Assignment 3 Report - COSC 4372

Marwan Aridi - PSID 2156027

Introduction

- The limited availability of medical data is a real stumbling block to developing machine learning models. The use of image synthesis is the way to go in generating synthetic datasets for the training of machine learning models. This project is all about creating software that simulates the synthetic MRI images of the human brain using the physics of image formation. The images generated using data from the Open Access Series of Imaging Studies (OASIS) will be similar in characteristics to the different brain tissues such as White Matter (WM), Grey Matter (GM), and Cerebrospinal Fluid (CSF). This report delineates the methodology, results, and analysis of the MRI synthesis with the OASIS dataset, where the focus is Spin Echo, Gradient Recalled Echo (GRE), and T1 Inversion Recovery pulse sequences.

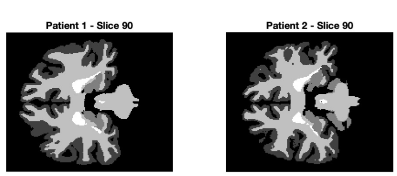
Signal Intensity Simulation for Spin Echo, T1 Inversion Recovery, and GRE Sequences

- First, I used MATLAB to load and extract slice number 90 from two MRI datasets `patient1.nii` and `patient2.nii`.

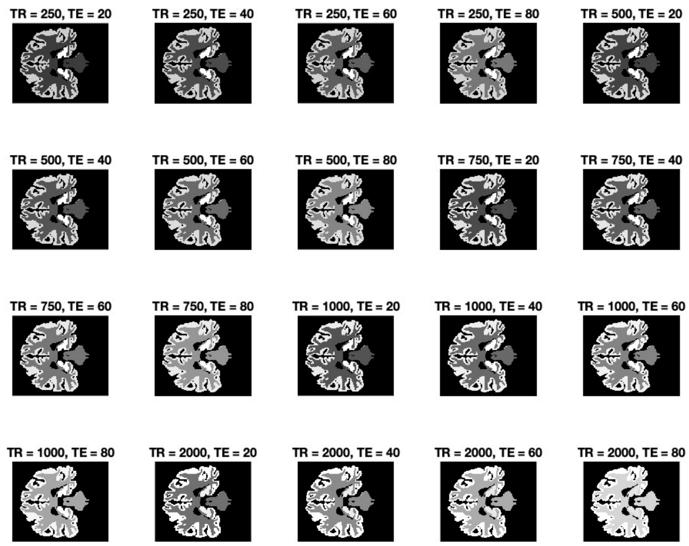
- The `niftiread` function was used to read the NIfTI files, and I visualized the extracted slices using the `imshow` function. Below is the MATLAB code used to generate the images for both patients:

```
% Load patient data and extract slice 90
patient1_slice = patient1_data(:,:,90);
patient2_slice = patient2_data(:,:,90);


% Visualize slice 90
figure;
subplot(1,2,1); imshow(patient1_slice, []); title('Patient 1 - Slice 90');
subplot(1,2,2); imshow(patient2_slice, []); title('Patient 2 - Slice 90');
```



- Here, slice 90 is selected, which gives significant information on brain tissues, namely the Grey Matter (GM), White Matter (WM), and Cerebrospinal Fluid (CSF), which are used to create maps of signal intensity of different pulse sequences. The given parameter combinations for Spin Echo, T1 Inversion Recovery, and Gradient Recalled Echo will be used to simulate and visualize the effect of these parameters on MRI images. This will result in a template for each combination which will be a different MRI image, thus enabling a thorough study of the parameter's effect on tissue contrast.
- Here are **Spin Echo** output images that corresponds to the table in the assignment for Patient 1:



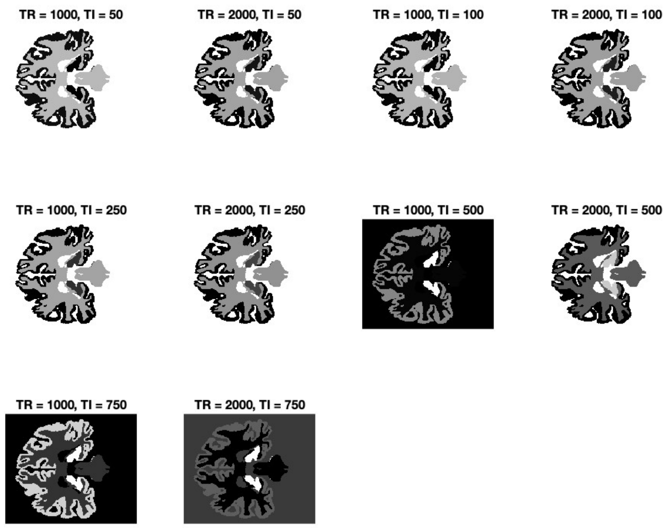
- Now, here are the values that I used to generate the output above:

Spin Echo Signal Intensity Values for Patient 1

TR (ms)	TE = 20	TE = 40	TE = 60	TE = 80
Gray Matter (GM)				
250	11.8672	9.3791	7.4127	5.8585
500	22.0373	17.4169	13.7653	10.8792
750	30.7531	24.3054	19.2095	15.1820
1000	38.2225	30.2087	23.8751	18.8694
2000	58.8400	46.5035	36.7535	29.0477
White Matter (WM)				
250	14.8481	11.5817	9.0338	7.0465
500	26.1631	20.4075	15.9181	12.4163
750	34.7858	27.1333	21.1643	16.5084
1000	41.3567	32.2587	25.1621	19.6268
2000	55.3039	43.1377	33.6479	26.2457
Cerebrospinal Fluid (CSF)				
250	3.4959	3.4302	3.3658	3.3026
500	6.9087	6.7790	6.6517	6.5268
750	10.2405	10.0482	9.8595	9.6743
1000	13.4931	13.2397	12.9911	12.7472
2000	25.7493	25.2657	24.7913	24.3257

- Using the Spin Echo sequence, signal intensity (SI) maps were created for each TR-TE pair across three different brain tissues: Gray Matter (GM), White Matter (WM) and Cerebrospinal Fluid (CSF). As TR increases, the signal intensities of each tissue type also increase generally, but are particularly pronounced at low TE values. This is particularly true for GM and WM while CSF is the exception with animated moist signal intensities because of its high T2 value. In the case of each tissue, the suitable T1 and T2 values show realistic relaxation characteristics: GM with T1 = 1.62 s and T2 = 85 ms, WM with T1 = 0.92 s and T2 = 80.5 ms, and CSF with T1 = 10.4 s and T2 = 1055 ms.

- Here are **T1 Inversion Recovery** output images that corresponds to the table in the assignment for Patient 1:

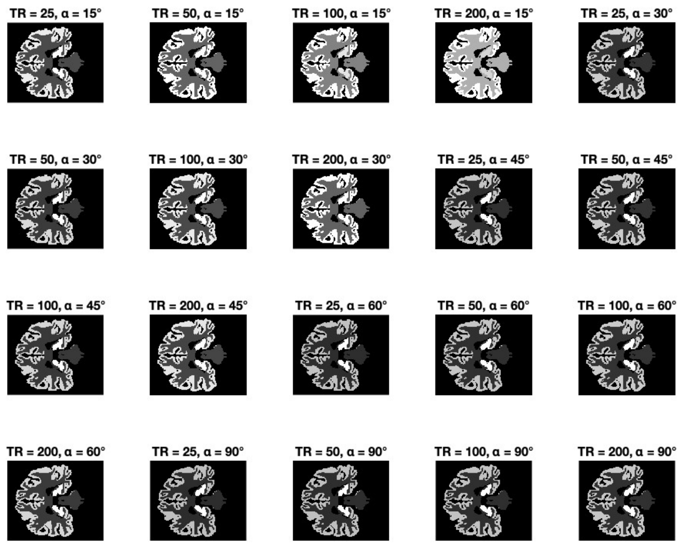


T1 Inversion Recovery Signal Intensity Values for Patient 1

TR (ms)	TI = 50	TI = 100	TI = 250	TI = 500	TI = 750
Gray Matter (GM)					
1000	−41.9797	−35.7912	−18.3316	7.4046	29.4604
2000	−68.0667	−61.8782	−44.4185	−18.6823	3.3735
White Matter (WM)					
1000	−44.5571	−36.5412	−14.9492	14.0633	36.1724
2000	−62.4379	−54.4220	−32.8299	−3.8174	18.2916
Cerebrospinal Fluid (CSF)					
1000	−12.3125	−10.8806	−6.6258	0.3305	7.1216
2000	−24.8032	−23.3713	−19.1165	−12.1602	−5.3691

