Practical
First steps in the MRI world

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Preamble

Expected skills

Here are the expected competencies by the end of the day, based on the lectures and practical session:

- Understanding the basic concepts of MRI
- Gaining a practical view of k-space
- Beginning to grasp the principles of quantitative MRI
- Initiating knowledge of processing non-standardized data

General Instructions

Here are some instructions to help you present a quality report. The following elements will be evaluated:

- It is necessary to present on the first page:
  - Last name;
  - First name;
  - Subject;
  - Date of document creation;
  - Current and total number of pages of the document.
- Spelling and overall presentation of the document will also be taken into account:
  - Clarity: document written with care and with particular attention to layout;
  - Emphasis on results: the answers must be constructed and the numbering proposed in the original document must be respected;
  - Introduction: it is necessary to always start your report with an introduction presenting the expected outcomes and the work that has been done;
  - Conclusion: it is imperative to end your report with a conclusion that summarizes the elements of the report and opens up with personal and professional perspectives;
  - Spelling: it is important to proofread before submitting the document. Poor spelling will be penalized.
- Plagiarism: all documents are checked for plagiarism at the time of submission.
- Delay: it is important to submit the documents within the given deadline. In case of non-compliance with the deadline, 2 points will be deducted per day started.

Organization of the Document

The document includes the theoretical part, the practical work as well as useful links that can help with the realization of the various exercises. It is important to use the document as a whole and to read it carefully.

Regarding the important elements, the exercises are always formalized in the same way and call for developed answers. Below is a question for which a constructed and developed answer is expected.

Question 0.1 : Instructions

This is a question.

The code or commands to be executed are always contained in a black box to allow you to identify them correctly throughout the document.

main.py Python

```python
def This_is_python (argument):
  print('Code type')
```

Contents

Chapter 1

Introduction

First and foremost, let's define what we mean by MR. MR stands for Magnetic Resonance, which refers to the phenomenon where atomic nuclei in a magnetic field absorb and emit electromagnetic radiation. This phenomenon is the basis for Magnetic Resonance Imaging (MRI), a powerful medical imaging technique that has revolutionized healthcare.

Now, let's talk about the principles behind MRI. MRI utilizes a strong magnetic field and radiofrequency waves to create images of the human body. The magnetic field aligns the atomic nuclei in the body, and the radiofrequency waves cause these nuclei to emit energy, which is detected and used to create an image.

To understand MRI in greater detail, we need to delve into the physics behind it. We'll start with the concept of magnetization. Magnetization is the process by which atomic nuclei in a magnetic field become aligned and polarized. This polarization creates a net magnetic moment, which can be manipulated using radiofrequency pulses to create an image.

Another critical concept in MRI is relaxation. There are two types of relaxation: longitudinal relaxation (T1) and transverse relaxation (T2). T1 relaxation is the process by which the magnetization returns to its original state along the direction of the magnetic field, while T2 relaxation is the process by which the magnetization loses coherence and becomes randomized in the transverse plane.

By understanding these concepts, we can begin to understand the various MRI pulse sequences used to create images of the body. These pulse sequences manipulate the magnetization of atomic nuclei to create contrast between different tissues in the body, which is used to identify abnormalities and diagnose diseases.

As master students, you will have the opportunity to explore the cutting-edge research being conducted in the field of MR physics. From developing new pulse sequences to improving image quality, the possibilities are endless. I encourage you to ask questions and challenge yourselves as you delve into the exciting world of MR physics.

Chapter 2

Playing with the k-Space

Magnetic Resonance Imaging (MRI) is a non-invasive medical imaging technique that has revolutionized clinical diagnosis and research. MRI works by detecting signals from the nuclear magnetic resonance of hydrogen atoms in the body, which are excited by radiofrequency pulses in a strong magnetic field. By measuring the signals emitted by the atoms, images of the body's internal structures can be generated with high spatial and contrast resolution.

However, the raw MRI signal data is not immediately interpretable as an image. Instead, it must be processed using mathematical techniques to reconstruct an image. One of the key steps in this processing is the transformation of the raw signal data from its original time-domain representation into a frequency-domain representation known as k-space. The k-space data is then manipulated to remove noise, correct for distortions, and generate the final image.

