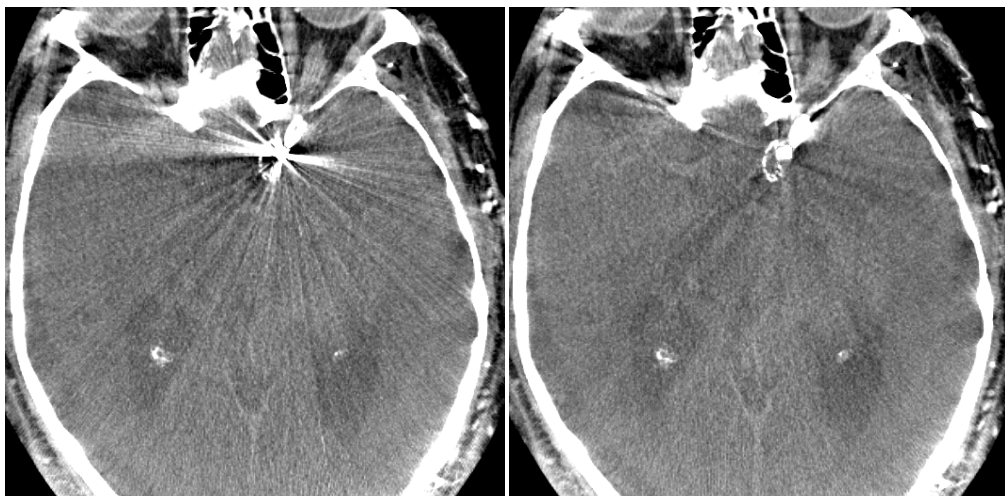


METAL ARTIFACT REMOVAL IN C-ARM CONE-BEAM CT

GROUP 4
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PROJECT PROPOSAL



CT image of coil before and after MAR algorithm application
Image provided by Radvany, MD

THE JOHNS HOPKINS UNIVERSITY
ADVANCED COMPUTER INTEGRATED SURGERY

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Abstract

Metal artifacts seriously degrade the image quality of CT imaging in interventional radiology procedures. Metal artifact removal (MAR) algorithms have been developed and are ready for clinical testing. Prior to clinical trials with such MAR techniques, quantitative analysis of their performance is essential. This project undertakes such quantitative assessment by testing a recently developed MAR technique in neurovascular interventions (e.g., treatment of aneurysms with surgical clips and coils) guided by tomographic x-ray imaging (e.g., cone-beam CT on a Zeego C-arm) using custom phantoms designed to emulate pertinent clinical scenarios and provide quantitative analysis of image quality and accuracy.

I. Technical Background

The primary purpose of medical imaging systems is to create images of the internal structure and function of the body for diagnostic purposes or interventional treatment of diseases. The ability of medical professionals to successfully accomplish these tasks strongly depends on the quality of the images, i.e. the degree to which the image successfully represents the anatomy. Degradations, distortions or artifacts introduced by the imaging system hinder the correct representation of the true objects. Fundamental knowledge of imaging principles, image quality and the factors that introduce image degradation provide tools for optimization of imaging systems.

X-ray computed tomography is a medical imaging modality that relies on the transmission of ionizing radiation through the body. Various tissues and organs within the body attenuate or decrease the intensity of the beam of ionizing radiation as it passes through the body. Since it is the physical characteristics of the tissues, organs or materials (e.g., effective atomic number and density) that determines their attenuation abilities, the resulting images depict structures within the body. The simplest measure of the strength of a burst of electromagnetic radiation is simply the number of photons N in the burst. The fundamental photon attenuation law can be used to compute the fraction of photons that will be stopped or transmitted by a noninfinitesimal layer of homogeneous material. Thus, the most basic measurement of a CT scanner is a line integral of the linear attenuation coefficient at the effective energy of the scanner.

For a fixed angle, CT data measures the line integral of the object, called a *projection*. An image of its projection with attenuation and angle as rectilinear coordinates is called a *sinogram*. It is a pictorial representation of the Radon transform of the signal, $f(x,y)$ and represents the data necessary to reconstruct $f(x,y)$. The reconstruction of object $f(x,y)$ uses three basic steps to reconstruct an image from a sinogram: (a) filtering, (b) backprojection, and (c) summation. Filtered backprojection and convolution backprojection are two approaches that use these steps.

CT imaging systems introduce some amounts of distortion or artifacts throughout the acquisition of the signal and reconstruction of the image. Image quality is a measure of this perceived degradation of an acquired image. Image quality assessments comprise the measurements of contrast, resolution and noise degradation.