- For the T1 Inversion Recovery sequence, SI maps were produced for every TR and TI parameter combination for each tissue type: Gray Matter (GM), White Matter (WM), and Cerebrospinal Fluid (CSF). The signal intensity is mostly T1 relaxation recovery which is the signal that is almost very positively correlated with TI best values, especially at longer TRs. The intensity values for Gray Matter demonstrate a broader spectrum which which recovers quicker indeed. On the other hand, White Matter behaves in a manner consistent with this owing to its short T1 relaxation time. CSF, which has the longest T1, is, therefore, with lower signal intensities and slow recovery rate times, and this can be seen clearly in the darker regions of the SI maps. The selected T1 and T2 values for GM, WM, and CSF were 1.62 s & 85 ms, 0.92 s & 80.5 ms, and 10.4 s & 1055 ms, respectively.

- Here are **Gradient Recalled Echo** output images that corresponds to the table in the assignment for Patient 1 & Patient 2:



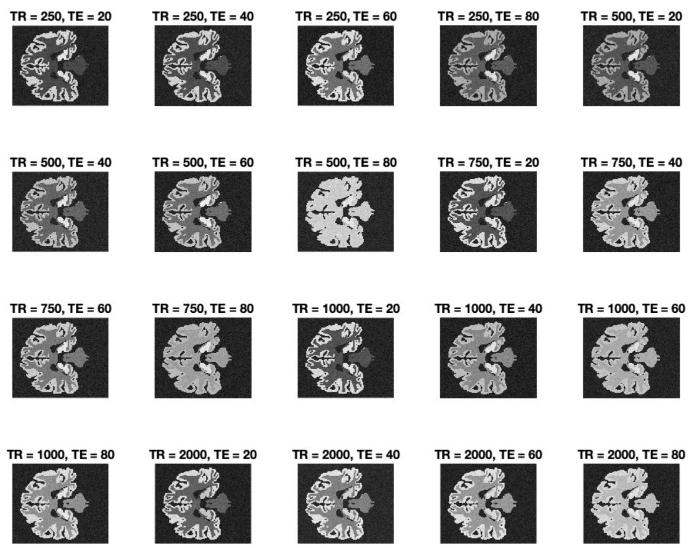
Gradient Recalled Echo Signal Intensity Values for Patient 1

