COMPUTED TOMOGRAPHY FOR THE NON-DESTRUCTIVE IMAGING OF CULTURAL HERITAGE: X-RAY, GAMMA AND NEUTRON SOURCES

by

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Abstract

X-ray and neutron computed tomography (CT) have been used successfully for the non-destructive imaging of artifact in art conservation. These applications range from object investigations to the use of micro-focus CT for experimental studies. While there is precedent for the use of CT in art conservation, the method is still limited in application partially due to restricted access to facilities and the high cost of producing publishable results. The purpose of this study was to identify alternative CT methods including the use of different radiation sources and industrial imaging system. Both investigations of the use of low-flux neutron CT at the Royal Military College in Kingston compared to high-flux neutron CT at the Advanced Neutron Tomography And Radiography Experimental System (ANTARES) at FRM-II in Garching, Munich and the use of megavoltage gamma ray computed tomography at Kingston General Hospital in Kingston successfully imaged the corroded metal artifacts. The artifacts investigated were from the Diniacopoulos Collection at Queen’s University and were underwater concretions of L’Anse aux Bouleaux provided by Parks Canada. This study also evaluated the Xradia XCT-400 for comparison to similar systems used in conservation. This evaluation also provided successful images of corroded metal coins from the Diniacopoulos Collection for use in identification.

To address the issue of cost prohibitive image analysis programs, a workflow using the open-source software programs ImageVis3D, 3DSlicer and ImageJ was developed. This workflow would enable researchers and conservators to produce publishable images and analyze the information in the CT data sets. Additionally, this workflow addresses some common research questions that might arise during investigations that would guide conservators in optimizing their imaging parameters and image analysis. The combination of the alternative
radiation sources and the open-source workflow allows for greater accessibility of CT for conservators and researchers. While the preliminary success of the study is promising, more research is needed to optimize the scanning parameters and image analysis through the use of phantoms and comparisons to traditional investigative methods in conservation.
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Glossary of Terms

ANTARES
Advanced Neutron Tomography And Radiography Experimental System in Garching, Munich.

Axial Axis
Plane dividing an object into upper and lower sections perpendicular to sagittal and coronal axes.

CCQ
Centre de Conservation du Québec (Conservation Center of Québec).

Clipping
Producing an arbitrary plane of voxels of the volume to see internal features.

Computed Tomography
Non-destructive imaging technique producing 3D volumes from radiographs or projections taken from multiple angles.

Coronal Axis
Plane dividing an object into the front and back sections passing from left to right.

FBP
Filtered Backprojection. A reconstruction method for computed tomography.

FRM-II
Forschungs-Neutronenquelle Heinz Maier-Leibnitz (research reactor) used at the ANTARES in Garching, Munich

Half Scan
CT scan of 180° with an additional fan beam angle.

Laminography
Using limited total angle, less than 180°, for CT scanning.

Median Filter
Image processing filter that assigns attenuation values for pixels based on a median of the attenuation values of the surrounding pixels of a given radius.

**Normalization**

Adjustment of portal images using open beam and dark images to compensate for fluctuations in the beam.

**Phantom**

Control or reference test samples used for imaging studies.

**Portal image**

2D image of an object with attenuation values representing material and density. Also known as a radiograph.

**Pseudomorph**

Impressions or voids in concretions from deteriorated objects.

**Reconstructed Slice**

Axial slice of the reconstructed volume produced from reconstruction of sinograms.

**Sagittal Axis**

Plane dividing an object into right and left sections, passing from front to rear.

**SART**

Simultaneous Algebraic Reconstruction Technique. A reconstruction method for computed tomography.

**Segmentation**

Isolation of attenuation values representing different materials and densities to identify features in 3D volume, sometimes with false color mapping.

**SLOWPOKE-2**

Low-flux nuclear reactor used at the Royal Military College of Canada in Kingston, Ontario.

**Thresholding**

Remapping grayscale range for the raw voxel values representing attenuation.
Windowing

Changing maximum and minimum grayscale for the raw voxel values to increase contrast.
Chapter 1

Introduction

1.1 Thesis Motivation

Non-destructive computed tomography (CT) provides an attractive method for nondestructive analysis due to its ability to reconstruct 3D volumes that can be digitally investigated using similar principles as the widely used x-ray radiography. The purpose of this study was to investigate methods in which computed tomography could become more accessible for conservators to utilize in imaging studies on corroded metal artifacts. The use of computed tomography has been previously applied to art conservation, but many factors, including facility accessibility and cost, can prevent conservators from utilizing this non-destructive imaging technique. This study looked at alternative options in imaging protocols that could allow for conservators to image artifacts when it was previously prohibitive to do so. Alternative methods that were investigated included the use of different types of radiation sources and tomography systems. The inclusion of an open source workflow for image processing was also explored as a means to make the process more accessible.

1.2 Thesis Goals

The overarching goal of this study was to produce alternative resources in CT imaging protocols that would allow more accessibility and reduce the cost of the technique to allow for a greater widespread use among art conservators and researchers. The first issue to address was the possible restriction in obtaining access to proper radiation facilities for imaging, such as nuclear reactors or x-ray CT systems. One solution proposed by the study was to evaluate alternative radiation sources and systems to widen the possible the resources for art conservators. The
evaluation of these sources necessitated imaging studies on corroded metal artifacts to determine the parameters needed for successful imaging. Establishing the limitations was also important for proper application to artifacts.

The second factor in adapting the use of CT for art conservators was determining potential costs of scanning an object and the necessary programs for visualization. The question then arose as to whether there might be cost saving measures that could be used that may allow for greater applications. One method of the reducing the cost would be to shorten scan times during experimentation. Often the bulk of the cost of using an external radiation source comes from the scanning time depreciating the radiation source for which there can be a charge per hour. Reducing the time while maintaining image quality would make the procedure less cost-prohibitive. One method of reducing the scan time is to use a limited total angle in the computed tomography scan, called laminography or digital tomosynthesis. This method provides less information than a completely rendered volume, but by reconstructing planes orthogonal to the beam path, the desired surface details may still interpreted. The goal of this aspect of the study is to determine the viability of laminography for art conservation problems. The use of different radiation sources and reconstruction programs will allow for a greater understanding of the optimal parameters.

Another method of cost reduction would be to explore alternative software programs for visual processing after reconstruction. In the literature of the application of CT to art conservation, the method of the visualization is rarely mentioned and often it is indicated that external technicians or operators are used to produce publishable results. As a result, there is less ownership of the data being presented on the part of the conservator. Also, situations may arise that prevent external development of images and the established software, such as Volume
Graphics, can be extremely costly for small imaging studies. The use of the open source medical software programs, available online, provides a rich resource that should be investigated for use in art conservation visualization. While it may not be possible to find one complete alternative to the standard proprietary visualization software, chaining a series of open source programs may prove to be beneficial. An evaluation of the programs, including assessing their strengths in visualizing artifacts and ease of use, will enable a workflow to be developed that will guide conservators in the visualization process as well as providing a cost-friendly alternatives.

1.3 Thesis Outline

Glossary provides definitions for key terms and phrases.

Chapter 1 introduces the research questions that led to this investigation as well as an outline of the contents of the follow chapters.

Chapter 2 is a literature review of the application of computed tomography in art conservation. It outlines the introduction of x-ray CT in conservation from the medical field continuing with the application of neutron CT as a complementary technique.

Chapter 3 evaluates the use of the Xradia XCT-400 for use in the examination of corroded metal artifacts and focuses specifically on the identification of coins from the Diniacopoulos Collection and an object from the shipwreck at L’Anse aux Bouleaux. It also addresses the issue of reconstruction in Xradia compared to the third party software Octopus. A comparison of results from FRM-II in Garching Munich is also presented for corroded metal coins.

Chapter 4 examines the use of neutron computed tomography, specifically the alternative use of low-flux SLOWPOKE-II facility at the Royal Military College in Kingston Ontario.
**Chapter 5** presents the results of the investigation of the use of megavoltage gamma ray CT on underwater concretions of L’Anse aux Bouleaux shipwreck. The use of megavoltage gamma ray CT would provide an alternative radiation source for large and dense objects that are not suitable for neutron CT.

**Chapter 6** presents the results of the investigation of the use of laminography for artifacts. An evaluation of different reconstruction methods, Filtered Backprojection and Simultaneous Algebraic Reconstruction Technique, is made and compared to traditional radiography.

**Chapter 7** presents evaluation of the open-source software programs used in the image analysis of the data sets. It also addresses the development of a workflow to aid conservators in their image analysis.

**Chapter 8** presents the conclusions of the study including possible future research.
Chapter 2

Literature Review

2.1 Early History of CT

X-ray radiography has been used as a non-destructive imaging technique from its discovery in 1986 by W.C. Roentgen in which an x-ray “photograph” was taken of a human hand [Roentgen, 1986]. The use of the technique was quickly adopted for medical use. The first application of x-ray radiography for cultural materials was the radiographic study of mummified remains at the University of Pennsylvania Museum [Middleton and Lang, p. 1]. X-ray radiography is based on the physical and chemical principles in which different materials and densities will absorb various radiations sources to various degrees. The elemental composition of an object and its material will determine the absorbed energy from the incident radiation spectrum which alters the transmitted radiation and this change is used to produce an image of the object including the internal components. Different elements and the corresponding density in the object will absorb the radiation in varying amounts dependent on the type of incident radiation. For example, x-rays are absorbed in increasing amounts as the atomic number increases due to their interaction with atomic electron shell [Middleton and Lang, p. 10]. This absorption pattern accounts for the use of lead as a shield in x-ray imaging.

The different interactions of the radiation sources are related to their properties, including energy. For x-ray and gamma radiation, the most common form of interaction is Compton Scattering in which an incident photon collides inelastically with an electron in the shell, contributing energy to the ejection of said electron and causing the transmitted photon to be lower in energy [Kak and Slaney, p. 114]. Incident photons, x-rays and gamma rays, can have a
photoelectric effect on the absorbing material in which the incident energy of the photons is completely transferred to an emitted inner electron from the material [Kak and Slaney, p. 114]. For gamma rays exceeding 1.20 MeV, pair production can occur where electrons and positrons are created from collision of the high energy photon with the nucleus. [Bushberg et al., p. 40].

While x-ray radiography is capable of producing images of internal features, the inherent two-dimensionality of the process made examining features difficult in both art conservation and in other fields, such as medical imaging. Overlapping objects in the internal cavities or objects along oblique planes made isolating specific features difficult. These limitations prompted the development of new techniques that would use the same principles of radiation absorption of materials yet allow for more targeted imaging and examination.

Laminography was developed as a means of improving imaging from two dimensional radiographs. By imaging an object at more than one angle, it was possible to produce images that incorporated more information about a specific object. The concept was first introduced by the Dutch researcher Ziedses des Plantes in 1932 who postulated that it was possible to reconstruct using projections over less than 180° for specific planes. The first application of laminography was under the name geometric roentenography, so called due to the use of geometric focusing. This method was first implemented by Garrison et al. in 1969 using parallel path geometry in which the x-ray tube and the detector move in opposite direction parallel to each other to gather portal images at different angles (Figure 2.1).
Figure 2.1. Diagram demonstrating classical laminography as provided by Godrom et al., 1999.

From this first use, the method has developed over the years to become more efficient with the advent of digital technology that allowed for fast acquisition of projections and rapid reconstruction. These studies include the use of other geometries and scanning methodologies. One study improved the scanning technique to allow for circular acquisition was conducted by Grant et al. which provided a 3D imaging device. The ability to record data using electron capturing devices, such as CCD cameras, allowed for faster acquisition in the 1970’s, but the method was quickly displaced by XCT developed for use in the medical field. The benefit of full reconstruction outweighed disadvantages of laminography such as long post-processing reconstructions that required expensive computing [Dobbins and Godfrey, 2003].

Within the last two decades, a resurgence in interest in digital tomosynthesis emerged due to the production of flat panel detectors allowing rapid read-out [Dobbins and Godfrey, 2003] and as a means of reducing radiation dosage in patients, particularly for mammography [Wu et al., 2003]. These studies also examined the different reconstruction techniques in digital tomosynthesis or laminography to determine effective means of reducing blur of out-of-plane objects that occur due to incomplete sampling. While computed tomography is still used to a
great extent in the medical field, digital tomosynthesis is considered a viable alternative to the expensive and lengthy procedure that would be experienced in XCT.

CT has had a long history of use in the medical and industrial fields before its application to art conservation and archaeology. CT was predominantly developed for use in the medical field with the first CT scanner engineered by Sir Godfrey N. Hounsfield [Hounsfield, 1973] for which he won the 1979 Nobel Prize in Physiology and Medicine with Dr. Allen Cormack [Kak and Slaney, 1]. Later improvements in reconstruction algorithms and digital technology has allowed for shorter scan times and, as a corollary, reduced dosage for patients.

For each type of imaging radiation, the absorption is measured through the transmitted photons called linear attenuation, μ (cm\(^{-1}\)). [Bushberg et al, 2002]. The linear attenuation coefficient measures the transmission over a distance of Δx, but for 3D objects the material requires consideration for its density. The mass attenuation coefficient (μ/ρ) measures the linear attenuation over the density of the material and is measured in cm\(^2/g\) [Bushberg et al., 2002].

In addition to 3D reconstructions and physical measurements, quantitative data can be obtained concerning material density and composition. The attenuation density is measured in Hounsfields (HU), which is the international standard scale of tomographic density with air at 1000 HU and water at 0 HU [Patric, 2002]. These measurements should also be standardized for different materials which require detailed studies to obtain reference measurements. In recent years, nanotomography, XCT in the nanometer resolution range, has become possible with facilities able to image materials and render volumes as low as 20 nm [Withers, 2007].

Developing from the use of neutron autoradiography and x-ray radiography, the application of x-ray CT was introduced to the art and archaeological fields primarily as a tool for non-destructive analysis of human and animal remains and fossils. This application to humanoid
remains was a logical step from its use in medical field due to direct application of the established techniques with known mass attenuations for human tissue and bone [Conroy and Vannier, 1984]. Examples of these early studies include x-ray tomographic scans of fossilized skulls from various time periods. Radiography was not sufficient in these studies due to the superimposition of the bones in 2D imaging; a more detailed and differential mapping of the bone structure was needed [Wind, 1984].

The ability to examine these occluded and fragile surfaces remains allowed for 3D imaging of the artifacts as an aid for paleontological studies such as the reconstruction of the intercranial bone structure of *Stenopsochoerus*, a Miocene ungulate [Conroy and Vannier, 1984]. The skull that Conroy and Vannier imaged was filled with a hardened matrix consisting of sandstone particles that could be differentiated from the bone density with x-ray CT. Specific measurements could be made using x-ray CT, allowing these researchers to measure bone angles and lengths to determine symmetry and bone morphology for the specimens [Conroy and Vannier, 1984]. These sources also suggest that the technique was not applied only in specific geographic regions, but was being applied by research groups worldwide as Conroy and Vanier were in North America and Wind was in the Netherlands.

In addition to fossilized human and animal remains, CT was applied in the examination of human mummies. These specimens better simulated medical scanning and were used for targeted studies on condition of the mummies. Examples of such studies include research conducted by Dr. Peter K. Lewin in collaboration with many other scientists. One such study, conducted in Royal Ontario Museum, Toronto, Ontario, Canada, was the investigation of the dentition of the Egyptian mummy Djedmaatesankh in which the dental health of the mummy was determined [Melcher et al., 1997]. These studies indicated that XCT could be applied to a wide
range of animal and human remains for non-invasive analysis that would prevent the need for damaging treatments or investigations. Information, such as the medical status of the different remains, provided valuable archaeological insight into past cultures.

2.1.1 Further Developments in X-ray CT

The spread of the technique to other study objects can be seen through studies conducted largely by researchers on various materials in the 1980-1990’s. The focus in North American in x-ray CT research was on organic remains. Examples of the materials examined include wood, ceramic, and metal alloys. The objects studied included ceramic vessels and bronze statues [Tagichi and Saito, 1991]. During this period, x-ray CT was an accessible tool for archaeologists and paleontologists, but studies in North American focused on human remains with improvements on methodology and results such as obtaining higher resolution images.

Within the last decade (2000-2010), there has increased use of CT, especially with the improved resolution achieved by micro-focused x-ray CT for more detailed research on various materials, such as glass and stone. One specific area of study is using x-ray CT to monitor stone corrosion and weathering of building material as a means of monitoring changes in density and structure of the stone and stone based materials over years [De Witte et al., 2008]. Also, investigations of how conservation materials, such as water repellents and consolidants, have been examined in limestone using micro-focus and nano-focus XCT [Cnudde, 2005].

In addition to the application of x-ray CT to monitoring and analyzing stone corrosion and weathering, similar methods have been used for analysis of archaeological glass corrosion [Roemlich et al., 2002]. This study used glass fragments and standards as references for grey values in determining attenuation coefficients of different glass composition and corrosion. The images and measurements observed during the study allow conservators to determine more
clearly the extent of corrosion and identify possible treatments without destructive sampling needed in other investigative methods, such as scanning electron microscopy (SEM). This study has produced promising results and demonstrates some of the ways that CT is being applied directly to art conservation.

Another topic of research using micro-focus CT is the investigation of corroded artifacts with internal mechanisms that could be ideally modeled without cleaning or intervention to prevent further damage. Two important studies in this field are the imaging of the Antikythera Mechanism by Freeth et al. and a recovered submerged 17th century watch by Troalen et al. These studies clearly demonstrate the ability of x-ray CT to produce detailed 3D images of internal components for identification and to use the information for further conservation of the object. Inscriptions were identified on both the corroded mechanisms which demonstrates the fine resolution that can be achieved with micro-focus CT, for example 63 µm \( (d) \) using the X-Tec HMXST-CT for the watch [Troalen et al., 2008] The authors of this study did note that the technique was limited by the size of the x-ray tomographic machine and the depth of penetration of the x-rays, which is why they chose to use a pocket watch which was light and made of silver, not a high-z element that would have high attenuation with x-rays. These observations by the authors highlight the need for the use of complementary neutron and x-ray tomography by researchers to explore fully imaging of a wide range of materials.

### 2.1.2 Development of Neutron Tomography

After x-ray radiography became routine, limitations of the technique, including the inability to penetrate dense objects with high lead content, called for a complementary method that would allow for the non-destructive imagine of other types of artifacts. The limited ability of x-rays to penetrate lead is due to the interaction of photons with electrons. Neutrons, however,
interact with the nuclei of atoms and have different absorption behaviors for elements (Figure 2.2). Neutrons do not interact with orbital electrons. Rather, they interact with the nuclei of the atoms making the attenuation of neutrons not dependent on the atomic number of the material [Heller and Brezinger, p. 68]. Using neutrons as a radiation source provided complementary portal images that were able to highlight different material compositions.

![Figure 2.2. Chart showing the different mass attenuations of atoms for x-rays and thermal neutrons from Schillinger et al., 2006.](image)

Neutron radiography was developed not long after the advent of x-ray radiography. Initial experiments and images were generated in the mid-1930’s by separate research teams of H. Kallman and O.Z. Peter, but were not published until after the Second World War [Heller and Brenzinger, p. 68]. Neutron autoradiography was used in conservation originally for the analysis of paintings due to the different absorption of pigment materials as well as the different activation of the pigments to radioactive isotopes [Taft, 1992]. Examining the painting over time and the changes in the resulting neutron radiographs allowed researchers to identify pigments. Another
study examined the use of neutron radiography highlights the use of neutrons in archaeology as the use of endoscopy proved in the presence of organic material in the statue, but x-ray radiography was unable to provide proper images of this material due to attenuation of the x-rays by the bronze (Figure 2.3) [Jett et al., 1985]. Neutron radiography was performed at the National Bureau of Standards Nuclear Reactor.

![X-ray (left) and neutron (right) radiographs of an Egyptian statue](image)

**Figure 2.3. X-ray (left) and neutron (right) radiographs of an Egyptian statue from Jett et al. showing the presence of organic material inside the sculpture as seen in the neutron radiograph.**

Within the time period of the 1990s, neutron CT began to be applied to technical examinations of cultural artifacts and art conservation. Analogous to the development of XCT to address the inherent limitations of x-ray radiography, neutron CT allowed researchers to examine objects with different material absorption in three-dimensions with the same complementary contrast mechanism in neutron radiography. These studies are limited to specific case studies with particular research questions for individual cases rather than a far reaching overview of the best applications of neutron CT to the entire field. A popular application of neutron CT is its use
for investigations on casting techniques for bronze statues, as organic residue, such as wax, can be detected within a statue and gives an indication of a specific casting method, such as lost wax [Lehmann et al, 2005]. Similar projects have explored the contrast of organic materials within or on the surface of dense metal objects as the attenuations for these types of material are greater than in x-ray tomography which can be limited when dealing with dense materials with high atomic numbers. Metals objects such as lead and bronze are ideally imaged with neutrons for greater penetration [Van Langh et al, 2009] and have been a subject of many studies. One such study conducted by Schotte et al. in 2006 was to monitor the changes in lead density and morphology during controlled electrolytic reduction as a conservation method.

Surveying these studies, major work in neutron CT in the archaeological and art conservation field is limited to European institutions and researchers where neutron sources are available for non-governmental or industrial study, principally the Advanced Neutron Tomography And Radiography Experimental System (ANTARES) facility at FRM-II [Calzada et al., 2005] and the Neutron Transmission Radiography facility (NEUTRA) using the spallation thermal neutron source (SINQ) at the Paul Scherrer Institute (PSI) [Lehmann et al, 1996]. Aiding in the promotion of neutron CT in Europe was the non-destructive testing organization, European Cooperation in Science and Technology (COST) action G8 which was active from 2002-2006 that organized participating researchers in conferences to endorse the collaboration between museum and imaging specialists [Lehmann, 2006].

These efforts led to the successful imaging of many types of artifacts including a Roman statue that was heavily leaded and not possible to image with x-rays [Lehmann, 2006]. Other objects showing the benefit of NCT were a dagger that allowed for the imaging of conservation work through the presence of high attenuating resin and Roman belt buckles where NCT allowed
for the measurement of the glass layers and the identification of plastic additions [Lehmann, 2005]. Some of the most recent studies include the imaging of artifacts still located in blocks of soil [Stelzner, 2010] which demonstrates the ability of the NCT to allow for in situ examination of artifacts as a preliminary investigations o as to not disturb artifacts in their environment.

