Medical Physics Coursework

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Medical Physics PHC801

Contents

1 Plain Language Summary of potential Image artefacts during a CT scan

1.A What is a CT scan? How does it work?

A CT (Computed Tomography) scan is a medical technique which uses X-rays to create internal images of your body. Inside a CT scanner, an X-ray source goes around your body, shooting X-rays at different angles that pass through your body and get detected by an X-ray detector, thus generating image slices of that particular cross-section of your body part. These Image slices are then processed and compiled computationally to develop the entire image of the organ of interest to diagnose potential tumour growths, disorders, injuries etc.

1.B What are Image Artefacts?

Image artefacts are anomalies, distortions, irregularities or unexpected or unwanted patterns that appear in an image which are not actually present, thus degrading the image quality. These artefacts can lead to erroneous representation of the organs and can make it difficult for the doctors to interpret the Images accurately. These artefacts commonly occur during a CT scan for various reasons, especially in the case of hip implants.

1.C Why do they occur?

[1]Many reasons cause CT artefacts and can be classified broadly based on their underlying cause, such as Patient based artefacts which include motion artefacts (caused due to movement during image acquisition), clothing and jewellery artefacts etc. Then there are Hardware-based artefacts like rings (single or concentric) which can be caused by miscalibration or failure of the detector or tube arcing caused due to a short circuit or an electrical surge within the x-ray tube. Image noise itself is an artefact which is always present and can only be reduced and never eliminated. Physics-based artefacts caused by beam hardening, aliasing (caused by undersampling), scattering and photon starvation (because of high attenuation,

fewer photons reach the detector, and so the noise is greatly magnified in these areas causing streaks) are also among the most commonly found artefacts during a CT scan. In particular, in the case of hip implants which are likely to be made at least partly from a dense metallic material, it can interact with the X-rays causing distortions such as metallic "streaking". This happens because the metals absorb the X-rays, thus preventing them from reaching the detectors and causing dark streaking bands around the material. Beam Hardening can also occur because the X-rays used in a typical CT procedure are composed of multiple energies, and different materials absorb different energies at different rates. Due to this selective attenuation, lower energy photons are absorbed more, making the remaining beam "harder" since it now comprises a relatively higher number of higher energy photons (this effect is similar to the working of a high-pass filter). The presence of a metallic object can make this effect even more pronounced again, leading to broad streaks, cuppings (appearance of cup-shaped profiles) etc.

1.D How to mitigate these/corrective steps

While the appearance of these artefacts can be problematic and annoying, these are very common, and the medical teams are experienced in dealing with them. There are several strategies to combat these; for instance, giving clear breathing instructions and using immobilisation devices or sedation can prevent motion artefacts from happening. Removing jewellery and clothing corresponding to the region of interest can also help with jewellery and clothing artefacts. Recalibration of the scanner and fixing/maintaining the cathode tube can reduce ring and tube arcing artefacts, respectively. Taking more samples/rescanning can fix aliasing. As for the beam hardening artefacts, image correction techniques or metal artefact reduction techniques, which leverage complex algorithms and software, can help remove a lot of these artefacts or even techniques proposed using Dual energy CT scan images such as in the paper by (Kuchenbecker et al.,2015)[3] can be helpful. Often, minor positioning and technique adjustments can make a significant difference in the image quality. It is, however, essential for you to openly communicate with the radiologist or the medical team and let them know, for example, in this case, about your hip implants so that they can prepare and adjust accordingly. If necessary, the doctor can even consider using other imaging techniques, such as MRI or an ultrasound, to obtain additional information if the artefact issue cannot be resolved satisfactorily.

Word Count- 686

2 Image Artefact Corrective Techniques

In the paper by (Kuchenbecker et al., 2015)[3], They reviewed, analysed and compared a few Image artefact reduction techniques.

