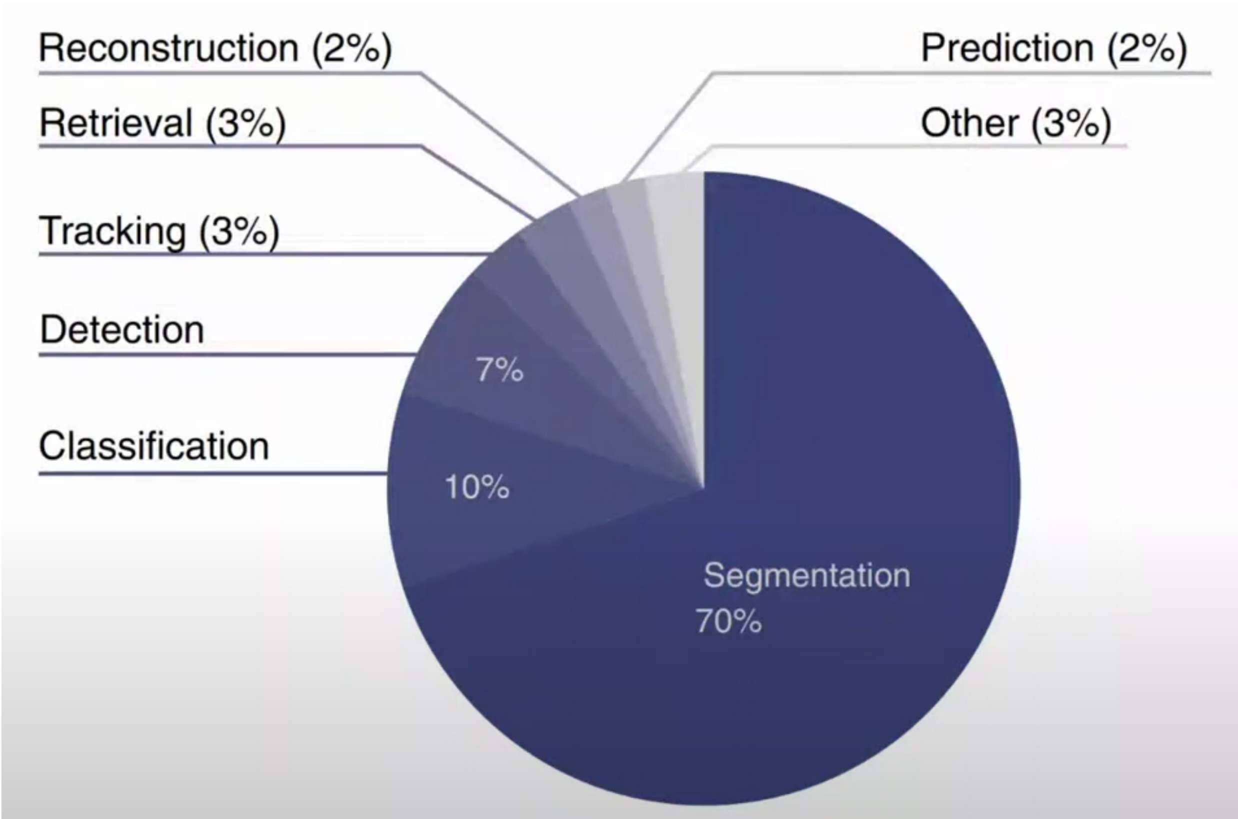
Demystifying Medical Imaging: Modalities, Data Formats, and Segmentation

Introduction

Imagine a world where doctors can peek inside the human body without making a single incision. This is the reality of medical imaging, or radiology, a pivotal field of medicine that encompasses a range of non-invasive tests, enabling physicians to diagnose injuries and diseases with precision while minimizing patient discomfort.