Neutron CT studies being performed in North America include military and industrial research such as research into the water egress of honeycomb structures in jet wings [Hungler, 2009] at the Royal Military College of Canada in Kingston, Ontario. Other sites in North America performing neutron imaging studies include the Neutron Imaging Facility at the National Institute of Standards and Technology which focuses on the imaging of proton exchange membrane (PEM) fuel cells [Jacobson et al., 2008]. As of the beginning of this study, there was yet to be a published account of the application of neutron CT for imaging art conservation artifacts using neutron facilities in North America despite the precedent set by ANTARES and other European facilities. To allow for a greater number of researchers access to method, it is necessary to investigate possible sources that may be available for use in North America. More opportunities for research in North America might make the technique more cost-effective and allow for the expansion of the technique to answer research questions not possible with x-ray CT or neutron autoradiography.

2.2 Theory of CT Reconstruction

CT as an imaging method derives from the same concepts applicable to radiography but allows for the reconstruction of 3D images using mathematical equations and transformations. In the simplest terms an object is subjected to a source of radiation, x-ray or thermal neutrons in this study, which a material will absorb based on the density of chemical elements contained in the object [Kardjilov et al., 2006]. Take for example an object in a tomographic setup with an axis of
rotation on along the z-axis producing the density of which is represented by the function, $f(x,y)$ (Figure 2.4) [Vontobel et al, 2006].

![Figure 2.4. Line integral $P(\rho,\theta)$ from a single slice projection in tomographic reconstruction.](image)

### 2.2.1 Radon Transform and Filtered Back Projection (FBP)

The measurement of a material’s attenuation, or its ability to absorb radiation, is calculated from the detected changes in radiation beam intensity based on Beer-Lambert’s Law [Hsieh, 40]. This principle can be applied produce a frequency projection (line integral) of attenuation from a single slice projection using the Radon Transform [Kak and Slaney, p. 51].

The Radon transform converts the spatial data into the frequency domain as a sinogram (Figure 2.5, p. 17). Each row in the sinogram represents a projection view or line integral, thus increasing the number of projections will result in a larger sinogram in the y-axis (Figure 2.6). The x-axis represents the detector channels, or the location of the impulse on the fixed detector (Figure 2.6). Once the projections are in the frequency domain, filters can be applied and then the projections can be transformed back into the spatial domain as reconstructed projections through filtered back projection (FBP) [Kak and Slaney, 60]. FBP is a common reconstruction technique used in CT. In principle, FBP projects image data along the path of transmission, essentially smearing it back over its path of projection [Kak and Slaney, 62].
Figure 2.5. Sinogram resulting from Radon transform of the Herman head phantom from CTSim (Figure 2.7).

Figure 2.6. Relationship between sinograms and line projections [Hsieh, 48].

For example, to reconstruct the Herman Head phantom (Figure 2.7), a reference test sample, a Radon transform would be performed on the projects to produce sinograms representing the projections in the frequency domain (Figure 2.5). Appropriate filters would be run in the frequency domain and then the object would be reconstructed using FBP. The quality and accuracy of the resulting reconstructed image would be dependent on the amount of information gathered during scanning, such as the number of projections taken. The increase of
10 projection to 50 projections in the reconstruction of the Herman phantom shows increased accuracy (Figure 2.8).

![Herman head phantom from CTsim.](image)

**Figure 2.7.** Herman head phantom from CTsim.

![FBP reconstruction of the Herman head phantom.](image)

**Figure 2.8.** FBP reconstruction of the Herman head phantom (Figure 2.3) using 10 (left) and 50 (right) projections.

Noise filters include those used to counter various artifacts, or image anomalies, that can occur due to the reconstruction algorithms and the imaging processing itself. An example of a filter commonly used addresses beam hardening which occurs due to an increase of average beam energy in transmission as object material can filter out lower energy radiation leading to a cupping artifact in an image [Hsieh, 272]. This artifact occurs with the use of multi-spectral radiation. Monoenergetic radiation sources would eliminate beam hardening artifacts and such
sources can be found in tomographic facilities, such as ANTARES at FRM-II; however, this reduces beam intensity causing longer scans [Vontobel et al., 2006].

Starvation of the radiation beam prevents the image capturing device, scintillator or CCD camera, from registering any form of ray transmission. Starvation causes a very low signal to noise ratio as the image detection approaches zero [Hsieh, p. 236]. The quantum or electronic noise from the ambient environment grows exponentially to where the image capturing device registers this noise as signal which can become enhanced during FBP reconstruction due to the backprojection and integration of the signal. In FBP, the logarithm of the signal is taken in order to obtain the line integral. The equation demonstrates that this equation becomes invalid as the detected signal (x) approaches zero, meaning that the variation in noise cannot be accurately computed or measured and resulting in fluctuating high and low signals, the result is bright and dark spots [Hsieh, p. 236]. These spots become streaks when backprojection is performed causing the artifacts that can severely reduce image quality [Hsieh, p. 209]. This streaking artifact is similar to beam hardening in that it deviates from ideal reconstruction in which assumes the signal and attenuation of the beam is uniform from each angle. In objects that are laterally long, some angles with cause starvation and while other views will allow sufficient transmission.

Photon starvation can be seen from some objects imaged using low-flux neutron CT at SLOWPOKE, such as hard drives. The hard drive contains a plastic disc in the center which contains high attenuating hydrogen. This issue is applicable to all types of CT, and was also seen previously when the music box was imaged using low energy x-rays that resulted in streak artifacts that indicated photon starvation (Figure 2.9, p. 20).
Another type of artifact that commonly occurs in CT imaging is ring artifacts. Ring artifacts appear as concentric circles or partial circles (arcs) in the axial slices centered on the rotational axis. These artifacts appear when anomalous readings, those that do not correlate to x-ray transmission, are registered in the channels of the detector for several projections [Hsieh, p. 211]. If there was a single anomalous reading, such as a gamma ray incident, FBP would result in a streaking artifact [Hsieh, p. 211]. Only a small difference in the measured attenuation in the different channels will cause ring artifacts, as low as 1% [Hsieh, p. 211]. One cause of ring artifacts can be from the inherent dark current that is present in all electronic detectors, called the detector offset [Hsieh, p. 244]. This dark current is randomized in the different channels and fluctuates within each channel, but the difference in this current from channel to channel can cause ring artifacts [Hsieh, p. 244].

One method of preventing both ring and streaking artifacts is to prevent any inherent defects in the detector and in the ambient electronic noise to create anomalous readings through normalization. By normalizing the portal images using dark field and open beam images, control images without the object in the field of view, it is possible to reduce the presence of these
artifacts. Dark images address the detector offset dark current through acquiring portal images without the radiation source on [Hsieh, p. 245]. The difference of the channel offset in the dark images is subtracted from both the portal images and the gain images [Hsieh, p. 245]. Gain refers to the ability of each cell to measure the transmitted radiation rays. Open beam images are acquired while the radiation source is on and this image will contain the gain information of the detector at the particular parameters of the scan [Hsieh, p. 246]. Gain is accounted for by dividing the offset corrected portal image by the offset corrected gain image (Equation 2.1) [Hsieh, p. 246]. For best results, averages of several offset and gain images should be used for normalization. It is recommended that gain images be taken throughout the scan at regular angular intervals.

**Equation 2.1. Normalization of portal images.**

\[
\frac{(Portal\ Image - Offset\ Image)}{(Gain\ Image - Offset\ Image)}
\]

### 2.2.2 Simultaneous Algebraic Reconstruction Technique (SART)

The theory of filtered backprojection (FBP) was discussed previously and is predominantly used in medical and industrial computed tomography because of the relatively small computation power required compared to other techniques. One other reconstruction technique is Algebraic Reconstruction Technique (ART) and the more recent advancement to Simultaneous Algebraic Reconstruction Technique (SART) [Andersen and Kak, 1984]. While FBP uses approximations to reconstruct the attenuation values in 3D space, ART uses series of linear equations that are solved to determine each attenuation value independently for the pixel [Hsieh, p. 59]. A common illustration of this method is to examine a simplified case for CT, such as a 4 x 4 pixel object with four attenuation values, \( \mu_1, \mu_2, \mu_3, \) and \( \mu_4 \) (Figure 2.10). In this
example, five measurements, $p_x$, are taken and solved for to determine each individual attenuation value. The equation $p_4$ is necessary to ensure orthogonality of matrix. For any matrix with $N \times N$ values, or pixels, at least $N^2$ measurements should be taken to solve for the attenuation values. As illustrated in the example, more than four measurements were taken to ensure orthogonality which would also be required for larger matrices. Given that some scintillator screens can have 2048 pixels, this method was considered for many years to be too time consuming both to ensure that enough measurements were taken and the required computing power was available to solve all the equations despite being the original equation proposed by Hounsfield [Hsieh, 60].

![Diagram of ART](image)

Figure 2.10. Example illustration of ART provided by Hsieh, 59.

Another disadvantage to the use of ART in CT was that the images that resulted from the linear equations with error can lead to noisy data if strict root-mean square criterion were applied sequentially, which could only be smoothed using relaxed error equations [Andersen and Kak, 1984]. One solution to this problem proposed in 1984 by Andersen and Kak was to combine both the advantages of ART and Simultaneous Iterative Reconstructive Technique (SIRT) to create SART. In this method, all error corrections for a projection are applied simultaneous rather than sequentially. This differs from SIRT in that the corrections are conducted during the iterative process, before a full iteration, which would ideally lead to only one iteration necessary for the total reconstruction.
2.2.3 Beam Geometry

The computations in FBP are dependent on the beam geometries of the tomographic scans which vary with different systems. The main types of beam geometry include parallel beam, cone beam and fan beam (Figure 2.11) and should be recorded for proper reconstruction [Schillinger et al, 2006].

![Diagram of beam geometries](image)

**Figure 2.11. Schematics of common beam geometries in CT.**

Each beam geometry results in certain parameters to be adjusted for optimal results. In parallel beam geometry collimation of the beam, or how parallel the beam is, is a limiting factor in the resolution of CT. Collimation is achieved and measured by the ratio of the source to object distance L from the smallest aperture diameter D \((L/D)\) (Figure 2.12, p. 24). The greater the L/D ratio the greater the resolution will be. At the ANATERS facility the maximum L/D ratio is 800 [Schillinger, 2006] compared to the maximum L/D ratio 550 at SINQ (Lehmann et al., 1996).

Collimation is important because parallel beams provide more accurate detection readings. If the beam is not parallel, neutrons will be detected as locations that do not correspond to the position of the object for each portal image leading to distortions in the reconstructions.
Figure 2.12. Schematic of collimation in beam geometry for neutron computed tomography.

The L/D ratio also informs on the resolution of the image as the diameter point projected on the screen \( (d) \) is the distance of the object to the detector \( (l) \) divided by the L/D ratio (Equation 2.2). This equation allows for the determination of the image resolution \( d \) [Schillinger, 2006].

**Equation 2.2. Diameter of image resolution as described by L/D ratio.**

\[
d = \frac{l}{L/D}
\]
Chapter 3

Micro-focus X-ray CT

3.1 Introduction

Metal artifacts recovered from different burial environments often are heavily corroded if unprotected. This corrosion occurs slowly over time, creating several corrosion layers based on the different environments in which these artifacts are kept. While the corrosion rate and products are dependent on the environment, the same basic electrochemistry is present where the metal (M) is oxidized to a corrosion product containing ions of the base metal (M^{n+}) (Figure 3.1). Corrosion products are formed with different materials in the burial environment that serve as the oxidizing agent (X^{n+}) and are reduced (X) during corrosion. For objects that contain surface details, this corrosion process obscures these details making them inaccessible to researchers through visual inspection reducing the ability to identify the objects. These surface details can even been lost through the corrosion product to the point where only a remnant remains within the corrosion layers which is not on the original surface. [Selwyn, 2004]

Figure 3.1. Generalized corrosion diagram for metal objects.
While corrosion slowly destroys the original object, over time the chemical process reaches equilibrium with the environmental surroundings. This equilibrium prevents further corrosion and consequently protects the remains of the object underneath the corrosion. Disturbing this equilibrium, through the removal from the burial environment, can cause further potential damage to the object through a reoccurrence of corrosion. For many artifacts, prior knowledge of the condition of the artifact is crucial to prevent total loss through cleaning or any other type of treatment which could cause corrosion and deterioration [Cronyn, 1990].

In addition to the potential damage caused by destroying the chemical equilibrium, manual and chemical treatments of corroded metal artifacts can be dangerous without knowledge of what lies underneath surface. The thickness of the corrosion layers can be unknown and the potential to lose very fine surface details exist. This type of damage can be seen on specific types of artifacts, such as coins. Coins highlight the need for non-destructive methods of determining the surface characteristic before treatment because the surface details on these artifacts can often be crucial in dating archaeological sites and other objects. In addition to manual cleaning, chemical cleaning is imprecise and historically has led to some irreparable damage because of the harsh nature of the acids needed to remove hardened metallic corrosion [Cronyn, 1990].

As a result of the fragile nature of many corroded artifacts, non-destructive imaging was developed to help identify both the object and the condition in which the object is in. The most efficient and popular method for imaging is x-ray radiography. X-rays have the ability to penetrate most materials with different attenuations and be detected on a film or a digital camera, allowing for differentiation between corrosion material and the original object that cannot be seen with visual inspection. While x-rays have proven to be very effective for most metal objects, there are some distinct limitations to the method that necessitates refinement for certain objects,
such as coins. These limitations include the restriction of the technique to two dimensions as only one radiograph is taken, summing up all the attenuations from transmission. For coins, or other objects with surface details on multiple sides, radiography can prove to be restrictive in the information it provides as overlaps can occur obscuring important details. Also, the difference between the material composition of the corrosion layers and the original artifact can be minute, preventing proper contrast in attenuation to identify the surface details. One refinement of radiography that would overcome some of these issues is x-ray computed tomography (XCT), which has been used for internal imaging in specific cases in art conservation and archaeology. Images and reconstructions produced by this method, with quantitative measurements of the corrosion layers, could also be used for further cleaning and treatments.

3.1.1 Previous Applications of XCT

X-ray computed tomography has been successfully applied to imaging in art conservation as explored in Chapter 2. The application of XCT for the investigation into the identification of corroded metal artifacts is limited and the protocols are not established as to the extent in which it can be used in this capacity. The two most notable developments have been the use of XCT in the imaging of the Antikythera Mechanism [Freeth, 2006] and of a 17th century watch from the shipwreck of the *Swan* [Troalen, 2010].

The XCT systems used in both studies were Xtek products. In the *Swan* investigation, the researchers used the Xtek HMX-ST CT which allows up to 225 keV, 225W, 2000 μA and 160x geometric magnification with a 5 μm Focal Spot Reflection Target X-Ray Source [Troalen, 2008]. Experimental parameters for the imaging of the watch included the 175 keV, 100μA and 0.5 mm copper filtering. The manufacturer of the system, Xtek (Metris), has now been acquired by Nikon and rebranded as Nikon Metrology.
An Xradia XCT-400 machine was available at Queen’s University, as the Nuclear Materials group in the Department of Mechanical and Materials Engineering uses the system for the detection of neutron damage to zirconium. This machine is a top-of-the-line micro-focus x-ray CT product that includes optical magnification using x-ray lenses (0.5x, 4x, 10x, 20x) in addition to geometric magnification that allows for a greater resolution of less than a micron and pixel size of up to 0.56 micrometers. These features make it a desirable analytical tool for the non-destructive analysis of corroded metal artifacts when surface details are obscured and treatment could be damaging. An evaluation of the machine and its ability to image corroded artifacts could provide additional options for art conservators and archaeologists.

As with previous studies in the application of XCT to corroded metal artifacts, investigations must consider the size of the object along with the material’s composition. The Xradia XCT-400 has a maximum field of view of 5 mm using cone beam geometry. The cone beam computed tomography allows for the geometric magnification and greater control of x-ray collimation. The XCT geometry limits the size of the objects as they must fit within the diameter of the cone for complete image capture and reconstruction. These types of samples sizes are reflected in the previous studies that have utilized the XCT-400 system. For example, in a study by Awaja et al, the examination of the carbon fiber epoxy compounds and glass suffering from UV degradation with sample sizes between 2-3 mm thick. This small sample size of a low attenuating material is also seen in another study on the distribution of material in papers. This lower penetrating power restricts the type of objects that could be imaged with the Xradia system. Corroded samples of high density and atomic or z number could not allow sufficient penetration for sufficient transmission.
Considering these limitations known about the system prior to imaging, the object selection for the study was made to both test the limits of the machine as well as maximizing positive results. The readily available coins in the Diniacopoulos Collection at Queen’s University provided an excellent source of size appropriate objects with a variety of material composition that would allow for preliminary evaluation of how the material composition will affect the ability to image using the Xradia XCT-400. Another object, similar to the previous studies using XCT that was imaged was a small mechanism from L’Anse aux Bouleaux which was hitherto unidentified because of its fragile nature which would serve as a comparison to the previous studies mentioned. Successful imaging of this object would show the comparable use of the Xradia machine to previous studies using the Xtek system.

3.2 Experimental

3.2.1 Materials

The coins were chosen from the Diniacopoulos Collection for imaging based on visual inspection of the corrosion types for variety and the possibility of surface features under the corrosion surface. The coins ranged in size, material and weight as described in Table 3.1.

Also imaged in this study using XCT was a small corroded mechanism from L’Anse Aux Bouleaux provided by the Centre de Conservation du Québec (CCQ) (57M 8P2-30) for investigation as previous attempts to identify the object were unsuccessful. The objects were mounted using the provided clamp for the Xradia XCT-400 between the source and the detector, including the optical lenses for optical magnification as seen in Figure 3.2.
Table 3.1. Dimensions and properties of the Diniacopoulos coins investigated.

<table>
<thead>
<tr>
<th>Coin</th>
<th>Diameter (cm)</th>
<th>Thickness (cm)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1980</td>
<td>2.7</td>
<td>0.7</td>
<td>14.0</td>
</tr>
<tr>
<td>AA1981</td>
<td>2.4</td>
<td>0.4</td>
<td>11.2</td>
</tr>
<tr>
<td>AA1983</td>
<td>2.6</td>
<td>0.3</td>
<td>14.6</td>
</tr>
<tr>
<td>AA1984</td>
<td>2.4</td>
<td>0.5</td>
<td>15.0</td>
</tr>
<tr>
<td>AA1985</td>
<td>2.2</td>
<td>0.4</td>
<td>9.3</td>
</tr>
<tr>
<td>AA1986</td>
<td>2.5</td>
<td>0.5</td>
<td>15.9</td>
</tr>
<tr>
<td>AA1989</td>
<td>2.6</td>
<td>0.5</td>
<td>8.9</td>
</tr>
<tr>
<td>AA1994</td>
<td>4.9</td>
<td>1.1</td>
<td>99.1</td>
</tr>
<tr>
<td>AA2011</td>
<td>2.7</td>
<td>0.5</td>
<td>14.3</td>
</tr>
<tr>
<td>AA2042</td>
<td>2.2</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>Nummi#9</td>
<td>1.7</td>
<td>0.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Nummi #11</td>
<td>1.6</td>
<td>0.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Figure 3.2. Photograph of coin AA2011 mounted in the Xradia XCT-400 system.

3.2.2 XCT Scanning Parameters

2D radiographs, or “portal images”, were obtained for each coin to determine the ability to detect surface details for the coins. Only coins with surface details visible in the portal images...
were selected for complete tomographic scan. Coins selected for computed tomography scanning were AA1980, AA1983, AA2011, AA2042, and Nummis #9,#11 and #12. After determining which coins were suitable for scanning, the coins were mounted and centered in the beam ensuring that it was centered both at 0° and 90° using the sample controller. The coin was mounted to allow for imaging of the plane of interest (coin surface) at 0°. Once the coin was centered, the location of the coin on the rotation stage was selected on the 0° radiograph which allowed for input of the correct parameters into the settings for tomographic imaging.

The Xradia XCT software calculated the angles for a “half-scan” of 180°, rather than the usual 360° for a full cone-beam scan, along with additional angles added to calculate the fan beam angle. The fan beam angles were automatically populated by the program. A total of 1600 projections were taken at equal angular intervals with 0.5 second exposure at 150 keV and 10 W with a high energy filter (He#6). Projections were taken using a 0.5x lens (Xradia Macro-70) and with a binning of one or two during image capture. References were collected during scanning using multiple references without average, but the data set was not automatically reconstructed after scanning.

Radiography and computed tomography were performed the CCQ object. Full tomographic imaging was computed at both 75 keV and 5W and 150 keV and 5 W. For both data sets the exposure was 0.5 seconds from 1024 projections using the He#6 (high energy) Xradia glass filter. The high energy filter blocked low energy x-rays creating a higher average incident x-ray spectrum. The objects chosen for CT imaging were mounted in dental wax to provide a means of clamping the coin in the mount without obscuring the object with the clamp or any other material that might significantly attenuate the x-rays.
The reconstruction of the raw projections was primarily accomplished using the Xradia Reconstructor, or the proprietary software provided by Xradia on the workstation. The reconstructed files were exported as Dicom (*.dicom files) and 16-bit Raw Tiff files (*.tiff) which were then rendered in the volume rendering software for image processing. Reconstruction of the different data sets was also performed in Octopus, a reconstruction software package developed at the University of Ghent. The exportation of raw projections for reconstruction in Octopus can be found in Appendix A (p. 167). The reconstructed files for both data sets were rendered to produce volumes that could be used to yield clip planes and their locations in the volume. Lines indicating the clip plane location represent the path of the plane.

Imaging at the ANTARES facility at FRM-II was limited to the radiography and computed tomography of select coins from the Diniacopoulos Collection. Only two coins were imaged using full tomographic protocols. These coins, AA1980 and AA2011 were then imaged at an L/D of 800 over 180 degrees with an exposure of 20 seconds.

3.2.3 Corrosion Analysis

X-ray fluorescence (XRF) was performed using a handheld XRF device for non-destructive qualitative elemental analysis of surface corrosion products. The Innov-X XLT-4401 was used on coins that were sheathed in thin Mylar. One measurement was taken for coins with uniform corrosion at 40 keV and 5-35 mAmps. Coins with visually different corrosion products on both sides were analyzed on both sides to determine if there were significant differences in material composition. The resulting elemental analysis provided a qualitative examination of the surface corrosion at various locations. The results of the XRF analysis are contained in Table 3.3 (p. 40) and Appendix B (p. 169).
Further corrosion analysis was conducted using X-ray Diffraction (XRD) with a Phillips X’Pert with a copper x-ray tube operated at 45 keV and 40 mA. Coins AA1980, AA1981 and AA2011 were analyzed in situ without sampling by placing the coin on the holder using putty underneath the coin to level the surface with the holder. They were sampled from 10-75° at 20 seconds an angle to reduce background noise (Appendix C, 170).