The field of view (FOV) of an MRI image refers to the spatial extent of the anatomy being imaged. The FOV determines the amount of information contained in the k-space data, and thus plays a critical role in the quality and resolution of the final image. In this context, understanding how k-space processing relates to the FOV is crucial for optimizing image acquisition and reconstruction parameters to achieve the desired image quality.

In this tutorial, we will explore the basics of MRI k-space processing and its relationship to the field of view. We will cover the key concepts and mathematical tools involved in k-space processing, and provide practical examples of how to apply these techniques to real MRI data.

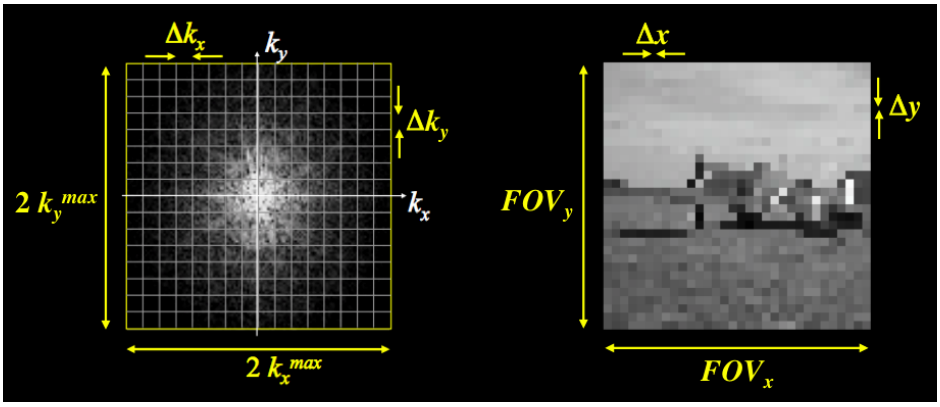


Figure 2.1: k-Space representation linked to FOV in image space

To begin with, ensure that you have the complete list of downloadable files : `https://drive.google.com/drive/folders/1ZQcJs1_4USZdm8zWDCVyGZdatJbflmRd?usp=sharing` :

- DICOM image
- artifact.npy

2.1 DICOM processing

DICOM (Digital Imaging and Communications in Medicine) is a widely accepted standard for handling, storing, and transmitting medical images and related data. It is particularly important in the field of magnetic resonance imaging (MRI), where it is used to ensure interoperability and compatibility between different imaging systems and software.

In MRI imaging, DICOM plays a crucial role in the acquisition, processing, and sharing of imaging data. It allows MRI images to be stored and retrieved in a standardized format that can be easily accessed and shared by healthcare professionals across different institutions and systems.

DICOM also includes important metadata that provide valuable information about the imaging parameters, patient demographics, and clinical history. This metadata can be used to ensure accurate and consistent interpretation of the imaging data, and can aid in the diagnosis and treatment of various medical conditions.

Overall, the use of DICOM in MRI imaging ensures that imaging data is consistent, compatible, and easily accessible, improving the quality and efficiency of healthcare delivery.

You can download ImageJ to have a quick look of the DICOM files.

Question 1.1 : Instructions

Open the only DICOM image available in the dataset with `pydicom`, and give me the important informations of it (use pydicom documentation).

Question 1.2 : Instructions

Change the name, surname of the file and save it with the new name. Re-open it and ensure that the modifications were taken into account

Question 1.3 : Instructions

Add a white square within the image and save it in a new DICOM. Open this new image and ensure the white square presence in the center of the image.

2.2 Basic k-Space Processing

In the field of magnetic resonance imaging (MRI), k-space processing plays an important role in the reconstruction of images. Essentially, k-space is a mathematical representation of the MRI signal, and by applying a Fourier transform to the signal, we can transform it from image space to k-space. This allows us to manipulate the signal in various ways, such as applying filters or undersampling the data, before transforming it back to image space.

To start exploring k-space processing, we will first need to download a DICOM image and open it in a Python code. We can do this using the `pydicom` library, which is specifically designed for working with DICOM images in Python.

Once we have the image displayed, we can move on to exploring k-space. To do this, we will apply a Fourier transform to the image, which will convert it to k-space. I recommend taking the `log` of the absolute value of the newly created image, which can help with visualizing the data. From there, we can begin to explore different k-space processing techniques and their impact on the resulting image.

