Evaluation of Non-Rigid Registration for Motion Correction in PET/CT Imaging

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Outline

Introduction to PET/CT Imaging

PET/CT imaging is a combination of the cross-sectional anatomic information provided by Computed Tomography (CT) and the metabolic information provided by Positron Emission Tomography (PET), which are acquired during a single examination and fused.

Problem's associated with PET/CT imaging:

- Scan time
- Patient movement
- low dose CT

Problem Statement

Motion Correction in PET/CT images

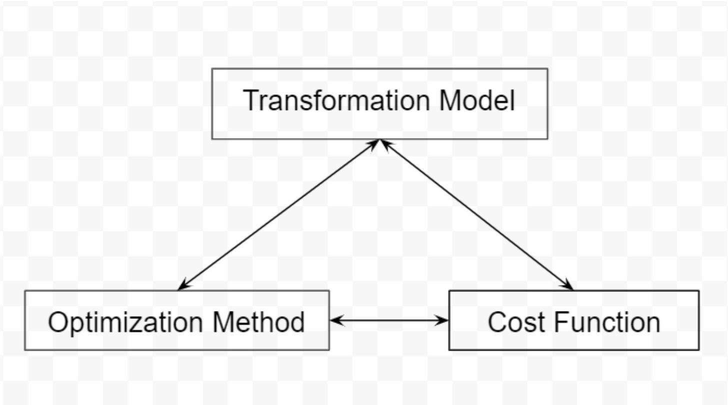
- We want to correct for the movement of patient head and patient hand that takes place while PET imaging which causes the streak artifact.
- Anatomic details in CT is missing.

Solution Approach

- Fast, accurate Multi-modal Non-rigid Motion Correction.
- For better diagnostic information, we will denoise the low dose CT.

Registration Process

Each registration process involves an interplay between three main components:



Deformable (Non-Rigid) Registration

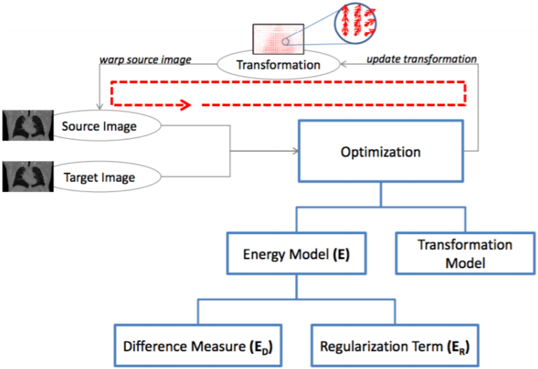


Figure: Deformable Registration framework

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[1]Ref: http://www.cs.ucf.edu/ bagci/teaching/mic17/lec16.pdf

Registration Algorithm

- Fixed and Moving Images **(PET Image and CT Image)**
- Preprocessing **(Thesholding, resizing)**
- Define Similarity Measure **NMI (Multi-modal registration)**
- Define Spatial Transformation **(Demon's Algorithm)**

- **Implementation**
    1. Initialize and Preprocessing.
    2. Transform (and Interpolate) moving image
    3. Measure similarity
    4. Optimize **(L-BFGS)**
    5. Repeat step 2-4 until convergence.

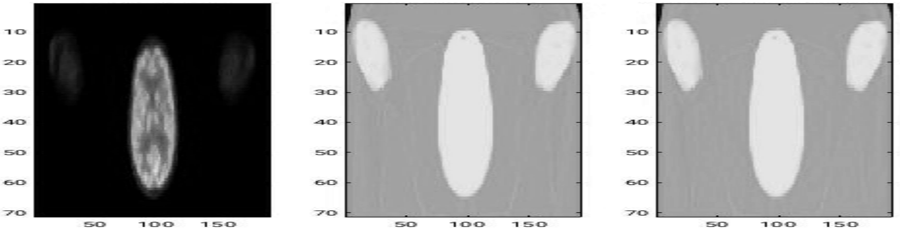
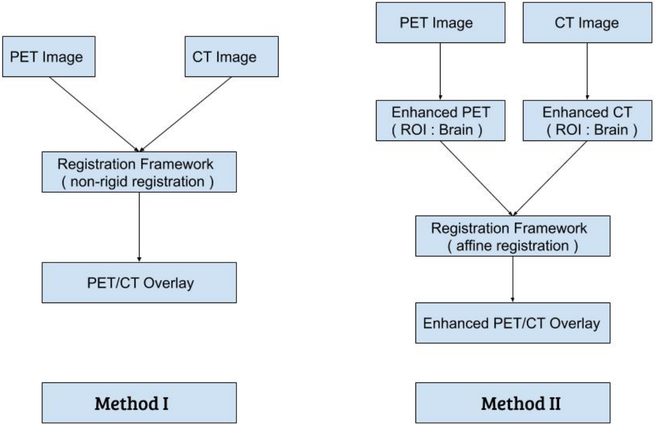