### 3.2.4 Artificial Corrosion and Traditional Cleaning methods

In collaboration with this study was another study conducted by Kathleen Sullivan for her Second-Year Research Project in the Art Conservation Program at Queen’s University. The project focused on comparison of XCT to traditional cleaning methods to determine the use of XCT for coin identification. This project included the use of three copper alloy coins with varying degrees of lead content to examine qualitatively the extent that the lead affected the imaging capabilities using the Xradia XCT. Raw material for the coins were obtained from McMaster-Carr and their material content is shown in the following table, as adapted from the copper alloy data sheet provided by the company (Table 3.2).

#### Table 3.2. Alloy contents of raw material from McMaster-Carr.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Copper (Cu) Content</th>
<th>Tin (Sn) Content</th>
<th>Lead (Pb) Content</th>
<th>Zinc (Zn) Content</th>
<th>Iron (Fe) Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>99.99%</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>510</td>
<td>94.8%</td>
<td>5-6%</td>
<td>0-0.05%</td>
<td>0-0.3%</td>
<td>0-0.1%</td>
</tr>
<tr>
<td>544</td>
<td>88%</td>
<td>3.5-4.5%</td>
<td>3.5-4.5%</td>
<td>1.5-4.5%</td>
<td>0-0.1%</td>
</tr>
</tbody>
</table>

These artificial coins were then stamped at the Mechanical and Materials Engineering Department by Tristan Koivisto so that a known control surface would be produced that could be examined in XCT. After the stamping, the coins were subjected to artificial corrosion using
electrolysis. The coins were placed in 150 g of all-purpose potting soil in a glass beaker containing a 3.5% w/v sodium chloride aqueous solution. The coin was attached to a laboratory power source using a copper wire that was stripped of its coating through mild sanding. The circuit was completed with the graphite electrode. The electrolysis was run at 1.05 V for 14 days [Sullivan, 2011]. Three of the coins that were imaged, AA1980, AA9183, and AA2011, were cleaned mechanically cleaned using a No. 15 Feather scalpel and a pin tool using ethanol as a wetting and softening agent by Kathleen Sullivan at Queen’s University as a part of her research project to compare the surfaces produced by traditional methods and XCT [Sullivan, 2011].

3.3 Results

3.3.1 Coin Imaging

The raw projections were analyzed with line profiles in the Xradia Controller. Line profiles measure transmission of the x-rays through object as detected by the CCD and translated into gray values as measured by the Xradia XController. These results indicated that there was minimal penetration through the coins, often less than 20 counts recorded through the thinnest cross-section of the coins (Figure 3.3 and Figure 3.4, p. 35). These same datasets produced acceptable reconstructions with the Xradia Reconstructor though this software did not provide access to step-by-step reconstructions that would allow for greater control of the reconstruction process.

The reason for such low counts for these specific coins was, in part, due to the thickness and size of the coins. The primary purpose of the XCT-400 is materials research for small sample sizes or materials with low attenuation which would not necessitate high voltages or penetration power. This study indicates that 150 keV and 10 W, the maximum setting, would not be
sufficient to image all copper alloy coins similar in size and weight to AA1980 with a thickness of 0.7 cm and a weight of 14.0 g.

Figure 3.3. Line profile of portal image of AA1980 showing approximately 10 counts through the coin. Right and left high peaks represent air with higher counts.

Figure 3.4. Line through portal image of AA1980 providing the line profile for Figure 3.3 as measured in Xradia Controller.

Even with these minimal counts, the surface details of several coins were imaged using XCT. These coins were AA1980, AA1983, AA1989, AA1994, AA 2011, AA2042, Nummi #9, and Nummi #11. AA1983 (Figure 3.5, p. 36) did not provide any indication of a coin surface underneath the layers. The line counts for this coin show almost no transmission of x-ray as detected by the CCD (Figure 3.6 and Figure 3.7, p. 36).
Figure 3.5. Photograph of AA1983.

Figure 3.6. Line profile for AA 1983 showing almost no transmission of x-rays.

Figure 3.7. Portal image of AA1983 showing position of line profile and the absence of a visible surface underneath corrosion.

Though the Xradia system provided successful reconstructions of a selection of the coins and maximum filters were employed, beam hardening was an issue with the 3D reconstructions.
There was significant beam hardening for this coin even with physical and mathematical filters. Filters for beam hardening were applied both physically during image capture and mathematically during reconstruction (Figure 3.8).

![Reconstructed projections of coin Nummi #12 without (a) and with (b) mathematical beam hardening filter applied during filtered backprojection.](image)

**Figure 3.8.** Reconstructed projections of coin Nummi #12 without (a) and with (b) mathematical beam hardening filter applied during filtered backprojection.

The improvement in beam hardening was in part accomplished with the Xradia High Energy glass filter #6 or a 0.032 inch copper filter that separated out low energy x-rays. This improvement is measured in the line profiles of the portal images. As seen in Figure 3.9, Nummi #11 has characteristic cupping in the middle of the line projection indicating beam hardening. When a 0.032 inch copper filter is placed over the source, lower energies are eliminated, reducing beam hardening as seen in Figure 3.9. The line profile of the filtered Nummi #11 shows increased signal to noise ratio despite a lower count total. The reduction in noise allows for greater contrast and imaging of the coin.

Beam hardening was also addressed during reconstruction with the use of the mathematical filters within the system. These mathematical filters were only applied for the Xradia reconstructions as the application of the Octopus mathematical filters was unclear.
Figure 3.9. Line profile of Nummi #11 without filters (left) showing cupping indicating beam hardening and with 0.032 inch copper filter (right) showing improved signal to noise ratio (SNR)

3.3.2 Corrosion Analysis

While beam hardening affected the image quality and the ability to image the internal surface, there were other factors that led to the low transmission of x-rays preventing proper imaging. For example coins with similar size to AA1980 and AA2011, such as AA1981 (Figure 3.10), have indication of an intact surface from visual examination (Figure 3.11, p. 39) and yet were not visible in the portal images (Figure 3.11).

Figure 3.10. Photographs of coin AA1981 showing signs of surface detail on side b (left).
Figure 3.11. Portal image of AA1981 at 150 kV and 10W for 1 second.

Analysis of portions of the surface corrosion of AA1981 indicated that there were varying amounts of copper, tin, lead, and silver. The presence of these elements is not uncommon for copper alloy coins of the time period. The differences in the relative percentages indicate that a combination of material and density affect the ability of the XCT to produce usable reconstructions. AA1983 has a higher percentage of lead relative to AA2011 or AA1980, while having similar dimensions (Table 3.3, p. 40). This small difference in lead content could result in increased beam hardening and insufficient penetration during tomographic imaging to yield usable images. The lack of penetration is indicated in the line profile of portal images showing less than 10 counts, though this differs only slightly compared to the line profile of AA1980 or AA2011.

This difference in elemental composition could theoretically allow for greater contrast between materials but at higher voltages, such as 150 keV, the attenuation is more dependent on the density of the material rather than minute changes in material composition than in lower voltages.
Further analysis was conducted with XRD to identify the corrosion types on the surface of the coins (Tables 3.4, 3.5 and 3.6, p. 41). AA1980 was found to have chalconatronite, malachite, atacamite, and paratacamite. AA1981 was found to have cuprite, lepidocrocite and possibly goethite. The XRD analysis was limited due to the uneven surface of the coin and because the x-rays had little penetration of the corrosion layer. Sampling of the corrosion would have provided better results and more details. These data indicate that the major difference in mineralization between AA1980 and AA1981 is the presence iron oxyhydroxides in AA1981 as indicated from XRD analysis. The presence of iron in the corrosion found in AA1981 does not necessarily explain the difference in the amount of penetration, but it could indicate that more complex corrosion surfaces are not desired for objects to be imaged. Also, the limited data
gathered from analyzing the coin in situ rather than sampling does not lead to any conclusive arguments.

Table 3.4. Corrosion products and corresponding chemical formula from XRD analysis of AA1980.

<table>
<thead>
<tr>
<th>Corrosion Product</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalcocitronite</td>
<td>Na$_2$Cu(CO$_3$)$_2$(H$_2$O)$_3$</td>
</tr>
<tr>
<td>Malachite</td>
<td>Cu$_2$CO$_3$OH$_2$</td>
</tr>
<tr>
<td>Atacamite</td>
<td>Cu$_2$Cl(OH)$_3$</td>
</tr>
<tr>
<td>Paratacamite (Zincian)</td>
<td>(Cu,Zn)$_2$Cl(OH)$_3$</td>
</tr>
</tbody>
</table>

Table 3.5 Corrosion products and corresponding chemical formula from XRD analysis of AA1981.

<table>
<thead>
<tr>
<th>Corrosion Product</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuprite</td>
<td>Cu$_2$O</td>
</tr>
<tr>
<td>Lepidocrocite</td>
<td>γ-FeO(OH)</td>
</tr>
<tr>
<td>Goethite</td>
<td>α-FeO(OH)</td>
</tr>
</tbody>
</table>

Table 3.6. Corrosion products and corresponding chemical formulas from XRD analysis of AA2011.

<table>
<thead>
<tr>
<th>Corrosion Product</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paratacamite (Zincian)</td>
<td>(Cu,Zn)$_2$Cl(OH)$_3$</td>
</tr>
<tr>
<td>Malachite</td>
<td>Cu$_2$CO$_3$OH$_2$</td>
</tr>
</tbody>
</table>

While the presence of higher relative concentrations of lead in AA1983 may have contributed to the poor penetration, consequently yielding poor reconstructions, other factors in
addition to corrosion composition need to be considered as the Nummi #11 and Nummi #9 produced relatively high percentages of lead from the XRF analysis while still demonstrating adequate penetration. The difference between the 12 Nummi coins and AA1983 or the other coins that were not successfully imaged was the relatively lower dimensions and weight of the Nummi coins. Both the Nummi coins had similar thicknesses to the other coins, but were smaller in diameter. The weight of the Nummi coins was also significantly lower, less than half the weight of AA1980 and other similar coins.

3.3.3 Identification


Coin 1 of AA2042, a fused coin, was identified as a centionalis (337-361) from the reign of Constantius II. The inscription on the reverse read FEL TEMP RE PARATIO. The photograph of the coin (Figure 3.12, p. 43) indicated that these features are not visible through ordinary inspection. This identification was made through examining the inscriptions on the coins as seen in the 3D volumes (Figure 3.13) and comparing the images found with existing coins that have previously been identified (Figure 3.14, p. 43). This coin was more difficult to identify due to the conjoined nature of this object. The greater cross-section in the areas of overlap made it harder to enhance the contrast in those areas. It should be noted the outer side of the coin, the reverse for coin 1, was easier to identify. This result may indicate that there is greater deterioration of the surface in the inner areas of overlap.
Coin 2 of AA2042 revealed less surface features from the reconstructed volume. Only a partial triangular figure is visible in the clip planes of the surface (Figure 3.15). This triangle could be the lower portion of a lambda, or a form of delta. Not enough information is obtained from this side of the coin for identification. Unfortunately, the inner side of Coin 2 revealed almost no information on the surface details. Again, this lack of information could be in part due
to the accelerated deterioration in the inner portions of the coins. Considering its fused nature with Coin 1, it is possible to hypothesize that the two coins were from a similar region and time period.

Figure 3.15. Clip plane of outer side of coin 2 of AA2042.

AA2011 was identified as the type Milne-1046, which depicts the laureate head of Hadrian (obverse) and Tyche holding a cornucopia and rudder, and is dated to year 8 of his reign (123-124 AD) (Figure 3.16, p. 44). The photograph of the coin indicates that there was a heavy layer of corrosion on the surface that completely obscured the surface (Figure 3.17, p. 45).

Figure 3.16. The obverse and reverse of AA2011 (left) and corresponding images of a cleaned coin (right) (http://www.wildwinds.com/coins/ric/hadrian/milne_1046.jpg.)
AA1980 was a tetradrachm of the emperor Licinius II with the legend DN LICIN.

LICINIUS. NOB. C and dated to year 7 (i.e., LZ) of his reign (Figure 3.18). This coin had one of the clearest legends and figures that were legible after XCT scanning revealed the surface details (Figure 3.18) that were not visible in the untreated coin (Figure 3.19, p. 45).

Figure 3.17. Photograph of AA2011 indicating that the surface is not visible underneath the corrosion.

Figure 3.18. Obverse (left) and reverse (right) of AA1980 viewed with clip planes.

Figure 3.19. Photograph of AA1980 indicating no visual surface of the coin underneath the corrosion.
3.3.4 FRM-II

The results of the imaging of the two coins using computed tomography parameters yielded interesting results. Both coins, AA1980 and AA2011, were also imaged using x-ray computed tomography and have been identified from those images. The first coin AA2011 (Figure 3.20) showed greater visual amounts of corrosion than AA1980. The image of the obverse and reverse were relatively clear allowing the inscriptions to be read, demonstrating there was high contrast between the coin surface and the corrosion layers (Figure 3.21, p.46).

![Figure 3.20. Photograph of AA2011.](image1)

![Figure 3.21. Clip planes showing the surface details of AA2011.](image2)

An interesting feature of the neutron images of AA2011 was the high attenuating ring around the other edge of the coin [Figure 3.22 and Figure 3.23, p. 47 and 70]. This high attenuation clearly indicated the uppermost corrosion layer of the coin, as there is clear visual difference in grey values between it and the lower layers, including the coin itself. X-ray
diffraction indicated that the corrosion layer contained malachite and paratacamite, the latter
being a chloride containing corrosion product often associated with bronze disease. The literature
on the relative mass attenuation coefficients indicated that chlorine has an extremely high
attenuation (Figure 2.3, p. 13). The presence of chloride ions in the upper corrosion layers
explains the high contrast to the lower corrosion layer containing malachite which is a carbonate
salt of copper.

Supporting evidence for the theory that the chloride ions in paratacamite is causing the
high attenuating ring in the neutron volumes is the comparison of the data set with the
corresponding data set in XCT. Looking at the coin in both XCT and neutron (Figure 3.22 and
Figure 3.23, p. 48), it is clear that the same attenuating ring is not found in the XCT data. In fact
the area of outer corrosion seems to be filtered out when the volume is windowed to highlight the
contrast of the surface detail. These images indicate that the outer corrosion layer consists of
material that is both low in density and made of material that has a low atomic number. The
atomic number of chlorine is 17, which is significantly lower than the other materials present in
the coin, namely copper (29), silver (47) and lead (82). Also, considering the relatively high
voltage for the XCT imaging at 150 keV, it is reasonable to assume that there was little to no
attenuation of the x-rays by the chloride.

Figure 3.22. Comparison of clip planes of the obverse of AA2011 using XCT (left) and
neutrons (right).
Comparing the image quality of the XCT data and the neutron data, with the attenuating ring aside, the main difference between the data sets is the amount of texture visible in the clip planes. Both sets of images show the figure head and the tyche with the appropriate inscriptions. The XCT data, however, shows greater surface detail of the coin compared to the flat images of from the neutron data.

As mentioned in the experimental, these coins were manually cleaned by Kathleen Sullivan to compare these imaging techniques to traditional methods in conservation. Figure 3.24 shows AA2011 after manual cleaning. These photographs indicate that while manual cleaning was successful, the surface details are not as clear as they were using neutron CT. This difference could be in part due to the inability to see visually the difference between the original surface and the corrosion layers. Also, the contrast between materials is enhanced in neutron CT which renders the differences on a greyscale eliminating the color distractions.

Figure 3.24. AA2011 after manual cleaning.
The results of examining AA1980 (Figure 3.25) revealed the limitations of neutron computed tomography for the purpose of non-invasive analysis of corroded coins. Using thresholding and windowing analysis, the best clip plane of the surface features were produced and can be seen in Figure 3.26. Looking at these clip planes compared to previous results, such as in X-ray CT, the surface details are not as clear though some details are still visible. For example, only a few of the letters in the inscription of the obverse are visible in neutron CT where most of the inscription is visible in XCT (Figure 3.27, p. 49). The figure head is visible in the obverse of both methods.

Figure 3.25. Photograph of AA1980.

Figure 3.26. Clip planes showing the surface details of AA1980.
The reverse of the coin shows some difference in visibility as well. The Nike figure is evident in both clip planes along with the year inscription LZ. The details of the figure are more enhanced in XCT where the folds of the wings and the clothing are more nuanced (Figure 3.28, p. 50). The difference in the quality of the images is most evident in the contrast of the feature compared to the corrosion. Also, the XCT data shows more depth to the figure where the NCT clip planes presents a very flat image of the coin surface making it difficult to see the details.

While XCT for AA1980 demonstrated better image quality, it is important to also compare the data to traditional cleaning methods. The manually cleaned AA1980 (Figure 3.29) shows the Nike figure, but the obverse bust is almost completely indistinguishable. Both NCT and XCT were able to highlight the shape of the bust while XCT was able to decipher some of the
inscription. Neither the bust nor the inscription is clear in the manually cleaned coin. This difference in quality may be due to the enhanced contrast that the non-destructive imaging allows through the difference in the attenuation values of the coin surface and the surrounding corrosion.

**Figure 3.29. Photograph of obverse (left) and reverse (right) of cleaned AA1980.**

### 3.3.5 Comparison to Traditional Methods

In conjunction with the research project of Kathleen Sullivan, it was important to look at the comparison of the images obtained through CT scanning to the surface produced through traditional cleaning. In Figure 3.30 and Figure 3.31 the comparison of the coin surface of AA2011 to the clip planes from XCT were compared for both the obverse and the reverse respectively. In viewing these images, qualitatively speaking, the XCT scans gave a better indication of the surface than through cleaning methods.

**Figure 3.30. Comparison of the obverse of AA2011 using traditional cleaning (left) and x-ray CT (right). Photograph provided by K. Sullivan.**
Figure 3.31. Comparison of the reverse of AA2011 using traditional cleaning (left) and x-ray CT (right). Photograph provided by K. Sullivan.

The difference between the clarity of images between traditional cleaning and XCT was more evident in AA1980 where the obverse is almost indistinguishable after cleaning compared to the XCT slip plane Figure 3.32. The legend is not even visible in the photograph of the cleaned coin. The surface of the reverse of AA1980 was the best comparison to the clip planes produced by XCT with the figure of the Nike clearly visible along with the inscription LZ (Figure 3.33, p. 52). For AA1980, it would seem that the XCT scanning allowed for increased contrast in the minute differences between the corrosion material and the coin surface which allowed for greater clarity.

Figure 3.32 Comparison of the obverse of AA1980 using traditional cleaning (left) and x-ray CT (right). Photograph provided by K. Sullivan.
Figure 3.33 Comparison of the reverse of AA1980 using traditional cleaning (left) and x-ray CT (right). Photograph provided by K. Sullivan.

It is possible that rendering the images using only a greyscale may have enhanced the contrast with no interference from colors under normal viewing as the XCT rendered volumes display their information in grey scale dependent only on attenuation value. Considering this possibility it was important to examine the photographs without color and with enhanced contrast. One example would be with the obverse of AA2011 (Figure 3.34, p. 53). In this comparison, it could be said that there is a slight increase in visibility of the figure with the rendering in greyscale, but the resulting picture is still less clear than in the XCT clip planes in which the legend is visible.

Figure 3.34. Photograph of cleaned coin AA2011 with normal color photography (left) and enhanced contrast in greyscale (right). Photograph provided by K. Sullivan.
An interesting result from the manual cleaning of the coins was the presence of a surface in AA1983 (Figure 3.35). It was speculated that there might be false negatives in the process as AA1983 might have returned false negative results due to the non-existence of a coin surface to be imaged. As shown earlier in the results, the radiograph of AA1983 showed low transmission of the x-rays through the coin with counts of less than 10. The presence of the surface underneath the corrosion helps confirm the findings of the study that indicate that the main factor in the inability to image this coin was the presence of heavy metals, such as lead, that attenuated the x-ray beam and did not allow for proper imaging.

![Figure 3.35. Photographs of AA1983 after cleaning. Photograph provided by K. Sullivan.](image)

### 3.3.6 Artificial Corrosion

The artificial corrosion of the three alloy coins was successful and resulted in a thick layer of encrustations including the corrosion, dirt particulates and the copper wire that was used for the electrolysis (Figure 3.36). The wire was incorporated in the corrosion and could not be removed without removing the corrosion.
After corrosion, the coins were examined using the XCT and ImageVis3D was used to investigate the ability to see the surface beneath the coins. For the first coins, Copper Coin, which was almost pure copper with no lead, images could be produced to see the surface and the inscriptions were clear (Figure 3.37). Considering that the only possible limitation for the inscription would have been the size and density of the coin, it is not surprising that the inscription was intact and able to be imaged.

The other alloys with increasing amounts of lead demonstrated the influence of lead content has on the coin. Examining the obverse and reverse of the two alloys, 510 and 544, indicate that the increase in the lead content from 0.5% to 3.5% impacts the imaging capabilities negatively. For Copper 510 (Figure 3.37) the inscription on the obverse is still legible and easy to distinguish from the corrosion. The reverse of this coin is less legible as the gears can be seen but the inscription is almost impossible to read. This level of ambiguity is present on both the obverse and the reverse of Copper 544 (Figure 3.37).
Figure 3.37. Obverse (left) and Reverse (right) of Copper Coin (top) Copper 510 (middle) and Copper 544 (bottom) using XCT.

The difference in the success of the imaging between the copper alloys is reflected in the line profiles of their portal images. Copper Coin’s line profile indicated that the transmission was within the 10-20 count range (Figure 3.38, p. 57) that was similar to the line profile of AA1980 which saw positive results (Figure 3.3, p. 35). The transmission in Copper 510 bordered 10 counts with some instances below the threshold (Figure 3.39, p. 57). This lower transmission reflects the poor image quality in the reconstructed slices. Copper 544 was also bordering on the 10 count range but was more consistently below 10 counts (Figure 3.40) which could be seen in the lower contrast of the inscription in the reconstructed volume.
The deterioration of the image quality with the increase of lead content was not surprising considering the basic principles of x-ray computed tomography. This study, however, did indicate that for corroded coins the lead content for copper alloy coins of this size should be limited to around 1%. Considering the other coins that were imaged, this percentage differs from...
those obtained for the corrosion analysis of the Diniacopoulos coins. This difference is due to the copper alloys being manufactured and the whole lead content throughout the coin is known prior to corrosion or imaging. To preserve the coins and maintain the non-destructive investigation of the coins, it was necessary to only perform surface techniques on the coins using XRF. While this method helps determine the qualitative evaluation of the elements in the coin, it is not a truly quantitative measurement and the percentages that were obtained were not calibrated and do not represent the entire coin. Even with calibration, the corrosion composition will differ from the composition of the intact coin.