Question 2.1 : Instructions

The first task is to open the DICOM image (`t1.dcm`) and display it using the `matplotlib` library. Display also the k-Space. You can create a function, il will be used often.

Question 2.2 : Instructions

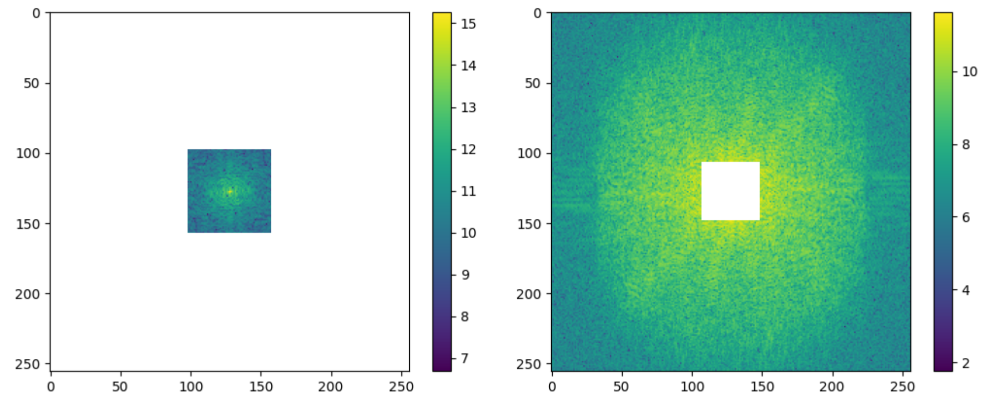
The, rotate 90 degrees the image and observe the impact in the k-Space. What is the impact of the rotation ?

We want to transform an image from the Fourier space to the image space. You can do it with the same function design previously.

Question 2.3 : Instructions

Transform file `test.npy` into the image space.

The next step will be to modify the k-space and analyze how the proposed treatment will impact the final image. You will have to go back from k-space to image space. We propose two k-space treatments: removing the center and removing the outside



(a) Remove the center (b) Keep the center

Figure 2.2: Main figure caption.

Question 2.4 : Instructions

Describe the impact of each treatment in the k-Space on the final image.

2.3 Manipulating k-Space Shape

The size of k-space determines the resolution and quality of the resulting image. A larger k-space matrix results in higher spatial resolution and better image quality, but also requires a longer scan time and generates more data.

In some cases, it may be necessary to modify the size of k-space to achieve a desired balance between image quality and scan time. This can be done by either increasing or decreasing the number of data points acquired in k-space.

For example, increasing the size of k-space by acquiring more data points can improve the spatial resolution and signal-to-noise ratio of the image, but also increases scan time and may lead to motion artifacts.

Conversely, decreasing the size of k-space by acquiring fewer data points can reduce scan time and motion artifacts, but may result in lower spatial resolution and image quality.

Therefore, modifying the size of k-space is a trade-off between image quality, scan time, and practical considerations, such as patient comfort and accessibility. It is an important consideration in MRI scanning and requires careful optimization for each individual case.

Question 3.1 : Instructions

First, remove one line over two and reconstruct the corresponding image.

Question 3.2 : Instructions

Second, instead of removing lines you will fill by 0 these lines. Again, compute the resulting image.

Question 3.3 : Instructions

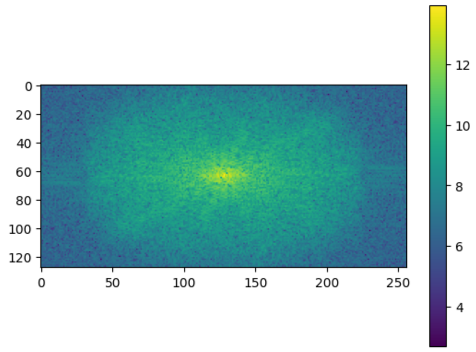
Third, you will interpolate the lines filled by 0 to closest values in the k-Space. Compute the corresponding image and comment the result regarding the two previous exercices

Question 3.4 : Instructions

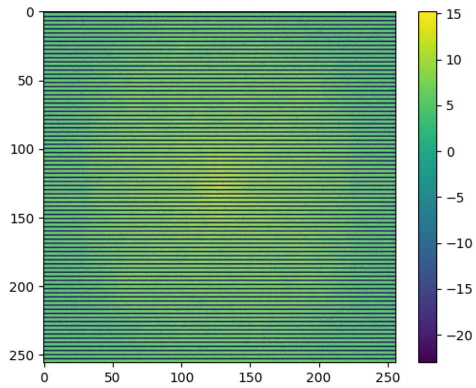
Please repeat the entire exercise, but instead of applying the processing steps to each row, apply them to each column. Once complete, please provide commentary on the results and compare them to the results obtained from the row approach.