Segmentation, the process of isolating specific areas within an image, has emerged as a focal point in medical imaging, driving innovation in over **70% of biomedical image analysis competitions**. In this blog, we will explore the multifaceted purpose of medical imaging, delve into the most commonly used imaging modalities and data formats, and explain the nuances of 2D versus 3D image processing. We'll tackle the inherent challenges in the field, from data variability to technological limitations. Further, we will break down the concept of segmentation, introduce key evaluation metrics used to measure its efficacy, and focus particularly on brain segmentation, highlighting the modalities that offer the most insight. Join us as we navigate the complex yet fascinating world of medical imaging



Overview of biomedical image analysis challenges

Purpose of Medical Imaging

Medical imaging uses a range of technologies such as ultrasound, magnetic resonance imaging (MRI), nuclear medicine, and X-rays. Each of these modalities plays a crucial role in modern healthcare:

- **Diagnosis**: By providing clear images of internal organs and structures, medical imaging is instrumental in diagnosing a wide array of conditions, from fractures and tumors to infections and vascular diseases.
- **Surgical Planning and Guidance**: Imaging technologies are essential in planning surgical procedures, allowing surgeons to navigate complex operations with higher precision. For instance, MRI and CT scans can be used to map out a surgical path before making an incision.
- **Treatment Monitoring**: Medical imaging is vital in tracking the progress of treatments, such as the shrinkage of tumors during chemotherapy or the healing of bones after surgery.

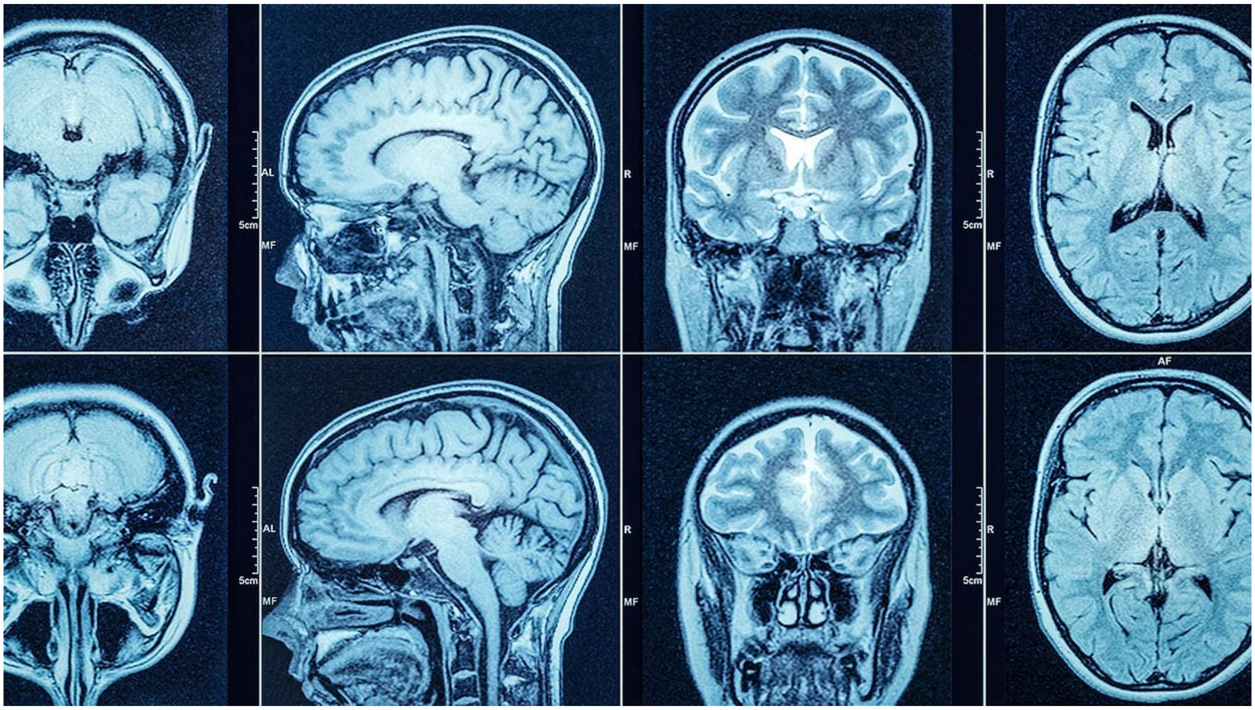
- **Research**: Beyond clinical applications, medical imaging contributes to medical research by offering insights into disease progression, treatment responses, and more, facilitating the development of new therapies and interventions.