Contrast refers to the differences between the image intensity of an object and surrounding objects or background. It is common on CT imaging modality to consider an object of interest (e.g. tumor) that is referred to as the target. If the target has a nominal intensity of f_t and the background has the nominal intensity of f_b then the difference between the intensities of the target and the background is captured by *local contrast*, defined as

$$c = \frac{f_t - f_b}{f_b}$$

In general terms, resolution is the ability of a medical imaging system to accurately depict two distinct events in time, space or frequency as separate. Therefore, we can talk about *spatial*, *temporal* or

spectral resolution. Resolution can also be thought as the degree of smearing or blurring a medical imaging system introduces during the acquisition and reconstruction of data.

Noise is a generic term that refers to any type of random fluctuation in an image, and it can have dramatic impact on image quality. The source and amount of noise depend on the physics and instrumentation of the particular imaging modality and the particular medical imaging system at hand. In projection radiography, x-rays arrive at the detector in discrete packets of energy, called *quanta* or *photons*. The discrete nature of their arrival leads to random fluctuations, called *quantum mottle*, which gives an x-ray image a textured or grainy appearance.

A useful way to quantify noise degradation is by means of the *signal to noise ratio* (SNR). The SNR describes the relative strength of a signal f with respect to the noise, n . Higher SNR values indicate low noise, while lower SNR values indicate higher noise degradation. In x-ray imaging systems, photon count follows a Poisson distribution. Consider the signal f to be the average photon count per unit area and the noise n to be the random variation of this count around the mean, with amplitude quantified by the standard deviation of the number of photons. Therefore, the *intrinsic SNR* of x-ray is defined as,

$$SNR = \frac{\mu_n}{\sigma_n} = \frac{\mu}{\sqrt{\mu}} = \sqrt{\mu}$$

SNR can be defined and measured in various ways, but any useful definition of it must contain contrast and noise. Therefore, a basic SNR measurement should contain,

$$SNR = \frac{c \mu}{\sigma_\mu}$$

The term artifact is applied to any systematic discrepancy between the CT numbers in the reconstructed image and the true attenuation coefficients of the object. Artifacts do not represent valid anatomical objects and can obscure important targets or be falsely interpreted as valid image features. Physics-based artifacts result from the physical processes involved in the acquisition of CT data. These can be caused by *beam hardening*, *partial volume*, *photon starvation*, and *undersampling*.

An x-ray beam is composed of individual photons with a range of energies. As the beam passes through an object, it becomes “harder,” that is to say its mean energy increases, because the lower energy photons are absorbed more rapidly than the higher-energy photons. This phenomenon is called *beam hardening*. Two types of artifact can result from this effect: so-called cupping artifacts and the appearance of dark bands or streaks between dense objects in the image. One type of *partial volume* artifact occurs when a dense object lying off-center protrudes partway into the width of the x-ray beam. The inconsistencies between the views cause shading artifacts to appear in the image. Partial volume artifacts can best be avoided by using a thin acquisition section width. A potential source of serious streaking artifacts is *photon starvation*, which can occur in highly attenuating areas. When the x-ray beam is traveling horizontally, the attenuation is greatest and insufficient photons reach the detectors. The result is that very noisy projections are produced at these tube angulations. The reconstruction process has the effect of greatly magnifying the noise, resulting in horizontal streaks in the image.

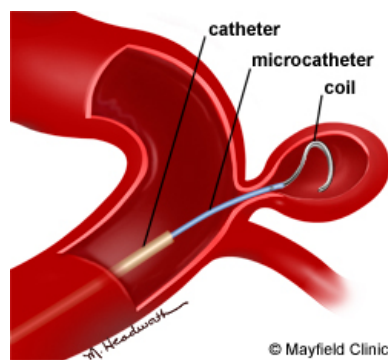
Metal artifacts on CT are caused by the manifestation of several effects discussed in previous sections. (a) Metal artifacts represent the extremes of the beam hardening phenomenon since the complete attenuation of the beam results in gaps on the data from these shadows in the projection data. When using a filtered backprojection method, these gaps in the projection data produce dark bands on the images around the metallic object. (b) The actual density of metallic object is another factor to consider. (c) Motion of the interface between the metal and surrounding tissue can cause an accentuation artifact.