Question 3.5 : Instructions

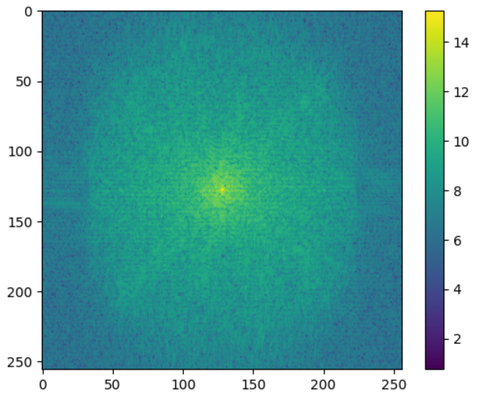
Assuming your code is functional, please replicate the same image processing steps using the file named flair.dcm



(a) k-Space of the first question



(b) k-Space of the second question



(c) k-Space of the third question

Figure 2.3: k-Space exercice overview

2.4 Panic at the MRI machine

In the field of medical imaging, it is not uncommon to encounter image artifacts or anomalies that can affect the accuracy and reliability of diagnostic information. In some cases, these artifacts can be caused by technical issues during the acquisition process, while in other cases they may be related to the patient's condition or movement during the scan.

In this particular exercise, we have detected spikes in an image acquired through magnetic resonance imaging (MRI). These spikes can be seen as bright lines or dots that appear in the image, disrupting the clarity and detail of the anatomical structures being imaged.

As MRI is a complex imaging technique that relies on the precise manipulation of magnetic fields, radiofrequency pulses, and signal processing algorithms, identifying the cause of these spikes requires a careful investigation of the imaging parameters and the scan environment.

In this case, our technologists displayed a strange image on their console and asked for your help. They want to understand why these lines are appearing and how they can get rid of them.

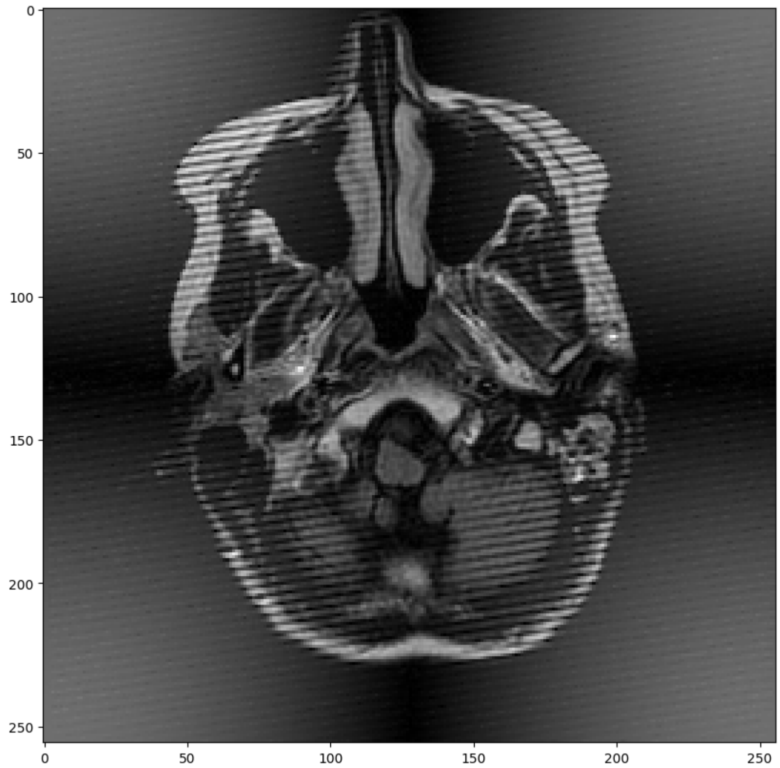


Figure 2.4: MR image with spikes

Question 4.1 : Instructions

Find the cause of the artifact in file `error.npy` and try to remove it. Can you name this artifact ?