Common Imaging Modalities

- **X-Ray:** X-rays are a type of **electromagnetic radiation** that can pass through the body, capturing images primarily of the bones and other dense structures. This modality is frequently used for detecting bone fractures, dental issues, and chest imaging, such as looking for lung abnormalities.

Xray Skeleton scans

- **CT Scans:** CT (Computed Tomography) scans use X-rays to create detailed cross-sectional images of the body. They **measure the X-ray absorption of different tissues**, which is outputted as a **grayscale image where each pixel represents a specific density.** The scale in CT scans is **absolute**, meaning the intensities relate to real physical properties and can be compared across different scans. CT scans are invaluable in diagnosing internal injuries, tumors, and complex bone fractures.

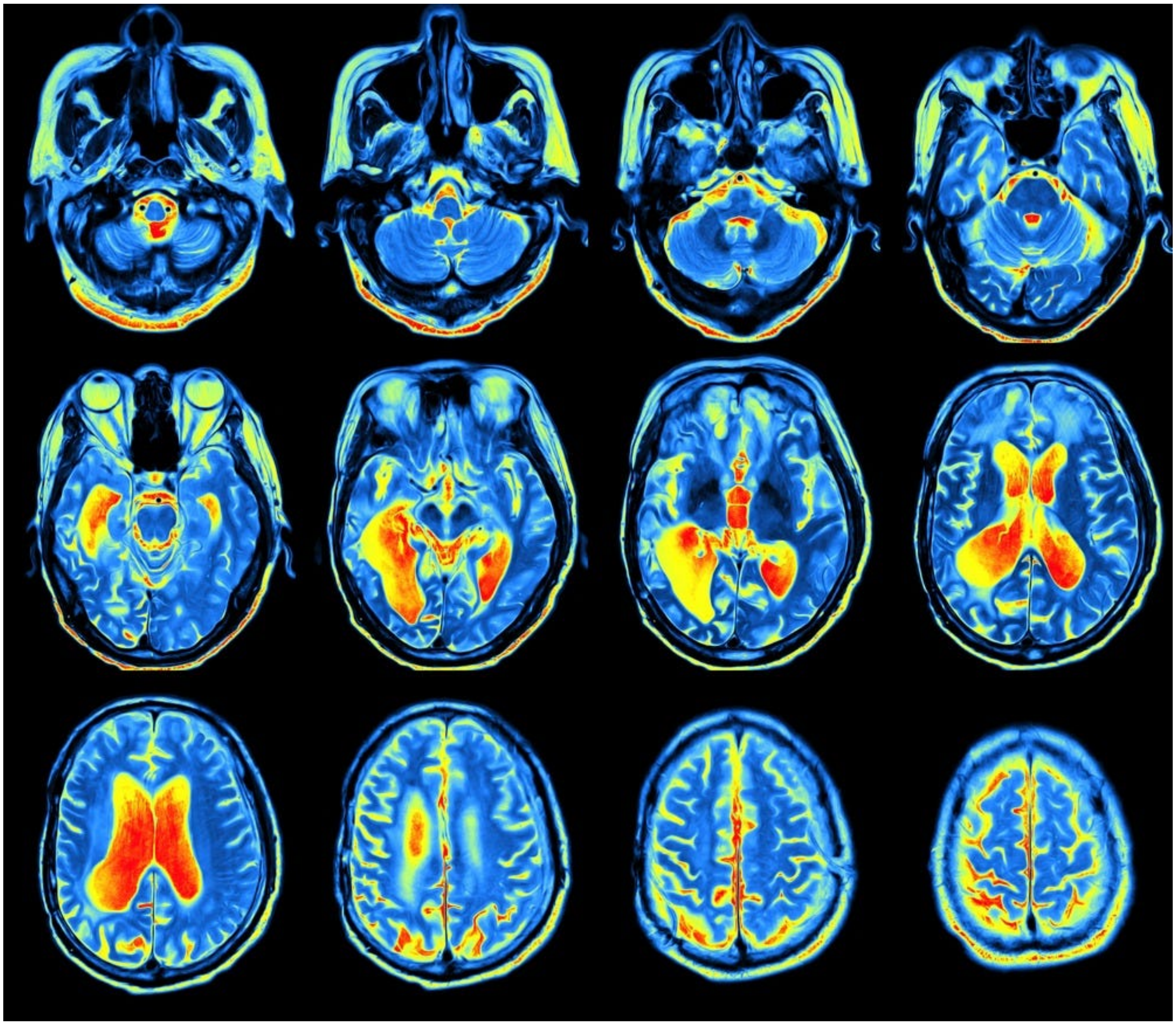


<u>CT Scan</u>

- **MRI (Magnetic Resonance Imaging):** Unlike CT scans and X-rays, MRI uses **magnetic fields and radio waves** to produce images. This modality is highly effective for imaging soft tissues such as the brain, muscles, and connective tissues. The intensity scale in MRI is relative, varying with different signal properties, which means **images can differ across scanners and even within the same scan under different settings.**