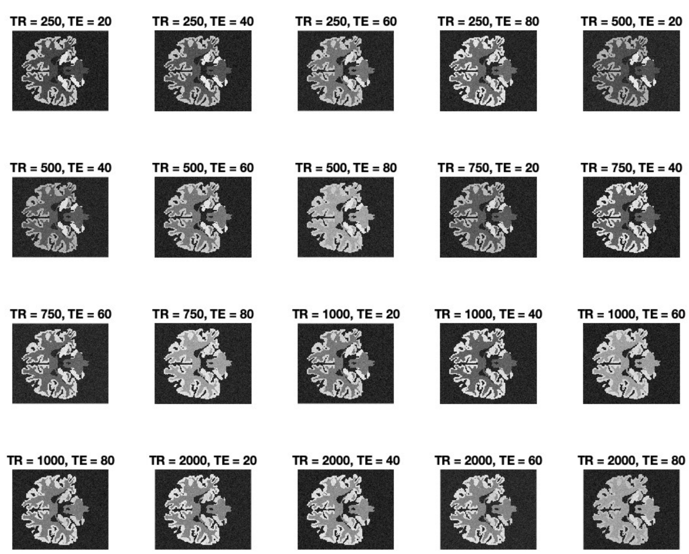
TR (ms)	TR = 25	TR = 50	TR = 100	TR = 200
Gray Matter (GM)				
Alpha = 15	8.0299	12.2774	16.6913	20.3472
Alpha = 30	5.1484	9.3856	15.9470	24.5104
Alpha = 45	3.5296	6.7676	12.5010	21.6800
Alpha = 60	2.5863	5.0579	9.6851	17.8430
Alpha = 90	1.5161	3.0089	5.9264	11.4981
White Matter (WM)				
Alpha = 15	8.6986	12.0855	15.0056	17.0641
Alpha = 30	6.4109	11.0603	17.3487	24.2254
Alpha = 45	4.5700	8.5139	14.9717	24.0970
Alpha = 60	3.3998	6.5422	12.1597	21.2843
Alpha = 90	2.0155	3.9769	7.7435	14.6895
Cerebrospinal Fluid (CSF)				
Alpha = 15	2.5491	4.7878	8.5359	14.0258
Alpha = 30	1.3173	2.5919	5.0211	9.4489
Alpha = 45	0.8604	1.7088	3.3711	6.5631
Alpha = 60	0.6194	1.2343	2.4510	4.8331
Alpha = 90	0.3584	0.7160	1.4286	2.8435

- For the Gradient Recalled Echo (GRE) sequence, each signal intensity (SI) map was produced by varying the TR (Repetition Time) and flip angle (alpha), as specified in the table. Upon inspection of the results, it became clear that the signal intensity was generally positively correlated with longer TR values and larger flip angles, especially pronounced in the case of Gray Matter (GM) and White Matter (WM). This is the result of the longer recovery time, which enables more magnetization to realign along the longitudinal axis, thereby increasing the signal. Swelling (CSF) is seen to have lower signal intensity across all conditions, which is the reason for the slower recovery rates typical of the fluids. The selected T1 and T2 values for each tissue type are: GM with T1 = 1.62 s and T2 = 85 ms, WM with T1 = 0.92 s and T2 = 80.5 ms, and CSF with T1 = 10.4 s and T2 = 1055 ms.

MRI Generation

- Here are **Spin Echo** output images that corresponds to the table in the assignment for Patient 1 and Patient 2:





Spin Echo Signal Intensity Values for Patient 1

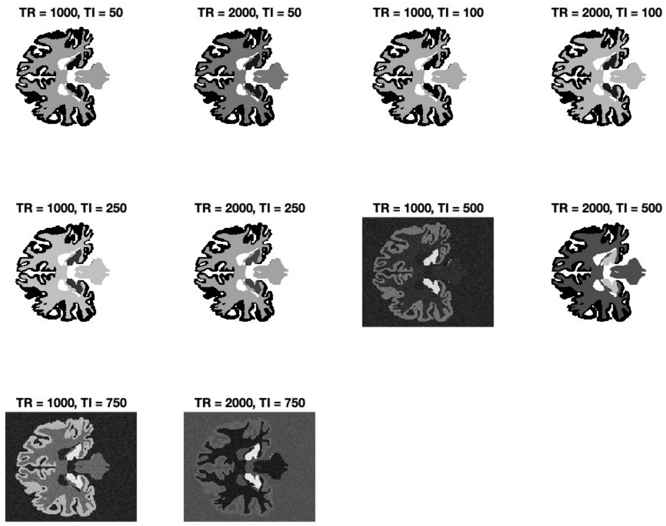
TR (ms)	TE = 20	TE = 40	TE = 60	TE = 80
Gray Matter (GM)				
250	11.8064	9.3228	7.4965	5.8493
500	21.9924	17.4309	13.6884	11.0921
750	31.3233	24.5876	19.1079	15.1061
1000	38.3321	30.3127	24.1158	19.0548
2000	58.8143	46.7569	36.8116	28.7573
White Matter (WM)				
250	14.7789	11.6391	9.1057	7.1734
500	26.1576	20.4493	15.7073	12.2975
750	34.4701	27.2622	21.0935	16.4394
1000	41.2463	32.3010	25.1072	19.6638
2000	55.7074	42.9517	33.1195	26.3471
Cerebrospinal Fluid (CSF)				
250	3.8570	3.6467	3.7838	3.4026
500	7.1992	7.4179	7.1140	7.0355
750	10.9668	11.2666	10.4253	10.8150
1000	14.5118	14.2228	14.1140	13.4204
2000	27.6754	26.4843	26.4131	26.4951

