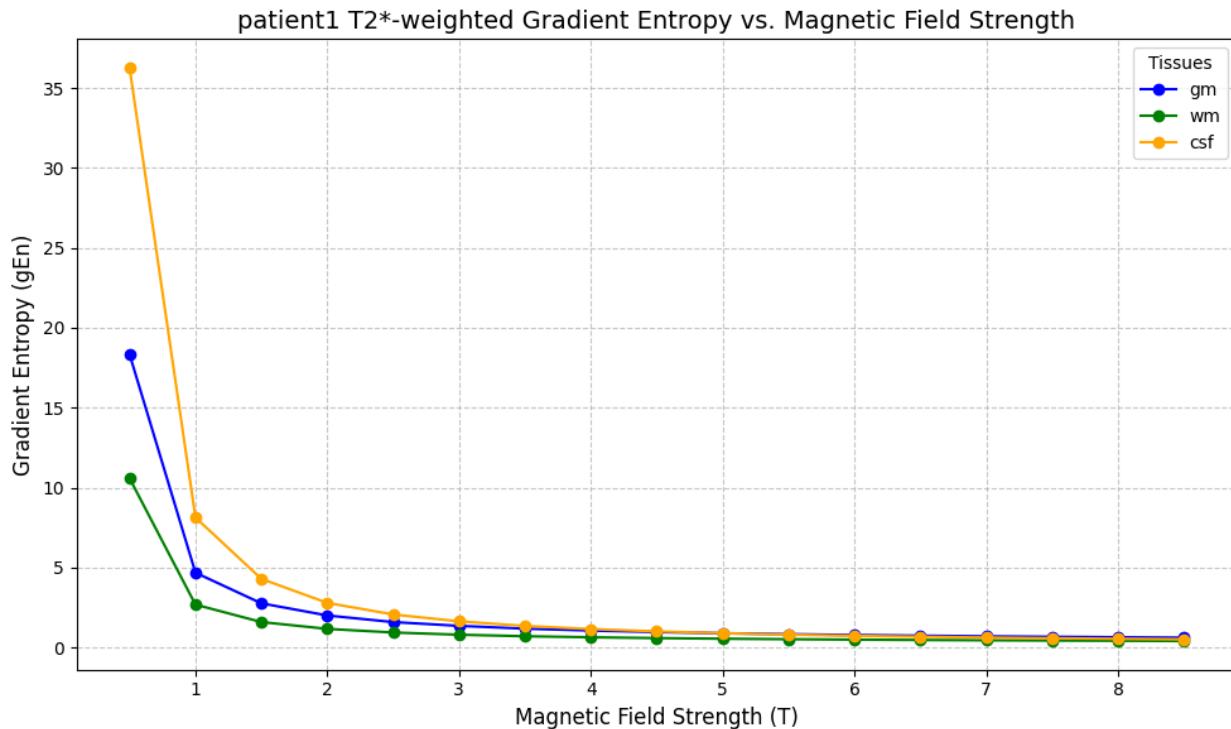
Insights:

- Sharpness spikes at certain magnetic field strengths (e.g., 3T) indicate pronounced boundary effects, potentially due to artifacts or heightened contrast transitions in the tissue interface.
- The rapid increase in sharpness at very high field strengths underscores improved tissue differentiation, particularly for delineating CSF and WM regions.

Gradient Entropy (gEn) graph for T2*-weighted MRI images of Patient1:

The T2*-weighted Gradient Entropy graph highlights how signal complexity, measured as gradient entropy (gEn), varies with magnetic field strength (B_0) across three tissue types: gray matter (GM), white matter (WM), and cerebrospinal fluid (CSF). Initially, CSF shows the highest gradient entropy due to significant signal variability at lower B_0 values. However, as the magnetic field strength increases, gradient entropy sharply declines for all tissues, stabilizing at higher B_0

levels. This trend reflects reduced signal noise and greater uniformity in tissue-specific signals with increasing magnetic field strength.