Recently developed Metal Artifact Removal techniques include: sinogram interpolation-based methods, length normalization methods, transmission maximum a posteriori algorithm, and frequency split metal artifact reduction methods. These techniques are ready for clinical testing, but require thorough testing and analysis before being used in a clinical environment.

II. Clinical Background

The use of CT imaging in the surgical environment provides fast, low-dose imaging for safer more accurate surgical treatment. Neurovascular interventions, minimally invasive interventional radiology procedures performed inside the blood vessels of the head and neck, include treatment for aneurysms, intracranial stenosis, and arteriovenous malformations (AVMs), among others. Treatments of these diseases involve the use of clips, coils, stents and other metal-based materials, which can cause metal artifacts and degradation of image quality.

Aneurysms in the brain occur when there is a weakened area in the wall of a blood vessel. Surgical clipping is one neurovascular interventional treatment option for aneurysms. The goal of clipping is to place a small metallic clip or clips, usually made of titanium, along the neck of the aneurysm, preventing blood from entering into the aneurysm sac so that it can no longer pose a risk for bleeding. Once an aneurysm is clipped, the clip remains in place for life. The aneurysm will shrink and scar down permanently after clipping.



An alternative neurovascular interventional treatment to surgical clipping that does not require open surgery is endovascular coiling, which blocks blood flow to an aneurysm to prevent bursting. The coils used in this procedure are typically made of flexible platinum and are shaped like thin springs. The coil conforms to the aneurysm shape and seals off the opening of the aneurysm and it may take several coils to seal off the aneurysm. The coil is left in place permanently in the aneurysm. Depending on the size of the aneurysm, more than one coil may be needed to completely seal off the aneurysm.

Intracranial stenosis is a narrowing of an artery by a buildup of plaque (atherosclerosis) inside the brain that can lead to ischemic stroke. Balloon angioplasty is a minimally invasive endovascular procedure in which a small balloon is slowly inflated within the narrowed artery to dilate it. Plaque is compressed against the artery wall and the balloon is deflated and removed. In some cases, after the balloon angioplasty is removed, a self-expanding mesh-like tube called a stent is inserted, holding open the artery. The stent systems include a self-expanding, nitinol mesh in the shape of a tube.

Arteriovenous malformations are defects of the circulatory system that are comprised of snarled tangles of arteries and veins that lack an intervening capillary network. The absence of capillaries creates a short-cut for blood to pass directly from arteries to veins: arteries dump blood directly into veins through a passageway called a fistula. In endovascular embolization, one treatment option for AVMs, an embolus is introduced through a catheter that travels through the blood vessels, eventually becoming lodged in the fistula, correcting the abnormal pattern of blood flow. The embolic materials used to create an artificial blood clot in the center of an AVM include fast-drying biologically inert glues, fibered titanium coils, and tiny balloons.

Other sources of metal artifacts in CT include metal dental fillings and intraoperative CT stabilizing pins. Intraoperative CT scanning requires a special fixation system of the head to avoid artifacts that may lead to reduced image quality. For most of the iCT scanners, titanium pins and a clamp are used. Some artifact-free pin holders have been developed to avoid pin-related artifacts without compromise in regard to head fixation; however titanium pins are still utilized in some procedures.

In summary, arterial aneurysms, stenosis, and AVMs are prevalent pathologies that may be treated with a variety of interventional techniques (including clips, coiling, stenting, and other measures). Such interventions are often performed with spatial localization and guidance provided by X-ray CT imaging methods available in the interventional suite. However, the interventions often utilize devices consisting of dense material (metal) that can result in artifacts that degrade CT image quality. Such artifacts can challenge the visibility of structures of interest and reduce the precision and effectiveness of the intervention. As such, the development of metal artifact correction techniques is an important aspect of a high-performance interventional image guidance system.

III. Mission

1. Construction of anthropomorphic brain phantoms to simulate varying metal artifacts (coils, clips, etc.) and the surrounding contrast vasculature.
2. Image acquisition using a C-arm Cone-Beam CT scanner.
3. Quantitative data analysis of image quality and segmentation accuracy.
4. MAR algorithm application, analysis, assessment and potential improvement

IV. Relevance and Importance

Optimizing image quality through MAR algorithms will facilitate safer, more accurate use of CT imaging in the surgical environment. Construction of brain phantoms comprised of various metal materials used in interventional treatments and simulated contrast vasculature will provide CT imaging data for quantitative analysis and assessment of image quality and MAR algorithm segmentation accuracy. This data analysis will aid in the recognized critical requirement for throughout testing of a novel interventional approach before its clinical use. Acquired data analysis might also provide suggestions for improvements of the MAR algorithm and its approach.