Figure: Showing Non-Rigid Registration of Different Modality, PET and CT image.

- **Algorithm :** Demon's Registration.
- **Cost Function :** Normalized Mutual Information
- **Initial NMI**=0.5501 **After Registration**=0.7661

Proposed Methods



Simulating Noise

Standard deviation of the noise

$$\sigma = K * \sqrt{\frac{1}{mA} - \frac{1}{mA_0}}$$

where,
mA - Current level for simulated low dose CT,
mA_0 - Current level for high dose CT,
K - parameter controlling the relationship for human brain.

Generating Noise

$$noise = conv2(noise, acf)$$

$$noise = \sigma * \frac{(noise - \mu_{noise})}{\sigma_{noise}}$$

where,
acf - Noise auto-correlation function.

Generating low dose CT Image

By taking mA=50, mA_0=190 and k=103.09, we have generated the low dose CT image as,

$$ld_{ct} = hd_{ct} + noise$$

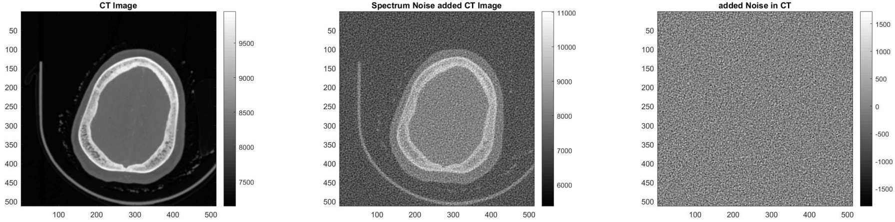


Figure: Showing high dose CT, simulated low dose CT and difference images.

Denoise Low Dose CT

We have simulated the low-dose CT (LDCT) Image from high dose CT Image by adding the spectrum noise.

Denoising Methods

- Non Local Means
- Bilateral filter
- Block-matching and 3D filtering (BM3D)
- Bitonic filter
- Guided Filter

Non Local Means Filter

Non-local means filtering takes a mean of all pixels in the image, weighted by how similar these pixels are to the target pixel, this is the basic principle that used while denoising the image.

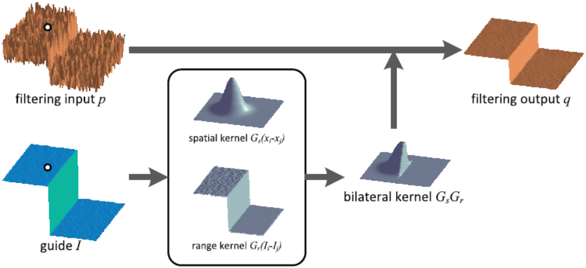
Suppose, we have a noisy image Y = X + noise

$$\hat{\mathbf{X}}_i = \frac{\sum_{j \in \mathbf{S}_i} \omega_{ij} \mathbf{Y}_j}{\sum_{j \in \mathbf{S}_i} \omega_{ij}}$$

where, $\hat{\mathbf{X}}$ is a denoised image.

$$\omega_{ij} = \exp\left(-\frac{\|\mathbf{Y}_i - \mathbf{Y}_j\|^2}{h}\right)$$

Bilateral Filter



$$BF[I]_p = \frac{1}{W_p} \sum_{q \in S} G_{\sigma_s}(\|p - q\|) G_{\sigma_r}(|I_p - I_q|) I_q$$

A bilateral filter is a non-linear filter for denoising. It replaces the intensity of each pixel with a weighted average of intensity values from nearby pixels. The weight depends on both distance and range difference.