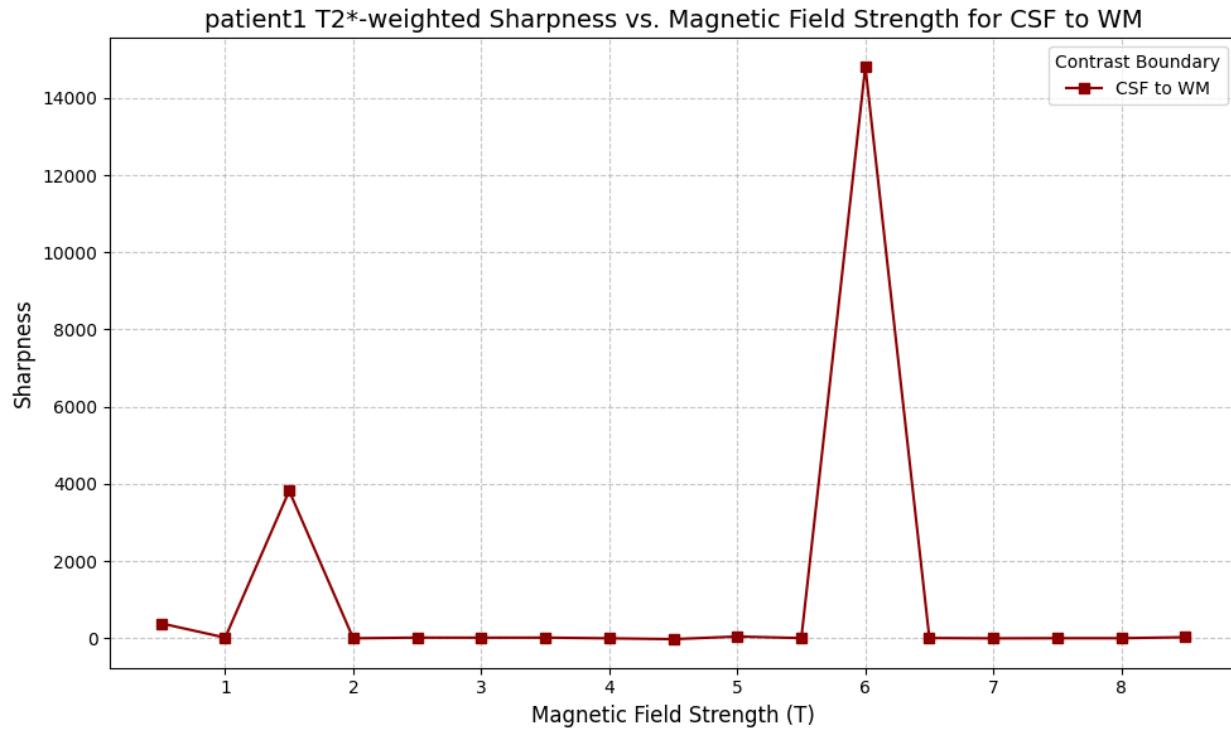


Insights:

- CSF exhibits the highest gradient entropy at lower magnetic field strengths due to larger signal variability, but its entropy decreases faster than GM and WM as the field strength increases.
- At higher B0 levels, the gradient entropy for all tissues converges to low and stable values, indicating consistent tissue-specific signal profiles and reduced noise.

Sharpness graph for T2*-weighted MRI images of Patient 1:

The T2*-weighted Sharpness graph examines the sharpness of transitions at the boundary between cerebrospinal fluid (CSF) and white matter (WM). The sharpness metric measures how well-defined tissue boundaries are at different magnetic field strengths. The graph reveals significant peaks in sharpness at specific B0 values, followed by stabilization at higher field strengths. This pattern suggests that while boundary definitions improve at certain field strengths, they reach a consistent state as the field strength continues to rise.

