COSC 4372 – Assignment 3

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10/24/2024

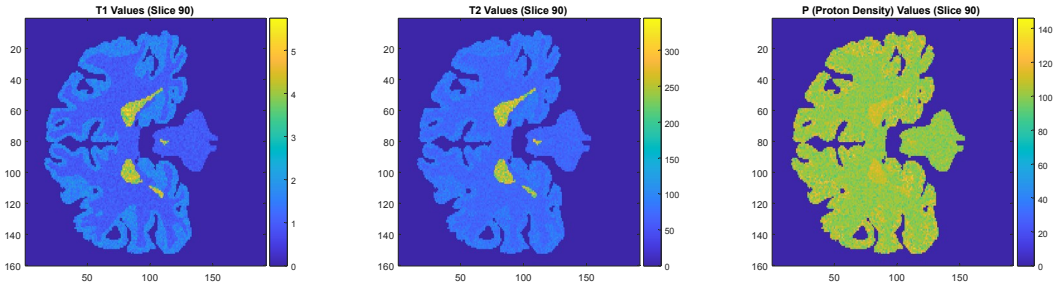
github link: https://github.com/DanKalh/4372-hw3-fall2024-DanKalh

I Problem

In this project, our goal is to generate and analyze synthetic MRI images by manipulating different acquisition parameters (TR, TE, TI, and flip angle) across three MRI pulse sequences: Spin Echo (SE), T1 Inversion Recovery (IR), and Gradient Recalled Echo (GRE). By assigning T1, T2, and proton density (P) values to segmented tissue regions (Gray Matter, White Matter, and CSF), we study how changes in these parameters affect signal intensity (SI) and tissue contrast.

II Method

We used the OASIS dataset to load MRI images. The focus was on axial slice 90, where the compartments representing GM, WM, and CSF were segmented.



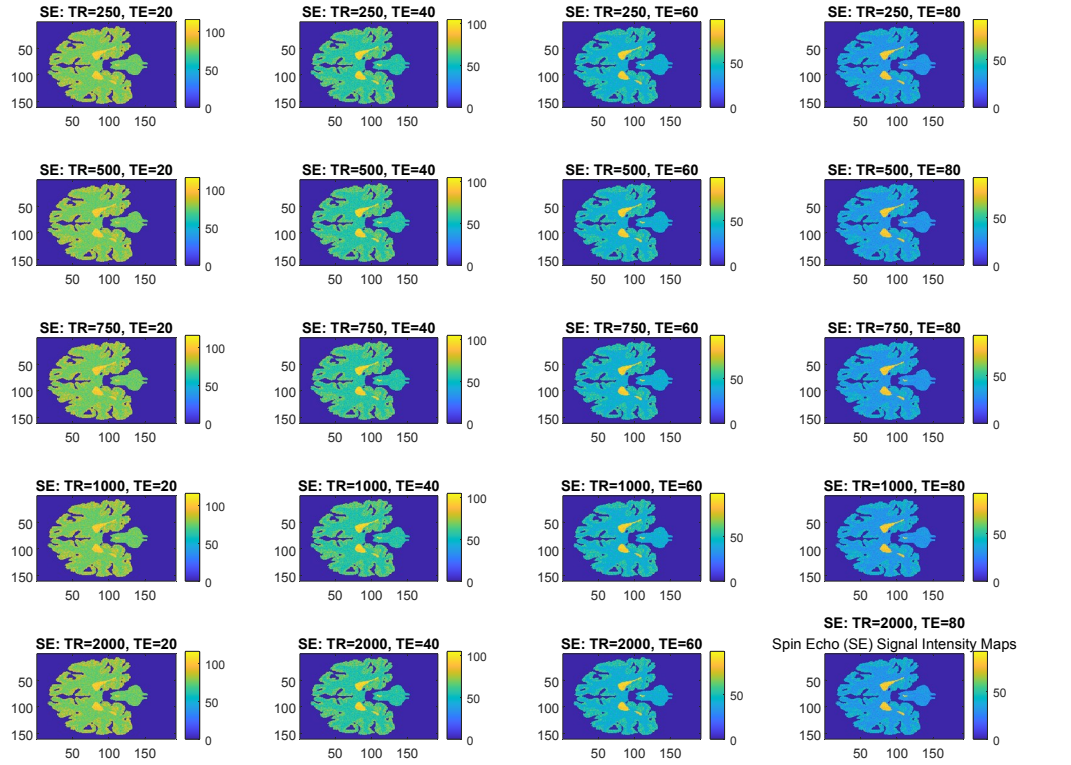
By isolating these compartments, we can accurately simulate the signal intensity for each tissue type based on its physical properties.