Block matching and 3D filtering

The BM3D, utilizes the principle of the block matching. Here we process blocks within the image in a sliding manner and utilize the block-matching concept by searching for blocks which are similar to the currently processed one.

The matched blocks are stacked together to form a 3D array and due to the similarity between them, the data in the array exhibit high level of correlation.

The algorithm is divided in two major steps:

- The first step estimates the denoised image using hard thresholding.
- The second step is based both on the original noisy image, and on the basic estimate obtained in the first step and then uses Wiener filtering.

Bitonic Filter

Bitonic filter is a rank filter, it is more concerned with the ordering than the value based on the principle of bitonicity.

Filtering operation

$$r_{w,c}(x) = c^{\text{th}} \text{ centile} \{x_i\}$$

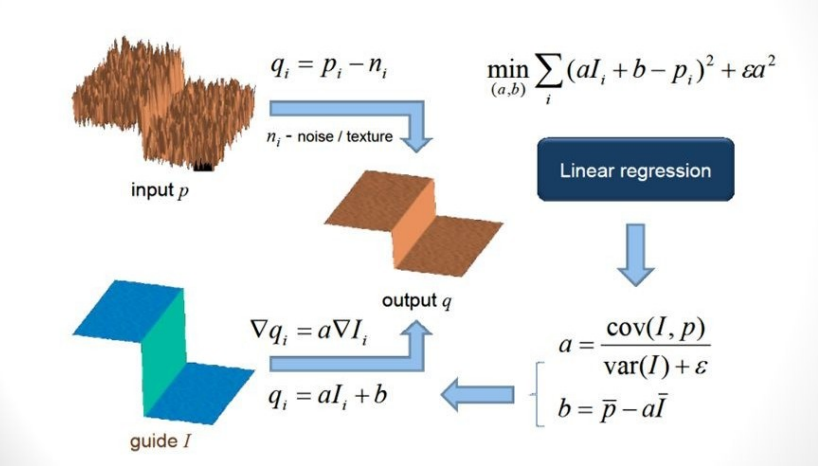
$$O_{w,c}(x) = r_{w,100-c}\left(r_{w,c}(x)\right)$$

$$C_{w,c}(x) = r_{w,c}\left(r_{w,100-c}(x)\right)$$

$$b_{w,c}(x) = \frac{\epsilon_O(x) C_{w,c}(x) + \epsilon_C(x) O_{w,c}(x)}{\epsilon_O(x) + \epsilon_C(x)}$$

where, $r_{w,c}(x)$ is a rank filter, w is the filter window, $O_{w,c}(x)$ and $C_{w,c}(x)$ are the opening and closing, $\epsilon_O(x)$ and $\epsilon_C(x)$ is opening and closing error calculated by gaussian linear filter. $b_{w,c}(x)$ is the output of the bitonic filter.

Guided Filter



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[2] Ref: HE ET AL.: GUIDED IMAGE FILTERING

Performance Metric

To evaluate the performance of image denoising methods, we use 3 different quantitative measures:

- **PSNR**

$$\mathrm{PSNR} = 10\log_{10}\frac{\text{peak}^2}{\mathrm{MSE}}$$

- **SSIM**

$$\text{SSIM}(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$$

- **RMSE**

$$RMSE(x,y) = \sqrt{\frac{\sum_{m=1}^{M}\sum_{n=1}^{N}|x_{mn} - y_{mn}|^2}{m * n}}$$

	sigma*=10 (low noise)			sigma*=15 (medium noise)			sigma*=30 (high noise)		
Filter	PSNR	SSIM	RMSE	PSNR	SSIM	RMSE	PSNR	SSIM	RMSE
No Filter	17.4233	0.3431	0.1345	15.8369	0.2603	0.1615	12.7275	0.1578	0.2310
Bitonic	17.6285	0.5050	0.1314	16.1382	0.4686	0.1560	13.0490	0.3912	0.2226
SV Bitonic	17.6529	0.4971	0.1310	16.1582	0.4517	0.1556	13.0506	0.3611	0.2226
MRV Bitonic	17.6534	**0.5096**	0.1310	**16.1695**	**0.4739**	**0.1554**	**13.0647**	**0.3931**	**0.2222**
NLM	17.6163	0.4458	0.1316	16.0886	0.3731	0.1569	12.9746	0.2539	0.2245
Bilateral	17.5555	0.4265	0.1325	16.0277	0.3499	0.1580	12.9239	0.2325	0.2258
Guided	17.4972	0.3812	0.1334	15.9037	0.2822	0.1603	12.7675	0.1664	0.2299
BM3D	**17.6830**	0.4383	**0.1306**	16.0967	0.3402	0.1567	12.9193	0.2031	0.2260
Weiner	16.0089	0.3373	0.1583	16.0089	0.3373	0.1583	12.9025	0.2216	0.2264
Gaussian	16.7747	0.3934	0.1450	15.5356	0.3722	0.1672	12.7985	0.3339	0.2291