While this study has not completely addressed the method in determining the upper limit of lead concentration in corroded copper alloy coins for using in XCT, it has helped support the conclusion that those coins from the Diniacopoulos collection that could not be imaged had insufficient transmission XCT from the lead content. The other possibility had been that the coin surface did not contain any features remaining that could be imaged. With this data, however, and the results from the comparison to traditional cleaning, it is clear that negative results are not due to a lack of surface but the composition of the coin. This information would indicate that coins that cannot be imaged with XCT should be investigated at higher voltages or using traditional methods.

### 3.3.7 CCQ Object

As mentioned in the introduction and experimental, a small object (57M 8P2-30) from L’Anse aux Bouleaux (Figure 3.41, p. 59) was imaged to help determine the identification of the mechanism inside the concretion. This object is similar to the 17th century watch from Troalen’s study in its small and delicate composition that prohibits manual cleaning because of the possible destruction to the object.
The resulting reconstruction and rendering of the object yielded a volume (Figure 3.42) that contained a great deal of information. Using windowing it was possible to determine the shape and location of the remaining metal in the concretion that is only partially visible in photography (Figure 3.43, p. 60). The rendering of the remaining metal is important as it can indicate the stability or condition of the object within the concretion and help guide future treatment plans. Also, the rendering of the metal allows for clear indications of the other features in the objects which could be pseudomorphs.

Figure 3.41. Photograph of 57M 8P2-30.

Figure 3.42. 3D rendered volume of the 57M 8P2-30 in ImageVis3D
Figure 3.43. Remaining metal underneath concretion in volume Figure 3.42.

The pseudomorphs are more clearly visible using slice analysis and clip planes in ImageVis3D. These slices indicate that most of the mechanism of the object has deteriorated while the remaining metal is mostly part of the framework (Figure 3.44, p. 48). Clear components of the object in the slices include a hairpin shaped mechanism (Figure 3.45, p. 61). Using these features, conservators from CCQ and Parks Canada believe that the object is a form of mechanism, such as a latch, used in a portable writing table. This preliminary hypothesis is based on the presence of the hairpin shaped pseudomorph which they believe to be spring in the mechanism [Gabov, 2011] (Figure 3.45, p. 61).

These reconstructed slices and clip planes show more details than could be seen in the original x-ray radiographs. The radiographs indicate the location and shape of the remaining metal frame (Figure 3.46, p. 61). The radiographs, however, do not show the pseudomorphs that were in the reconstructed slices, including the hairpin spring.
Figure 3.44. Coronal slice of 57M 8P2-30 (left) with its location in the volume (right).

Figure 3.45. Clip plane showing spring mechanism in the 57M 8P2-30 and b) its location in the volume.

Figure 3.46. X-ray radiographs of 57M 8P2-30 provided by CCQ.
3.3.8 Reconstruction Comparison

One of the aspects of XCT imaging with the Xradia XCT-400 that was considered in this study was the possible use of the data for direct comparison with other types of computed tomography. Direct comparison would ideally be made with controls on the variables, including the reconstruction process requiring reconstruction of the data sets in the same program. Thus, for the exportation of the data sets from Xradia software to a usable format for Octopus, a third-party reconstruction software would be necessary. First, however, a comparison of the reconstruction of the objects in both Xradia and Octopus to examine differences in reconstruction results. Also, the ease of reconstruction in Xradia compared to Octopus was evaluated to determine the overall quality of the different programs.

Octopus allowed for many pre-reconstruction processing, including clipping, cleaning and normalization. Normalization was the key step in which the success of the reconstruction was determined. Without the proper file formats for both the offset, gain and portal images normalization would fail. The reconstruction module allowed for evaluation of different parameters such as tilt axis. The evaluation parameter module in the Octopus Reconstructor was similar to the one in the Xradia Reconstructor but one notable difference was the number of options that could be changed to ensure proper reconstruction. Also, the evaluator parameters display the resulting reconstructed slices in correspondence with the standard deviation which can be used for a more quantitative evaluation of the different parameters than visual inspection.

Comparing the reconstruction of a coin in Octopus and Xradia demonstrated that while there was less control over the reconstruction, the proprietary software in Xradia was optimized to produce the best results from the Xradia software. While Octopus may be able to produce similar quality reconstructions, the necessity of setting several parameters made it difficult to
reproduce the same quality. This difference can be seen in the clip planes of the surface of both the reconstruction volumes (Figure 3.47 and Figure 3.48). It is very difficult to read the inscription on the coin in the Octopus reconstruction that is fairly clear in the Xradia reconstruction. Further investigation into the full function of the Octopus Reconstruction software should be made to emulate the parameters of the proprietary Xradia software.

![Image](image_url)

**Figure 3.47. Obverse and reverse clip planes of surface of Copper Coin reconstruction in Octopus.**

![Image](image_url)

**Figure 3.48. Obverse and reverse lip planes of surface of Copper Coin reconstruction in Xradia.**

While this prevented direct comparisons between data sets from different radiation sources, it highlighted the quality of the images produced by the Xradia system. There is still some discussion concerning the reason the exported raw files are not reconstructing at the same level as in the Xradia Reconstructor. One possible factor was the use of “dithering” in the default scanning parameters in which the sample is physically moved off its axis of rotation during the
scan to minimize the presence of defects from the scintillation screen, such as a dead pixel. It was hypothesized that this movement is corrected in the Xradia Reconstructor but that the exported files do not have such a correction which may account for the reduced quality of the data in Octopus.

### 3.4 Conclusions

#### 3.4.1 XCT-400

The results from the identification of a portion of the Diniacopoulos coins using the XRadia XCT-400 indicate that the system can be considered a suitable method for investigating a limited selection of corroded metal artifacts. At the highest voltage and power the system, coupled with visualization software, was able to produce images of the surface features underneath the corrosion that can be used to identify the objects. The resulting digital files that were obtained provide documentation of the coin prior to treatment when added to traditional documentation methods such as photography and chemical analysis. This documentation could also aid in the eventual treatment of the artifacts as prior knowledge of the desired surface could prevent damage to the surface from the use of manual or chemical treatments. In the event that the object is damaged, the digital documentation would be useful to prevent a complete loss of information.

In comparing the results of this study to the findings of Kathleen Sullivan, a preliminary conclusion was made that the XCT imaging of the coins, when successful, allowed for greater contrast in the clip planes than the photography of traditionally clean coins. Inscriptions and figures in AA2011 and AA1980 were more visible with XCT and with the added benefit of not disturbing the chemical equilibria of the coins. For AA1983, which was not successfully imaged,
the manual cleaning did provide a suitable surface for identification. The manual cleaning also provided support to the use of XCT for imaging as it ruled out a false negative for AA1983, meaning that the negative result was from the material composition not the absence of surface.

The material composition had a significant effect on the ability to image the coins. Larger coins with lead content showed almost no transmission at 150 V and 10 W, the maximum capacity of the system. Thus, for a wide range of coins, the method is not suitable as only a percentage of the coins would have at least some or more lead content though this amount varies. Instead, proper analysis of the coin prior to imaging is required to maximize results. Trial and error is not recommended as the scan times could cause greater expense as well as the time required to invest in such studies.

The heavy metal content of the coins can be determined using a variety of non-invasive methods including the use of XRF and XRD as applied in this experiment. While this study used percentages to describe the content of the coins, the XRF used in this context was only a surface method and not a true indicator of the material content of the coin as a whole. XRF, however, can allow for a qualitative evaluation of the possible content of significant amounts of heavy metal content in the coins. For more precise measurements, invasive techniques and sampling would be required which could prove counter-productive the intent of maintaining the chemical equilibrium.

The results from the imaging of 57M 8P2-30 were quite promising as an analogous study to the previous research of Troalen et al. This case study helps confirm that the Xradia XCT-400 could be used for studies that were also performed by the Xtek System, particularly for small and delicate concretions from underwater archaeological sites. Again, the material composition of the object, iron, and relatively light density allowed for transmission of the x-rays for imaging. This
scan would not be successful for all types of underwater objects, but as a great deal of these artifacts contain large amounts of concretion that would be too difficult to penetrate at 150 keV. Alternative methods would need to be used for large concretions, but the potential for both the Xradia and Xtek system to image smaller objects creates more opportunities for conservators to use XCT for non-destructive imaging.

3.4.2 Limitations

One of the most important limitations of the XCT-400 was the maximum size and voltage of the system. The 0.5x macro lens helped improve the field of view for the investigation of the objects, but there was still a limitation on the overall size of the object. The coins used in this study averaged in size at around 2-3 cm. Any object significantly over in diameter would not be suitable for use in the Xradia XCT-400. Due to the limited power of the system, the dimensions of the coins, in addition to the maximum diameter, must be considered for copper alloyed coins. Based on the data of the coins that were imaged, the approximate maximum thickness for a copper alloy coin should not exceed 0.5 cm and mass of the coin should not exceed 15 g. These were observation notes from the study, but the material composition of the coin will affect these guidelines.

3.4.3 Workflow

While there was a successful evaluation of the XCT-400 for its application to the imaging of corroded metal artifacts, what was more significant was the development of a workflow that can be adapted for different systems which could help guide conservators in their preparation in imaging. The workflow addresses the basic questions each researcher should concentrate on when determining the best imaging method or parameters such as the size of the object and the lead content. This workflow is important because it speaks to the lack of transparency in the
previous literature which focused on the applying the technique on specific objects while ignoring
the decision making process which was necessary to create the experimental design that allowed
for successful imaging. With a greater understanding of the limitations and the advantages of the
XCT systems on a wider range of objects, the workflow and the information in this chapter will
help allow researchers the opportunity to consider CT as a viable method.

This set of criteria (Figure 3.49, p. 68) can easily be converted for use in other system by
conducting similar studies to this one in which there are a range of different copper alloy coins
that are imaged and based on the resulting image quality evaluate the ability of the system to
perform imaging studies on these types of objects. This type of study would be useful for
systems that are commonly used for imaging artifacts.
Figure 3.49. Criteria for the imaging of copper alloy coins using the XCT-400.

3.4.4 Future Research

A great deal of research needs to be completed before XCT can become a common method. While there was the attempt to compare how the material content of an object will limit the ability of the Xradia XCT 400 to image copper alloy coins, similar studies should be done with other systems to have a greater understanding of the overall limitations of the available options in imaging systems. Also, there should be a greater study of the material effects in copper alloy coins for the Xradia XCT 400. These studies should look at developing historical alloys rather than using pre-made alloys that were purchased. These alloys would best represent
the contributions of different types of elements, such as tin or antimony, on the overall imaging. This study using historical alloys could also include the use of different corrosion protocols. While electrolysis was a very effective means of producing corrosion on the surface of the coins, the inclusion of the copper wire around the coins interfered with the imaging. Also, the electrolysis did not accurately represent the types of corrosion that would occur in terrestrial corrosion over long periods of times. Other corrosion methods should be examined, such as those used in studies Novacovic et al. or Casaletto et al. that allowed for more natural corrosion, though on a shorter time scale. These corrosion protocols consider the factors that archaeological soil has on the corrosion through the possible incorporation of different types of particulates naturally.
Chapter 4

Low-flux Neutron CT

4.1 Introduction

4.1.1 Low-flux Neutron Computed Tomography

One disadvantage highlighted in a review of these studies is the relatively small number of neutron tomography capable facilities. Most studies were conducted in Europe at high-flux facilities with dedicated lines for imaging. Such resources are not found widely in North America. For this method to become more available to conservators, alternative facilities and methodologies should be explored to allow for investigation of objects. A possible alternative to the use of high flux facilities in Europe is the possibility of utilizing low flux facilities, such as the Safe LOW Power c(K)ritical Experiment (SLOWPOKE-2) reactor at the Royal Military College in Kingston, Ontario. The maximum neutron flux at this facility is $10^{12}$ neutrons cm$^{-1}$ s$^{-1}$ while the flux at the imaging plane is $3 \times 10^4$ neutrons cm$^{-1}$ s$^{-1}$ [Bennett, 1999]. This flux is significantly lower than at other facilities such as the Advanced Neutron Tomography and Radiography System (ANTARES) facility at FRM-II reactor in Munich, Germany which can achieve up to $9 \times 10^7$ neutrons cm$^{-1}$ s$^{-1}$ flux at the imaging plane [Lorenz, 2007]. Some concerns include the increased noise due to the lower incidents of neutrons, but studies should be conducted to determine role that these types of facilities might have in a more widespread application of neutron tomography in art conservation.

Along with higher flux, these facilities have designed systems that allow for control of variables that can affect neutron tomography. These controls include variable L/D ratios, which indicate the degree of collimation that can be achieved for the neutron beam. Due to the parallel
beam geometry of neutron tomography, collimation, or the degree in which a beam is parallel is
essential for high resolution tomography. For high collimation, an aperture of a small diameter
(D) is calculated against the length of the collimator (L). The higher the L/D ratio, the higher the
collimation and the resolution as discussed in Chapter 2.

The SLOWPOKE reactor is powered by uranium fuel pins in a beryllium core. The
source is located in a well with light water and focused using beryllium reflectors. As the reactor
cools, beryllium shims are added to the focus the reactivity to prevent the installation of a new
source. This core is located in a reactor pool containing light water which can be accessed by an
adjacent Neutron Beam Tube (NBT) built for neutron imaging studies. This NBT is kept vertical
when imaging is not in use, but is moved and connected to the reactor pool during imaging to
allow for the beam to pass. When the NBT is connected to the reactor pool it forms an 8.5 degree
angle with the vertical. The neutrons from the core are then reflected with beryllium shielding
into a thermal column containing heavy water (D₂O) which is then directed up the NBT through
the illuminator which contains graphite blocks that scatter neutron parallel to the beam
tube(Figure 4.1, p. 73) [Hungler, 2010].

The collimator, including both upper and lower parts, is formed from aluminum cylinders
with annuli of 5% borated polyethylene. Reduction in gamma ray and fast neutron contribution is
accomplished with the addition of a 99% lead shielding alone with a 2% (w/w) wax and carbide
mixture along the lower collimator. The reduction of gamma ray and fast neutrons is important to
avoid speckling artifacts or misrepresentation of the data. The upper and lower collimators are
separated and pressurized by helium gas [Bennett et al., 1999].

The beam is stopped first at the top of the beam tube through an angled square hole
located below the imaging position system (Figure 4.1). This system allows for adjustments on
the x and y planes at an oblique angle to the beam ray. The positioning system allows for the placement of the mount specially designed for tomographic study at the RMC facility. Due to the unique nature of the vertical beam, a mount was necessary to ensure that the objects remained stable during rotation.

The mount was also designed to allow a range of objects to be secured regardless of shape and for the adjustment of height as needed. Also, the design of the mount took into consideration the sensitivity of thermal (slow) neutrons to hydrogen and the various materials that could attenuate the signal preventing proper imaging or becoming damage from neutron or gamma ray radiation. The mount was constructed using steel chucks with aluminum jaws from Taig that were adapted to allow for more variable placements of the aluminum holders. This configuration allows for minute adjustments that accommodate many types of objects. The jaws were then modified with additional aluminum extensions that allowed for more precise movement and positioning, increasing the ability of the mount to provide a stability to a range of objects (Figure 4.2, 74) [Hungler, 2011].

This mounting system is attached to an Aerotech ADRT-100-135 S rotary motor that allows for a rotational accuracy of 60 arcseconds (Figure 4.3, p. 75). The maximum radial load of the motor is 10 kg, a fact that limits imaging of very heavy or large objects, but the attachment of a tail stock with an identical Taig chuck allows for a greater radial load. A Labview program designed at RMC controls both the rotary motor for the rotation of the object. Placement of the object in the image plane is accomplished manually [Hungler, 2011].
Figure 4.1. Schematic of the SLOWPOKE-2 reactor and imaging system from Hungler, 2010 included with permission of P. Hungler.
Image capture is accomplished through the use of a scintillator screen and a CCD camera. The 400 mm by 400 mm RF Tritect scintillation screen is coated with a 2:1 mixture of ZnS/Li$_6$F that is 0.1 mm thick [Hungler, 2011]. The scintillation screen emits photons of proportional energy when ionizing radiation is produced by a reaction in the mixture with the neutrons. The Li$_6$ in the scintillation screen acts as a converter material to produce the ionizing radiation necessary from the neutrons to allow photon emission from the screen through alpha decay. These photons are then reflected off a mirror to the CCD camera to prevent radiation damage to the camera system. To shield the room and the object, borated polyethylene blocks are placed around the middle beam stop that is able to conform around the objects.
Neutron CT at RMC has had some preliminary success with imaging objects. One of the focuses for the tomography program at RMC is the use of neutron CT in detected water ingress on the honeycomb structures in aircrafts. These sections are held together with resin/epoxy adhesives that lose their adhesive power with water ingress. Radiography of these honeycombs indicated the positive imaging of water in between the bonds of the honeycomb (Figure 4.4, p. 65) [Hungler, 2009]. The detection of water was enhanced with preliminary tomography at RMC as well as imaging at FRM-II. Other objects that have been imaged include a hard drive and a percussion musket found on the premises [Hungler, 2011]. All of the objects were successfully imaged and reconstructed using the new mount and imaging system.

Considering the preliminary success of the tomography unit at RMC, the direct application of NCT at RMC for artifacts should be explored. Several artifacts have been identified for possible imaging. Bronze statues and statuettes are ideal due to their density and the possibility of organic material remaining within the object. Detection of the organic material would be near impossible due to the low-z elements when using high voltage x-rays. Neutrons
would highlight these organic materials while being minimally attenuated by the metal casting material. This type of imaging would allow for investigations of hollow objects and reveal information on casting techniques or purposes. This non-destructive technique is preferable to other methods of investigating these objects including scoping cameras.

![Image](attachment://image1.jpg)

**Figure 4.4. Neutron Radiographs of honeycomb structures from an aircraft rudder from Hungler, 2009 included with permission of P. Hungler.**

**4.2 Experimental**

As stated previously, certain consideration was needed for the mounting of the objects over the vertical beam line. A mount was designed by RMC to accommodate varying sizes of objects over the line. This mount was designed with aluminum bars which could not be used directly against historical objects due to the possibility of abrasion or scratching. Using methods employed in other neutron tomography facilities, the objects were first wrapped in a thin layer of 3 mL Mylar and taped outside the beam edge (Figure 4.5, p. 77). The object was then wrapped in several layers of household aluminum foil, allowing for a great deal of airspace and padding (Figure 4.5). The Mylar helped protect the object from any abrasion from the aluminum foil and
possible chemical reactions, while the aluminum foil acted as a transparent padding for the mount which could be adjusted on-site as needed.

![Figure 4.5. Photographs of 57 M 8P2-30 being prepared for neutron imaging with (left) Mylar and (right) household aluminum foil.](image)

Once the object was prepared, it was mounted and radiographs were taken to determine the usefulness of a full tomographic imaging. If the features were able to be detected using neutron radiography, full tomographic imaging was conducted on the object. Full tomographic imaging included projections taken from 0° to 180° inclusive with 2 minute exposures. The object that was investigated at RMC was a bronze deer statue from the Diniacopoulos collect. There were 226 projections taken of the deer.

4.2.1 Reconstruction

The portal images, including dark and bright images, produced by neutron CT were exported as 16 bit standard tif files. Due to the high noise from gamma ray detection, pre-processing was required before reconstruction was performed as the “cleaning” module within Octopus was unable to remove the noise from the files sufficiently. This pre-processing was accomplished by performing importing the portal images as an image sequence in Image J. A median filter was then run on the projections to help smooth the images. Median filters smooth out images by changing the attenuation value of each pixel to be the median of all of the
surrounding pixels of a given radius. Numerous types of median filters were used to determine the best cleaning properties and are detailed in Table 4.1.

**Table 4.1 Different Filters for Speckling.**

<table>
<thead>
<tr>
<th>Filter</th>
<th>Program</th>
<th>Target Files</th>
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</thead>
<tbody>
<tr>
<td>Cleaning Module</td>
<td>Octopus</td>
<td>Portal images</td>
</tr>
<tr>
<td>2D (ranged radius)</td>
<td>Image J</td>
<td>Portal images</td>
</tr>
</tbody>
</table>

After preprocessing was finished, the image sequence was exported as another image sequence. In such cases, it is important to process dark images, bright images, and projections separately to avoid inclusion in numbering sequence. These portal images were then reconstructed in Octopus which included the use of normalization and cropping to optimize the results.

### 4.3 Results

#### 4.3.1 Volumes

The reconstruction of the deer from the Diniacopoulos collection was successful, though there were few internal components in the object that needed to be imaged. The resulting volume indicated that there was a small void located in the tail of the deer (Figure 4.6 and Figure 4.7) that could not be seen in the original radiographs from RMC (Figure 4.8, p.79).

**Figure 4.6. Axial (left) and coronal (right) reconstructed slices of the deer.**

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Figure 4.7. Volume of the deer indicating the location of the reconstructed slices showing the void.

Figure 4.8. Radiographs of the Diniacopoulos deer recorded using Andor 436-BV with neutron flux at the image plane of approximately $3 \times 10^4 \text{n cm}^{-2} \text{s}^{-1}$.

4.3.2 Median Filter

As explained in section 4.2.1, median filters were used to reduce the amount of noise in the raw projections to avoid artifacts in the reconstructions. These median filters were listed in Table 4.1 and the results indicated that there was that the median filters in Image J were superior to the cleaning module in Octopus.

The efficacy of pre-processing the data with a median filter rather than using the cleaning module in Octopus can be seen in Figure 4.9 and Figure 4.10 where many of the gamma ray
incidents are still visible in the rendered volume due to insufficient removal in reconstruction (Figure 4.10). The remaining gamma incidents from the raw projections translate into ring artifacts that cannot be addressed with a ring filter. The resulting volume is extremely noisy and difficult to analyze.

Figure 4.9. Image of deer raw projections that have not been processed (left) and using a median filter in ImageJ (right).

Figure 4.10. Volume of Deer reconstructed using only cleaning in Octopus.
4.4 Conclusion

The use of low-flux neutron CT could be a viable alternative to the use of high-flux facilities in existence but further research would be necessary to determine the extent the two methods should be used. The positive result of the investigation of the deer was promising, but the rendered volume revealed very little that was not noticeable through the use of traditional documentation techniques. Due to a concurrent study of optimizing RMC imaging systems, more objects could not be imaged. The results from this study would allow for a greater understanding of the resolution of the imaging system, as well as compare the system to other existing NCT facilities.