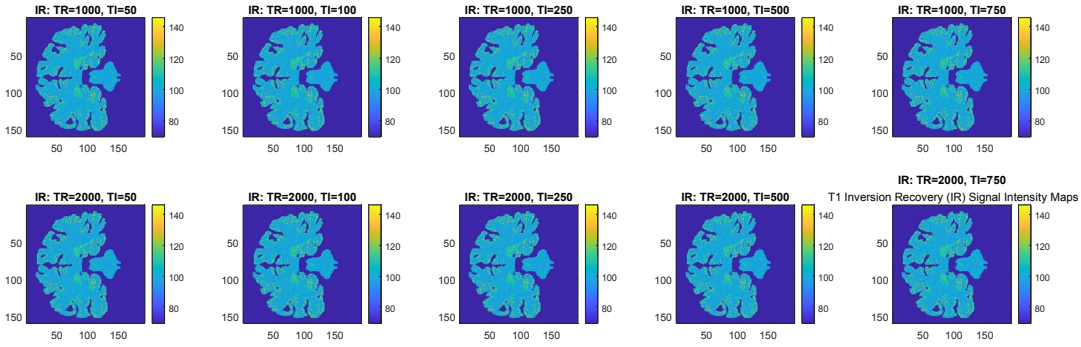
III Implementation

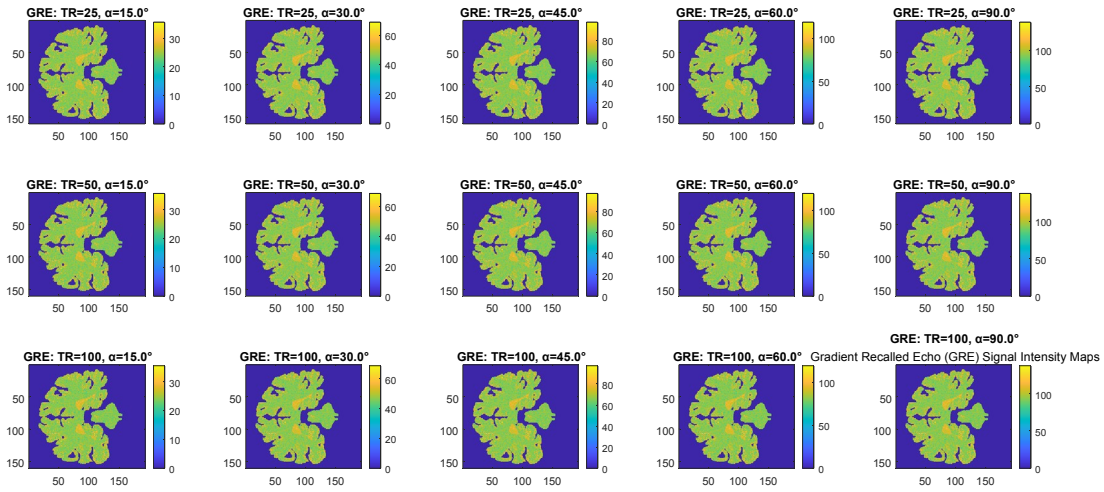
Spin Echo, T1 Inversion Recovery, and GRE Calculations:

For each pulse sequence, signal intensity was calculated using the respective formulas for Spin Echo, T1 Inversion Recovery, and Gradient Recalled Echo. The acquisition parameters TR, TE, TI, and flip angle were varied to generate the SI maps.

*label in bottom-right image for each







In each sequence, TR and TE significantly affect how quickly tissues recover their magnetization or lose their transverse magnetization. TI and α influence contrast by controlling when we observe the tissues during the recovery process or with a particular flip angle. These maps help visualize the changes in contrast and signal intensity across tissues.