Figure: Denoising filter has been applied at different noise level for LDCT Image.

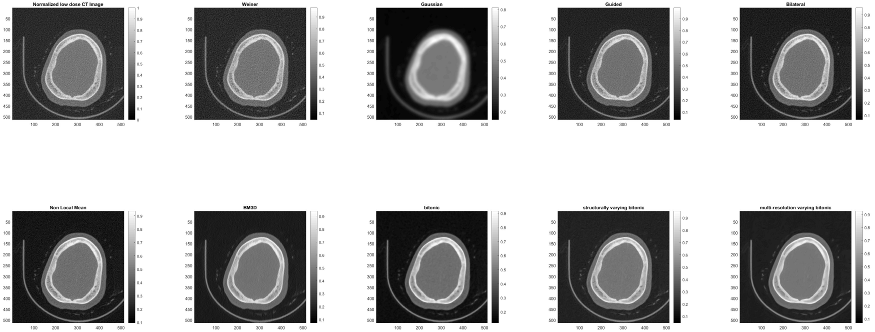


Figure: Showing denoised image after performing filtering operation at sigma*=10 (low noise)

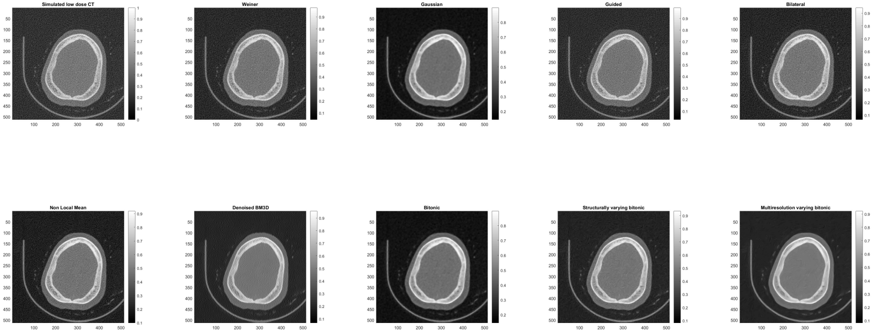


Figure: Showing denoised image after performing filtering operation at sigma*=15 (medium noise)

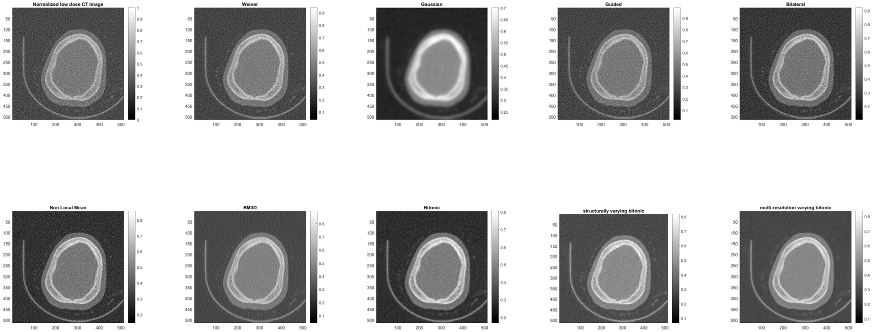


Figure: Showing denoised image after performing filtering operation at sigma*=30 (high noise)