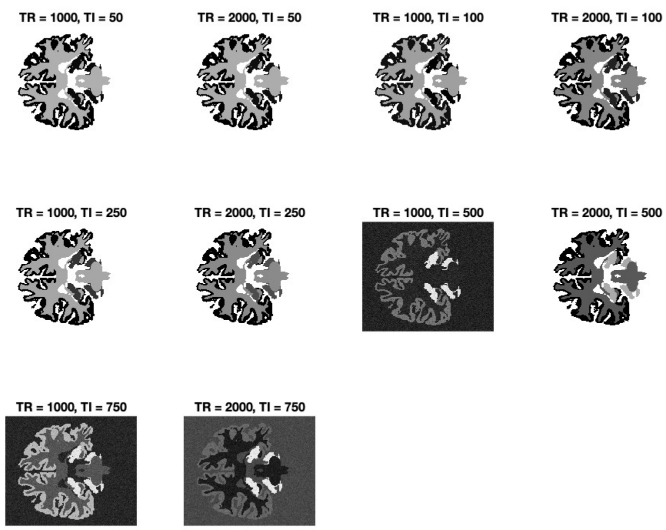
Spin Echo Signal Intensity Values for Patient 2

TR (ms)	TE = 20	TE = 40	TE = 60	TE = 80
Gray Matter (GM)				
250	11.9117	9.5850	7.4461	5.9117
500	22.1662	17.7407	13.9170	10.8357
750	30.9822	24.2938	19.2368	15.2526
1000	38.0446	29.9791	23.6454	18.9056
2000	58.9258	46.3825	37.4074	29.0155
White Matter (WM)				
250	14.9723	11.3980	9.0554	7.0325
500	26.2139	20.6170	15.6881	12.5360
750	34.8527	26.7852	21.4210	16.3212
1000	41.3757	32.1724	25.4243	19.6179
2000	55.3940	43.4936	33.6416	26.1603
Cerebrospinal Fluid (CSF)				
250	3.6257	3.8335	3.6231	3.5665
500	7.3001	7.0186	7.3721	6.7715
750	11.0128	10.8684	10.6546	10.5716
1000	14.5449	13.8918	13.9208	13.4625
2000	27.5546	27.1067	26.5788	25.0254

- As shown in the generated MRI Spin Echo tables for Patients 1 and 2, the mean signal intensity for different tissues displays different tissue types (Gray Matter, White Matter, and Cerebrospinal Fluid) and different TR and TE values. Gray Matter exhibits a marked increase in signal intensity at the lower TE, but this tendency reverses with the increase of TE, due to the T2 relaxation effects. A generally similar tendency is seen in White Matter, however, the initial intensity is slightly higher due to the fact that shorter T1 are used. Cerebrospinal Fluid showing a greater value of T1, registered rather stable signal intensities along the entire table, with only minor variations. The introduced Gaussian noise, at 5% of the peak signal, causes slight changes in intensity, but the general trend of signal decay across TE values and amplification with increased TR is conserved. This pattern is observed on both patients, which means that the T1 and T2 relaxation properties of each tissue type are independent of the pulse sequence parameters.