V. Project Resources

Available for project use are:

- Phantom: hollow anthropomorphic head phantom, referred to as 'scarecrow' (Fig. 1), which can be filled with materials that can simulate cerebral tissue, contrast vasculature and metal materials used in surgical interventions (coils and/or clips).
- Experimental Imaging bench: CT imaging system available at the I-STAR lab, Johns Hopkins Medical Campus, Traylor bld.
- Zeego/Axiom Artis Zee: C-arm, cone-beam 3D imaging system by Siemens Healthcare (Fig. 2) available at the Interventional Radiology department, Johns Hopkins Medical Campus.



Fig. 1 'scarecrow' brain phantom
Image provided by the I-star lab



Fig. 2 C-arm Cone-Beam CT
Image provided by Siemens Healthcare

VI. Technical Summary of Approach

The project is comprised of three stages: each will consist of the construction of a brain phantom, acquisition of phantom images and the assessment and analysis of image quality and MAR algorithm data. Below are quantitative and/or measurable variables and parameters.

Phantom Construction:

- *Dependent variables in metal fillings:* diameter, volume, sphericity, density, proximity to simulated vasculature structures, number and shape of coils and clips
- *Dependent variables in simulated vasculature:* number of vessels, contrast, volume, length, shape, material (silicon, brain-equivalent jello, among others), location in the brain representative of various anatomical structures including berry aneurysms, taking into consideration areas of the brain where aneurysms are most commonly found.

Manipulation of these variables will produce wanted measurable parameters (such as attenuation and contrast). Further investigation will be done to find the most efficient and effective way to construct these phantoms.

Image Acquisition:

- *Dependent variables in both systems:* Energy of beam (kVp), number of projections, dose, tube current, pitch, collimated detector row width, z-coverage, gantry cycle time

The Zeego/Axiom Artis Zee offers additional dependent variables (such as angulated-source detector orbits and acquisition modes). Further investigation will be done to acquire an extensive list of dependent and measurable parameters and their effects on image acquisition.

Data Analysis:

a. Image quality:

- *Measurable parameters:*
 - Contrast resolution (CNR, $c = \frac{f_t - f_b}{f_b}$)
 - Signal-to-noise ratio ($SNR = \frac{c\mu}{\sigma\mu}$)
 - Spatial resolution (*full width at half maximum* (FWHM) of the MTF(u) = $\frac{m_g}{m_f} = \frac{|H(u,0)|}{|H(0,0)|}$)
 - Artifact magnitude: we will develop a parameter that will quantify the degradation of the background and surrounding structures caused by the presence of a metal artifact.

b. Segmentation accuracy

The MAR algorithm will be available in the Syngo workstation (Software in the Zeego console). We will have constructed the phantom with objects of known size and shape in particular locations so that we will be able to accurately assess the precision of the MAR algorithm in improving the image. Parameters for quantifying the exact discrepancies in the reduction of metal artifacts will be developed as needed.

VII. Project Deliverables

Phantom Construction

- *Minimum:* phantom containing solid metal spheres and surrounding vasculature
- *Expected:* phantom containing metal coil and/or clip and surrounding vasculature
- *Maximum:* phantom containing highly attenuated liquid embolus ('ONYX') and surrounding vasculature

Image Acquisition

- *Minimum:* image acquisition on the Experimental Imaging bench
- *Expected:* image acquisition on the Zeego/Axiom Artis Zee
- 1. *Maximum:* Algorithm capable of transferring data from the Experimental Imaging bench to the Zeego console for MAR analysis.

Data Analysis

- a. Image quality
 - Minimum:* contrast resolution (CNR), signal-to-noise ratio (SNR)
 - Expected:* spatial resolution, artifact magnitude
 - Maximum:* other measurable parameters (expert observer image quality ratings of performance / utility on a hierarchical, ordinal 5-point scale)
- b. Segmentation accuracy
 - Minimum:* application of segmentation algorithm on acquired data
 - Expected:* measurable parameters to evaluate segmentation accuracy
 - Maximum:* segmentation algorithm improvement suggestions

MAR Algorithm

- *Minimum:* assess the image quality improvement due to the application of the algorithm
- *Expected:* run multiple iterations of the algorithm on an individual image to determine the advantages, if any, of repeated corrections, determine whether any other surface improvements or changes in the implementation of the algorithm are possible
- *Maximum:* implement changes in the source code of the MAR algorithm and test on the experimental imaging bench