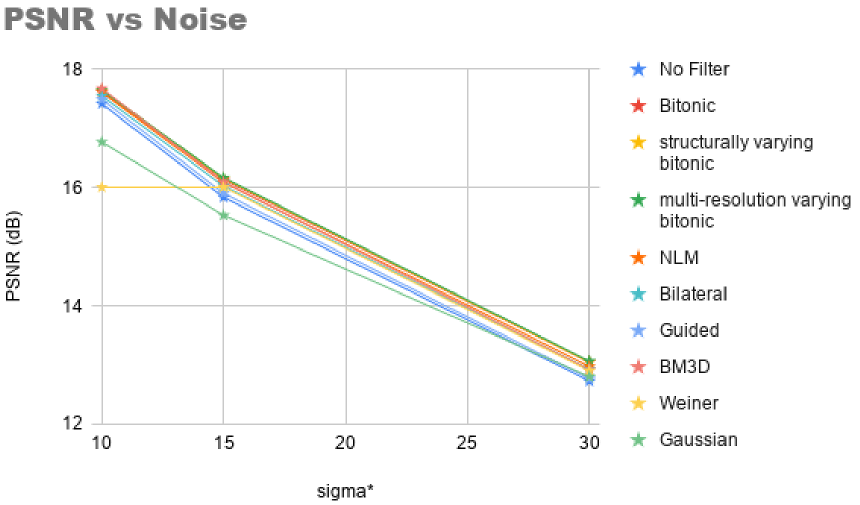


Figure: Plot showing PSNR at different noise level after performing filtering operation.

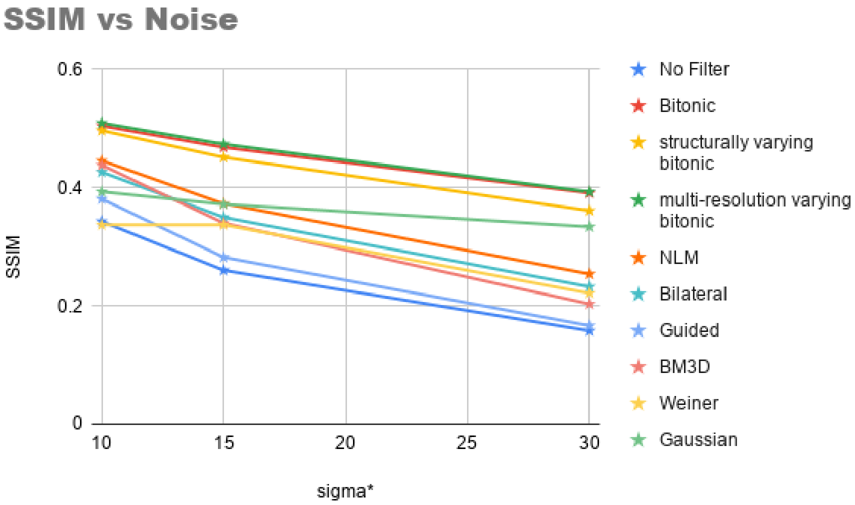


Figure: Plot showing SSIM at different noise level after performing filtering operation.

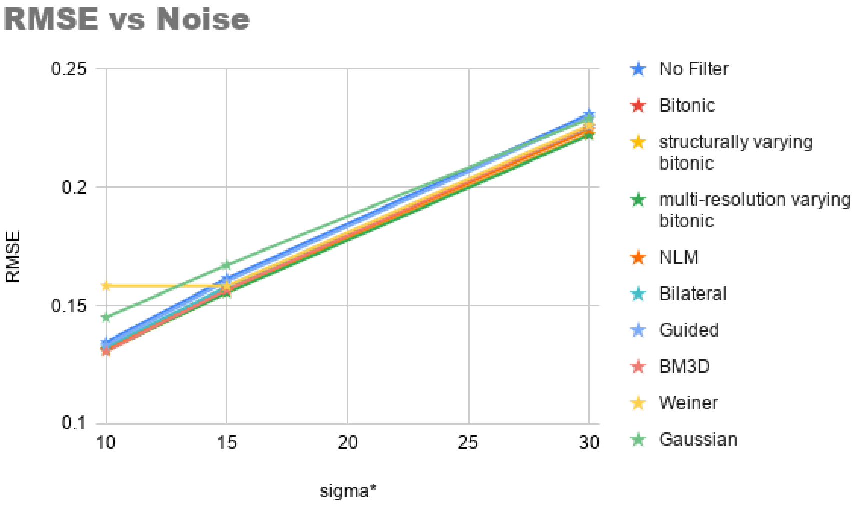


Figure: Plot showing RMSE at different noise level after performing filtering operation.