TABLE 7-1 Troubleshooting Artifacts on the CT Image

Manifestation	Possible Cause	Corrective Steps
Beam-hardening artifact (broad streaks, cupping, vague areas of low density)	X-ray beams are composed of different energies	Use appropriate filtration, calibration, and correction software. Increase kVp setting.
Aliasing effect (fine lines)	Too few samples	If a partial scan was used, rescan using a complete arc. Increase scan time. Reduce pitch.
Edge gradient effect (straight line radiating from high-contrast areas, such as barium adjacent to air)	Angle of x-ray beam varies between two similar views	Largely unavoidable. Somewhat reduced by thinner slices. Use low or neutral HU-value oral contrast in place of barium.
Motion (shading, streaking, blurring, or ghosting)	Voluntary or involuntary patient motion	Give clear breathing instructions to the patient and reinforce the importance of holding still. Use positioning aids or immobilization devices. Consider sedation, particularly for pediatric patients. Use shortest scan time possible. For cardiac protocols, consider β-blockers.
Metallic (streaks)	Objects present that are beyond the dynamic range of the scanner	Whenever possible, remove metallic objects from SFOV. Angle gantry. Increase technique, particularly kVp. Use thin slices.
Ring (a single ring or concentric rings)	Detector problem	Recalibrate; if rings persist, call service
Tube arcing (no specific pattern; can range from a single streak to severe mottling)	Electrical surge within the x-ray tube	Call service
Spiral interpolation artifacts (subtle inaccuracies in CT number)	Images are created from views that are not all in the same plane	Lower pitch
Cone beam effect (lines appear in a windmill formation)	Only on MDCT, from the cone-shaped x-ray beam	Use pitch selections recommended by manufacturer

Figure 1: Troubleshooting artefacts[2]

2.A Pseudo-virtual monochromatic images

Firstly, they used a simple linear combination technique (α-blending), combining polychromatic CT images at low and high energies to generate a pseudo-virtual monochromatic image. They carry out a series expansion of the polychromatic attenuation equations and then choose an optimal alpha by visual inspection which minimises the artefacts (minimal non linear terms). To check whether α was optimally chosen, total variation is calculated within a region of interest (ROI) which is low in the case of low artefacts and higher in presence of severe ones. Artefacts are then quantified by evaluating the sum of squared pixel values in the non-linear image terms within the region of all soft tissue pixels (since, we do not care about the surrounding air or bone). CNR (contrast-to-noise ratio) in two ROIs (soft tissue and fat/spine) is then used as a metric for judging the image quality.

2.A.1 Advantages

1. A monochromatic image should theoretically not contain any beam hardening artefacts because of absence of spectral shifts, hence the intent of approximating monochromatic images makes sense.

2. Such Linear combination methods can also be used to generate Virtual native images or Virtual noncontrast images (VNC)s which are comparable to a scan image without any contrast agents.

3. These virtual monochromatic image generation methods allow you to study beam hardening independently from scatter since scatter artefacts still persists even in monochromatic images.

4. Image reconstruction algorithm is Linear and hence the linearity can be leveraged.

2.A.2 Disadvantages

1. Each Energy corresponds to a particular α but not the other way around (for $\alpha > 1.8$ cannot be represented as a psuedo monochromatic energy anymore). However, minimal artefact image can have a greater alpha and so it won't correspond to any energy.

2. Artefacts caused by scatter radiation or photon starvation will still exist despite achieving monochromaticity and so this method can never remove them.

3. A water pre-correction simplification is assumed in the derivation of the new raw data which won't hold if the predominant material is not water, and so in the presence of metal implants or other prosethetic parts this appoximation can be wrong.

4. The non-linear terms responsible for the artefacts can not be eliminated completely through a linear combination of low and high energy images and hence, the artefacts can only be reduced and never completely removed.

5. If the specific value of α which minimally reduces the non-linear terms also causes the bone raw data term to become close to one, the CT-value of the bone will be close to 0 HU and bone contrast will be reduced or even inverted.

6. Although this method may be able to reduce the metal artifacts in the image, however it comes at the cost of a high CNR penalty (The CNR of the resulting image is highly reduced) and hence some post-processing might be required to restore the image quality.

7. Again this method could supress simple artefacts but in more complex scenarios with intense metal artefacts caused by eg. an artificial hip joint could not be removed completely (For instance, it may happen that some slices appear artefact reduced, while a different position remains unimproved).

2.B Virtual Monochromatic Images

Raw-data based material decomposition and dual energy processing is used to generate virtual monochromatic images. First, a series expansion is again done to determine water and bone raw data. These are then converted to images using Inverse Image transforms and from these two virtual monochromatic images at low and high energies are generated. We can even use these images to compute linear combinations and generate other virtual monochromatic images as well. Note that in the case of both virtual and pseudo-virtual images, the inversion can be done either numerically or through some calibration technique.

2.B.1 Advantages

1. Raw-data based virtual monochromatic images are free of beam hardening and metal artifacts irrespective of the monochromatic energy level chosen, (we're left with a degree of freedom) and hence one can use the blending factor α or the energy level to optimize other criterions such as improving the CNR.