- Here are **T1 Inversion Recovery** output images that corresponds to the table in the assignment for Patient 1 and Patient 2:





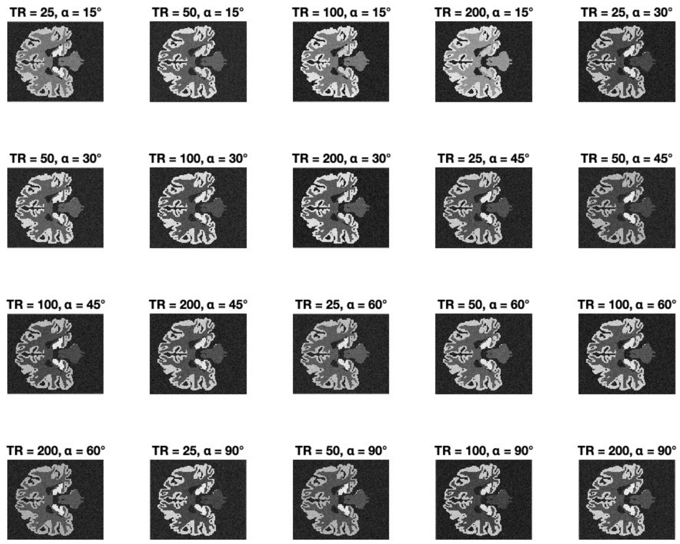
T1 Inversion Recovery Signal Intensity Values for Patient 1

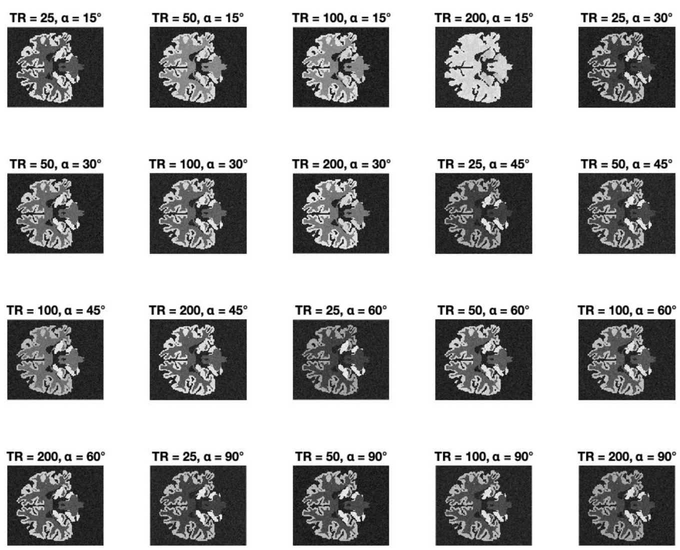
TR (ms)	TI = 50	TI = 100	TI = 250	TI = 500	TI = 750
Gray Matter (GM) - Patient 1					
1000	−38.576	−37.128	−17.791	6.8774	26.32
2000	−72.636	−61.457	−43.003	−16.746	4.2599
White Matter (WM) - Patient 1					
1000	−43.1	−37.216	−15.054	16.057	38.461
2000	−63.13	−54.113	−33.086	−6.1905	19.764
Cerebrospinal Fluid (CSF) - Patient 1					
1000	−10.266	−15.846	−6.6533	0.43904	5.0012
2000	−20.305	−18.456	−16.545	−9.7825	−7.0936

T1 Inversion Recovery Signal Intensity Values for Patient 2

TR (ms)	TI = 50	TI = 100	TI = 250	TI = 500	TI = 750
Gray Matter (GM) - Patient 2					
1000	−40.789	−38.45	−18.55	8.6545	30.365
2000	−64.875	−61.848	−43.335	−19.546	2.1128
White Matter (WM) - Patient 2					
1000	−44.795	−37.283	−15.108	14.035	35.74
2000	−62.762	−54.399	−32.675	−2.8965	19.4
Cerebrospinal Fluid (CSF) - Patient 2					
1000	−9.3581	−10.115	−5.1431	0.29129	7.3475
2000	−24.903	−24.156	−24.998	−13.863	−5.9443