- **Ultrasound:** Ultrasound imaging utilizes **high-frequency sound waves** to create images of the inside of the body. It is commonly used during pregnancy to monitor the developing foetus, but also serves well for examining organs like the heart, liver, and kidneys. Ultrasound is safe, non-invasive, and does not use ionizing radiation.

ultrasound scan

- **PET Scans:** PET (Positron Emission Tomography) scans are a type of **nuclear medicine imaging** that involves injecting a small amount of **radioactive material** into the body to help visualize function rather than structure. PET scans are particularly useful for detecting cancer, monitoring cancer treatment, and evaluating brain abnormalities such as tumors, memory disorders, and seizures.



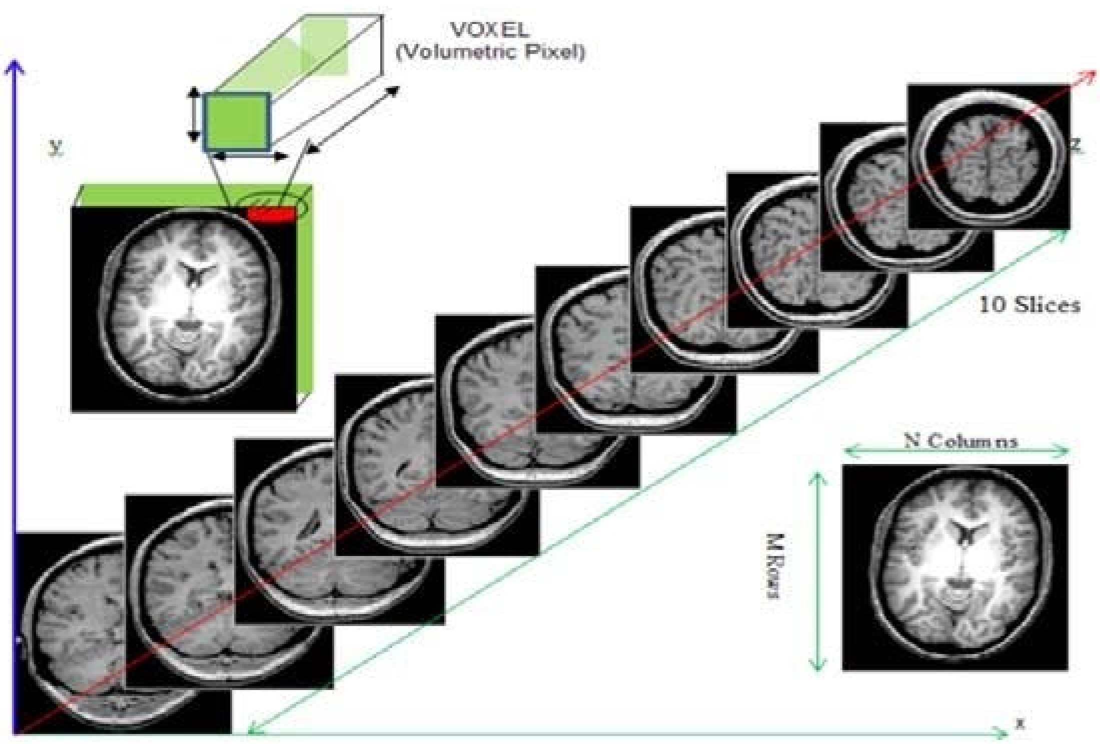
PET scan

Data Format

Several data formats such as Analyze, MINC, Interfile, ECAT, RAW, and MHA/MHD are used in medical imaging, each tailored to specific modalities and research needs. However, in this blog, we will focus primarily on the **most commonly used** formats—NIfTI and DICOM—due to their widespread adoption and critical role in everyday medical imaging processes:

- **NIfTI Files:** NIfTI (Neuroimaging Informatics Technology Initiative) files, typically with extensions `.nii` or compressed as `.nii.gz`, are widely used in medical imaging. These files represent **3D volumes** and can encompass an entire **series of DICOM images** in one file, making them highly efficient for storage and handling in medical research and analysis.

- **DICOM (Digital Imaging and Communications in Medicine):** DICOM is the **standard format for storing and transmitting** medical imaging information. Each DICOM file contains **one slice of a 3D dataset**, which can appear **almost 2D due to the very small depth of each slice**, but in reality, these slices comprise a 3D volume when assembled. These files are detailed, including patient information, imaging parameters, and the imaging data itself, **composed of voxels.**
- **Voxels:** Voxels are the **three-dimensional equivalent of pixels**, representing a value on a regular grid in a three-dimensional space. **Typically, the X and Y dimensions are larger than the Z dimension (depth)**, which allows detailed cross-sectional images while maintaining manageable file sizes.



Voxels Visualization

Voxel Spacing: Voxel spacing refers to **the distance between the centers of adjacent voxels**. This spacing **can vary significantly due to differences in scanners and scanning protocols.** Variations in voxel spacing can **affect the**

uniformity of the data, which necessitates **resampling** to ensure consistency across datasets for comparative and analytical purposes. Resampling adjusts voxel dimensions to a common scale, which is crucial for accurate volume measurements, 3D reconstructions, and application in computational models.

2D vs. 3D Imaging Approaches

2D Imaging:

2D models are trained on individual slices, creating masks for each slice. These 2D masks are then stacked along the z-axis to form a 3D segmentation. However, this method can **miss important depth information**, leading to less accurate results. This limitation can be critical in cases like tumor segmentation, where the presence of a tumor in one slice increases the likelihood of its presence in adjacent slices.

Advanced models use techniques like recurrent neural networks (RNNs) or pseudo-3D convolutions on stacked slices to address these limitations. Plus accurate 3D reconstructions depend on proper alignment and interpolation of these slices.

3D Imaging:

3D imaging captures comprehensive views including depth but has its own challenges:

- **Performance Issues: Anisotropic datasets, where voxel dimensions vary between the axes,** need additional processing to normalize, which is computationally intensive.
- **Computational Constraints:** Handling the large data volume in 3D scans often requires working with patches or subvolumes. This can be problematic for large organs, as each patch may lack sufficient context for accurate analysis. Brain scans are less affected since patches can still provide significant contextual data.

Challenges in Medical Imaging

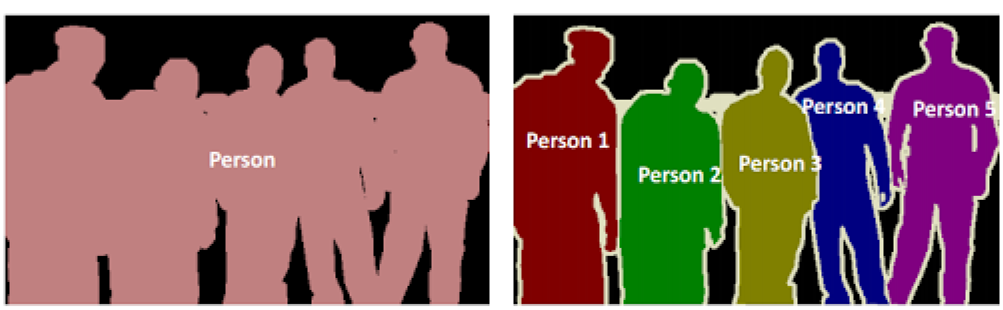
- **Variability in Data**: arises from several sources including **different imaging technologies**, **operator differences**, and **patient-specific factors** such as age, size, or medical condition. This variability can affect everything from **image quality** to the **interpretation of results.**