2. The CNR penalty is almost negligible and hence, the image quality is preserved without the need of any post-processing and so it clearly outperforms the existing Linear combination based techniques.

3. The normalized relative energies which quantifies the non-linearity (and hence the artefacts) is significantly lower for the case of raw-data based material decomposition methods compared to image-based psuedo-monochromatic imaging.

2.B.2 Disadvantages

1. In the paper, the low and high energy threads were geometrically inconsistent ($90°$ apart) and hence, they had to apply an MDIR algorithm which iteratively generates consistent rays by polychromatic forward projection of the material-specific volumes of the previous iteration. And so, pre-processing of the raw data may be required before virtual images can be generated.

2. The nonlinearity of the data is preserved and hence, linearity properties cannot be exploited for simplifications.

2.C FSNMAR corrected Images

Pseudo-virtual monochromatic images were also compared with Frequency Split Normalized metal artefacts reduction (FSNMAR) image reconstruction techniques, particularly for the case of a patient data set containing an artificial hip-implant.

2.C.1 Advantages

1. FSNMAR algorithm even works for single energy and hence, DECT data is not required for this to be implemented.

2. FSNMAR outperforms pseudo-monochromatic imaging in both artefact reduction and in CNR performance

3. FSNMAR images can also be linearly combined to better quantify it's performance in terms of CNR against pseudo-virtual monochromatic images. In which case, it was found that pseudo-monochromatic images were nearly artefact free for all α and hence could be used to optimize CNR even further, (or to accentuate certain materials)

2.C.2 Disadvantages

1. Dedicated metal artefact reduction algorithms can be complex and are not provided by all CT vendors and therefore, they may not be available for use.

A limitation of the study is the focus on beam hardening artefacts, while other artefacts caused due to scattering and photon starvation remain undisturbed. Photon starvation however, can be resolved through adaptive filtering but scattering artefacts are still being researched.

It is also proposed to use a similar frequency split approach by taking high frequencies of the CNR-maximized pseudo- or virtual monochromatic images and combining them with complementary low frequencies of the artefact reduced one

(this is done to mount the noise of a low noise image to the image of interest) and hence there will be no noise penalty and the CNR won't be affected by the increase in α. However, in this case the frequency-split in pseudo- or virtual monochromatic images would replace orignal data with data from different image, making it a "cosmetic" procedure rather than a physically correct procedure.
Note, one should keep in mind that DECT's strong suit is material decomposition and not artefact reduction.

Further on, [1]Patient-induced artefacts can again only be effectively reduced through patient preparation and education (keeping still, removing clothing etc.). Tube current modulation can result in a more uniform image quality, optimizing scan parameters, use of filters and post-processing, iterative reconstruction algorithms can all go a long way in artefact reduction.

Word count- 1201

3 CT image Enhancement

3.A Aim-

To enhance the Image quality of Monte Carlo generated CT images of a simple phantom containing a metallic region.

3.B Background/Theory

[13]An X-ray image is a projection through the object in a single direction. For a 2D projection image slices, it could look like

$$\lambda(x,y) = \int \mu(x,y,z)dz$$

However, in practice however, these projections are taken in multiple directions (in our case 0-360 in steps of 2 degrees), which can be used to form a sinogram, in which each column is a projection along a given direction. In our case, a particular row or a slice of interest is chosen and it's corresponding sinogram is used to reconstruct the image through back projection.

$$F(x,y) = \Sigma_{\theta=0}^{\pi} g(x cos\theta + y sin\theta, \theta)$$

where $g(\rho,\theta)$ corresponds to our sinogram. However, this unfiltered reconstruction leads to blurring (due to averaging/smearing) and faces a central oversampling problem. These problems in our initial back projection attempt can be resolved if we apply the reconstruction in the fourier domain. For instance, the blurring seen in raw back projection is a form of low frequency noise which can be corrected with a

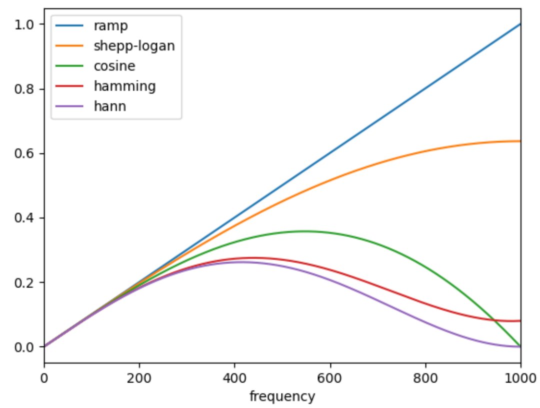

Figure 2: Filters[12]

low frequency filter. A few filters are illustrated in 2.
In our investigation, we also implement iterative reconstruction algorithms, SART (Simultaneous Algebraic Reconstrucion Technique), which formulates the inverse radon transform of the sinogram as large set of linear equations[12], and solves it using an iterative solver.
We then finally perform denoising through various filtering techniques while preserving the features.