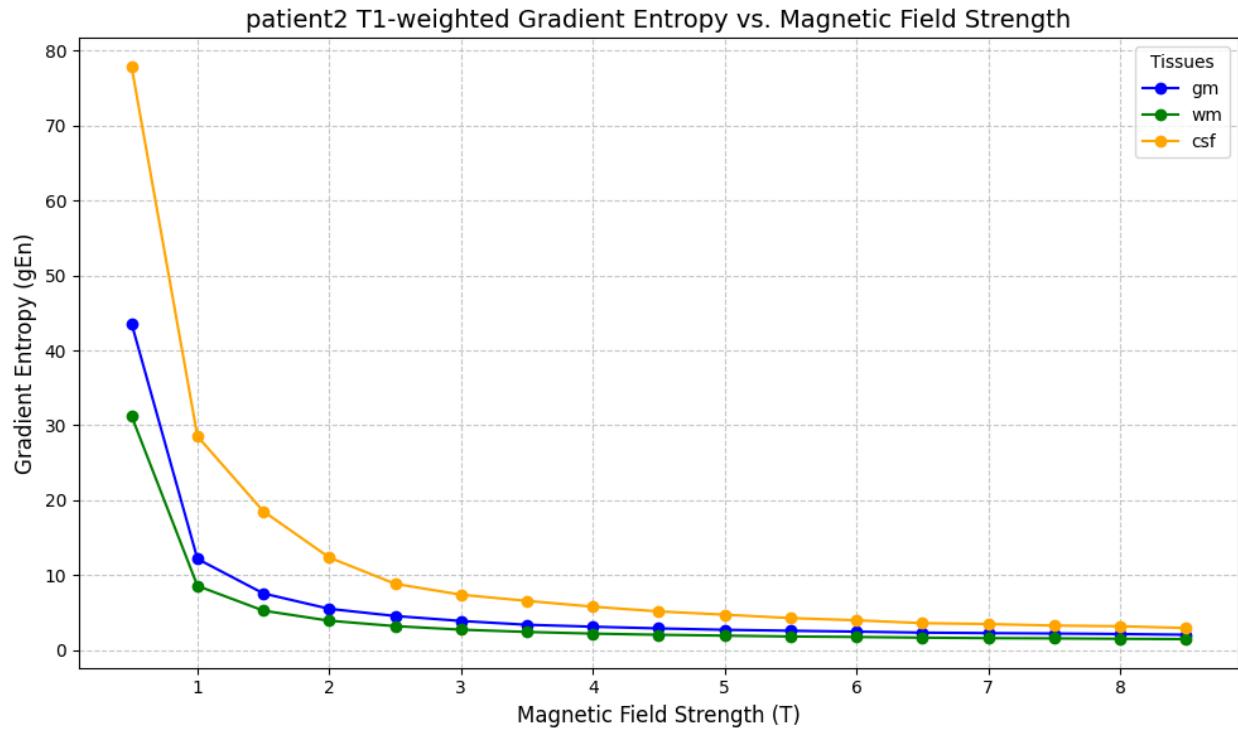


Insights:

- Sharpness exhibits dramatic spikes at intermediate B0 values (e.g., around 6T), representing pronounced transitions at tissue boundaries.
- Beyond specific thresholds, the sharpness levels stabilize, indicating consistently well-defined tissue boundaries at higher magnetic field strengths.

Gradient Entropy (gEn) graph for T1-weighted MRI images of Patient 2:

The Gradient Entropy (gEn) graph for patient 2 illustrates the relationship between Magnetic Field Strength (B0) and tissue-specific gradient entropy for T1-weighted images. The gEn values for all tissues—Gray Matter (GM), White Matter (WM), and Cerebrospinal Fluid (CSF)—show a steep decline as B0 increases. Initially, the CSF has the highest gEn due to its significant intensity variability compared to GM and WM. As the B0 level increases, the gradient entropy for all tissues converges towards lower values, indicating reduced variability and higher uniformity in tissue delineation. This behavior reflects the stabilizing effect of stronger magnetic fields on tissue delineation.