Chapter 3

First step in the quantitative MRI world

Classical magnetic resonance imaging (MRI) is a well-established imaging modality that has been used for decades to diagnose and monitor a wide range of medical conditions. It relies on the manipulation of magnetic fields and radiofrequency pulses to generate images of the body's internal structures, which are then interpreted by radiologists and clinicians.

However, while classical MRI is a powerful tool for imaging, it has some limitations. One of the major limitations is that it relies on qualitative interpretation of the images by trained experts, which can be subjective and prone to error. Additionally, classical MRI provides only limited quantitative information about the tissue properties, such as the relaxation times and diffusion coefficients.

To address these limitations, a new approach to MRI imaging has emerged called quantitative MRI (qMRI). Unlike classical MRI, qMRI is focused on extracting quantitative information from the MRI signal. This allows for a more objective and accurate assessment of tissue properties, such as water content, tissue microstructure, and metabolic activity.

QMRI techniques utilize advanced mathematical models and signal processing algorithms to analyze the MRI signal, providing detailed and quantitative information about the underlying tissue properties. These techniques include diffusion MRI, which provides information about the mobility of water molecules in tissue, and magnetic resonance spectroscopy (MRS), which allows for the measurement of metabolites and biomarkers in the body.

The potential benefits of qMRI are numerous, as it can provide a more comprehensive understanding of the underlying tissue properties, enabling clinicians to make more informed and personalized treatment decisions. It can also improve the sensitivity and specificity of MRI in detecting early signs of disease and monitoring treatment response.

However, the adoption of qMRI has been slow, due in part to the technical complexity and computational demands of the techniques. Nevertheless, with ongoing advancements in imaging hardware and software, and with growing interest in precision medicine, the field of qMRI is rapidly evolving and holds great promise for the future of medical imaging.

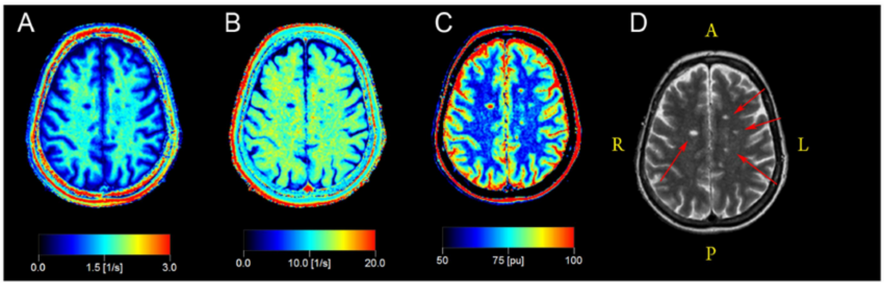


Figure 3.1: Sample qMRI data maps from a 45-years-old female MRI pos MS patient Source

3.1 Let's start with Shepp-Logan phantom

The Shepp-Logan phantom is a well-known mathematical model used in medical imaging to simulate the appearance of the human body. It consists of a series of mathematical equations that represent the different tissue types found in the body, such as bone, soft tissue, and air.

In the context of quantitative MRI (qMRI), the Shepp-Logan phantom is often used as a reference standard for evaluating the accuracy and precision of qMRI techniques. This is because the phantom provides a controlled environment in which the properties of the tissues can be precisely defined and varied.

For example, the phantom can be used to evaluate the accuracy of diffusion MRI (dMRI) techniques, which measure the mobility of water molecules in tissue. By generating simulated dMRI data from the Shepp-Logan phantom, researchers can compare the measured diffusion parameters with the known diffusion properties of the phantom, providing a quantitative assessment of the accuracy of the technique.

Similarly, the phantom can be used to evaluate the accuracy of magnetic resonance spectroscopy (MRS) techniques, which measure the concentration of metabolites and biomarkers in tissue. By generating simulated MRS data from the phantom, researchers can compare the measured metabolite concentrations with the known concentrations of the phantom, providing a quantitative assessment of the accuracy of the technique.