3.C Method

3.C.1 Initial Data pre-processing

The raw data files are loaded and converted to appropriate format and stacked in an image stack. A single row or slice is chosen and summed over the thickness of the slice and appended and transposed thus forming our sinogram.

3.C.2 Filtered Back projection

An inverse radon transform is done to reconstuct the image slice from the sinogram. This image is of low quality and has a lot of blurring, noise etc. A ramp filter is then used to get rid of the low frequency noise forming our filtered back projection. This then denoised through Non local means filtering. The non-local means algorithm replaces the value of a pixel by an average of a selection of other pixels values[12].

3.C.3 Iterative Reconstruction

SART is also used for image reconstruction. Performing SART over multiple iterations can help improve the sharpness of high frequency features and reduce mean

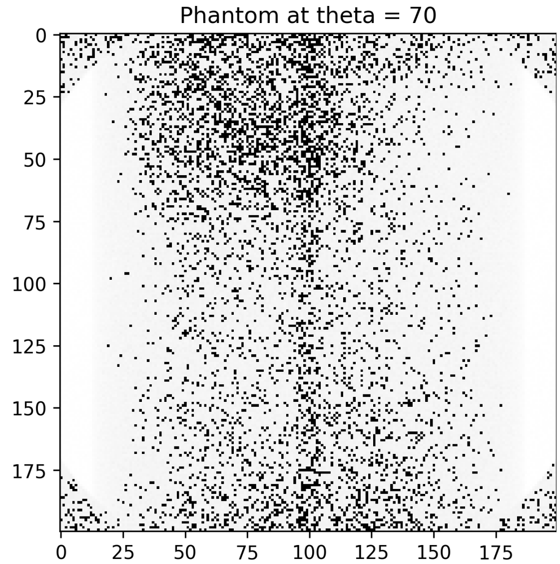

Figure 3: Phantom at theta = 70, 140keV

square error at the cost of high frequency noise.

3.C.4 Noise Reduction

Noise is then reduced through several filtering techniques including non-linear means, TV chambolle filter, bilateral filter, wavelet filer and TV bregman filter. Optimal filter parameters are also calibrated as an illustration for the TV chambolle filter.

3.D Results and Analysis

Figure 3 Shows the phantom slice at $\theta = 70°$ for the 140keV dataset. Figure 4 shows the sinogram (200x180 dim array) constructed from the image stack (by choosing the 40th slice, summing over the slide thickness 2°, and transposing). 5 Shows the initial back projection reconstruction. Notice the metal artefact which looks like a shadow. The image seems a bit blurry and faint. 6 shows the filtered back projection with ramp filtering. The artefact is not apparent however image looks very grainy and noisy. 7 Shows the denoised FBP image using NL-means filtering. The object is much clearer and the artefact is clearly reduced from the initial reconstruction. 8 Shows the image reconstruction through SART (1 and 2 iterations), the image formed does not have any artefacts. 9 Shows SART reconstructed images post different denoising filters. 10 Shows SART reconstructed image de-noised with TV-chambolle filter, with optimal calibrated parameters.
11 Shows the sinogram for slice=80, 140keV image, notice that this is flatter compared to the one with slice=40. 12 shows the corresponding unfiltered back projec-