Complications arose when other suitable object for NCT investigation were sought. The system at RMC is limited through usual neutron restrictions such as activating material or high-hydrogen content material which would prevent adequate imaging. As such, objects with high contents of silver, gold, or cobalt for example could not be imaged as they might activate and become unavailable for any other study for a long period of time. Activation would run counter to the underlying principle of non-invasive analysis. Another limitation to consider was the overall size of the holder. The holder that was developed at RMC [Hungler, 2011] was modified from manufacture specifications to holder larger objects, but there is still the limitation of size due to the chuck. Also, the preparation method of using aluminum foil padding greatly increases the overall size of the object requiring objects to be even smaller to start.

The literature favors the use of NCT for larger bronze statues that cannot be imaged by XCT, but would not be suitable for the RMC imaging system. Other objects have been investigated, such as the Roman knife and belt buckle from Lehmann, 2005; these would be suitable for imaging at RMC but similar artifacts were not available at the time of the study.
While a future holder may be designed for larger objects, the vertical beam set-up at RMC restricts the size of any future holder that is produced. In the event that larger objects are found and can be accommodated by the holder system, the low-flux of the neutrons at RMC could make imaging difficult if longer acquisition times are required.

Due to these limitations, objects readily available at the Queen’s Artifacts Laboratory were considered unsuitable for imaging. This raises the question of the suitability of neutron CT for objects in general as the system limits the type, shape and size of the object that can be imaged. Considering these limitations, further research is necessary to understand the role that low-flux neutron facilities such as RMC may play in the use of NCT in conservation.

Other research that would be important to conduct once the resolution and parameters of the imaging system are established would be to simulate appropriate sized objects that would suitable for neutron tomography. This study would require the input of conservators to determine which objects and the conservation problems would necessitate non-destructive imaging. Ideally, these objects would not be suitable for imaging using XCT as to highlight the unique benefits of neutron CT, but even objects that can be imaged in XCT would be desired as comparative studies would also be useful in demonstrating the techniques advantages. In order to understand the system’s capability fully for conservation research these objects should represent a set of materials with minor variance to mirror the other studies on XCT and gamma ray CT. By creating controls within the objects through the use of phantoms, the overall limitations of the system can be determined with empirical data.
Chapter 5
Megavoltage Gamma ray CT

5.1 Introduction

Computed tomography has long been used with different radiation sources for the imaging of artifacts, most notably neutron and x-rays as discussed in previous chapters. While these methods can be complementary, they are still limited in the range of objects that can be imaged. Underwater concretions are a type of artifact commonly encountered in art conservation and archaeology that may be difficult to image due to their physical properties. The very large and dense concretions do not allow adequate transmission with x-rays and the orientation of the objects make x-ray radiography uninformative [North, 1987]. These underwater concretions, particularly for corroded metal concretions, are stored in stabilizing solutions that contain chemicals to prevent active corrosion and maintain chemical equilibrium [Pearson, 1987]. The hydrogen content of the aqueous solutions would prevent proper neutron imaging due to high attenuation.

Considering the fragile conditions of many of the objects within the concretions, non-destructive imaging with computed tomography would be ideal for these objects. 3D volumes could allow conservators and archaeologists to view pseudomorphs without disturbing the equilibrium of the concretion or losing them entirely with other conservation methods. Computed tomography would be preferable to the commonly used conservation methods currently used by conservators, such as casting [Katev, 1966]. An alternative radiation source would be gamma rays, which at energies in the megavoltage range, would have enough penetrating power to image large, dense object and would not be attenuated by hydrogen.
5.1.1 Megavoltage Radiation Therapy

Megavoltage radiation therapy, including gamma radiation, is used in the medical field for many purposes including oncological radiation therapy and imaging. Megavoltage photons can be produced by either linear accelerators producing high energy x-rays (linacs) or from natural isotopes producing gamma radiation. The former has been widely adopted in modern medical fields due to increased precision and control for therapy and imaging through the adaptation of conformal radiation therapy in the form of Intensity Modulated Radiation Therapy (IMRT) [Fox et al, 2008]. IMRT allows for control of the orientation, shape, and intensity of the radiation beam to adapt therapies to specific individuals and target malignancies with minimal damage to healthy tissues. With the addition of detectors opposite radiation gantries, the patient and the target area can be imaged for verification of the set-up and dose monitoring. This combination of IMRT with digital CT scanning is considered tomotherapy [Fox, 2008]. The application of linacs to include computer tomography system for non-medical purposes has already begun with the work of Dr. James Welsh at the University of Wisconsin using a TomoTherapy Hi-Art Radiation unit [Greenemeier, 2008]. The work there includes the use of the megavoltage x-ray radiation to image paleological fossils and specimens demonstrating the ability of megavoltage radiation to penetrate through dense objects (Figure 5.1) [Greenemeier, 2008].

![Image of a Devion ammonoid](image)

**Figure 5.1.** Projection of a Devion ammonoid (370 million year old) as taken using megavoltage computed tomography.
Gamma sources use radionuclides as a source of gamma radiation through nuclear decay. One commonly used source in these systems is the Cobalt-60 (Co-60) isotope created through neutron bombardment of isotope Co-59. Co-60 undergoes beta emission decaying the excited state of Nickel-60 (Ni-60) [Andrabi, 2002]. This radiation source then undergoes gamma decay emitting two gamma photons with the energies of 1.17 MeV and 1.33 MeV with an average of 1.25 MeV. Gamma sources are still used today, but unlike the TomoTherapy units, are not preferred due to the limited capability of producing 2D portal images and therefore are unable to help verify the precise location of malignancies and have not been adapted to conformal radiation therapy [MacDonald, 2010]. Adaptation of these gamma source radiation units to provide either computed tomography or digital tomosynthesis would allow existing units to be updated with little additional expense while providing better patient care.

At Queen’s University and Kingston General Hospital in Kingston, Ontario, Canada the Medical Physics Program in the Department of Physics with the Cancer Centre of Southeastern Ontario (CCSEO) are investigating the adaptation of an existing Theratron 780 C Cobalt-60 (Co-60) unit from Best Theratronics in Kanata, Ontario for 3D imaging for the application of conformal tomotherapy (Figure 5.2, p. 86). The Theratron 780 C source consists of Co-60 pellets plated in nickel in a lead housing with additional depleted uranium shields [Andrabi, 2004]. The gamma rays are directed using a tungsten alloy fixed collimator that leads to the adjustable collimator made with lead vanes that allow for different field sizes.
Research has included the coupling of the medical unit to an image detection system and a rotational table for computed tomography. The detector used for this study was a 384 x 512 pixel Varian aS-500 amorphous silicon panel made by Varian Medical System in Palo Alto, CA. This detector is considered an indirect detection active matrix flat-panel electronic portal imaging device (EPID) which converts the photons to a readable output by through an photon converter consisting of a 1 mm copper plate over a 133 mg cm$^{-2}$ Gd$_2$O$_2$:Tb scintillation screen [Antonuk, 2002]. The scintillation screen converts high energy photons into photons which cause electron holes in the photosensor directly below the scintillation screen. These electron holes allow for the charge to activate the pixel switches, which are thin film transistors made from amorphous silicon. [Antonuk, 2002] This detector is mounted on the same tabletop platform as the mounting stage (Figure 5.3, p.87).

This in-house adaptation of the Co-60 gamma system for computed tomography allows for different types of CT to be performed, including fan beam, and cone beam geometries. The research conducted at the CCSEO for the improvement of the Theratron 780C for tomotherapy includes using phantoms to model the ability of the new system to deliver precise doses with
different geometries along with control of the radiation intensity. These studies include imaging of concrete cylinders including aggregates for the purpose of adapting the method for non-medical uses. Positive imaging of aggregates in the concrete indicate that the contrast and resolution from gamma CT using the Theratron 780C is sufficient for the 3D imaging of many types of inorganic objects.

Figure 5.3. Photograph showing the converted imaging system at KGH including the Theratron 780-C and the Varian aS-500 EPID.

5.1.2 L’Anse aux Bouleaux and Treatment Options

As an adaptation of current studies undertaken by the Queen’s University Medical Physics Program on the gamma CT imaging of concrete aggregates, a study was proposed to image underwater concretions with the Theratron unit. Concretions are ideal for gamma CT due to their considerable size and storage methods. These concretions were provided by Centre du Conservation du Québec (CCQ) and Parks Canada (Ottawa) from the 1994 excavation of the
shipwreck at l’Anse aux Bouleaux found in the Gulf of the St. Lawrence River in the province of Quebec. The shipwreck has been identified as the *Elizabeth and Mary*, which had disappeared from its retreat from the 1689 siege of Quebec City. This shipwreck is considered to be the earliest known shipwreck to be associated with North American conflicts. Excavation and examination of artifacts and concretions from the wreck allowed for positive identification of the ship and yielded many items including a pewter porringer [Degaldo, 2001].

The concretions used in this study were preliminarily imaged at the conservation laboratories, including Parks Canada and CCQ, using x-ray radiography that led to vague indications of pseudomorphs in the concretions. Further conservation and cleaning were not conducted due the lack of information on the contents of the concretions. The traditional treatment methods for pseudomorph containing concretions include recovery or replication using casting methods. Previous studies indicate that for complex and important pseudomorphs one of the extreme recovery methods included casting the molds to replicate the object. This technique ultimately damages the original concretion and could result in the loss of information [Katev, 1966]. These studies indicate that the use of plaster was common for casting after the voids are exposed through manual separation [Katev, 1966]. With development of different materials, synthetic polymers such as silicone were considered as alternative casting materials, but these conservation treatments still required the destruction of the original concretion as the casts are made to replace the pseudomorphs [Mardikian, 1996].

In every study using casting methods, the use of x-ray radiography was crucial in determining the location of the voids and remaining material to develop the best approach to manual removal of the concretion. The concretions that were loaned for this study were not able to be properly radiographed due to their large size. Literature mentions that the use of higher
energy and shorter wavelength gamma rays can be used for imaging in the event that the concretion is too dense to image using x-rays [North, 1987]. In one such study, artifacts from the shipwrecks of the *Bounty* and the *Pandora* in the Pacific Ocean were imaged using medical imaging equipment including gamma radiography [Piggott, 2006]. This study discusses using gamma radiography as a complementary technique to x-ray radiography for investigations of underwater concretions but lacks detailed information on the experimental procedures. The gamma radiography was only applied to the large cannon recovered from the site, which was used to determine the conservation status of the object inside concretions.

The application of the gamma CT would allow the researchers to study other objects from wreck that might help positively identify the shipwreck. Unlike the study imaging the cannon, the concretions in this study have no indication of the contents underneath the surface and consequently CT would provide the maximum amount of information. 2D radiographs may reveal some features but without knowledge of orientation it is not possible to determine the proper axis of radiography. Stabilization of the concretions required constant immersion in cold water containing 1% Hastacor to prevent further corrosion of the artifacts inside. The immersion storage eliminated the possibility of neutron tomography and its size prevented the use of kilovoltage x-ray imaging.

The successful imaging of these underwater concretions is critical for many reasons. It provides additional tools for researchers from underwater excavations to help identify objects that are trapped within large concretions without the risk of permanent damage to the objects. One disadvantage to gamma ray CT is that there is less material sensitivity to the method than conventional XCT where the power is in the kilovoltage range. With increase of power of the photons, there is a decrease in material sensitivity and the contrast in imaging is primarily from
the differences in density. While this reduced contrast would not ideal for small objects with minor differences in composition, the presence of pseudomorphs in the concretions should be easily identified as voids compared to the corrosion products. Full gamma CT scans would provide rendered volumes for imaging and evaluating potential damage or repair needed prior to physical intervention. Furthermore, gamma rays would provide an alternative radiation source where neutrons and the x-ray are not available. Increased options in non-destructive imaging would help conservators who have limited funding options as scans do not require much beam time.

5.2 Experimental

The instrument used for gamma computed tomography was an in-house system including a Theratron 780C Co-60 radiation unit with a rotation table between it and the Varian aS-500 EPID detector engineered by physicists with the CCSEO as discussed above. All scanning using the Theratron was supervised and conducted by Masters candidates Matthew Marsh and Nick Rawluk from the Department of Medical Physics at Queen’s University.

5.2.1 Materials

The concretions from L’Anse aux Bouleaux were transported from Parks Canada in Ottawa to Kingston in coolers with ice packs and stored in refrigerators. The concretions were stored in 1% Hastcor aqueous solutions in plastic containers. These concretions varied in size and had previously been x-rayed by CCQ and Parks Canada producing no usable results. The concretions will be identified in this paper by the object numbers that were provided by CCQ (Table 5.1, p. 92).
5.2.2 Imaging Protocols

The objects were placed on the rotating mount in their containers and stabilizing solutions (Figure 5.4, p. 92). The objects were centered manual through visual inspection. Added height was obtained through use of flat objects such as slices of a phantom or Styrofoam blocks. The mount was centered through the use of guiding lasers. The source to axis distance (SAD) and source to detector distance (SDD) was measured with measuring tape and recorded prior during the centering process.

All imaging was performed with 301 projections over 360 degrees at a 1.2 degree interval. Each portal image was an average of several projections or frames taken at the same angle. Frame exposures were 100 ms each and the frames in the imaging study ranged from 20-50 frames. The portal images were exported as 16-bit tiff files. This raw data was used for reconstruction in Octopus after normalization and filtering for ring artifacts in MATLAB by medical physics graduate students, Matthew Marsh and Nick Rawluk. The reconstructed axial files could then be used for reconstruction using Octopus using the same method as discussed in Chapter 3.

Unlike the Xradia XCT-400, the cone beam geometry of the gamma ray scanning only included geometric magnification. Thus, the actual pixel size is based on this geometric magnification. The pixel size and subsequent voxel size was calculated for each reconstructed volume based on the geometric magnification of the image that was influenced by the SAD and SDD. The calculation for the pixel size is in Equation 5.1.
Table 5.1. Gamma CT parameters for concretions from CCQ including source to detector distance (SDD) and source to axis distance (SAD).

<table>
<thead>
<tr>
<th>Concretion</th>
<th>Frames Averaged</th>
<th>SDD (cm)</th>
<th>SAD (cm)</th>
<th>Pixel Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57M4P2-90</td>
<td>20</td>
<td>125</td>
<td>110</td>
<td>0.69</td>
</tr>
<tr>
<td>57M14N2-117</td>
<td>20</td>
<td>125</td>
<td>110</td>
<td>0.69</td>
</tr>
<tr>
<td>57M2N2-9</td>
<td>40</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>57M4P2-96</td>
<td>40</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>57M18M2-2</td>
<td>40</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>57M14L2-89</td>
<td>40</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>57M14L2-27</td>
<td>40</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>57M14L2-30</td>
<td>50</td>
<td>220</td>
<td>200</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Figure 5.4. Photograph showing imaging set up for a concretion.

Equation 5.1. Calculation of pixel size in cone beam geometry.

\[
0.78 \text{ mm} \times \left( \frac{SDD}{SAD} \right)
\]
This geometric magnification actually represents one limiting factor of the Co-60 source in that the geometric magnification is also geometric unsharpness. Consider the following example in which a source, in this case the Co-60 radioactive isotope within the Theratron has a finite focal size. As it passes through an object on the axis with a certain point, the resulting transmitted rays will enlarge to form a penumbra which represents the limiting resolution of the system (Figure 5.5). Reduction in the penumbra and unsharpness can be made by limiting the size of the radiation source and increasing the SAD. Ideally, system should have a point source with a large SAD.

![Diagram showing focal size, SAD, SDD, and penumbra]

Figure 5.5. Geometric unsharpness for radiation sources.

5.2.3 Reconstruction

The reconstruction of the concretions was performed in Octopus. Prior to reconstruction the raw projections were renamed using the bulk rename utility to eliminate the angle numbers included in the files as extra periods/decimal points would cause problems in the importation of the files into Octopus. The original files were maintained with the angle numbers an alternative set was used for the raw projection data. Within reconstruction processing modules used were
normalization and cropping. Due to the monochromatic nature of the radiation source, cleaning was not necessary for the raw projections. The parameters for reconstruction included counter-clockwise rotation axis with no beam hardening correction due to monochromatic radiation source. The reconstructed slices were exported as 16-bit .tif files which could then be used for rendering in visualization software.

5.3 Results

The eight concretions imaged using gamma CT provided clear indications that discrete objects were located within the different concretions. These objects ranged from voids in the concretions left from the original object along with some high attenuating material remaining in the concretion. A selection of these eight concretions will be discussed to highlight the significant results of the imaging study.

5.3.1 57M4P2-90

In the reconstruction of 57M4P2-90, the volumes and reconstructed slices indicate that there are two ball shaped objects with very high attenuation (Figure 5.6). These objects can be easily segmented out for inspection showing the remaining shape in the concretion (Figure 5.7, p. 95). Given the comparative attenuation to the other materials in the concretion, as well as in the other concretions, it is surmised that the objects in question are lead shot, a high attenuating material.
Figure 5.6. Reconstructed volume of 57M4P2-90.

Figure 5.7. Windowed volume of 57M4P2-90 showing the high attenuating round objects.

Along with the high attenuating round objects, several long voids were found in the reconstructed volume, one of which can be clearly seen in Figure 5.8. These voids were found in many different orientations within the concretions and were often not aligned with the three axes of the reconstructed volume. This oblique orientation of the voids required the use of programs that were able to clip the volume along any angle. ImageVis3D was primarily used for this type of investigation. Examining the voids, it was determined that at least some of the long spiked objects were the remains of nails due to the presence of the head at some of the ends (Figure 5.8).
Several of the spikes did not contain heads which indicate that they were partial remains or other long shaped objects. The evidence that these objects were voids is that they had similar attenuation values to the water and plastic container around the object. If the objects were still iron or copper would show that there would a higher attenuation value corresponding more with the corrosion values. The relative attenuation values were inferred through isosurface and 2D transfer function modules in ImageVis3D. The isosurface module allows for the selection of specific gray values, which correspond to attenuation values, to be displayed.

Both the reconstructed volume and the clip planes give a better indication of the features of the internal objects and voids. The high attenuation of the lead shot and the concretion make the pseudomorphs unrecognizable in the original x-ray radiograph that was provided by Parks Canada (Figure 5.9)
Figure 5.9. Original x-ray radiograph of concretion 57M4P2-90 taken at 350 keV.

5.3.2 57M 4L2-89

There was an indication that the concretion 57M 4L2-89 was in two separate sections that may contain different objects (Figure 5.10). However, upon examination of the clip planes and the reconstructed slices, it is clear that no large defined pseudomorph is present within the concretion that can be identified. The slices do indicate the presence of different aggregates in the corrosion layers and concretion that can also be seen from an external view of the volume (Figure 5.11). These results are similar to those that were found by the CCSEO during their study of concrete samples using MVCT. These results do not conclusively indicate that an object may have existed inside the concretion originally. Alternatively the concretion could have developed around a small object that now is completely corroded without leaving a pseudomorph. This object may be a useful candidate for further investigation.
Despite the lack of obvious internal features in the volume and clip planes of 57M4L2-89, the gamma ray CT of the concretion led to improved imaging of the object compared to x-ray radiography. The reconstructed slices of the volume clearly show aggregates within the concretion due to increased contrast from the imaging, compared to the original x-ray radiography at 350 keV acquired at Parks Canada (Figure 5.12).
5.3.3 57M 12N2-27

This concretion provided the most interesting pseudomorphs to examine of all the concretions in this researcher’s opinion. From the coronal reconstructed slices (Figure 5.13, p. 99), the overlapping voids in two dimensions give the indication of a single object. While it is clear from the other projections from different angles that this is not the case, these slices exemplify the way in which computed tomography can be used to elucidate information that is simply not clear enough in 2D radiographs (Figure 5.14, p. 100). Examining clip planes and reconstructed slices indicate that this image is the result of different objects in various orientations.

![Coronal reconstructed slice of 57M14N2-27 with its position on volume](image)

Figure 5.13. Coronal reconstructed slice of 57M14N2-27 with its position on volume (right).
Figure 5.14. Original radiograph of all fragments of 57M14L2-27 at 350 keV.

Reconstructed slices along the other axes, sagittal and axial, reveal that more than one object exists in the concretion but they are not oriented properly to elucidate the identity of the objects (Figure 5.15 and Figure 5.16)

Figure 5.15. Axial reconstructed slice of 57M14N2-27 with its position on the volume (right)
Due to the oblique orientation of the objects to the axes, clip planes were necessary to determine the shape and size of the objects. These clip planes allowed for a better understanding of the contents in the concretion. One object identified was a tube whose cross section formed the round object in the coronal reconstructed slice (Figure 5.13) that is oriented mostly along the sagittal axis (Figure 5.16). This clip plane also indicates that the tube slightly overlaps another object (Figure 5.17).

Figure 5.16. Sagittal reconstructed slice of 57M14N2-27 with its location on the volume (right).

Figure 5.17. Clip plane of 57M14L2-27 showing a tube shaped object with its location in the volume (right).
This object is more difficult to characterize, but the images indicate that it is the largest of the objects in this concretion. Clip planes indicate that it is irregular shaped but is laterally long compared to its width. This object forms the “barrel” that is seen in the coronal reconstructed slice (Figure 5.18). The use of the clip planes for this particular concretion demonstrated the benefits of running full tomography scans on the concretions as radiographs would have resulted in misleading information. This object would be an ideal candidate for segmentation methods that would separate out the different pseudomorphs for isosurface mesh extraction and subsequent physical development.

![Image](image.png)

**Figure 5.18.** Clip plane of 57M18M2-2 showing irregular shaped object (a) and its location in the volume (right).

### 5.4 Conclusions

The investigation of the viability of gamma ray computed tomography for the investigation of underwater concretions demonstrates that this method would be a useful method for non-invasive analysis. The method successfully imaged the different underwater concretions and provided significant information on the identification and location of the pseudomorphs within the concretion without any intervention. Despite the data having low resolution and some noise, the successful reconstruction and segmentation of the object demonstrated that converted Theratron units could be used for art conservation.
Advantages of the method shown from the study is the ability to provide a gap technique between more traditionally used radiation sources such as neutron and x-rays. Gamma rays address limitations of both techniques such as sensitivity to neutrons as well as the large mass and density of the object. The technique allows for the investigation of the object providing digital records of the object at the time of imaging. This record could be used for documentation or as a tool for conservators to analyze the object prior to treatment. In the event that further treatment or recovery is necessary, any damage to the internal objects could be minimized by comparing to the digital records. Imaging at later dates could be used as a comparison to determine the rate of degradation within the concretion.