Generating Signal Intensity Maps:

For each tissue type, SI maps were generated using the T1, T2, and P values combined with the respective MRI acquisition parameters.

*screenshots from terminal output of c_generate_si_maps.m

```
--- Spin Echo (SE) ---
TR=250, TE=20 -> GM=82.5563, WM=74.9157, CSF=101.5912
TR=250, TE=40 -> GM=65.0284, WM=56.1458, CSF=93.7866
TR=250, TE=60 -> GM=51.2832, WM=42.1253, CSF=86.5887
TR=250, TE=80 -> GM=40.4903, WM=31.6404, CSF=79.9499
TR=500, TE=20 -> GM=82.5563, WM=74.9157, CSF=101.5912
TR=500, TE=40 -> GM=65.0284, WM=56.1458, CSF=93.7866
TR=500, TE=60 -> GM=51.2832, WM=42.1253, CSF=86.5887
TR=500, TE=80 -> GM=40.4903, WM=31.6404, CSF=79.9499
TR=750, TE=20 -> GM=82.5563, WM=74.9157, CSF=101.5912
TR=750, TE=40 -> GM=65.0284, WM=56.1458, CSF=93.7866
TR=750, TE=60 -> GM=51.2832, WM=42.1253, CSF=86.5887
TR=750, TE=80 -> GM=40.4903, WM=31.6404, CSF=79.9499
TR=1000, TE=20 -> GM=82.5563, WM=74.9157, CSF=101.5912
TR=1000, TE=40 -> GM=65.0284, WM=56.1458, CSF=93.7866
TR=1000, TE=60 -> GM=51.2832, WM=42.1253, CSF=86.5887
TR=1000, TE=80 -> GM=40.4903, WM=31.6404, CSF=79.9499
TR=2000, TE=20 -> GM=82.5563, WM=74.9157, CSF=101.5912
TR=2000, TE=40 -> GM=65.0284, WM=56.1458, CSF=93.7866
TR=2000, TE=60 -> GM=51.2832, WM=42.1253, CSF=86.5887
TR=2000, TE=80 -> GM=40.4903, WM=31.6404, CSF=79.9499

--- T1 Inversion Recovery (IR) ---
TR=1000, TI=50 -> GM=104.9384, WM=100.0744, CSF=110.0516
TR=1000, TI=100 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=1000, TI=250 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=1000, TI=500 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=1000, TI=750 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=2000, TI=50 -> GM=104.9384, WM=100.0744, CSF=110.0516
TR=2000, TI=100 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=2000, TI=250 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=2000, TI=500 -> GM=104.9384, WM=100.0744, CSF=110.0544
TR=2000, TI=750 -> GM=104.9384, WM=100.0744, CSF=110.0544
```

```
--- Gradient Recalled Echo (GRE) ---
TR=25, α=15.0 -> GM=25.5760, WM=24.0899, CSF=27.9169
TR=25, α=30.0 -> GM=49.4091, WM=46.5381, CSF=53.9149
TR=25, α=45.0 -> GM=69.8750, WM=65.8148, CSF=76.2102
TR=25, α=60.0 -> GM=85.5790, WM=80.6064, CSF=93.2791
TR=25, α=90.0 -> GM=98.8181, WM=93.0762, CSF=107.5457
TR=50, α=15.0 -> GM=25.5760, WM=24.0899, CSF=27.9198
TR=50, α=30.0 -> GM=49.4091, WM=46.5381, CSF=53.9368
TR=50, α=45.0 -> GM=69.8750, WM=65.8148, CSF=76.2781
TR=50, α=60.0 -> GM=85.5791, WM=80.6064, CSF=93.4209
TR=50, α=90.0 -> GM=98.8182, WM=93.0762, CSF=107.8725
TR=100, α=15.0 -> GM=25.5760, WM=24.0899, CSF=27.9198
TR=100, α=30.0 -> GM=49.4091, WM=46.5381, CSF=53.9369
TR=100, α=45.0 -> GM=69.8750, WM=65.8148, CSF=76.2783
TR=100, α=60.0 -> GM=85.5791, WM=80.6064, CSF=93.4215
TR=100, α=90.0 -> GM=98.8182, WM=93.0762, CSF=107.8739
```

These SI maps show how each tissue responds differently to changes in TR and TE. WM, with its shorter T2 time, tends to lose signal faster as TE increases, while GM shows a slower decay in signal. This difference in relaxation times is crucial for distinguishing tissue types in MRI.