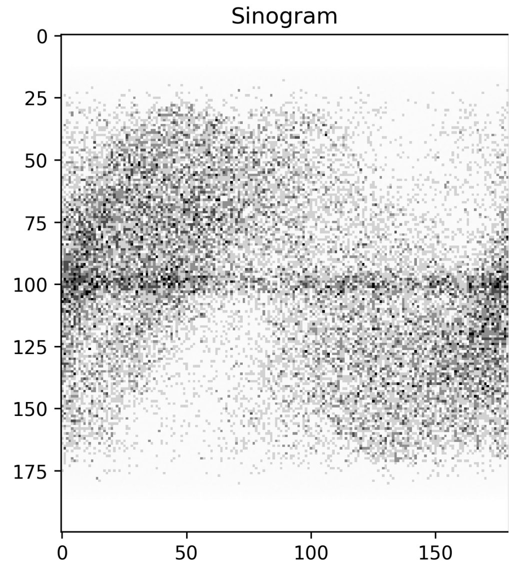

Figure 4: Sinogram, 140keV, Slice=40

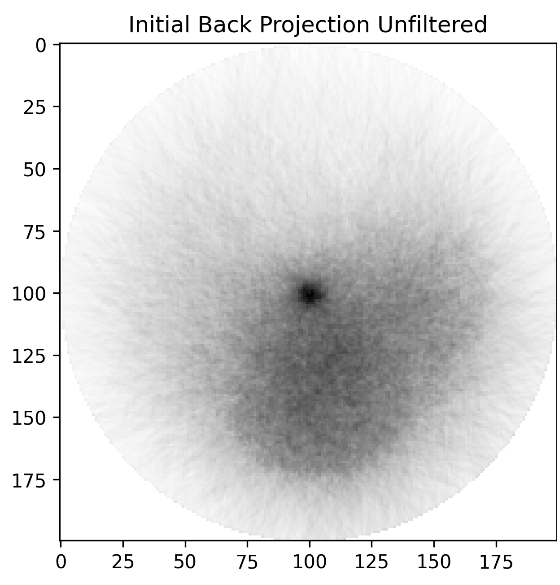

Figure 5: Initial Back Projection Unfiltered, 140keV, slice=40

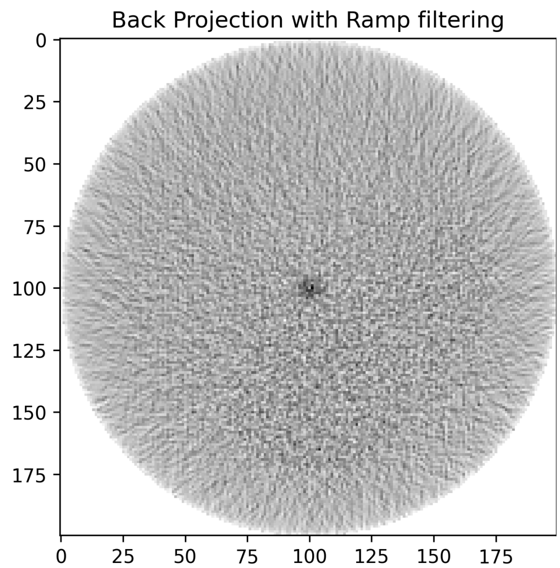

Figure 6: Back Projection with Ramp filtering, 140keV,slice=40

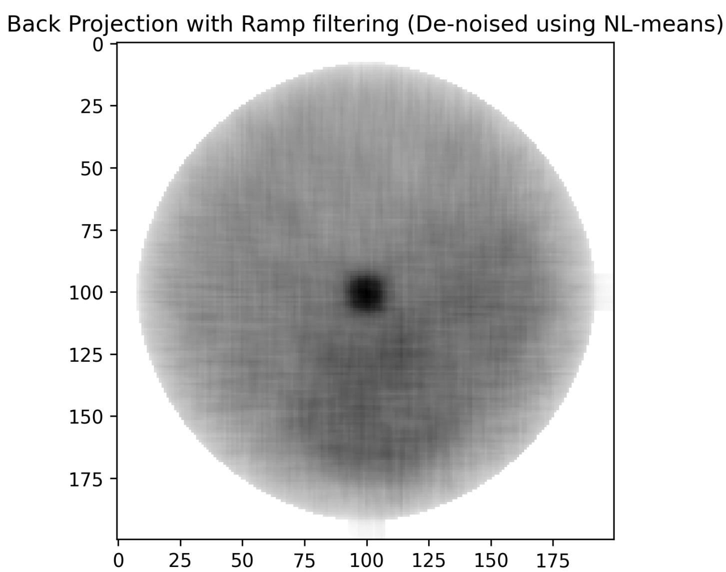

Figure 7: Back Projection with Ramp filtering (De-noised using NL-means)