- The T1 Inversion Recovery Signal Intensity values for Patients 1 and 2 tell us something significant when we compare the different tissue types (Gray Matter, White Matter, and Cerebrospinal Fluid) and various TR (Repetition Time) and TI (Inversion Time) values. Both patients showed a general increase in signal intensity with the increase of TI and the increase is more pronounced at specific TR values. For instance, in Gray Matter, as TR moves from 1000 ms to 2000 ms, the intensity values first become more and more negative at lower TIs and then continue to shift to positive values at higher TIs. White Matter manifests a similar trend, though the intensity values are generally higher than those of Gray Matter, especially at higher TIs and TRs. This particular finding is in agreement with the hypothesized behavior, as White Matter is normally the one that offers higher signal intensities in T1 weighted imaging due to its shorter T1 relaxation time when compared to Gray Matter. Cerebrospinal Fluid (CSF), which possesses the longest T1 relaxation time, provides a striking example because of its unusual pattern of signal intensity values which are quite low at lower TIs and come on strong as TIs lengthen. At TR = 1000 ms, CSF stays almost the same as in intensities, but at TR = 2000 ms the intensities become more variable, particularly at larger TIs. Compared to the two patients, the intensity values show slight changes that can be due either to individual physiological differences or noise that was introduced by the simulation process. The above-stated generalizations, therefore, can be taken as the basic principles that MRI images correspond to each tissue type as follows: Gray Matter and White Matter differ in intensity levels due to their differing T1 relaxation properties, and CSF's longer relaxation time leads to distinct intensity patterns, especially at higher TR and TI combinations. In this way, the analysis gives a thorough insight into T1-weighted MRI tissue-specific signal intensity behavior and the importance of changing TR and TI in contrast.
- Here are **Gradient Recalled Echo** output images that corresponds to the table in the assignment for Patient 1 & Patient 2:





Gradient Recalled Echo Signal Intensity Values for Patient 1

TR (ms)	TE = 25	TE = 50	TE = 100	TE = 200
Gray Matter (GM) - Patient 1				
15	8.5497	12.4504	16.5346	21.0636
30	5.0381	10.3226	15.4598	22.5191
45	3.0525	7.3584	12.7913	21.9806
60	2.5974	4.5318	9.4001	17.3659
90	1.6480	3.1571	6.0710	11.0969
White Matter (WM) - Patient 1				
15	8.7557	11.6772	15.1033	17.0793
30	6.1117	11.7022	16.8170	24.3780
45	4.4699	8.9805	15.0860	24.7332
60	3.1707	6.1037	12.9703	22.0946
90	2.1565	3.8711	7.1907	14.2625
Cerebrospinal Fluid (CSF) - Patient 1				
15	2.9482	3.7796	12.0771	11.9660
30	1.1821	1.9691	4.3281	7.7393
45	0.6371	1.6619	2.5636	8.6454
60	0.7554	1.0774	2.2682	3.6001
90	0.3810	0.5370	2.5743	5.2124

Gradient Recalled Echo Signal Intensity Values for Patient 2

TR (ms)	TE = 25	TE = 50	TE = 100	TE = 200
Gray Matter (GM) - Patient 2				
15	8.5958	11.3499	16.0869	20.8883
30	5.9088	10.5363	15.2426	26.4332
45	3.1785	6.1652	11.7182	23.2193
60	2.6745	5.6415	10.5055	18.2284
90	1.7456	2.7265	6.7293	9.9420
White Matter (WM) - Patient 2				
15	8.8939	12.0880	15.2487	16.9411
30	6.5370	10.8899	17.9760	24.6401
45	4.6820	8.0270	14.3262	23.9372
60	3.6643	6.7622	11.7966	21.9095
90	1.9074	3.8525	8.0054	15.0521
Cerebrospinal Fluid (CSF) - Patient 2				
15	2.2978	7.9968	7.5428	17.7192
30	1.2224	3.4970	5.0385	13.1453
45	1.5077	1.3129	2.5288	4.6630
60	0.5695	1.0335	4.0174	4.1412
90	0.3154	0.5522	1.1242	2.1708