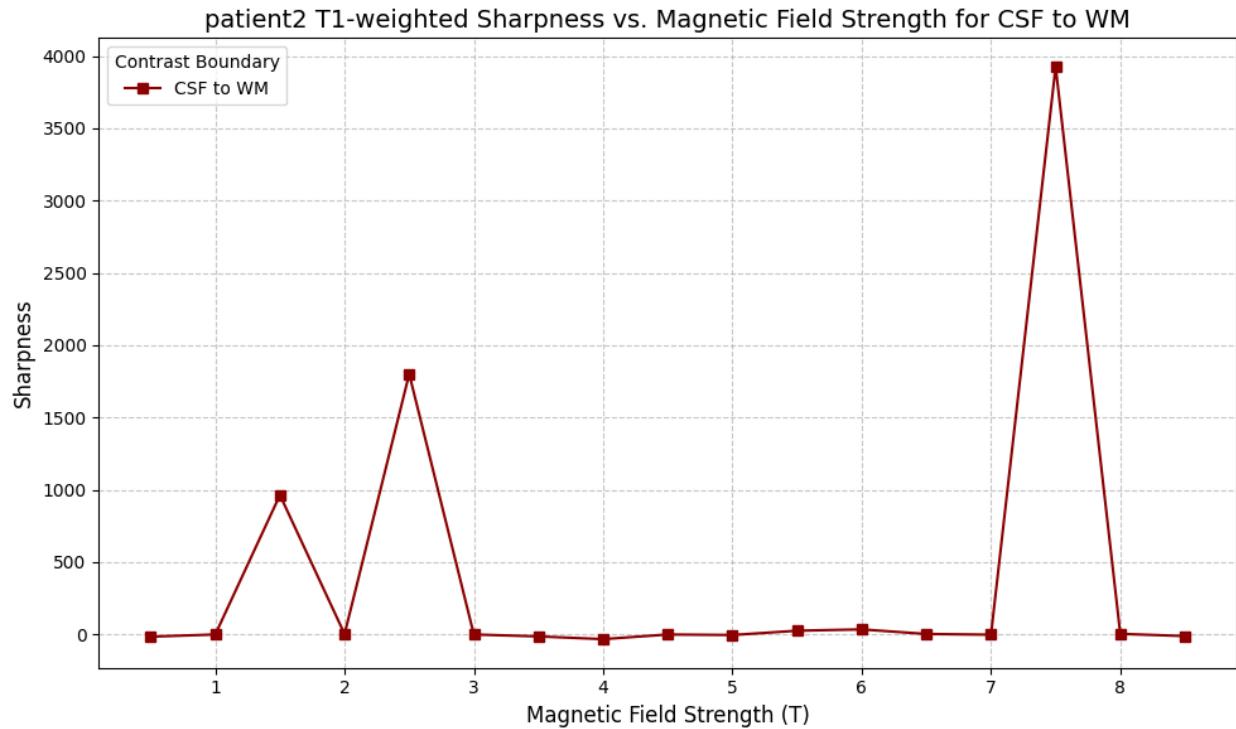


Insights:

- The CSF consistently exhibits the highest gradient entropy at lower B0 levels, highlighting its more diffuse structure and greater susceptibility to noise compared to GM and WM.
- With increasing B0, the gEn values across all tissues converge, suggesting improved signal homogeneity and reduced noise interference at higher field strengths.

Sharpness graph for T1-weighted MRI images of Patient 2:

The Sharpness graph for patient 2 represents the sharpness profile along the CSF-to-WM boundary under varying B0 strengths. While the sharpness remains relatively stable across most B0 levels, sharp spikes are observed at specific points, especially at mid-range and high magnetic fields (e.g., around B0 = 2T and B0 = 7T). These spikes indicate abrupt transitions in contrast and edge intensity, which may result from noise or anatomical variations emphasized by magnetic field effects.