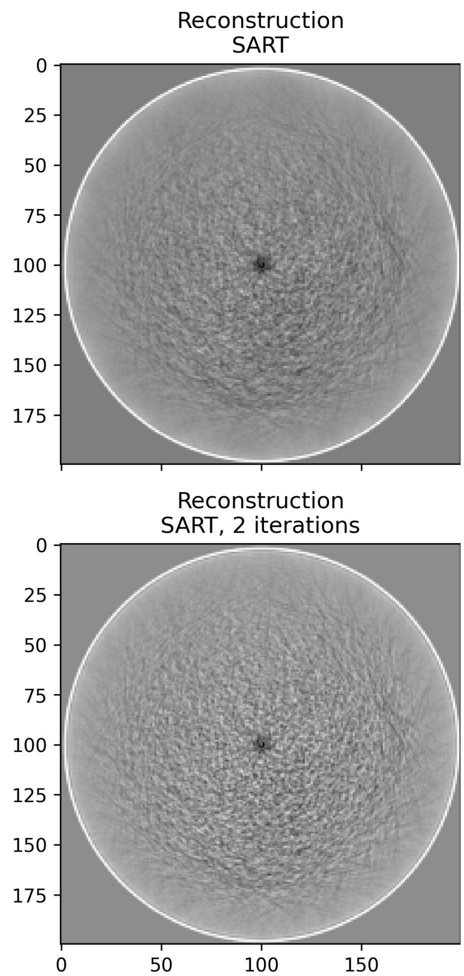

Figure 8: Reconstruction SART, 140keV, slice=40

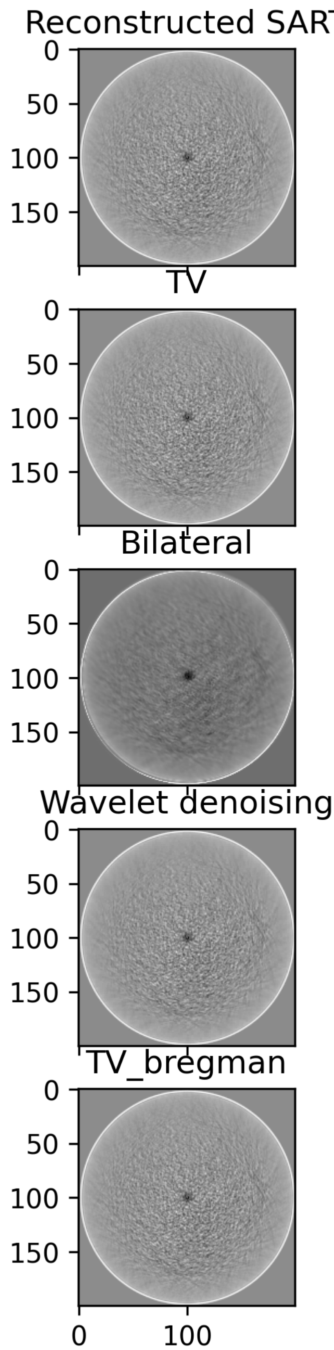

Figure 9: SART with different denoising.

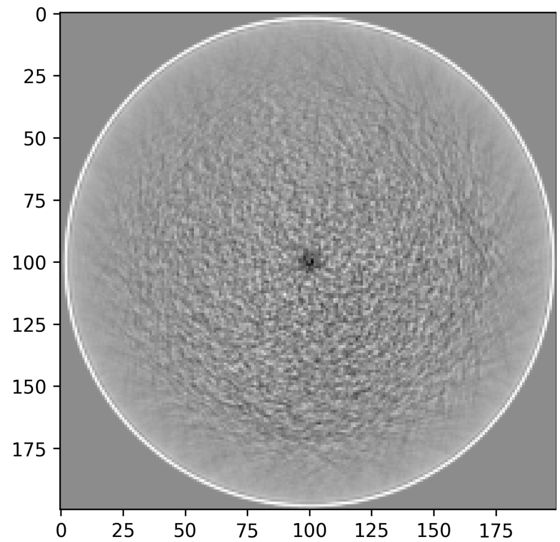

Figure 10: SART (2 Iterations) + de-noise TV (calibrated)