IV Results

Signal-to-Noise Ratio (SNR) Analysis:

SNR for GM, WM, and CSF was calculated to assess how noisy each tissue's signal is compared to the background noise. Higher SNR indicates better image quality and clearer tissue contrast.

*output from d_signal_to_noise_ration_GM_WM_CSF.m

```
--- SNR for Spin Echo (SE) ---
TR=250, TE=20 -> SNR_GM=1648.92, SNR_WM=1498.04, SNR_CSF=2030.85
TR=250, TE=40 -> SNR_GM=1299.12, SNR_WM=1122.94, SNR_CSF=1873.06
TR=250, TE=60 -> SNR_GM=1024.83, SNR_WM=842.73, SNR_CSF=1727.71
TR=250, TE=80 -> SNR_GM=809.44, SNR_WM=633.15, SNR_CSF=1593.78
TR=500, TE=20 -> SNR_GM=1648.92, SNR_WM=1498.04, SNR_CSF=2030.85
TR=500, TE=40 -> SNR_GM=1299.12, SNR_WM=1122.94, SNR_CSF=1873.06
TR=500, TE=60 -> SNR_GM=1024.83, SNR_WM=842.73, SNR_CSF=1727.71
TR=500, TE=80 -> SNR_GM=809.44, SNR_WM=633.15, SNR_CSF=1593.78
TR=750, TE=20 -> SNR_GM=1648.92, SNR_WM=1498.04, SNR_CSF=2030.85
TR=750, TE=40 -> SNR_GM=1299.12, SNR_WM=1122.94, SNR_CSF=1873.06
TR=750, TE=60 -> SNR_GM=1024.83, SNR_WM=842.73, SNR_CSF=1727.71
TR=750, TE=80 -> SNR_GM=809.44, SNR_WM=633.15, SNR_CSF=1593.78
TR=1000, TE=20 -> SNR_GM=1648.92, SNR_WM=1498.04, SNR_CSF=2030.85
TR=1000, TE=40 -> SNR_GM=1299.12, SNR_WM=1122.94, SNR_CSF=1873.06
TR=1000, TE=60 -> SNR_GM=1024.83, SNR_WM=842.73, SNR_CSF=1727.71
TR=1000, TE=80 -> SNR_GM=809.44, SNR_WM=633.15, SNR_CSF=1593.78
TR=2000, TE=20 -> SNR_GM=1648.92, SNR_WM=1498.04, SNR_CSF=2030.85
TR=2000, TE=40 -> SNR_GM=1299.12, SNR_WM=1122.94, SNR_CSF=1873.06
TR=2000, TE=60 -> SNR_GM=1024.83, SNR_WM=842.73, SNR_CSF=1727.71
TR=2000, TE=80 -> SNR_GM=809.44, SNR_WM=633.15, SNR_CSF=1593.78
```

Higher TR values tend to increase SNR since tissues have more time to recover magnetization, producing a stronger signal. However, increasing TE reduces SNR because tissues like WM lose signal quickly due to shorter T2 times. This analysis is important for determining the best parameter combinations for clear images with minimal noise.

Structural Similarity Index (SSIM) Analysis:

SSIM was used to measure the similarity between different pairs of MRI images (e.g., comparing images generated with TR = 50 ms and TR = 250 ms). The SSIM index quantifies how structurally similar two images are.