- **Anisotropic Data**: Anisotropic data refers to the situation where **voxel spacing varies among different dimensions**. For example, in some imaging modalities like MRI, **the resolution might be high in the plane (x and y axes) but much lower along the z-axis (depth)**. To address this, **resampling techniques** are used to achieve **isotropic voxel spacing**, where data is interpolated to ensure **uniform spacing** across all dimensions.

Segmentation

Segmentation in medical imaging is a critical process where specific regions or structures within an image are identified and separated from the rest of the image. This process can be broadly divided into two types:

- **Semantic Segmentation:** This technique classifies each pixel in an image based on its semantic meaning, effectively **treating all objects within the same category as a single entity**. In medical imaging, semantic segmentation is used to **delineate structures such as organs or tissues**. For example, in a brain MRI, semantic segmentation might be used to **differentiate various brain regions or to identify all areas affected by a certain pathology**, regardless of their specific instance
- **Instance Segmentation:** Unlike semantic segmentation, instance segmentation not only identifies the category of each pixel but also **distinguishes between different instances of the same category** within the image.



Semantic Segmentation Instance Segmentation

Semantic vs Instance Segmentation

Segmentation Techniques

- **Manual Segmentation:** This traditional method involves a human expert who meticulously outlines the areas of interest within an image. While manual segmentation is **highly accurate**, it is extremely **time-consuming and labor-intensive**.
- **Automated Segmentation:** In contrast, automated segmentation uses algorithms to quickly and consistently delineate structures within an image. While **faster and less subject to human error in repetitive tasks**, automated methods require careful setup and validation to ensure accuracy.

Latest Advances in Segmentation:

The field of automated segmentation has seen significant advancements with the integration of sophisticated neural network architectures. The **nnU-Net framework**, for instance, adapts itself to any given dataset, optimizing its configuration to enhance segmentation performance. Moreover, the incorporation of **Transformer** technology in U-Net architectures, exemplified by TransUNet, leverages attention mechanisms that significantly improve the model's ability to focus on relevant features for more accurate segmentation. Additionally, **the Medical Open Network for AI (MONAI) framework** provides tools and pre-trained models that facilitate the development and deployment of AI-based medical imaging applications...

Evaluation Metrics

In the field of medical imaging, particularly in segmentation, it's crucial to have robust metrics to evaluate the accuracy and efficacy of different techniques. The following are **some of the standard metrics used**:

Dice Coefficient (Sørensen-Dice Index): This metric **measures the similarity between two sets of data**. In the context of segmentation, it calculates the **overlap between the predicted segmentation and the ground truth**, providing a score between 0 (no overlap) and 1 (perfect overlap).

$$Dice = \frac{2 \times TP}{(TP + FP) + (TP + FN)}$$

Intersection over Union (IoU): Also known as the **Jaccard Index**, this metric is used to quantify the **percent overlap** between the target mask and the prediction output. Similar to the Dice coefficient, IoU is a measure from 0 to 1. https://medium.datadriveninvestor.com/deep-learning-in-medical-imaging-3c1008431aaf

$$IoU = \frac{TP}{(TP + FP + FN)}$$

Hausdorff Distance: This metric measures the extent to which each point of a predicted segmentation lies near some point of the ground truth segmentation, providing a measure of the **largest error between the predicted and true boundaries**. It is particularly useful in contexts where the most extreme values are significant, such as in ensuring that no part of a tumor is missed in segmentation.