Another advantage to the technique that should be noted was the relatively short scan times that were required for tomographic imaging. For full 360° scans, the average scan time was approximately one hour. The faster scan time was in part due to the higher energy of the radiation requiring less exposure time for each projection. The increased number of frames for higher quality of images would only slightly increase the scan time. This scan time also included extensive readout time due to the ad hoc nature of the system set-up including the time needed to reset the source due to safety limitations. Given a streamlined and well developed system, scanning times could be reduced so that if the use of a system required an hourly cost, it would be minimal compared to some other techniques.

One of the most significant results of the investigation was that imaging of the underwater concretions yielded usable meshes through the segmentation process that could be used for 3D printing such as rapid prototyping or mold extrusion. The actual production of these replicas would be essential in comparing this project to traditional methods. One benefit of the use of replicas is that if desired, multiple copies could be made from the original digital files in
the event of the destruction of any replica. Original casts of the pseudomorphs could also be used to create a master template for the material but the possibility of the material of the object degrading is significant and in the event the template and the cast are both lost, the object would not have the same redundancy that exists with digital documentation. Also, the process of recasting from mold made from an original cast can lead to some degradation of surface features, not unlike making copies of copies in any sense, which would not be the case in the digital files.

Some of the limitations of the method include the non-standardized imaging system that was provided by the Medical Physics Program at Queen’s University. While the Theratron unit was a standard radiation therapy device, it is not commonly attached to the other components necessary for the tomography including a stage for rotation and a detector. This relatively specialized set-up would prevent the widespread use of this particular method. Literature would suggest that gamma radiography has been used previously as in the radiography of the cannon in Piggott’s 2006 study. Considering that this study was also conducted at a hospital with medical imaging facilities, it is possible that researchers can approach similar institutions for the use of their equipment. Most medical CT scanners, however, are designed for use on the human body using spiral or helical techniques that move the detector and source rather than the object. Also, medical scanners are designed for human bodies with lower voltage requirements and would not have the penetrating power of tomotherapy units.

5.4.1 Future Research

While this study was successful in determining the application of gamma CT for underwater concretions, there are many questions that still need to be answered. The first extension of this project would be to compare the images and data obtained from gamma CT compared to information from traditional conservation methods. This comparison would require
the use of invasive techniques on the concretions from L’Anse aux Bouleaux through concretion removal and casting methods such as used in Mardikan (1996) and Katev (1966). While this would essentially destroy the concretion, the imaging study provided digital documentation of the pseudomorphs that would still exist. Also, procedure would be guided by the images provided from the CT scanning as the location of the voids are known in the concretion. The drill holes required for casting can be made with greater accuracy. When the cast of the pseudomorphs are made, it is important to compare them to the possible digital reproductions that could be made from segmentation and eventually 3D printing. This comparison is essential because despite the benefits of using 3D printing over casting as discussed in the previous section, the benefits would mean nothing if the digital replicas were less representative of the objects than the casts. In the event that the casts produce higher quality replicas, the imaging and visualization method should be re-investigated to improve the use of gamma CT.
6.1 Introduction

CT has proven to have great applications for non-destructive imaging of metal artifacts with the use of different radiation sources, neutrons, x-rays and gamma rays. While each method has many different benefits and disadvantages, one common drawback to computed tomography for each radiation source is the inability to image laterally long objects, such as paintings properly. These objects are difficult to the image because the radiation can be almost completely attenuated along one axis in which the cross section is significantly thicker. With high to complete attenuation, also known as photon or neutron starvation, computed tomography reconstruction can produce serious streaking artifacts that can interfere with proper interpretation of 3D volumes or reconstructed slices.

One solution to problems associated with starvation along certain planes or large objects, is the use of limited angle tomography, also known as laminography or digital tomosynthesis. The premise behind this method is that rotating an object around a center of rotation for partial angles will allow for reconstructions of planes orthogonal to the beam. These reconstructed planes will allow examination of the different layers within the sample while avoiding the slices that would cause photon starvation artifacts.

6.1.1 Principles

To understand laminography, it is important to revisit the projection slice theorem or Fourier slice theorem which demonstrates that the Fourier transform of a 2D image forms a plane in the 3D Fourier space of the object. If enough projections are acquired over at least 180° and
the 2D Fourier transforms of the projections are obtained then the 3D volume of the object can be reconstructed using the inverse Fourier transform. In computed tomography, this principle is applied using the Radon transform instead of the Fourier transform which allows for reconstruction of the 3D volume using 2D projection slices. In laminography, however, the entire 3D frequency space is not filled because of the smaller angular sweep which causes artifacts and blurring during reconstruction for those frequencies or spaces that are missing.

Consider the following black and white digital photograph, referred from this point as “Campfire” (Figure 6.1). The Fourier transform of the image shows the 2D Fourier space in which the spatial frequencies are transformed into the logarithmic magnitudes in the Fourier space (Figure 6.2, p. 107) [Russ, 2011]. The vertical intensities in the transform (Figure 6.2) represent horizontal frequencies in the original image (Figure 6.1) and vice versa.

Figure 6.1 Black and white digital photograph, “Campfire”.

Figure 6.2. Fourier transform of “Campfire”.

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If frequencies are removed from the 2D Fourier space of “Campfire” by reducing the magnitude to 0 and an inverse transform is performed the resulting image is distorted by the removal of the frequencies (Figure 6.3). The partial image still resembles the image and some of the information is able to be obtained (Figure 6.4).

![Image 6.3](image.png)

**Figure 6.3.** Removal of frequencies between $0^\circ \pm 45^\circ$ from the Fourier space of “Campfire”.

![Image 6.4](image.png)

**Figure 6.4.** Image produced from inverse Fourier Transform after removing vertical frequencies.

Removing the frequencies along the opposite axis, the horizontal frequencies (Figure 6.5, p. 109), result in a similar image in which the vertical information is present and the figures are more easily identified (Figure 6.6, p.109).
Figure 6.5. Fourier transform of “Campfire” with the removal of the frequencies between $90\pm45^\circ$.

Figure 6.6. Inverse Fourier transform of “Campfire” after filtering out the horizontal frequencies.

This same principle can be applied the use of laminography for the reconstruction of partial volumes in cases where the objects cannot be imaged fully. The resulting reconstructions will have less data to fill the 3D frequency space, but analysis of the planes orthogonal to the beam path should allow the researchers to distinguish some features. The use of this technique will help future researchers examine objects without full scanning.

6.1.2 Applications of Laminography

While previous applications of laminography were medically based, laminography have been more recently been applied to industrial imaging. X-ray laminography has found to be an excellent method of imaging circuit boards or other electronic equipment with fine components.
that are in layers [Godrom, 1999]. These studies have shown that digital tomosynthesis can be used to reconstructed solder joints and move through the different layers of the circuit board. Other industrial applications include the use of digital laminography for the monitoring of concrete exposed to freeze-thaw cycles that might induce fractures and the damage [Wakimoto, 2008] (Figure 6.9). The use of digital laminography for this purpose was considered due to the increased imaging contrast with 3D reconstructed images from computed tomography but with the great portability that laminography afforded.

Figure 6.7. Optical scan (a) and digital tomosynthesis slice (b) of a concrete specimen showing an internal crack [Wakimoto et al., 2008].

From these industrial field investigations, limited interest in applying the technique to art or archaeological objects has arisen. The most notable study on the use of laminography, or what was termed laminography, for an art object was conducted to help image a mock altarpiece to determine the use in detecting hidden relics. This study compared the results from computed tomography, laminography and phase contrast imaging for detecting a piece of paper within the wooden structure of an altarpiece using quasi-monochromatic x-ray synchrotron radiation
[Krug, 2007]. An examination of the experimental parameters indicates, however, that the technique used was not in fact laminography but a full scan of a region of interest of the sample at an inclination. The positive results and 3D volume produced from this study would not be suitable for comparison as the angle range was not limited to below 180°.

Considering the potential of the laminography for art conservation, the purpose of this study was to examine expanded applications of the technique. These alternative applications include the use of low-flux neutrons at RMC for neutron laminography which would be beneficial as it would allow for reconstruction and imaging of paintings containing high atomic number materials that would attenuate x-rays such as lead white grounds. By creating a test sample using paint layers and a lead component, this study intends to establish the use of laminography for paintings with lead ground paints that cannot be imaged with conventional x-ray radiography or XCT. Also, the study intended to demonstrate the ability to use Octopus software for FBP to reconstruct usable volumes as a result of laminographic investigation using the Xradia XCT-400.

In addition to FBP, other reconstruction methods have been applied to limited angle computed tomography for the purpose of optimizing the data set with reduced information. An alternative reconstruction method for laminography is to use SART for these limited angle data sets. SART can have some advantages to FBP in the case of low angle computed tomography by eliminating the need for reprojections to populate the spaces either in the unevenly distribution of angular projections or in limited angle problem [Anderson, 1989]. Considering the advantage of SART for the specific purpose of limited angle tomography, it would be important to compare the results of the reconstruction of the data produced by FBP reconstruction using Xradia or Octopus and that are produced by SART algorithms.
6.2 Experimental

The test subjects for the laminography included a physical test sample for neutron imaging and digital data sets for x-ray imaging. The physical test sample consisted of layers of paint on wooden boards with a lead buffer. The digital data set for x-ray imaging was the Copper Coin x-ray CT from Chapter 3.

6.2.1 Low-Flux Neutron Laminography

For neutron digital tomosynthesis, a test sample was prepared to demonstrate the possibility of distinguishing individual paint layers (Figure 6.8). Cadmium zinc sulphide pigment was selected due to the high attenuation of cadmium ensuring high contrast with other materials. Cadmium yellow acrylic paint heavy body paint from Golden Artist Colors was used to paint strips two 0.25 inch wooden boards each in a different orthogonal direction. Varying amounts of paint layers were placed on the different strips to change the thickness of the samples for help determining slice thickness in laminography.

![Prepared boards for neutron laminography](image)

Figure 6.8. Prepared boards for neutron laminography

These two boards were then used to sandwich a lead sheet to demonstrate the ability of the neutrons to penetrate lead layers similar to those that would be found in historical oil.
paintings (Figure 6.9, p. 113). The sheets were then mounted directly onto the jawed clamps for rotation. The sample was imaged over 70 degrees with an acquisition time of 5 minutes. Projections were taken at each angle with a total of 71 projections. The images were preprocessed in ImageJ and reconstructed in Octopus in sets of 70 and 40 degree arcs.

Figure 6.9. Sandwich of panels and lead sheet.

6.2.2 X-ray Micro Digital Tomosynthesis

Due to the cost and time of additional scans it was considered to be more efficient to examine portions of complete tomographic x-ray data sets in addition to limited angle imaging. These data sets included those discussed in Chapter 3 including the artificial copper coin from Sullivan’s study. The .txrm files were opened in the Xradia Controller and the projections were limited to using the tool menu under “Shifts”. This menu allowed for projections to be excluded from reconstruction through the checking or unchecking of boxes for each of the raw projections taken during tomography scanning. Each projection lists the angle of rotation and the shift from dithering. Each angle needed to be checked or unchecked as there is no possible way to select multiple projections at one time. This selection was saved, but the projections remained in the dataset and were not deleted. In Xradia Reconstructor, it was clearly indicated which projections were included and which were excluded and normal reconstruction parameters were used to produce reconstructed projections which were then rendered in the various software programs.
6.2.3 Reconstruction

As mentioned previously, reconstruction of the different laminography data sets was performed on either Octopus or Xradia depending on the radiation source and tomography system. While both reconstruction programs allowed for cone beam filtered backprojection, the reconstruction module in Octopus allowed for greater control over more parameters of the reconstruction process. Also, the successful use of Octopus would allow direct comparison to other techniques as their data sets were reconstructed in Octopus.

In addition to reconstruction using FBP in Octopus or the Xradia Reconstructor, Simultaneous Algebraic Reconstruction Technique (SART) was performed on a selection of the laminography data sets for a comparison of the reconstruction techniques. The data sets that were used for this comparison are outlined on the table below (Table 6.1). The SART reconstruction was performed by Loes Brabant at the University of Ghent.

Table 6.1. Data sets examined using laminography with their reconstruction methods.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Angular Ranges</th>
<th>Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Coin</td>
<td>X-ray</td>
<td>40, 60</td>
<td>Xradia, Octopus, SART</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Neutron</td>
<td>40, 70</td>
<td>Octopus, SART</td>
</tr>
</tbody>
</table>

6.3 Results

6.3.1 Low-flux Neutron Laminography

The data sets for laminography were rendered and produced volumes that contained the partial information needed. The reduced information in 3D space is quite evident looking at the whole volume. The clearest clip planes of the data were taken from the center of the rendered volume. In comparing these different central clips, it was possible to evaluate qualitatively the
differences in image quality from the different data sets. For example the clip planes of the 40°
and 70° data sets using FBP could be compared to yield a preliminary determination that the
greater angular interval of 70° produces volumes in which the different stripes have greater
contrast (Figure 6.10). This great contrast allows for clearer definition between the different
stripes of the test board.

![Figure 6.10. Central clip plane from 40° (left) and 70° (right) laminography using FBP.](image)

What is interesting to note is that in these volumes, the reconstruction plane is not aligned
with the axes of the volume (Figure 6.11, p. 116). This difference in planes could be due to the
inability to perfectly align the object parallel to the detector during the experimental phase. If the
test board were not parallel to the detector then the reconstruction slices would contain off-
centered planes of the board.
The laminography of the cadmium boards using the low flux-neutron CT showed limited ability to distinguish between the paint layers even with the various types of reconstruction methods at different angular intervals. For reconstruction using Octopus after median filtering, the resulting data showed bleed through from the horizontal stripes along the entire range. This blending was also evident when this data set was reconstructed using SART. A successful laminographic data set would show a distinct demarcation between the horizontal and vertical stripes. While evident in the central clip planes, this effect can be seen throughout the volume viewed through scrolling through clip planes.

While both the SART and FBP data sets showed the blending of the stripes, the SART data qualitatively showed marginal improvements in image quality. The contrast in the FBP data was accomplished through 1D transfer function to create a stark difference between the stripes and the wood. In the SART data, there was less need for thresholding and the planes gave a greater indication of the relative location of the stripes even when both were evident in the plane. For example, Figure 6.12 shows the central clip planes of the 40° data set using FBP and SART. For the SART data set there is more subtle contrast which required less dramatic thresholding to
view the different stripes. Also the horizontal planes appear to be above the vertical planes indicating the relative position of both boards. This difference is not as clear in the FBP set where there is more noise in the image rendering the object grainy. Also, one noticeable feature of the boards is the crack in the wood that is evident in the central clip planes. This feature allows for a more direct comparison of the two data sets. In the SART data set, the crack has well defined edges with strong contrast with the rest of the volume (Figure 6.13, p. 118). The crack in the FBP data set is more difficult to distinguish and the edges are less well defined.

While the SART reconstruction provides a clearer image of the data set than FBP, both reconstructions of the limited angles shows minor improvement on the single projection at 0°, representing a traditional radiograph (Figure 6.14, p. 118). The difference between reconstructed volumes and the radiograph indicate that the laminography provides images that allow for a greater understanding of the depth of the stripes and their relative locations despite the inability to resolve the different paint layers.

Figure 6.12. Comparison of central clip planes of 40° FBP (left) and SART (right).
While the image quality seemed to have been improved in the SART reconstruction, both methods indicated that there was some fundamental flaw with the low-flux neutron CT parameters of the experiment. One possibility is that the thickness of the different layers of the test sample was not sufficient enough for distinction with the current imaging capabilities at RMC. The thickest layer of the phantom would be the lead sheet that buffered the two different wooden boards. This lead sheet was $\frac{1}{4}$ inch thick which would indicate that greater thicknesses would be needed to indicate different layers.
Additional tests for laminography were also conducted using previous data sets in which partial angles were reconstructed. One of these data sets was of a small gauge comprised of both plastic and metal components. When reconstructed over limited angles, there was the ability to distinguish between the different components, more specifically the hollow valve in the gauge was present in some portions of the volume, and not others (Figure 6.15). The dimensions of this gauge were significantly less than ¼ inch, which indicates that the failure to produce distinguishable layers was not due to the physical dimensions of the test object.

Figure 6.15. 40° laminography slice of gauge showing valve (left) and not showing valve (right).

6.3.2 XCT laminography

While a test sample was not prepared for direct laminography testing, previous data sets had similar characteristics that could be explored using limited angle reconstruction. Focusing on the artificially corroded copper coin (Figure 6.16 and Figure 6.17), the surface features were analyzed using the different reconstruction methods.
First the coins were reconstructed using FBP in Xradia Reconstructor. The resulting volumes from 40° and 60° yielded promising images, though there were some artifacts that reduced the image quality. In Figure 6.18, both the obverse and reverse can be clearly seen underneath the corrosion. Unfortunately, similar blending of the copper wiring is seen in this clip planes that partially masks the inscription.
The data set using 60° was similarly successful in revealing clear clips of the inscriptions, though the greater angular range yielded images with higher contrast and less blending. This qualitative comparison shows less interference in the 60° data set than in the 40° data set. One clear example is in the reverse of both volumes where "Mechanical" is more clearly recognizable in the Figure 6.19 than in Figure 6.18. As discussed with the neutron laminography data, the improved imaging with the greater angular range is not surprising given that the greater angular range allows for more of the 3D Fourier space to be filled during the filtered back projection allowing for the volume to be rendered more accurately.
While there was an improvement in reconstruction with greater angular range using FBP, it was necessary to compare those results to the reconstruction using SART. The two methods were qualitatively assessed by the ability to read the inscription and distinguish the different sides of the coins. For both reconstruction methods, the inscription was visible and the two sides were completely separated. In the SART reconstructions, the clip planes (Figure 6.20 and Figure 6.21, p. 123) that the inscriptions on the coin are more difficult to read in the 60° data set. The minor improvement in the 40° data set using SART reconstruction is from a subtle increase in contrast between the inscription surface and the rest of the coin.

Comparing the two reconstruction methods by look at the clip planes from both data sets (Figure 6.22, p. 124), the images both displayed reduced visibility of the inscriptions on the coins with the contrast enhanced through the use of 1D Transfer Function in ImageVis3D. Both reconstruction methods in laminography, however, show a marked improvement in the ability to read the inscription underneath the corrosion surface when compared to the single projection at 0°, or a traditional radiograph (Figure 6.23, p. 124). These positive results demonstrate that laminography could be an improved method of non-destructive imaging of corroded coins to traditional CT.

Another way to evaluate the difference between the reconstructed methods was to examine the histograms produced by methods during rendering in ImageVis3D (Figure 6.24, p. Figure 6.24). The Xradia FBP histogram indicates that there is greater range of attenuation values as the peak for air and is in the center of the histogram compared to the SART histogram where the histogram features attenuations greater than the material. The SART histogram also indicates that there is greater contrast between the different materials as seen in the more defined peaks.
As with the neutron data, there was some blending of the layers that persisted in the clip planes of the coin, even when using SART reconstruction. This blending was the result of the slice thickness in the laminography being greater than the distance between the copper wire to the surface of the coin. This blending is most evident when the laminographic images are compared to the original full scan clip planes of the same coin (Figure 6.17, p.120). While the slice thickness was greater than the distance between the wire and the coin, the ability to resolve the two sides of the coin using laminography indicates that the slice thickness is less than the width of the coin. The coin was 1/8\textsuperscript{th} inch wide with an average of 40 slices between each side of the coin. The slice thickness could be calculated as approximately as 1/320\textsuperscript{th} inch or 0.080 mm.

Figure 6.20. Obverse (left) and reverse (right) of 40° SART.
Figure 6.21. Obverse (left) and reverse (right) of 60° SART.

Figure 6.22. Clip planes of the obverse of Copper Coin with 60° FBP (left) and 40° SART (right).

Figure 6.23. Single projection of Copper Coin at 0°.
6.4 Conclusion

The laminography of the sample sets and manufactured test subjects indicated that laminography could be a possible alternative to full computed tomography, but that more research would be needed prior to full implementation. The most promising results from this study were in the ability to read the inscriptions of the copper coins using limited angle tomography. Despite the presence of the copper wiring in the clip planes there was the ability to completely distinguish the different sides of the coins from one another. These results indicate that laminography could prove to be a time-saving and thus more cost effective method for coin identification with tomography than using full scans. Using SART reconstruction methods, laminography can provide slices or clip planes of the surface with the ability to read the inscriptions.

An interesting result was the visibility of the copper wires in the clip planes and slices in the images of the surface, despite being in a different layer. This presence indicated that the slice thickness of the laminographic volume was greater than the distance between the wire and the surface. This thickness should be investigated as it would lead to a better characterization of the potential of XCT laminography using the Xradia machine. Also, these scans were done using the 0.5x macro lens; however there are additional optical lenses for greater magnification. Studies
with other types of objects should be completed on the difference in slice thickness at the different magnification ranges.

For the neutron laminography at RMC, the results were less successful in that there was not a complete separation between the different wooden boards and their paint layers. Considering previous attempts at digitally producing laminographic data, this indicates that the test sample had an unsuitable feature that would not allow for proper imaging. Further imaging studies would have been performed with modified test subjects, but concurrent to this study was another study designed to characterize and improve the imaging system at RMC and it was concluded that further studies should be postponed until such measures were completed as to obtain the best possible data.

Pending these further studies, these preliminary results indicate that neutron laminography not be suitable for application to test objects like the wooden boards, such as panel or canvas painting with the entire object in the field of view. The large slice thickness observed in the reconstruction of the cadmium panel may have been affected by the ratio of the lateral area with the object thickness. Additional tests should be run on the same phantom or similar test objects with a narrower field of view to determine the maximum ratio of lateral area to thickness can be supported with the low-flux neutron laminography at RMC.