Overall, the Shepp-Logan phantom serves as a valuable tool in the development and validation of qMRI techniques, enabling researchers to accurately and objectively evaluate the performance of these techniques in a controlled and standardized environment.

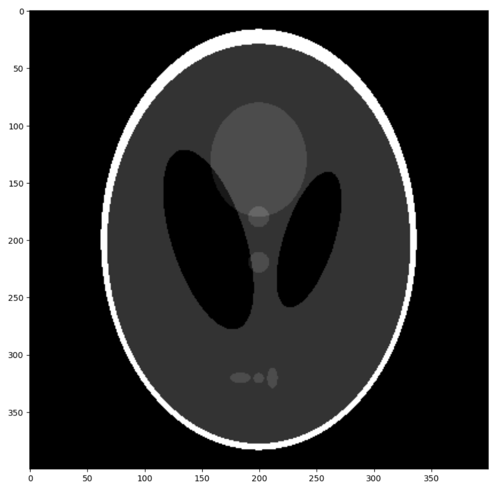


Figure 3.2: The Shepp-Logan MR phantom

You can easily use it in python using the `scikit-image` library.

main.py Python

```python
from skimage.data import shepp_logan_phantom

image = shepp_logan_phantom()
```

Question 1.1 : Instructions

Open the Shepp-Logan phantom and display it using matplotlib (resolution 512x512). How many grey levels are present in the phantom ?

3.2 qMRI approach

We will simulate a qMRI approach using Shepp-Logan phantom. The imaged phenomenon will be a T2* decrease.

$$S = e^{-TE/T2^*} \tag{3.1}$$

The T2* phenomenon is an important aspect of quantitative MRI (qMRI) that relates to the decay of the MRI signal in the presence of magnetic field inhomogeneities. In qMRI, T2* is a parameter that can be used to provide information about tissue properties, such as the iron content in tissues like the brain.

Mathematically, T2* is related to the transverse relaxation time (T2) of the MRI signal, which describes the rate at which the signal decays due to interactions between protons in the tissue. However, in the presence of magnetic field inhomogeneities, such as those caused by the presence of iron in tissues, the decay of the MRI signal can be much more rapid, leading to a shorter T2* time.

The T2* phenomenon is particularly relevant in neuroimaging, where changes in iron content can be indicative of various neurodegenerative diseases, such as Parkinson's and Alzh-eimer's disease. For example, in Parkinson's disease, there is an accumulation of iron in the substantia nigra, a region of the brain that is involved in the control of movement. By measuring the T2* time in this region, qMRI techniques can provide information about the iron content and potentially be used as a biomarker for the disease.

Additionally, T2* can be used in conjunction with other qMRI techniques, such as diffusion MRI and magnetic resonance spectroscopy, to provide a more comprehensive understanding of the tissue properties. For example, the combination of T2* and diffusion MRI can be used to assess the microstructural integrity of white matter in the brain, while the combination of T2* and magnetic resonance spectroscopy can be used to measure the concentrations of different metabolites in tissue.

In summary, the T2* phenomenon is an important aspect of qMRI that can provide valuable information about tissue properties, particularly in neuroimaging. By measuring T2* times, qMRI techniques can be used as a powerful tool in the diagnosis and monitoring of various medical conditions, and as a potential biomarker for disease progression.