Data

PET and CT images

- The raw data collected during PET/CT scanning is processed by the scanner computing unit and stored as sinogram file.
- Sinogram Data is then reconstructed to PET image.
- Dimension of PET image : 192x192x319 across 5 bed positions.
- Dimension of CT image: 512x512x319

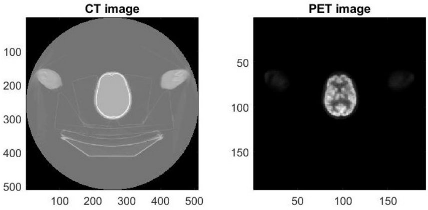


Figure: A single corresponding slice of PET image and CT image.

Demon's Registration

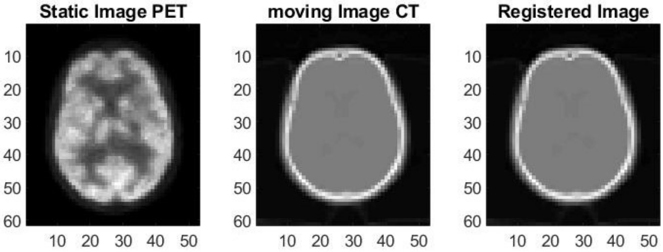
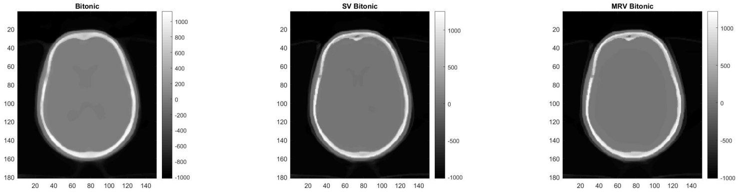


Figure: Preprocessed PET and CT images are registered without denoising.



Bitonic= 4234.1 SVB= 2171.7 MRVB= 2184.2

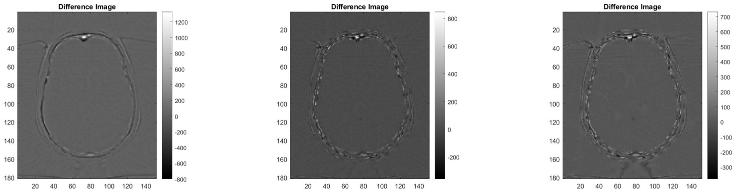


Figure: Showing the output, L2-norm of difference image and difference image when bitonic, Structurally varying bitonic and Multi-resolution varying bitonic filter applied on low dose CT image.

Demon's Registration

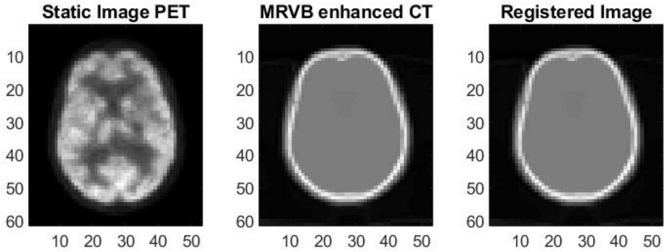


Figure: Preprocessed PET and CT images are registered with multi-resolution varying bitonic filter denoising.

Difference Images after Registration

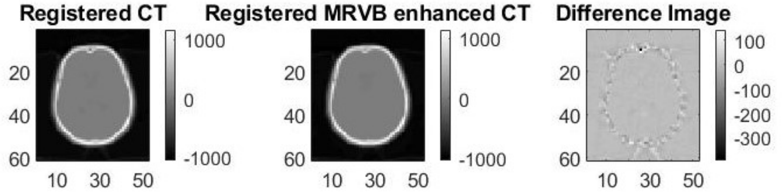


Figure: Registered CT, registered multi-resolution enhanced CT and Difference image (**L2-norm= 500.4284**)

Discussion and Conclusion

- We have enhanced the low dose CT image to an extent, such that we are getting a comparable result to the high dose CT image.
- While denoising the low dose CT, multi-resolution varying bitonic filter outperforms all other denoising method at all noise level.
- In the later method, we have cropped the images to get a region of interest as brain only, and then the affine registration is used to register the images, that makes this method faster.