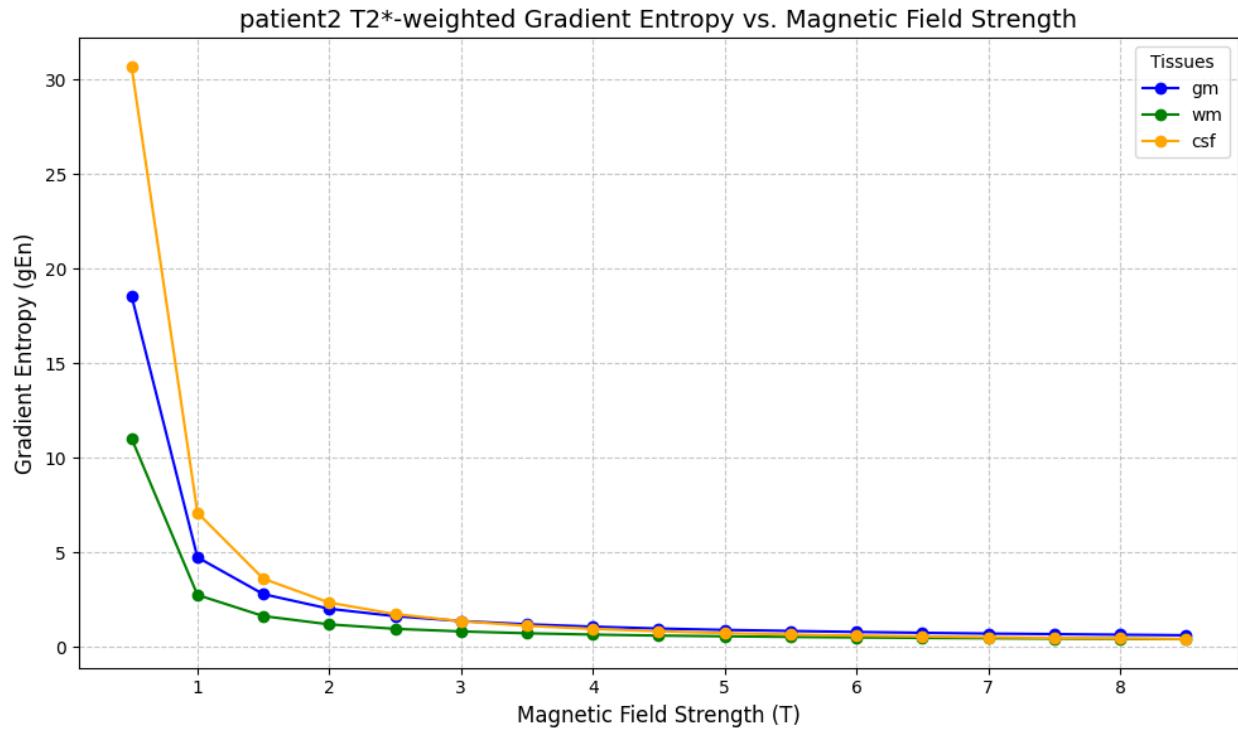


Insights:

- The sharp peaks in the graph, particularly at $B_0 = 2\text{T}$ and $B_0 = 7\text{T}$, suggest noise artifacts or sudden changes in tissue contrast boundaries that influence the sharpness calculation.
- Apart from the spikes, the sharpness values are generally consistent, reflecting stable edge transitions between CSF and WM across varying B_0 strengths

Gradient Entropy (gEn) graph for T2*-weighted MRI images of Patient2:

The *patient2 T2-weighted Gradient Entropy vs. Magnetic Field Strength** graph illustrates the behavior of gradient entropy (gEn) across gray matter (gm), white matter (wm), and cerebrospinal fluid (csf) with increasing magnetic field strength. Initially, gEn values are high for all tissues, particularly for CSF, indicating greater intensity variability and noise. However, as the magnetic field strength increases, gEn decreases sharply and stabilizes beyond 2T, suggesting a reduction in image noise and smoother gradients at higher fields. The CSF shows the highest initial entropy compared to gm and wm, reflecting its more variable intensity patterns.