VIII. Key Dates / Milestones

The project is compromised of three major stages. Following is the schedule:

Task Name	Week number													
	3	4	5	6	7	8*	9	10	11	12	13	14	15	16
1. First stage														
1.1 construction of phantom: metal sphere														
1.2 image acquisition: bench														
1.3 image acquisition: zeego														
1.4 data analysis														
2. Second stage														
2.1 construction of phantom: coils and/or clips														
2.2 image acquisition: bench														
2.3 image acquisition: zeego														
2.4 data analysis														
3. Third stage														
3.1 construction of phantom: ONYX														
3.2 image acquisition: bench														
3.3 image acquisition: zeego														
3.4 data analysis														
4. CIS course key dates														
4.1 project plan														
4.2 seminar														
4.3 project checkpoint														
4.4 poster session														
4.5 final report														

Metal Artifact Removal in C-arm Cone-Beam CT

week	date	MAR project milestones	CIS course due dates
2	2/3-2/9		Project selection
3	2/10-2/16	<ul style="list-style-type: none"> Clinical and technical research 	
4	2/17-2/23	<ul style="list-style-type: none"> Visit I-STAR lab Familiarize with bench equipment/ plan for measurable parameters in image quality assessments Gather necessary materials/plan for first phantom construction 	Project plan presentation
5	2/24-3/2	<ul style="list-style-type: none"> Completion of first phantom Begin obtaining images in bench 	Web page contains approved proposal
6	3/3-3/9	<ul style="list-style-type: none"> Obtain bench images Visit Zeego radiology suite Familiarize with equipment Begin obtaining images in Zeego 	
7	3/10-3/16	<ul style="list-style-type: none"> Obtain images in Zeego Plan for measurable parameters for MAR algorithm assessments Gather necessary materials/plan for second phantom construction 	Paper seminar
8*	3/17-3/23	<ul style="list-style-type: none"> Data analysis for first stage If ONYX will be included in third phantom, obtain it 	
9	3/24-3/30	<ul style="list-style-type: none"> Completion of second phantom Begin obtaining images in bench 	
10	4/1-4/6	<ul style="list-style-type: none"> Obtain bench images Begin obtaining images in Zeego Gather necessary materials/plan for third phantom construction 	Project checkpoint
11	4/7-4/13	<ul style="list-style-type: none"> Obtain images in Zeego Data analysis for second stage 	
12	4/14-4/20	<ul style="list-style-type: none"> Completion of third phantom Begin obtaining images in bench 	
13	4/21-4/27	<ul style="list-style-type: none"> Obtain bench images Begin obtaining images in Zeego 	Begin writing project report
14	4/28-5/4	<ul style="list-style-type: none"> Obtain images in Zeego Data analysis for third stage 	Prepare poster
15	5/5-5/11		Poster session
16	5/12-5/14		Final report

IX. Dependencies and Constraints

Experimental Imaging bench:

- *Dependency: Availability*
 - Resolution: Image acquisition will be done in a two-week period in every project stage. Scheduling depends on Dr. Siewerdsen and lab members.
 - Back-up plan: Zeego system will be used instead.
 - Resolved by: End of each brain phantom construction period.
 - Affects: Image acquisition for image quality assessment.
 - Status: Incomplete
- *Dependency: Training/Supervision*
 - Resolution: Training of equipment will occur during 2/17-2/23. Lab member supervision (if required) will be scheduled previously.
 - Back-up plan: Zeego system will be used instead.
 - Resolved by: 2/17-2/23 Affects: Image acquisition for image assessment.

Zeego/Axiom Artis Zee

- *Dependency: Availability*
 - Resolution: The Zeego imaging system is in clinical use and therefore has an undependable schedule. Image acquisition will be done on a three-week period range once in every project stage. Late afternoon/outside of clinical hours schedule will be preferred. Scheduling depends on Dr. Ehtiati.
 - Back-up plan: Imaging bench system will be used instead.
 - Resolved by: End of each brain phantom construction period.
 - Affects: Image acquisition for segmentation and MAR assessment.
 - Status: Incomplete
- *Dependency: Training/Supervision*
 - Resolution: Supervision (by Dr. Ehtiati or technician) will be needed during each image acquisition. Schedule will correlate with availability of Zeego.
 - Back-up plan: Imaging bench system will be used instead.
 - Resolved by: End of each brain phantom construction period.
 - Affects: Image acquisition for segmentation and MAR assessment.
 - Status: Incomplete