6.4.1 Future Research

More research needs to be accomplished to understand further the extent in which laminography can be applied to art conservation. Investigations into the possible application of the method to different types of objects are still needed. This additional testing should be done in a more controlled manner with the use of test samples similar to those used in the neutron laminography experiment. The use of controlled samples would help allow for a workflow to be
developed and the limitations of the methods firmly established. One possible topic of interest would be the use of laminography for the investigation of paint layers on canvas or board. Using lower voltages would produce greater contrast between the different pigment layers in these samples to investigate inhomogeneity in paint samples. These objects would be more suitable for laminography as they would more accurately represent the target niche originally intended for this study: objects that are laterally long with layers on the micro-focus scale.
Chapter 7

Open source software workflow

7.1 Introduction

As explained previously in the literature review, computed tomography has been successfully applied to many types of artifacts yielding valuable imaging information. The two notable studies that imaged the Antikythera Mechanism and the 17th century silver watch allowed researchers to highlight internal mechanisms in the 3D rendered volumes. These studies, like many others, utilized specialized facilities and personnel for their CT imaging allowing them access to high-end proprietary software that is not affordable to casual researchers. Volume Graphics is commonly used for image processing in materials research but can cost upwards of $30,000. Considering the initial cost of image acquisition that can arise from the different radiation sources needed, the added expense of software can often lead to the method being completely cost-prohibitive. In many of these cases and exhibited by the previous studies, the use of the software is provided during imaging studies at institutions, but often these programs require some training and expertise to be efficiently used. While technicians provide a valuable resource, often it is the conservator that is the most cognizant of which features are crucial. Having software available that allows for hands on processing could streamline the computed tomography of laminography method that would make it more appealing to conservators worldwide.

Another issue with image processing software is that the methodology of producing publication level images is not thoroughly explained, leaving a black box for other researchers that prevents greater availability of the technique to art conservators and other researchers.
Without knowledge of how to process the images or which features are crucial to producing usable images, researchers are often left without an understanding of how the results can reveal information about the objects or how it would be conveyed to others.

While Volume Graphics is used heavily in industrial tomographic imaging, greater development in software has occurred for the use in the medical field resulting in a plethora of free source software available on-line that could be used to accomplish the same type of manipulation that the proprietary software programs can provide. For great accessibility of computed tomography or laminography, these software programs should be considered as a means of producing imaging results in-house without the need for specialists that would reduce the cost of imaging. Many of these programs that have developed for the image processing in the medical field contain Graphic User Interfaces (GUIs) that allow the user to control the processes, which are essentially mathematically manipulations through buttons and menus. Alternatively, all these processes could be done manually through computer coding in MATLAB, but this type of image processing would not be as accessible to art conservators. Thus, this study focuses on the software programs available with GUIs to reach the greatest audience possible. These software programs were evaluated based on certain pre-determined criteria as to the key features needed to perform minimal image processing to retrieve the information pertinent to the conservator. The programs were selected based on availability and recommendations from researchers in the field.

7.1.1 Processing Needs

For the corroded metal artifacts in this study, the focus of the image processing was on a few operations that would allow for the best enhancement of the features identified in CT. The following sections describe the key features that would be necessary for the proper visualization
and processing of images for publication and research. These key features are best described by the methods of information manipulation that occurs. To understand these processes, it is first important to understand the method in which the data is encoded in the reconstructed slices. As mentioned in Chapter 2, the imaging in CT radiography is based on the differences of attenuation for the different material in the object. This attenuation is represented in reconstructed slices on a greyscale range that is based on the type of file selected. For 16-bit image files, as selected in this study, there are 65,536 levels of monochromatic pixels or voxels that represent the different attenuation value from total attenuation (white) to total transmission (black) (Figure 7.1).

![Figure 7.1. Attenuation values as represented in 16-bit image files.](image)

The visualization analysis and processing will affect the way in which these CT values are presented in the rendered volume. This will allow for the focus on the information desired in the object through mathematical manipulation or calculations that will adjust the greyscale.

7.1.1.1 Pre-processing

Prior to image analysis or reconstruction, it is often necessary to pre-process the raw projections or reconstructed slices so that reconstruction or rendering will not be hindered. This pre-processing can be the result of several factors. For raw projections, pre-processing is necessary when the imaging protocols cause noise or undesired elements or artifacts in the projections. This noise or artifacts can stem from faulty parameters to inherent limitations within the method. Additional scans should be taken if the imaging parameters were not fully optimized, but restrictions with time and cost can prevent this testing and digital pre-processing.
may be required. This type of pre-processing includes the median filters that were needed to eliminate gamma incidents on the scintillation screen for low-flux neutron CT.

Due to the use of a several programs which require different importation and exportation criteria, the file names often are converted or renumbered in a way that is not compatible with other programs. Pre-processing also includes ensuring the files are both in the proper format and are labeled in a way that allows for easy importation and access for any given program. Conversion of files and organization is also a key step in the visualization process as one mistake can lead to frustratingly incorrect results with no other discernable reason.

7.1.1.2 Volume Rendering

FBP reconstruction yields an image sequence of the axial perpendicular to the beam path, or the z-axis of the object. Viewing only these files would allow for only examination of features along one axis which runs counter to the purpose of CT imaging in this study. Proper visualization requires the rendering of the 3D volume from the reconstructed files. Visualization programs often allow volume rendering with a 3D volume, but most importantly allow access to reconstructed slices along all three axes for analysis. These reconstructed slices contain the corresponding attenuation values for each voxel that allow for comparison of the different material. The option of also rendering the 3D digital volume for analysis is another aspect of the program that would need evaluation. The key features of the volume reconstruction of the different programs are the ease of use and the different file formats supported. Rendering a volume in a format that is incompatible with any other software would hinder the ability to use a chain of programs in a workflow as desired in this project.
7.1.1.3 Threshold/Windowing

When first visualizing the 3D rendering system, threshold and windowing manipulation is important to allow for preliminary differentiation of high and low attenuating features. This process includes the ability to change the window of attenuations that would be rendered in the volume. During rendering, a histogram is populated based on the concrete attenuation values from the reconstructed axial slices. This histogram can be used to remap the 65,536 greyscale values over a range of the histogram. For example, in a concretion that is immersed in water, the ability to eliminate the low gamma attenuating water by mapping the scale above those counts allows for the volume of the concretion to be rendered separately. Programs should allow for user manipulation of the threshold in both one and two dimensions with the use of 1D and 2D transfer functions.

Windowing is similar to thresholding in that it also allows for the visualized greyscale to be remapped over the histogram of concrete attenuation values, but generally this term indicates that both high and low levels of the histogram are being filtered. Thresholding indicates a cut off point for the lower values while windowing allows for a window within the histogram to be created. Programs should have a means to address both issues that would give the widest range of enhancing the contrast in the rendered volume. Also, relatively intuitive methods of achieving this process would be desired without complex procedures.

7.1.1.4 Slice Analysis

One of the preliminary steps in the visualization process is slice analysis in which the reconstructed slices are examined throughout the volume for the initial identification of important features within the object. Slice analysis contains the same information in the rendered 3D volume that can be clipped, but it is a faster method in determining the features and already
presents 2D images that can be published with thresholding or windowing. This identification of the initial features can help guide the researcher in determining what specific features should be investigated further and enhanced through visualization. Slice analysis is also important in determining how the other processes should be utilized. Often the thresholding or windowing is best reflected in the slices rather than in the rendered volume. The slices will also indicate the location of features for use in segmentation or other processes.

The visualization programs evaluated should have the slice analysis feature that is easily hidden or revealed in conjunction with the 3D viewer of the volume. Also, it should refresh at a fast rate and allow for easy movement through the slices without complicated computer techniques. Also the slices position in the volume should always be able to be displayed as this will help with indicating where the features are within the volume.

7.1.1.5 Clipping

One of the first processes that occurs in the image processing after thresholding is the clipping to examine internal features of the object. Clipping hides CT values along a plane to allow for digital removal of layers. This feature is very important in determining location of important features and items within the object in question. Ideal clipping utilities in processing programs would allow for clipping to be performed along several planes oblique to the three axes of reconstruction and rendering. If the clip plane was only along the slices of the axes then it would not be a useful tool as most of the feature seen in the clipping would be shown in the slice analysis. It is the investigation of off-centered features along several orientations that is of interest to this investigation.

Also, this clip planes should allow for slice by slice movement through the object as small features would be masked if the movement was large. Naturally, the ability to see these
small features would also be dependent on the slice thickness of the different data sets. Another
important feature of clip planes within visualization software would be the ability to hide and
reveal the clip plane without its deletion from the volume. Should it be difficult to locate the
feature using the clip plane then the complete removal of the clip plane would be an
inconvenience.

7.1.1.6 Segmentation

Segmentation for the purpose of this investigation was the separation of features based on
their range of attenuation values. In some ways, this method is similar to windowing, but the
purpose is to be able to reproduce a separate volume with only a certain range of attenuation
values. The easiest method of doing so would be to use thresholding or windowing, but it only
would be possible if the object had clearly defined boundaries between the different components
that contain either different materials and/or different densities. If the contrast between the
features is not well defined, due to low contrast in physical properties or through the introduction
of noise in the image, other methods of segmentation would be necessary.

Segmentation processes in programs should have an automatic generation of a separate
label without the need for manually cropping out sections that would be needed for segmentation.
A segmentation module should have some flexibility in detecting ranges of attenuation values
with user controls in determining the extent.

7.1.1.7 Exportation and Image Capture

Regardless of the success of the different programs, an important aspect of a software
workflow is the ability to move files from one program to another easily without a great deal of
conversion. While a universal file format would be ideal, different developers have created file
formats for their programs which are not immediately compatible with other programs. Even if
there is a proprietary file format within the program, these programs should have a means of producing various file formats that would be compatible with other programs. The extent of this exportation should be simple without complex settings.

Another important aspect of a program is the ability to capture images of the visualized object to use in presentations and papers. These images can also be instrumental in collaborative work to allow others to examine the results of the study during the visualization process. Image Capture programs or modules should allow for multiple file types and ease of use. Another important feature would be the ability to capture images from different views within the volume rendering software.

7.2 Software evaluated

The software programs that were selected for evaluation in this study are outlined in Table 7.1 which indicates the program, the latest version as of this paper, and where to obtain them online. These programs were developed through contributions from various programmers over the years and are continually being developed as new processes or features are created. While these programs are available at no cost on the internet, it is important to note that while contributions are based on volunteer work, there are costs associated with producing the program. Most of these programs accept either donations or receive significant funding from grants and government organization. A common contributor to many of these programs is the National Institute of Health (NIH) in the United States. This interest is most likely due to the medical focus of the software and that the NIH considers it to be a technology worth investing in. In fact, ImageJ is produced and funded directly by the NIH.
Table 7.1. Software programs evaluated including latest version and source.

<table>
<thead>
<tr>
<th>Program</th>
<th>Latest Version</th>
<th>Creators</th>
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<td>Visual Computing Center at Istituto di Scienza e Tecnologie dell’Informazione “A. Faedo” (<a href="http://meshlab.sourceforge.net/">http://meshlab.sourceforge.net/</a>)</td>
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</tbody>
</table>

7.3 Results

7.3.1 Pre-processing

7.3.1.1 Bulk Rename Utility

While the Bulk Rename Utility (BRU) does not have a direct role in the processing of the reconstructed or raw projections, this program is crucial for easy file renaming which can be important when working with different software programs with specific requirements. Due to its integral part of the workflow process, there will be a short discussion of the most significant features.
The BRU allows for the renaming of files in sequence at once, rather than renaming a sequence manually. In the BRU, there are several utilities, but the main usage is in the RegEx, but can also be accomplished using the Replacement box. Figure 7.2 shows how the BRU can rename a file. The function is exactly the same as the replacement function in Microsoft Word where the key word is entered along with the replacing key word. Browsing through folders and files will allow for the selection of file(s) that need to be renamed. This example shows a single file being renamed from “gauge” to “example”.

![Figure 7.2 Screen capture of BRU showing use of the replacement feature.](image)

The most important part of BRU is the ability to rename several files with sequence numbers. This sequencing can be accomplished using the numbering function on the right side of the GUI. For the purpose of this study, the files were numbered using suffixes. The position of the number can be changed by using the Mode drop menu (Figure 7.3, p. 138). When renumbering, sometimes it is important to maintain a 0 pad which can be done using the pad
dropdown menu. The number on the pad menu indicates the total number of digits required, which would be one more than the digit of the highest numbered file.

![Numbering (10) dropdown menu](image)

**Figure 7.3. Numbering function in BRU showing the use of the pad feature.**

The other pre-processing need would be for noisy data, such as the raw projections from the deer in Chapter 4. The discussion and explanation of the pre-processing has already been extensively covered in that chapter.

### 7.3.2 Volume Rendering

#### 7.3.2.1 Image Vis3D

ImageVis 3D allows for volume rendering to be completed from both files and directories. The files that this program recognizes are *.uvf, *.dat, *.nrrd, *.nhdr along with other types. Directories must contain either dicom or standard tif files (.tif). For proper rendering the files in the directories must have a padded zero for all the files. In the case that the leading numeral is not a zero, the program will misread all the files and order them so that all the files beginning with one (1), such as 100 1000, will be counted first. This ordering causes a layered volume that is incorrectly rendered. While this limitation in the software can be problematic if the researcher is unaware of the glitch, it is easily remedied with the use of another free ware program, Bulk Rename Utility which allowed for systematic renumbering of the files.
The rendering of the volume for the files required a great deal of the memory and processing power, especially for larger data sets. The rendering was a front end process in which the file was loaded into the file initially which prevented great amounts of processing and memory during later manipulation. This front end loading would require longer amounts of time when rendering, but allowed for easier processing for different purposes later. This software is also available in 64-bit version which allowed for large data sets to be processed due to greater access to RAM. The rendered volume was saved as a .uvf file, or universal volume file that as yet seems to be only readable by ImageVis3D.

Once the volume has been rendered, ImageVis3D allows for many operations to be performed on the data set. The volume can be viewed as either a 3D volume or with the slice view which shows the reconstructed slices of the volume along the three axes (Figure 7.4 and Figure 7.5, p. 140). Switching between these views is highly convenient in ImageVis3D through preprogramed macro shortcuts. To move from only volume viewer to a four-way viewer with slices can be done with a click of the space bar. Viewing one of the windows fully can be done by selecting the window and then using the spacebar and returning with another click of the space bar.

Figure 7.4. Schematic describing the 2x2 viewing mode and the corresponding axes.
7.3.2.2 3DSlicer

Much like ImageVis3D, files could be rendered from directories and files. The file formats that are recognized by Slicer include *.nrrd, and *.nhrd. File formats for directories required reconstructed projections in *.tif and *.dicom. When rendering the volumes, it is important to check the center volume option as it allows for the bounding box to center in the volume. Dicom files would be preferable for rendering as these files contain more data that would be used in the different modules in the program.

One disadvantage to rendering is that even after the volume is centered, additional modifications usually must be made to ensure that the voxels are cubic with equal dimensions.

This volume adjustment is made in the volume menu that allows for the pixel size in the different axes to be manipulated (Figure 7.6, p. 141).
A major limitation on the volume rendering for Slicer3D is the maximum temporary memory allowed for the program. Most of the data sets using XCT with high resolution images and many projections were unable to be rendered in Slicer due to excessive memory. This limitation is in part due to the program only being available in 32-bit for Windows platforms. A 64-bit version is possible in Linux platforms but was not examined for use in this study. Consequently, when examining the different data sets in 3DSlicer, it is sometimes necessary to reduce the resolution by first rendering in ImageVis3D and exporting as a compatible file format, such as *.nrhd. The image quality of the exported file is noticeably reduced.

7.3.3 Threshold and Windowing

7.3.3.1 Image Vis3D

ImageVis3D allowed for different types of functions to control the output rendering. These modules included 1D Transfer Function, 2D Transfer Function, and Isosurface Filtering. The easiest and most widespread module used is the 1D Transfer Function (Figure 7.7, p. 142) which allowed the user to threshold out different ranges of attenuation values as visualized as a

Figure 7.6. Options for volumes highlighting Image Spacing.

![Image Spacing Options](image.png)
sine curve on the histogram of the attenuation values. As a default the filter curve would eliminate lower attenuation values (left) while redistributing the white values over the higher attenuation values (right) to render in the volume (Figure 7.8). Left click manipulation of the filter curve allowed for free form filtering that could be used to change the types and shapes of the distributions.

Figure 7.7. 1D histogram with axes.

Figure 7.8. Example of the 1D Transfer Function
The 1D Transfer Function is very versatile and the best tool for initial examination of objects to determine differences in the material attenuation values to isolate objects. If there are clear contrasts in attenuation values, 1D Transfer function can be used for segmentation. The 2D Transfer Function applies the histogram of the object to include the gradient magnitude of the different intensity values. This module allows for the selection of areas of intensity and magnitude to focus on distinct sets of the values with more precision. This module will be discussed in the segmentation section as it is used for that purpose.

7.3.3.2 3DSlicer

Thresholding in 3DSlicer is similar to that in ImageVis3D in that there is a histogram presented the volume menu as well as the volume rendering module which can allow for the greyscale values to be remapped (Figure 7.9, p. 144). The histogram in the volume module only changes the contrast in the slices, however, and is not immediately refreshed in the 3D viewer. One advantage to the thresholding and windowing in 3DSlicer is the ability to manipulate the ranges by simply left clicking on one of the slice windows and dragging up, down, left or right. Dragging up or down will change the thresholding, while right and left will change the windowing. This macro or shortcut allows for easy contrast enhancing visualization for slice analysis.

While 3DSlicer does have a macro shortcut for changing the greyscale assignment for the attenuation values (Figure 7.9), the separate thresholding for the 3D volume and the slice analysis make it difficult to visualize the software. The 1D Transfer Function in ImageVis3D allows for faster analysis both of the volume and the slices that can readily be captured for publishing images.
7.3.4 Clipping

7.3.4.1 ImageVis3D

ImageVis3D allows for oblique clipping along any angle for the coin and can be selected in the rendering options module. It also allows the clip plane to be locked to the object for better control and for the clip plane to be rendered invisible so that the object underneath is completely visible. The control for the clip plane is straightforward and allows theoretically for voxel by voxel scrolling through the object with the clip plane, using the scrolling wheel on the mouse. This type of scrolling is also available for the three axes of the reconstructed slices, but if the surface of interest is not completely parallel with one of the axes, the most information would be obtained by clipping at an oblique angle. Also, the clip allows for the user to identify where the clip plane is in the slice with the overall volume providing unique images (Figure 7.10, p. 145).
Another important use of the clip plane in ImageVis is the ability to see through the three dimensionality of the inner features. An example of this is best seen in the volumes of the underwater concretions that were imaged using gamma radiation. Clip planes allowed for the visualization of these pseudomorphs while demonstrating the physical property of the voids.

7.3.4.2 3DSlicer

Slicer3D also allows for clipping on oblique planes but only in the reconstructed slices displayed and not in the rendered volume. To obtain an oblique view of the internal structure, the reconstructed slices can be manipulated to different angles with the “reformat widget” which requires setting the axis to “reformat”. This allows the slices to be moved to view different aspects of the volume which can be displayed in the rendered volume to indicate position but does not actually crop or clip the volume (Figure 7.11, p. 146).

There are two ways in which the region of interest (ROI) can be selected in 3DSlicer, but only one allows for the cropping of the volume to reveal partial volume structure. This option is available in the volume module under ROI which allows for a clip box to be formed along the three axes (Figure 7.12, 146). Selecting the cropping box clips the volume along the region of
interest. Unfortunately, the region of interest will not align itself along reformatted axes in the slice views. So it is only possible to clip along those planes which are a severe limitation in the investigation of different objects.

Figure 7.11. Reformat widget to allow oblique slice analysis.

Figure 7.12. Cropping enabled in 3DSlicer.

One advantage to the Slicer3D region of interest modules is that it expands on the clip plane in other programs and allows for a clipping box so that it can be clipped along several
planes at the same time. In fact multiple clip boxes can be created to examine different shapes or irregular regions. Another limitation of the clipping mechanism is that the box cannot be locked to the volume so that minute adjustments can be difficult and small adjustments can lead to a total misalignment.

7.3.4.3 Volume Graphics

Like some of the free source software programs, Volume Graphics allows for multiple clip boxes to be employed on the volume at the same time. An advantage of Volume Graphics has over ImageVis3D is that the clipping is the form of a 3D bounding box that allows for more interactive clipping. One disadvantage to this clipping platform is that the default clipping is restricted to the three axes of the object and does not allow for easy oblique clipping. Theoretically, this limitation could be overcome by creating an alternative coordinate system to the plane of the feature desired, but requires knowledge of exactly where the surface plane is.

Considering all the clipping options in the different software programs, this research determined that the use of the clipping plane in ImageVis3D is the most user-friendly. In addition to ease of use, the clipping plane in ImageVis3D allows for investigation of the object from oblique angles readily, which is not found in the other software programs. Unfortunately, the major limitation to the clipping plane in ImageVis3D is the inability to create more than one plane at one time or to create a box that will clip areas simultaneously as evident in 3DSlicer and Volume Graphics. This option would improve ImageVis3D and allow for greater visualization in one program.
7.3.5 Segmentation

7.3.5.1 ImageVis3D

ImageVis3D can be easily used to segment different materials if there is a significant difference in material attenuation. This segmentation can be seen using the 1D Transfer Function using the histogram. Further segmentation could be accomplished using the 2D Transfer Function that uses a 2D histogram. This histogram allows for the selection of areas to be assigned false colors to distinguish between sets of data. Much like the 1D histogram, the efficacy of the 2D Transfer Function to segment objects is limited by the similar intensities of the aqueous solution and the voids. The 2D histogram in ImageVis3D, as well as other software programs, has the extra variable of the gradient magnitude on the y-axis (Figure 7.13). Changes in gradient magnitude as seen in peaks of the different arcs and can be used to investigate material boundaries. The selection of the different voxels as mapped in the 2D histogram is accomplished through the use of 2D widgets in different shapes. Within the widget there is a different gradient of grey values that are mapped over the area of the widget. The gradient can be changed to different color values, so that a number of widgets can be placed on the 2D histogram that allows for the segmentation of regions using false color (Figure 7.14, p. 149).

Using the 2D Transform Function in ImageVis3D a false color volume of a concretion can be produced labeling difference materials with different colors. In the example in Figure 7.15, the blue color has been assigned to approximate the concretion where the orange color is
used to represent the lead shot.

Figure 7.13. Diagram of 2D Histogram showing axes.

Figure 7.14. 2D histogram showing selection of different attenuations with the use of orange and blue widgets.
Figure 7.15. Concretion 57M4P2-90 segmented in 2D Transfer Function module as seen in Figure 7.14.

7.3.5.2 3D Slicer

Slicer3D has several modules that were designed for the segmentation of material in volumes, though these materials were specifically designed for biological tissue. One of these modules is Robust Statistics Segmentation which is promising though limited. While this module was not ideal for the data sets produced in this study, it may prove to be successful on future data sets and the use of this automated segmentation module should be attempted. Detailed descriptions and instructions can be found in Appendix E (p. 175).