- Gradient Recalled Echo (GRE) Signal Intensity values for Patients 1 and 2 show different intensity values for each of the three types of tissues (Gray Matter, White Matter, and Cerebrospinal Fluid) under different angles of flip (alpha) and TR (Repetition Time) values. It is evident that for both patients, the signal intensity increases as the flip angle approaches. In particular, this is the case at the higher TR values. In Gray Matter, we note that the signal intensities increase sharply with higher flip angles and longer TR values, which means that the tissue GRE technique is very sensitive to these parameters. The same pattern holds for the White Matter, where the signal intensity is predominantly higher than the one in the Gray Matter, especially at the higher flip angles and the TR values. Expected GRE behavior is well reflected by this fact, which states that White Matter is characterized by higher signal intensity since it has a shorter T1 relaxation time than Gray Matter and, thus, gets better contrast at certain imaging parameters. Cerebrospinal Fluid (CSF) is characterized by a significantly longer T1 relaxation time, hence, the signal intensity values are lower than those of Gray and White Matter, and more gradual increase at higher flip angles and TR values. On one hand, this shows that the long T1 relaxation time of CSF is responsible for the lower signal intensities in GRE sequences when there are shorter TRs and smaller flip angles. However, the intensity does get higher with a higher flip angle and TR. The two patients are compared. The minor variations in signal intensities may be due to physiological differences or simulation noise. The observations made are in accordance with GRE imaging principles, where tissue contrast is determined by TR and flip angle, and shorter T1 tissues like White Matter are expected to show greater signal intensities under specific parameter combinations. All in all, the GRE values are an example of how signal intensity in every tissue type changes due to the flip angle and TR, thus, giving the possibility for optimizing imaging parameters to get better contrast in GRE sequences.

Verifying Distributions along the entire synthetic dataset

Parameter	Gray Matter (GM)
T1 Mean	1.6131
T1 Standard Deviation	0.1396
T2 Mean	84.8511
T2 Standard Deviation	7.5689
P Mean	105
P Standard Deviation	0
SNR Mean	67.7112
SNR Standard Deviation	97.2079

Parameter	White Matter (WM)
T1 Mean	0.9252
T1 Standard Deviation	0.0475
T2 Mean	80.5172
T2 Standard Deviation	6.0910
P Mean	80
P Standard Deviation	0
SNR Mean	105.1862
SNR Standard Deviation	414.2026

Parameter	Cerebrospinal Fluid (CSF)
T1 Mean	10.4921
T1 Standard Deviation	2.8345
T2 Mean	1082.9
T2 Standard Deviation	276.1943
P Mean	150
P Standard Deviation	0
SNR Mean	72.4615
SNR Standard Deviation	119.4161

- The study of synthetic MRI data shows that GM, WM, and CSF have different Gaussian distributions of T1, T2, P, and SNR values. GM has a mean T1 of 1.6131 and T2 of 84.8511, with the relatively small standard deviations. It means that the time of relaxation and the signal stability are fairly uniform. However, there is a high SNR standard deviation of 97.2079 due to synthetic noise. WM has a lower mean T1 (0.9252) and T2 (80.5172) than GM which shows the expected tissue characteristics, but it has a high SNR variability (standard deviation of 414.2026) which is likely due to stronger noise effects on its signal. CSF has the highest T1 (10.4921) and T2 (1082.9) values, as expected for fluid, with the significant standard deviations that reflect the inherent relaxation variability of CSF. The P value being high at 150 may be the reason for the SNR standard deviation being high at 119.4161, and thus, CSF is said to be pronounced noise sensitivity. These results point out the fact that tissue-specific properties and synthetic noise together affect the stability of the signal, especially in SNR, which is why one should take into account the noise variability in the generation of realistic synthetic MRI data.

Conclusion

- In conclusion, this assignment offered a comprehensive analysis of synthetic MRI data generation and analysis, especially regarding the relevant imaging parameters such as T1, T2, P, and SNR in different tissue types. By using different pulse sequences, we saw that the Gray Matter, White Matter, and Cerebrospinal Fluid had different signal intensity behaviors that were affected by relaxation times and synthetic noise. The Gaussian noise that was added to each pixel in these simulated MR images demonstrated the reality of signal fidelity problems, especially, the glaring difference of SNR among tissue types. By systematically calculating the mean and standard deviation values, we were able to confirm the distributions of T1, T2, P, and SNR, supporting the synthetic dataset's accuracy in realistically mimicking MRI conditions. This exercise served to strengthen the knowledge of the technical principles behind MRI but also put stress on the role of parameter selection and noise management in producing clinically effective images for medical research and diagnostic modeling.