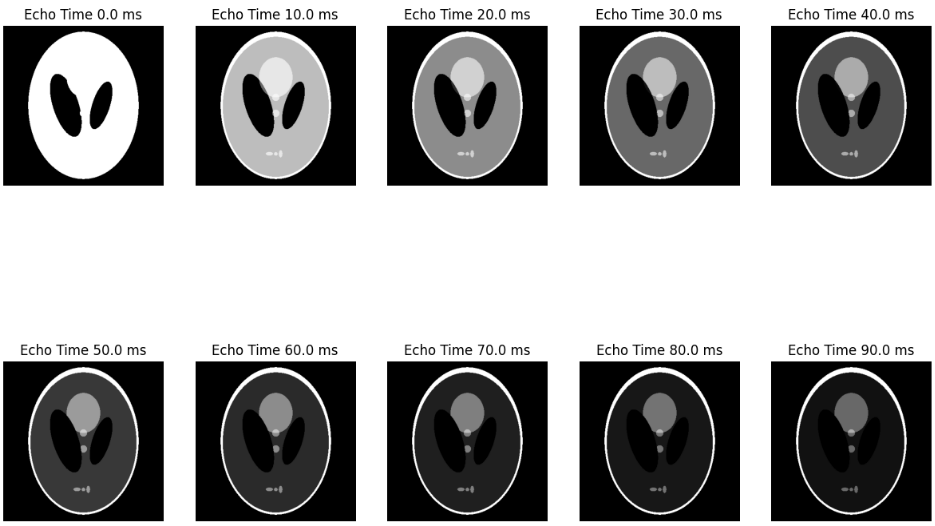


Figure 3.3: Phantom at different echo time

Question 2.1 : Instructions

Open the file named `qmri.npy`. You have to display images in the same way as the Figure 3.2.

Question 2.2 : Instructions

Create a function that can evaluate the R2* (1/T2*) by computing the mono-exponential decay for each voxel along the images. Ensure that the echo time is correctly set in your fitting function. Once you have implemented the function, use it to compute the R2* values for the image data.

Question 2.3 : Instructions

Create a matrix of contrast to know when the contrast between tissues are maximized (which echo and which contrast value).

3.3 Work with noisy data

Quantitative magnetic resonance imaging (qMRI) techniques are highly sensitive to noise in the acquired images. This is because the underlying physical models used to calculate the quantitative parameters are based on assumptions of an ideal noise-free signal. In reality, however, there is always some level of noise present in the image data, which can lead to errors in the quantitative measurements.

The impact of noise on qMRI data depends on several factors, such as the magnitude of the noise, the specific qMRI technique being used, and the tissue properties being imaged. In general, noise can lead to a reduction in the accuracy and precision of the calculated parameters. This reduction can be quantified by the relative error or uncertainty in the measurements, which is defined as the ratio of the standard deviation of the noise to the signal amplitude.

For example, in T1, T2 and T2* mapping, noise can cause bias in the calculated relaxation times, leading to over- or under-estimation of the true values. To mitigate the impact of noise on qMRI data, various strategies can be employed, such as increasing the signal-to-noise ratio by increasing the number of averages or the magnetic field strength, using noise reduction techniques such as filtering or regularization, and performing careful quality control checks on the image data. Additionally, it is important to report the level of noise and uncertainty in the quantitative measurements to accurately reflect the reliability of the data.

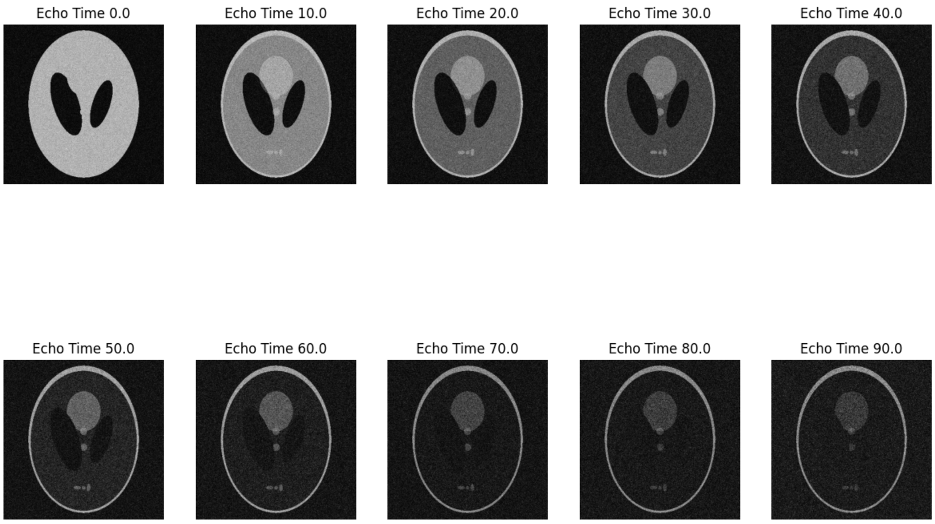


Figure 3.4: Phantom at different echo time with noise

Question 3.1 : Instructions

Compute the error map between noisy and non noisy T2* map.

Question 3.2 : Instructions

Compute the SNR for each tissue (background comparison)