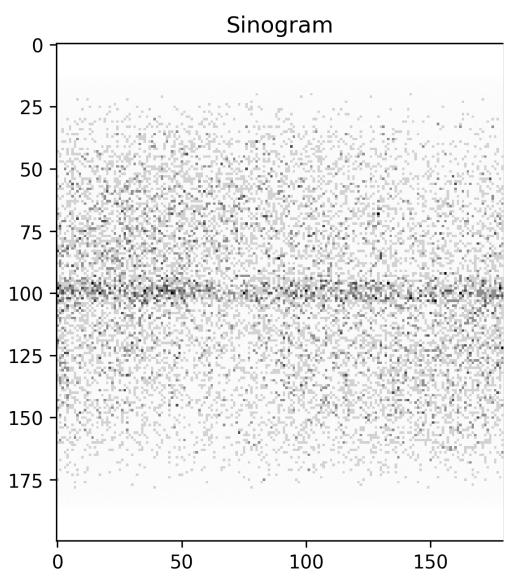

Figure 11: Sinogram, slice=80, 140keV

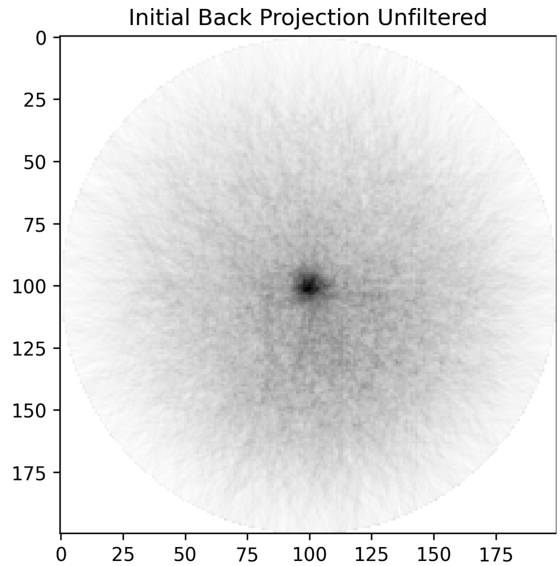

Figure 12: Initial Back Projection Unfiltered,slice=80, 140keV

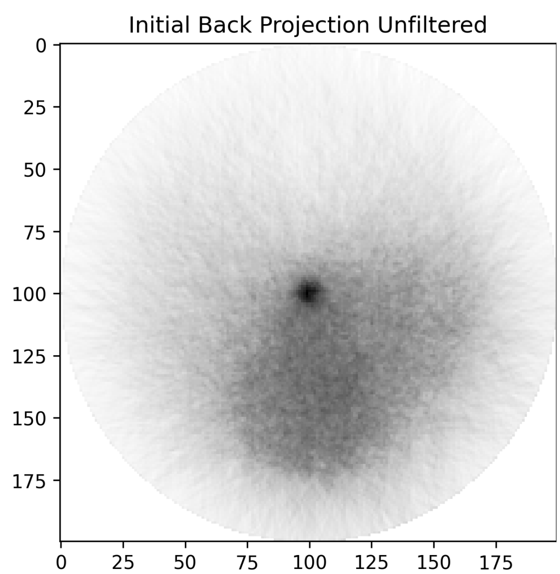

Figure 13: Initial Back Projection Unfiltered,slice=40, 160keV

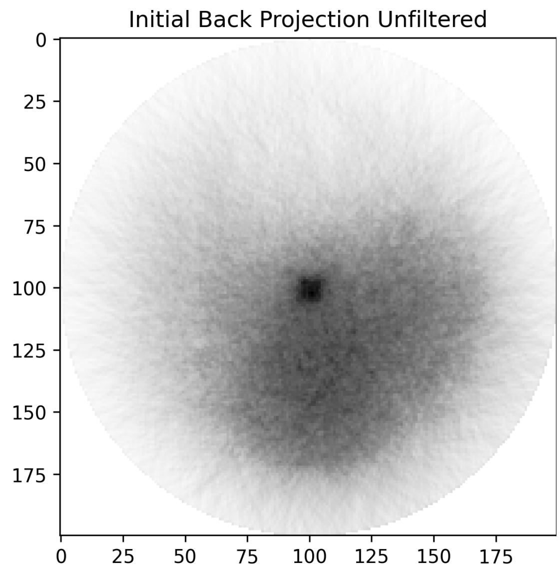

Figure 14: Initial Back Projection Unfiltered,slice=40, 100keV

tion. Notice there is no artefact in this one. Hence, the presence of an artefact also depends on the slice depth.
13 Shows unfiltered back projection for slice=40, 160keV. 14 Shows unfiltered back projection for slice=40, 100keV. Notice as the energy decreases, the artefact becomes darker.