Software in Experimental Imaging bench

- *Dependency: Availability*
 - Resolution: The software available on the workbench is MATLAB coded. The workbench does not contain MAR algorithm capabilities. It will be mainly used for image quality assessments. Training will occur during 2/17-2/23.
 - Back-up plan: Zeego imaging system will be used instead.
 - Resolved by: End of each brain phantom construction period.
 - Affects: Image quality assessments.
 - Status: Incomplete
- *Dependency: Zeego and Imaging bench software incompatibility*
 - Resolution: A maximum deliverable includes writing a conversion algorithm between the imaging bench software and Zeego software
 - Status: Incomplete

Syngo workstation: Software available in Zeego

- *Dependency: Availability*
 - Resolution: This software is available in the Zeego console. Scheduling depends on Dr. Ehtiati and availability of the Zeego.
 - Back-up plan: Imaging bench system will be used instead.
 - Resolved by: End of each brain phantom construction period.
 - Affects: Segmentation and MAR assessments.
 - Status: Incomplete
- *Dependency: Training/Supervision*
 - Resolution: Time for acquaintance with the software needs to be taken into consideration. Confirmation if it can be used independently from the imaging system is needed.
 - Status: Incomplete

Anthropomorphic head phantom: 'scarecrow'

- *Dependency: Availability*
 - Resolution: The phantom will be needed throughout the semester. It needs to be confirmed if other lab members need it so that the phantom construction schedule is not affected.
 - Back-up plan: If for some unpredicted reason it becomes unavailable, the contrast medium and metal artifacts can be placed in another plastic phantom available in the lab
 - Resolved by: End of each image acquisition period.
 - Affects: Segmentation and MAR assessments.
 - Status: Incomplete

Materials: brain-equivalent jello, soft-tissue inserts, coils, clips, ball bearings, simulated vessels, model aneurysms, among others

- *Dependency: Availability*
 - Resolution: The I-STAR lab already is in possession of materials needed for the construction of the anthropomorphic phantom. Any material needed will be requested at least a week prior of its intended use.
 - Back-up plan: If the material is not available in the lab, then a request will be made to Dr. Siewerdsen for ordering at least two weeks prior of its intended use
 - Resolved by: End of each image acquisition period.
 - Affects: Phantom construction
 - Status: Incomplete

Time constraints

- Travel to/from Homewood/Medical Campus
- Availability of Dr. Radvany for meetings
- Availability of lab technicians

Permissions constraints (these will be investigated and requested if needed)

- Responsible conduct for experimentation
- Permission to operate Zeego and/or bench
- Access to the hospital interventional radiology suite and the I-STAR lab
- MAR software algorithm: the algorithm has IRB/FDA approval, so any suggested improvement might not be implemented if not allowed by permissions.

X. Management Plan / Assigned Responsibilities

- Weekly group meetings (members and mentors) every Thursday at 8:00 am.
- Two weekly meetings (members) every Saturday 2:00 to 5:00pm and Monday 6:00 to 8:00pm.
- All documents related to the MAR project will be available in a Dropbox account accessible to both members.
- The web page will be edited weekly (every Saturday after the member meeting)
- A sign-up sheet document will keep track of the members' hours and tasks.

Task	Cay	Wells	Both
Schedule management	X		
MAR algorithm edit approach		X	
Project write-ups and web editing updates	X		
Conversion from bench to Zeego algorithm		X	
Phantom construction			X
Image acquisition and analysis			X

XI. References

[1] Barrett, J. F., and N. Keat. "Artifacts in CT: Recognition and Avoidance." *Radiographics* 24.6 (2004): 1679-691. Print.

[2] Meyer, Esther, Rainer Raupach, Michael Lell, Bernhard Schmidt, and Marc KachelrieB. "Normalized Metal Artifact Reduction (NMAR) in Computed Tomography." National Center for Biotechnology Information. U.S. National Library of Medicine, n.d. Web. 09 Feb. 2013.

[3] Prell, D., Y. Kyriakou, T. Struffert, A. Dorfler, and W. A. Kalender. "Metal Artifact Reduction for Clipping and Coiling in Interventional C-Arm CT." *American Journal of Neuroradiology* 31.4 (2010): 634-39. Print.

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[5] clinical background references available in the "clinical background" research paper

[6] technical background references available in the "technical background" research paper