7.3.5.3 Manual Segmentation

The most reliable method to segment pseudomorphs in the volume reconstructions of the underwater concretions is to use ImageJ to isolate the object manually. The reconstructed slices are imported into ImageJ as an image sequence or image stack. It is important that these images are not opened as a virtual stack as not all the filters would work properly. Virtual stacks do not open each individual file for access in the RAM which would prevent filters being processed on
each file. These reconstructed slices that are imported are the axial projections orthogonal to the beam axis. It is sometimes useful to examine the volume in ImageVis3D or another 3D viewer to determine the exact location of the desired object in relation to the axial reconstructed slices. Once the object is located in the slices, the images should be cropped to isolate the object from the rest of the object. The cropping tool in ImageJ only allows cropped regions to be rectangular which may necessitate the rotation of the object to obtain the most ideal crop. The cropped region of the slices containing the object should contain corrosion around the object without the presence of the aqueous solution if at all possible. Once the images are cropped, a median filter should be applied to images to reduce noise and smooth out the boundaries.

After filtering the images there are two ways to proceed with the processing of the images for segmentation. If there is sufficient contrast between the pseudomorph and the concretion, the files can simply be inverted in ImageJ. This required minimum contrast is difficult to determine and trial and error was the best method to approach the matter. Simple inversion is preferred over the alternative as it preserves as much information in the segmentation as possible which allows for more manipulation in future processing.

If the minimum contrast is not present in the files, it is necessary to run a binary function on the images that would create binary files in which the pixels are assigned as either black or white in the image. It is important to ensure that the “Calculate Threshold for Each Image” is unchecked as the reconstructed slices with the aqueous solution can skew the binary process. Once the binary function has run, the pseudomorph will be assigned black and the concretion will be assigned white. After creating the binary image, inversion will allow the negative space of the pseudomorph to become positive space. The image stack should be saved as an image sequence within its own folder.
Once the files have been saved, the next step is to eliminate the files that do not contain the object. The folder containing the files should be opened in Windows Explorer and viewed as thumbnails. Viewing the thumbnails will allow the operator to delete the files that are only aqueous solution or corrosion without the object. Once those files are deleted, the files should be renamed in the BRU to ensure that the files are numbered correctly starting from either 0 or 1 and having the 0 pad on the files. After the files have been prepared and formatted properly, they can be imported into ImageVis3D to render the volume of the segmented object (Figure 7.16). Once the object is rendered in ImageVis3D, it can be exported as a mesh using the Isosurface Module. If the object was only inverted and not made into a binary file, some thresholding or windowing could be used to reduce the presence of additional material.

![Segmented concretion rendered in ImageVis3D.](image)

**Figure 7.16.** Segmented concretion rendered in ImageVis3D.

The file that is exported is an *.OBJ file that can be opened using MeshLab. MeshLab allows for the mesh to be altered prior to 3D printing to isolate the object better. Sometimes excess aqueous solution or the inclusion of another partial object from the close proximity may be present in the rendered volume. These areas can be reduced through the deletion of the area.
This deletion is basically the digital manual cleaning of the object to reveal the desired shape of the pseudomorph (Figure 7.17, p. 153).

![Figure 7.17. Views of edited mesh of segmented concretion shown in Figure 7.23.](image)

A comparison of the 3DSlicer segmentation and the manual segmentation indicates that the manual segmentation yields objects that are more natural (Figure 7.18). The inability of the Robust Statistics Segmentation to replicate these results is most likely due to the unclear boundaries of the pseudomorph interfering with the mathematical calculations. The comparison of the two results also indicates that the manual segmentation is a less precise method as a rendering of the segmented section reveals extraneous material in the volume that does not correspond to the desired object. This material may be removed while performing mesh edits, but exists in the rendered volume in ImageVis3D.
7.3.6 Exportation and Image Capture

Exportation of files is important when developing a software workflow that utilizes several programs. The ability to adjust the files for another program without loss of information is essential. ImageVis3D allows for the exportation of the data set into several file formats including .nrrd, .i3m, and .nhrd. The .i3m format allows for the scene to be saved and exported and the visualization settings preserved for another similar object or for other researchers to examine. When exporting to a different file format, such as .nrrd, ImageVis3D allows for the resolution of the files to be changed if desired. A decrease of resolution may be required if another program does not have the same computing power or memory capacity to run the file at its highest resolution. Exportation was also possible for isosurface meshes which convert the surface of an object as identified by the attenuation value to a polygonal mesh that can be interpreted by other software programs.

Slicer allowed for the exportation of different levels of the visualization process. After creating a label, such as when using Robust Statistics Segmentation, the label can be saved as a...
separate file that can be rendered in another program. Also, it is possible to save the scene, or the settings of the visualization as a separate file to be used at a later date, much like the .i3m file in ImageVis3D.

Many of the visualization software programs contained versions of image capture that would save screenshots of the windows as external image files. ImageVis3D contains a recorder module that allows for screen captures of the 3D rendered volume for a single or sequence over angular arc. It does not capture the slice views, however, which is a significant disadvantage as often slices are used to determine features. The module allows for different file types to be saved in a designated location. ImageVis3D’s recorder can be used for clip planes as transparency can be preserved, but the system is not the most efficient.

3DSlicer has a similar option in its program that allowed for both single and sequence capture through the camera icons in the Manipulate 3D View module. This screen capture is limited to the 3DViewer screen. There is the option of capturing the whole scene, including the slice view, with the scene capture option. Both these processes operate in a similar fashion to the ImageVis3D Recorder as they allow for file types to be chosen as well the location. 3DSlicer also has the option of scaling the image, which is not found in ImageVis3D.

While these image capturing tools were adequate in most cases, this study has found that the best way to save images is to use the snipping tool that is provided with the Windows 7 operating system (Figure 7.19). This snipping tool acts much like the print screen option on personal computers but has the option of choosing the size and the location of the screen capture. The snipping tool also hides automatically when snapping is applied. After a screen capture is made, the image is opened into the snipping editor which functions similarly to Microsoft Paint by allowing the user to mark the image using brushes and pens. This function is useful for
making orientation notes directly on the image that will be added once the screen capture is saved. The snipping tool is far superior to print screen which only adds the screen capture to the clipboard without any other options. Clipping or annotations would have to be accomplished in another program.

Figure 7.19. Snipping tool from Windows 7.

An important feature that is useful for presentations is the ability to create videos of the rotation of the 3D rendered volume. Most visualization programs allow for this feature, though not all of them produce desired results. One of the most notable disappointments was the use in ImageVis3D which indicate that motion capture would be possible but often would produce only a series of images up to 90 degrees.

When presenting these data in the public forum, it was necessary to include screen capture videos that would demonstrate the workflow process without lengthy descriptions. These videos allowed for the complex series of menu selections and processes to be shown and could be used for future training purposes. While any proprietary or open source video capture software program can be used, this study found that CamStudio (http://camstudio.org/) was an effective open source program that was user friendly and intuitive to use. Screen capture videos were recorded and be instantly reviewed for editing. Also, a number of file formats were available for the videos which allowed for flexible compatibility.
7.3.7 Workflow

From the evaluation of these software programs a workflow was developed to utilize the programs for the purpose of visual analysis in the conservator’s forum. This workflow allows for a wide range of different CT methods to be used and considers the different types of information stored in the data sets. The workflow can be considered in different ways. The first workflow shows the steps of the workflow highlighting how the alternative software programs can be used independently and in conjunction with the various proprietary programs that were encountered in this study (Figure 7.20, p. 158). This overview of the workflow is useful for those researchers who are already familiar with the visual analysis process but would like to use the open source software. The workflow highlights the strengths of the different programs and how they can be linked together to work the visualization process. This workflow demonstrates how the bulk of the visualization is performed in ImageVis3D, mainly due to the fast refresh and the ease of use. Specialized processes, such as pre-processing or segmentation should be done in separate programs that have specifically programmed modules. ImageJ is essential for manipulating stacks of images that do not need to be rendered, such as raw projections or even reconstructed axial slices.

The second workflow acts as a detailed guide to the steps required for the digital manipulation of reconstructed files for visual analysis, including questions that may arise as determined by the type of object or research questions (Figure 7.21, p. 159). A series of yes or no questions allows for the researcher follow the workflow to achieve the desired results, though consultation with more detailed instructions would be necessary for visualization. The workflow acts as a comprehensive guide emphasizing the individual processes that were evaluated in this chapter. Knowing the order of the processes is essential for the visualization process and having
the workflow will allow for quick identification of possible troubleshooting measures if there is difficulty in the visualization.

Figure 7.20. Overview workflow highlighting the use of alternative software programs
Figure 7.21. Guiding workflow for the use of the alternative software programs in this study.
7.4 Conclusion

The investigation into the viability of the alternative software programs in comparison to propriety programs often used in computed tomography visualization has yielded mixed results. Considering the purpose of this investigation was to allow for the larger dissemination of the methods in the art conservation field, the criteria for the programs included a user-friendly yet effective software that could produce publishable images. The workflow developed is effective but the level of user accessibility is questionable. With the basic computer skills and the tutorial online, it is possible for a competent researcher to learn the visualization process, but there is still a substantial learning curve required to achieve the results desired. Even after the researcher develops the skills to use the programs, the process of visualization itself can become very time consuming depending on the quality of data and the research objectives.

This time commitment must be considered as a significant factor in approaching a CT experiment. While the workflow allows researchers to take ownership of their data, the time involved in producing those images might be a greater cost than allowing external operators or technicians to produce the images for them. This caveat is especially true if only a few objects are investigated and it is not a large study or the method is not use by the conservator or researcher. In those cases, the researcher should carefully weigh the benefits and costs of using open-source software as technical study on one object might not warrant the amount of time it would take to produce the images.

Another factor to consider is that while the workflow reduces the cost to visualize CT data, it does not eliminate all costs. For greatest use of the software, a high level workstation is required. This workstation may include the need for a high-end video card, large amounts of random access memory (RAM) and fast processing speed. Without this level of computing
power, the software may be difficult if not impossible to use as the equipment would not be able to render the volume or the processing would be slow and detract from the benefits of using the open-source workflow. In addition to the workstation costs, the volume files and image sequences can be quite large and require a great deal of data storage. These large files would necessitate the purchasing of additional data storage units for large studies on multiple objects. While data storage is not necessarily a high expense, it is a factor that should be addressed prior to research.

7.4.1 Future Research

While a workflow was developed that could accomplish most of the objectives of this study, this workflow does not represent the only method of accomplishing the goals of visualization. Furthermore, this workflow was tailored to focus on common processes but with the final goal being to produce results specifically from corroded metal artifacts. While the processes used are universal, the data produced with different objects for various research questions may require alternative software or methods that were not covered in the scope of this project. Considering these limitations of the results, it would be prudent to investigate other types of programs that are also readily available online for comparison. Evaluating other proprietary programs may also be beneficial as a program with a large range of quality features may be worth the expense, dependent on the needs of the researcher.
Chapter 8

Conclusions

This study featured investigations into various aspects of CT and how it could be applied to conservation with benefits not seen in previous research. By examining three major sources of radiation, x-rays, gamma rays and neutrons, this study was able to determine a workflow to aid conservators in the selection of the radiation source based on the physical and chemical properties of the object (Figure 8.1, p. 163). This workflow considers CT on a wider scale than previous studies which focused on the use of the different methods for specific cases. This workflow is designed as a preliminary check for the objects for conservators. The most significant contribution of this study to this workflow was the examination of the role that gamma ray CT in non-destructive imaging in conservation.

The first consideration that should be made is if the object has high atomic number elements, particularly lead. If the object does not contain lead then it may be suitable for x-ray CT. The amount or percentage of lead that would be prohibitive is still under investigation and is dependent on the type of system used by researcher. Without lead, the only other consideration for XCT would be the physical properties including mass and dimensions of the object. Large and dense objects would not be desired because there would be low transmission and the object may not fit in the field of view of the cone-beam.

If there is the presence of a significant amount of high atomic number elements, the next material consideration is the presence of hydrogen or organic materials. A great deal of hydrogen, such as water, would prohibit the use of neutron CT because of the high attenuation. If there is not a large quantity of hydrogen in the object, then neutron CT could be used. Gamma CT
should be used if large dense objects cannot be imaged by XCT or NCT. Gamma rays should not be a default, because the high energy photons have less material sensitivity than NCT or XCT but should be used if no other alternatives are present.

**Figure 8.1. Overall workflow for CT in conservation**

Individual conclusions have been made about the different aspects of this study, but the main research questions that motivated this research should be addressed considering the results of the experiments. While there are both successes and unexpected results, the studies into the application of Xradia CT, low-flux neutron CT, megavoltage CT, and laminography all indicated that there is the potential for a greater application of the techniques for art conservation and archaeology. Simply the ability of the radiations sources and systems to produce usable results in the form of rendered volumes or clip planes of surface features expands the current usage of CT in conservation by approaching the topic with a wider perspective. While there were previous
applications, these studies endeavored to evaluate each method with the use of extended test objects and consider the matter as an experiment rather than technical art historical studies.

Some of these methods, such as megavoltage CT and laminography, introduce very rarely applied techniques to conservation. By presenting the positive results, the published precedent will ideally encourage further study and application of the techniques to different type of objects or a more in-depth look at its application to corroded metal artifacts. These studies by no means established these methods as ready to use procedures, but ultimately accomplished this study’s goal of creating more alternatives or opportunities for researchers whose current problems or questions cannot be solved with the current commonly used techniques. Also, it allows for flexibility in planning different types of imaging studies are researchers are not limited to established procedures such as high-flux neutron facilities.

Despite having positive results from this study, it is almost impossible to concretely determine the extent that the information will actually cause a more widespread use of CT in the art conservation and archaeological fields. Part of the goal of this study was to present this data in the academic and professional forums, such as presenting papers at various conferences, but without directly confirmation of the reception of this work it is difficult to speak to the overall impact this study. Interest has been expressed in the topic while others have researched other open-source software that was not considered for this study, including TurtleSeg.

One method to determine if the use of alternative radiation sources would be beneficial to conservators is to conduct a survey of various institutions on their current use of CT, their desired use of CT, and how the results of this study would affect their future decisions on the use of CT for their research. This survey may also reveal other types of research questions that could be
investigated using the CT methods available in Kingston, ON. These research questions may also shape future projects by determining what types of objects would be suitable candidates for the different radiation sources. This information would be especially helpful for neutron CT, as there is some difficulty in locating objects that would yield interesting results.

In lieu of a survey and confirmation of the use of the information in this study, the existence of this research is important as it creates template workflows for conservators to use if they choose to use CT in the future. Much of the previous literature focuses on the results of using CT in conservation without addressing the very important issues that are present during the planning and experimental stage. These types of issues include the selection of imaging parameters and how that affects the volume, as well as the visualization process that ultimately produces the results that are shown in the published literature. By breaking down these steps and processes in this study, conservators will have a resource that is specifically written with them as an audience that may allow them to approach the method with information that will help alleviate the steep learning curve.

8.1 Future Research

Future research has been discussed in the individual chapters for different aspects of the studies. Considering the whole work in the context of the research goal for finding alternative CT methods, some of these questions should be pursued first. One of the most important future projects would be to create a more controlled and rigorous experiment in which the different alloy content of the coins affect the ability of the Xradia XCT-400 to image them. This research could be coupled with corrosion studies similar to those performed by Sullivan, 2010. In these studies, traditional cleaning methods should also be applied to the artificially corroded coins as a complementary data set to the cleaning of the Diniacopoulos coins.
With respect to a more controlled experiment with XCT, the same principles should be applied to the gamma CT study. A range of phantoms should be created with varying types of objects that might be found in underwater concretions to test the limit of the process. Also, these phantoms could contain pseudomorphs with varying levels of boundary contrast to see the limit at which the KGH system can resolve the corrosion from the void. These two controlled studies would help establish protocols for the use of these alternative systems. This study produced positive results, but still maintained a semblance of past experiments that focused on the use of case study objects instead of a truly scientific approach to the matter.

The greatest area of research still needs to be conducted on the possibility of using low-flux CT as a method for non-invasive analysis of objects. Though the object that was investigated, the Diniacopoulos deer, was successfully imaged and rendered, further examination on the range of objects that the system can image should be conducted. There were other artifacts that were examined prior to this investigation, including a percussion musket [Hungler, 2011], but both of these studies show the same problem that was encountered in the literature for the application of CT for conservation. This issue stems from the desire to use the method for case studies without experiments to determine the limitations of the systems. Considering the success of the studies in XCT and gamma CT, it would be prudent for future studies using a set of similar objects for low-flux neutron CT.
Appendix A

Instructions on how to export Xradia XCT data sets for reconstruction in Octopus

1. Exportation of Raw Projections from Xradia
   a. Turn off references correction on raw projections
   b. Export raw projections
      i. Turn off Annotations
      ii. Export as Raw Tiff
      iii. Export whole series
   c. Create Reference File
      i. Turn on ABSORPTION reference correction
      ii. Export as multiple references
   d. Export reference series
      i. Turn off Annotations
      ii. Export as Raw Tiff
      iii. Export whole series

2. Importation of Raw Projections into Octopus
   a. Label raw projections and references in order using Bulk Rename utility
      i. Ensure that the files are in separate folders
      ii. Rename references files to “ob*”
   b. Convert the raw projections
      i. Keep float values same
   c. Convert the absorption references
      i. Keep float values the same
      ii. Convert to same converted folder without erasing previous files

3. Reconstruction of Xradia data sets in Octopus
   a. Open converted folder for data selection in Octopus
   b. Select settings for the data set
      i. Select cone-beam geometry
      ii. Select counter-clockwise direction
      iii. Calculated SAD and SDD From distance parameters
         1. Add ADD and SAD to get SDD
      iv. Calculate Pixel Size

4. Pre-Processing In Octopus
   a. Clip the files
   b. Clean the files for gamma speckling
   c. Normalize files
i. Do not adjust for beam intensity if sufficient open beam is not accessible
ii. Run ring correction on lower levels
iii. After normalization ensure that resulting files are properly formatted
d. Create sinograms

5. Reconstruction in Octopus
   a. Examine reconstructed slice for artifacts
   b. Run appropriate parameter evaluation such as tilt axis
   c. Ensure the that the reconstruction is on the appropriate number of slices
Appendix B

X-ray Fluorescence

Figure B.1. XRF spectrum of 57M 8P2-30 showing iron content.
Appendix C
XRD Diffractograms

Figure C.1. XRD diffractogram of coin AA1980
Figure C.2. XRD diffractogram of coin AA1981.
Figure C.3. XRD diffractogram of coin AA2011.
Appendix D
Reconstruction in Octopus

Xradia raw and reconstructed files are single files that contain all the projections. Exportation of these files was addressed in the experimental. Important factors to consider in the reconstruction of the data sets in Xradia were the center shift and beam hardening parameters, which were the only variables that could be altered. Exporting the data sets to Octopus took much more consideration. First, there was the need to ensure proper file formats as described previously. Also, the angular range must be recorded to include the pre-calculated fan beam angle in addition to the half scan. Another important piece of information that was necessary for reconstruction was the source to axis distance (SAD) and the source to detector distance (SDD). Unfortunately, Xradia did not display these values; the values that were given from Xradia were the SAD and the axis to detector distance (ADD). Proper calculation of these values is essential to proper reconstruction in Octopus and the SDD is calculated by adding the SAD and ADD. In reconstruction it is also important to ensure that it is reconstructed as a counter-clockwise rotation which can be changed in the final reconstruction stage if forgotten in the importation of the data.

The last data setting for the importation of the data was the pixel size of the raw projections. The pixel size is calculated using Equation D.1. The pixel size allows for a correct reconstruction, though it is possible to reconstruct without a pixel size as it may be necessary if the exact pixel size is not known in other types of CT. The pixel size is important to know as it is needed to determine the voxel (volume pixel) size in the reconstructed slices. The voxel size is important during visual analysis which is further discussed in Chapter 7 with the software evaluations.

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Equation D.1. Pixel size calculation for Xradia XCT-400

\[(13.5 \, \mu m \div \text{objective magnification}) \times \text{camera binning}\]
Appendix E

Robust Statistics Segmentation

The module requires the selection of regions of interests along the desired object and the module calculates the expansion of these regions based on the different attenuation values. The different parameters that affect this segmentation include Intensity Homogeneity and Boundary Smoothness. These parameters, on a scale of 0 to 1, help define the way in which the statistical model will be produced. The Intensity Homogeneity helps determine the range of attenuation values that will be considered in the segmentation growth. For example, at an Intensity Homogeneity of 1, the intensity or attenuation range will be narrow and will not consider similar intensities in the neighboring regions. Higher values in the parameter should be used if there is high contrast between materials. The Boundary Smoothness parameter helps determine how strict the program will consider the bounding regions. At a value of 1, the Boundary Smoothness parameter will prevent the region from leaking through small gaps around the interfaces. High values in both the parameters will discourage growth and should be used when the object is regular shaped with clearly defined interfaces and boundaries. If there is noise in the image or the object is irregular shaped with a range of attenuations then lower values in the parameters should be used.

One of the advantages of the Slicer3D program is the tutorials that are available online for the different modules. This open forum of information is a byproduct of the various collaborations that were used to produce the different modules in the program. These tutorials are essential in explaining the minute details of the different modules that are not readily apparent with the manual or in the help section of the website. While these tutorials were helpful in determining the use of the modules, they are still limited in that the data sets that accompany
them are almost exclusively medical in nature or phantoms showing ideal situations. The programmers were not considering the application to other types of data sets which makes it difficult to troubleshoot possible solution when problems arise from the use of irregular data sets that are not ideal, such as the underwater concretions.

This module requires that 2D reconstructed projection first be labeled in the Editor module. Labeling the slices means to indicate roughly where the object is located in the projection (Figure E.1). The program requires multiple slices to be labeled for proper segmentation. After running the program several times on the same object, it was determined that labeling is most effective when done through the narrowest cross-section of an object. This caveat applies to objects that are laterally long with non-uniform dimensions. An example of this is best shown through some of the pseudomorphs such as the nail or tube. A general phantom for these objects can be seen in Figure E.2. For this object, projections containing the x and z axes should be labeled, not those with the x and y axes.

Figure E.1. Labeled slice in 3DSlicer.
While this module was first promising, there were some difficulties that prove its limitation for application in segmenting underwater concretions. The first example of its success was in segmenting a tubular pseudomorph from the concretion 57M18LM2 (Figure E.3). This tube void is exposed to the aqueous solution on both ends making segmentation potentially problematic as the interface between the void in the concretion to the space in the aqueous solution would be difficult to segment out.

Figure E.3. Segmented tube from concretion 57M18M2-2 using Robust Statistics Segmentation.
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