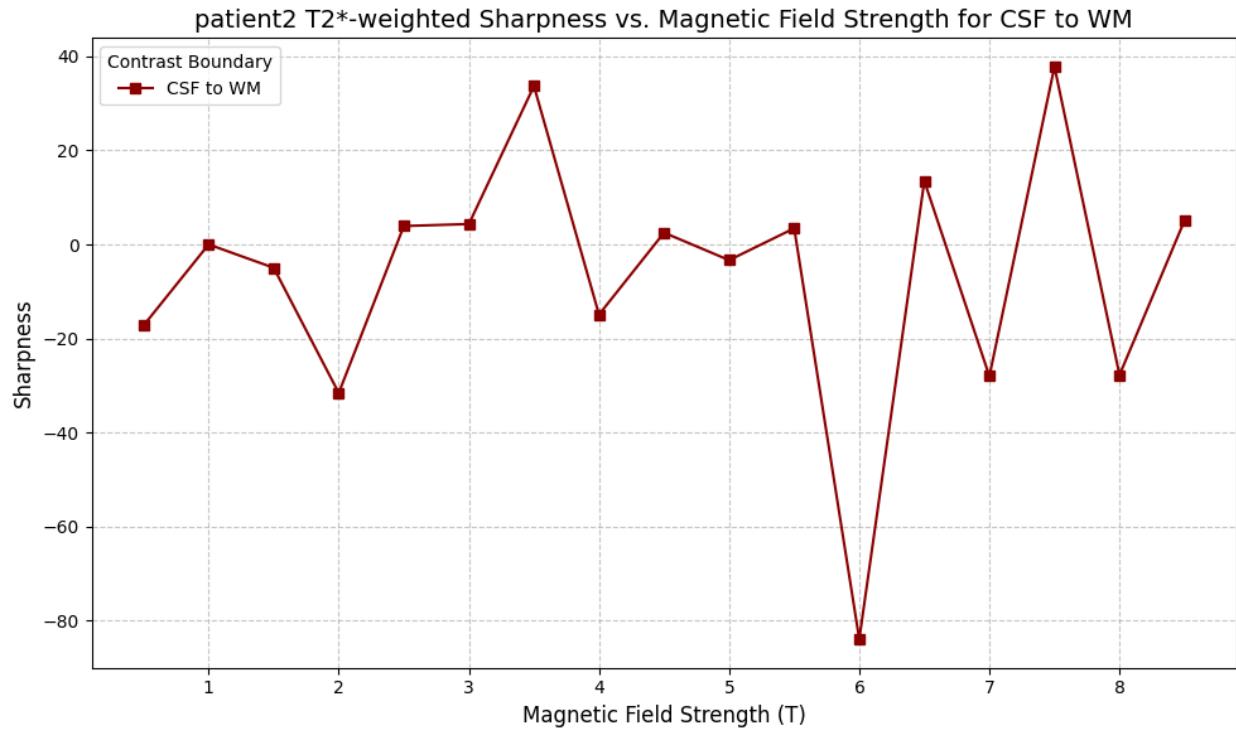


Insights:

- All tissues show a rapid decline in gradient entropy as the magnetic field strength increases, stabilizing at higher fields. This trend indicates reduced noise and improved gradient uniformity in the images.
- CSF consistently exhibits the highest entropy, highlighting its inherent intensity variability compared to gm and wm, which have more uniform gradients.