3.E Discussion

Different Byte-ordering (pre-processing of the data files) can yeild different looking images as can be seen in 15. The images also highly depend on the raw data type of the array and hence, it needs to be set appropriately. The images needs to be normalized to the permissible grayscale values (0-255), otherwise, for instance in the case of extremely low values, floating point errors and digitisation artefacts appear upon de-noising etc.
Peak signal to noise ratio (PSNR), along with structural similarity (SSIM) score could be used as metrics to evaluate the improvement in the image qualities, however the same issue with the re-scaling of the images gave errors and hence couldn't be done. We could've also incorporated Metal artefact reduction techniques, such as the one proposed in [3] for DECT images, but I would need to look at the implementation and pseudo-code for the same.

The code is attached along with this in a zip file (along with the result images, which couldn't be included in this file.) and is also available on [15].

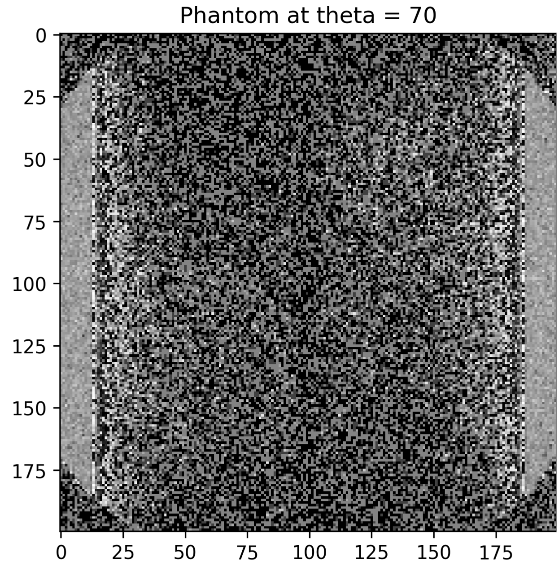

Figure 15: Phantom at theta = 70 (different byte ordering), 140keV

4 Elevating Patient Studies

Forms of patient studies and medical research include Laboratory-based research, clinical trials, and epidemiological studies, among others. Medical research possesses the power to transform healthcare paradigms. A few benefits to society are enlisted below-

4.A Personalized Medicine and Tailored Treatments:

(Hoeben A et al., 2021)[5] go through how personalized medicine (PM) or precision medicine can modify the tumour's immune environment and target therapy to the oncogenic drivers of the tumour.

Genomic and proteomic technologies are argued to be potential new tools for understanding cancer biology and the genetic underpinnings of interindividual variations in anticancer medication efficacy (Gasparini G et al., 2006)[6]. The reliability of these technologies can be significantly increased with further efforts through funding for medical research.

According to (Yan M & Liu QQ, 2013)[7], targeted treatments have created new opportunities for customizing cancer treatment by making medicines more tumour-specific and less hazardous. Increased development of targeted medicines will result from knowledge of the molecular pathways behind cancer initiation, progression, and tumour resistance and advancements in disease models and diagnostic tools (such as genome sequencing technologies).

4.B Precision Diagnostics and Early Detection:

(Rivera Franco et al., 2018)[8] Underline the significance of early breast cancer detection. Medical science has produced helpful tools like mammography that have reduced mortality by 20%. Similar to this, numerous additional efficient screening tools, including genetic testing, imaging approaches, and others, have been developed due to medical research.

4.C Enhanced Clinical Trial Design and Efficacy:

(Ajmera Y, et al., 2021)[9] Offers insight into the evolving clinical trial paradigm, their relative benefits and drawbacks, and the rise in popularity of these studies among doctors while once more highlighting the promise of improved clinical trial design and efficacy through patient and medical studies.

4.D Identification of Health Disparities and Inequities:

The Centres for Disease Control and Prevention (CDC)[11] conducted research that emphasized the social advantages of tackling these problems through evidence-based interventions and how patient studies have shown differences in mother and infant health outcomes.

4.E Impact Beyond Patient Studies:

Medical research has made significant advancements beyond the scope of patient studies. Advances in therapies, vaccinations, and medical equipment have entirely transformed disease management. Examples from the past, such as John Snow's epidemiological study, highlight how research may locate the origins of outbreaks and result in efficient interventions[10].

4.F Comprehensive Understanding and Informed Decision-Making:

Beyond remedies, medical research offers vital insights into illness trends, risk factors, treatment results, and healthcare expenditures. This thorough understanding supports evidence-based decisions, resulting in more efficient resource allocation and healthcare policies.

Word Count- 412

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[13] CT workshop pdf

[14] Chat GPT for understanding concepts

[15] GitHub