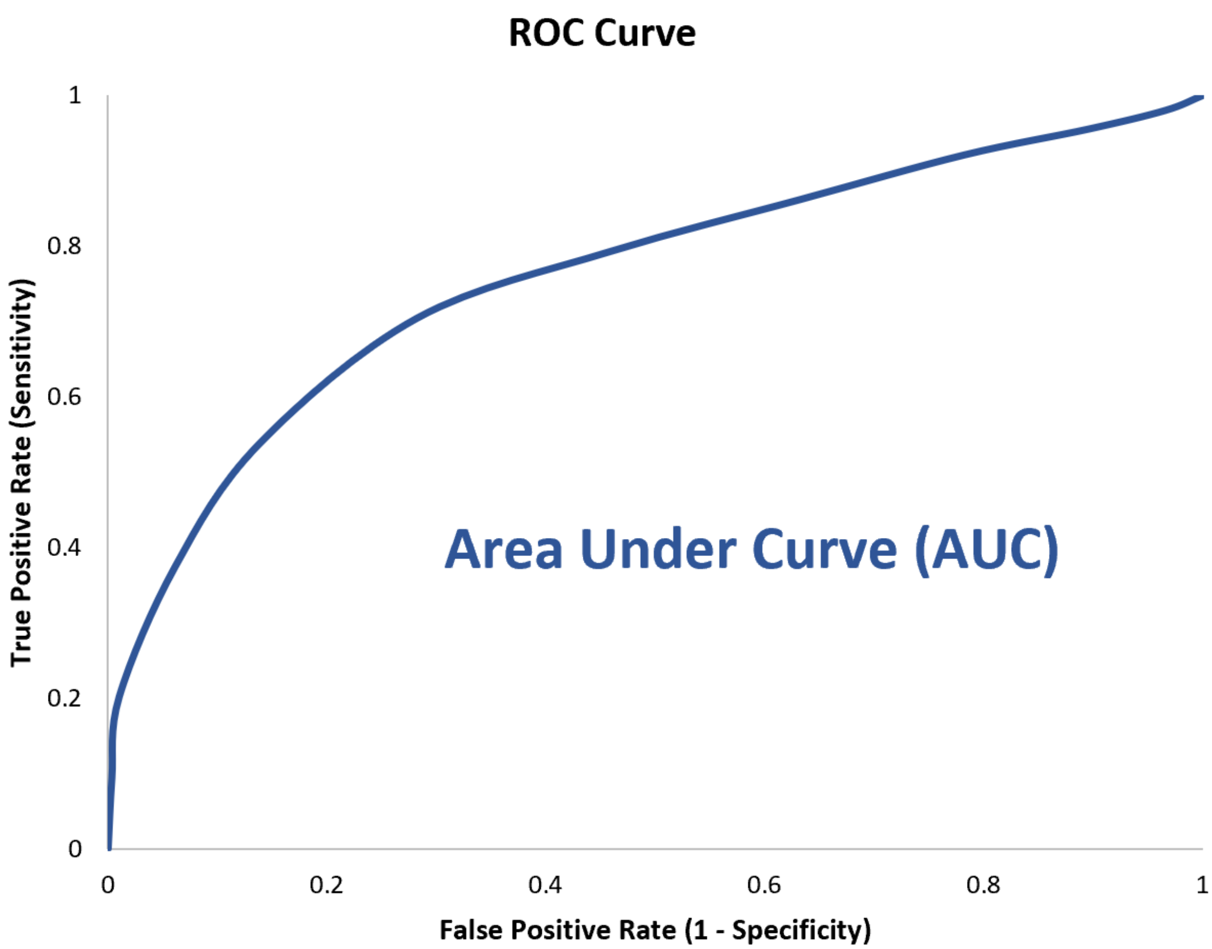
The Hausdorff Distance H between two non-empty sets A and B is defined as:

$$H(A, B) = \max(h(A, B), h(B, A))$$

where $h(A, B)$ is called the directed Hausdorff distance from set A to set B, defined by:

$$h(A, B) = \max_{a \in A} \min_{b \in B} d(a, b)$$

Area Under the ROC Curve (AUC-ROC): The ROC curve plots the true positive rate (sensitivity) against the false positive rate (1—specificity) at different threshold levels. The AUC represents **the degree or measure of separability achieved by the model.**



AUC ROC

Basics of Brain Tumors and Their Imaging

Types of Brain Tumors:

Brain tumors can be broadly categorized into two main types:

1. **Gliomas:** These are tumors that arise from glial cells, which support and protect neurons.
2. **Metastases:** These tumors originate from cancer cells that have spread to the brain from other parts of the body. Metastatic brain tumors are typically

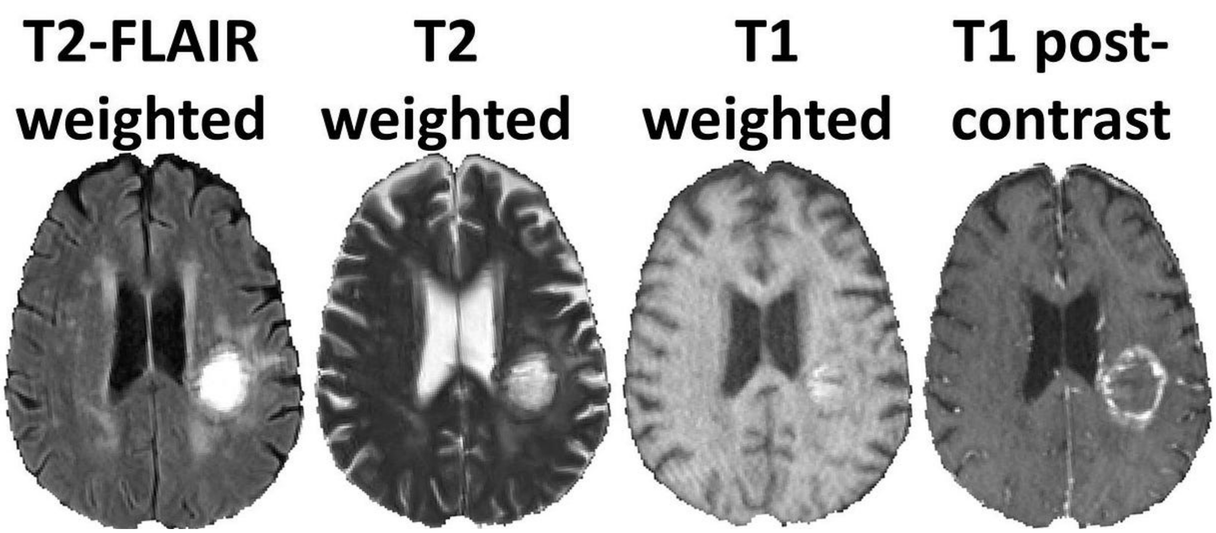
multiple and can appear anywhere in the brain.

Role of Imaging in Diagnosis and Treatment Planning:

Imaging plays a crucial role in the diagnosis, characterization, and treatment planning of brain tumors. Different imaging modalities and MRI sequences are used to gather detailed information about the tumor's size, location, type, and impact on surrounding brain structures.

Common modalities used :

MRI is the primary imaging modality used for brain tumors. Several **MRI sequences** provide complementary information:



MRI Sequences

- **T1-Weighted MRI:** Provides high-resolution images of the brain's anatomy. Tumors often appear as hypointense (dark) areas relative to the surrounding brain tissue.
- **T1 Post-Contrast (Gadolinium-Enhanced) MRI:** Enhances the visibility of the tumor. The contrast agent highlights areas of increased blood-brain barrier permeability, which is common in tumors, making them appear bright on the images.
- **T2-Weighted MRI:** Offers detailed images of brain tissue and fluid. Tumors typically appear hyperintense (bright) on T2-weighted images. This sequence

is useful for assessing tumor edema and the extent of infiltration into surrounding brain tissue.

- **FLAIR (Fluid-Attenuated Inversion Recovery) MRI:** Suppresses the signal from cerebrospinal fluid, providing clear images of lesions near the fluid spaces. FLAIR is particularly useful for detecting peritumoral edema and small lesions that might be missed on other sequences.

Conclusion

This blog covered the purposes of medical imaging, common modalities, data formats, and the differences between 2D and 3D approaches. We also explored segmentation techniques, evaluation metrics, and the specific use of MRI sequences in brain tumor imaging. Advancements in imaging technology and AI are continuously enhancing diagnostic accuracy and treatment planning. As these technologies evolve, they will further improve patient care and outcomes, making medical imaging an indispensable part of modern medicine.