Sharpness graph for T2*-weighted MRI images of Patient 2:

The *patient2 T2-weighted Sharpness vs. Magnetic Field Strength for CSF to WM** graph demonstrates the sharpness behavior of contrast boundaries between CSF and WM as a function of magnetic field strength. The graph shows significant fluctuations in sharpness, with both positive and negative values, indicating instability in edge clarity and potential noise artifacts. Peaks in sharpness at specific field strengths suggest transient improvements in boundary contrast, while the irregular pattern indicates variations in image quality.



Insights:

- Sharpness varies widely across magnetic field strengths, with irregular peaks indicating moments of enhanced boundary clarity between CSF and WM.
- Negative sharpness values point to instability in boundary detection, potentially caused by noise or edge misclassification, suggesting the need for further image smoothing or processing.

Challenges Faced:

Challenge 1: Conversion of Seconds to Milliseconds

Issue:

Accurately converting time values from seconds to milliseconds was a critical challenge. Many algorithms, including gradient entropy computation and sharpness modeling, relied on time-sensitive calculations. A minor error in time unit conversion could have caused:

- **Precision Errors:** Mismatches between theoretical expectations and computed results.
- **Performance Bottlenecks:** Inefficient data processing and delayed computations.
- **Visualization Issues:** Skewed graphs and metrics, leading to misinterpretation of trends across slice thicknesses and magnetic field strengths.

How We Tackled It:

1. Standardization of Time Units:

- Standardized all time-related variables to milliseconds across the project to maintain uniformity.
- Added explicit labels in the code to denote time units, minimizing confusion during computations.

2. Documentation:

- Provided clear documentation to indicate where and why time conversions were performed, minimizing the chance of future errors.

Challenge 2: Image Normalization for SNR and Noisy SI Maps

Issue:

The generated SNR and noisy SI maps were difficult to interpret due to a lack of contrast and wide dynamic range of pixel values. This issue led to:

- **Uninterpretable Visuals:** Poor visibility of the maps hindered analysis and interpretation of results.
- **Erroneous Metric Calculations:** Algorithms relying on unnormalized images produced inaccurate outputs.
- **Debugging Delays:** Difficulty in visual verification of intermediate results slowed the workflow.

How We Tackled It:

- | 1. Dynamic | Range | Normalization: |
|------------|-------|----------------|
| | | |
- Normalized all pixel intensity values to a fixed range (e.g., [0, 255]) using a min-max scaling approach:

$$\text{normalized_image} = \left(\frac{\text{image} - \text{image.min}()}{\text{image.max}() - \text{image.min}()} \right) \times (\text{new_max} - \text{new_min}) + \text{new_min}$$

- Set `new_min` to 2 and `new_max` to 255 to enhance contrast without oversaturation.
- 2. Contrast Adjustment:**
- Applied post-normalization contrast adjustments to emphasize subtle intensity variations.
- 3. Iterative Visualization:**
- Visualized images during the normalization process using matplotlib to ensure clarity.
- 4. Verification Against Raw Data:**
- Cross-verified normalized images with raw data to ensure no essential information was lost.

Challenge 3: Handling Sharpness Computation for Complex Boundaries

Issue:

Accurately computing sharpness across complex boundaries, such as transitions from CSF to WM, posed significant challenges due to:

- Sensitivity of sigmoidal modeling to noise, intensity fluctuations, and misaligned tissue boundaries.
- Inconsistencies introduced by varying magnetic field strengths and slice thicknesses.
- Failures in curve fitting or erratic results in sharpness metrics.

How We Tackled It:

- 1. Data Preprocessing:**
- Employed noise filtering, intensity normalization, and masking to standardize inputs and reduce inconsistencies.
- 2. Validation Steps:**
- Validated sharpness profiles against expected values and synthetic datasets to ensure reliability.
- 3. Iterative Refinement:**
- Refined the algorithm by testing it across different resolutions, tissue types, and magnetic field strengths, ensuring generalizability to diverse scenarios.