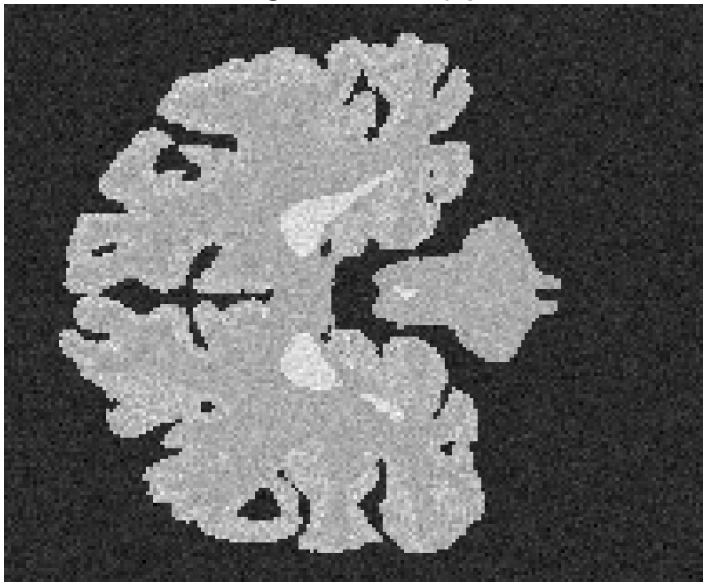
*output of e_structual_similarity_index.m

```
SSIM between image 1 (TR=250, TE=20) and image 2 (TR=1000, TE=20): 1.0000
```

Gaussian noise (5%) was added to the SI maps to simulate the random noise typically seen in real-world MRI images. Adding noise reduces the clarity of the images, especially for tissues with low contrast, like CSF. This effect is more pronounced in sequences with longer TE, where signal loss is already significant. Noise has less impact on GM and WM, which have higher inherent signal.

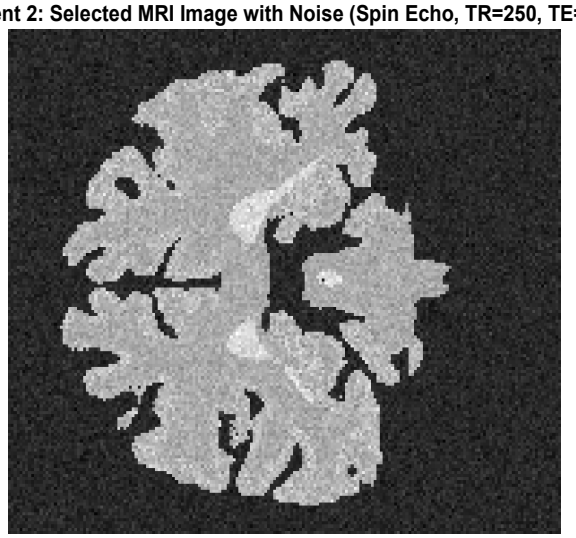
MRI Image Generation:
100 MRI images were generated by varying TR and TE for each pulse sequence (SE, IR, GRE). Gaussian noise was added to each image.

Patient 1: Selected MRI Image with Noise (Spin Echo, TR=250, TE=20)



Patient 1 (TR=250, TE=20): GM=65.5628, WM=73.7898, CSF=93.7605

Patient 2: Selected MRI Image with Noise (Spin Echo, TR=250, TE=20)



Patient 2 (TR=250, TE=20): GM=82.4070, WM=74.8962, CSF=101.5701

The generated MRI images clearly show the effect of varying TR and TE on tissue contrast. For shorter TR values, the images have higher contrast between GM, WM, and CSF. Longer TR values produce more uniform images with reduced tissue differentiation. TE primarily impacts WM, as it has a shorter T2 and loses signal faster.

V Conclusion

Increasing TR generally raised signal intensity but reduced contrast between tissues, while increasing TE decreased the signal, especially in tissues with shorter T2 values like WM. Varying TI in T1 Inversion Recovery sequences adjusted the visibility of different tissues, with shorter TI favoring WM and longer TI enhancing GM. Increasing the flip angle (α) in GRE sequences improved signal but could lead to signal saturation with shorter TR.

The addition of Gaussian noise impacted image quality, particularly in tissues with lower inherent contrast, like CSF. SNR analysis showed that longer TR improved signal quality, while shorter TE helped retain tissue contrast. SSIM analysis confirmed that increasing TR reduced structural similarity to the reference image, indicating a loss in tissue differentiation.

Overall, this project demonstrated the importance of carefully selecting acquisition parameters to optimize MRI image quality, balancing signal intensity, noise, and tissue contrast.