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CIS 2: Spring 2020

Group 10: 3D Imaging, Analysis, and Guidance for Robotic-Assisted Ankle Fracture /  
Dislocation Surgery

Critical Review: Polyenergetic known-component CT reconstruction with unknown  
material compositions and unknown x-ray spectra

### **Project Overview**

This project concerns developing and validating an image guidance framework for application to robotic-assisted fibular reduction in ankle fracture surgery. The aim is to produce and demonstrate proper functioning of a software for automatic determination of directions for fibular repositioning with the ultimate goal of application to a robotic reduction procedure that can reduce the time and complexity of the procedure as well as provide the benefits of reduced error in ideal final fibular position, improved syndesmosis restoration and reduced incidence of post-traumatic osteoarthritis. The focus of this product will be developing and testing the image guidance software, from input of preoperative images through the steps of automated segmentation and registration until output of a final transformation that can be used as instructions to a robot on how to reposition the fibula.

The first step in an image-guided approach is fast, automated segmentation of the preoperative images in order to identify and save the relevant anatomical features, in this case the fibula and other bones of the ankle. Problems arise in segmentation when various metal artifacts are introduced, reducing the quality of the CT images.

Paper Selected

[1] Xu, S., Uneri, A., Jay Khanna, A., *et al.* Polyenergetic known-component CT reconstruction with unknown material compositions and unknown x-ray spectra. *Physics in Medicine & Biology* 62 (8), 3352–3374 (2017).

### **Purpose & Significance**

This paper sought to improve upon the polyenergetic known component reconstruction (KCR) metal reduction model to account for the noise produced by metal artifacts during a CT scan. In particular, many of the current metal reduction models fail to improve CT image quality in regions immediately surrounding metal artifacts. This paper sought to prove that the polyenergetic KCR models produced high quality and accurate CT images, and that the only information needed about the metal component was its shape and that it is homogeneous in material composition. Ultimately, this paper demonstrated that specific knowledge of the X-ray beam spectrum and the material composition of metal components was not required to obtain high quality CT reconstructions.

## Background

Many imaging scenarios involve devices in the view of the CT scan. These devices could include pedicle screws and rods, knee and hip implants, and in the case of ankles, fixation screws in the fibula and talus. Furthermore, surgical tools are usually in the intraoperative imaging fields as well. When these components are metallic and one implements a 3D cone-beam imaging system, these components will create bright and dark streaks and other shadings of the reconstructed 3D volume. Effects could include beam hardening, photon starvation, and scattered radiation behind metal implants.

These artifacts can be a problem especially since the image quality is severely reduced in regions on the edge of these metal artifacts. At the same time, the edges of these regions are typically of greatest interest for many medical applications. For example, in the figure below, there is a metal rod in the fibula, but it is unclear where the edge of the fibula exists.

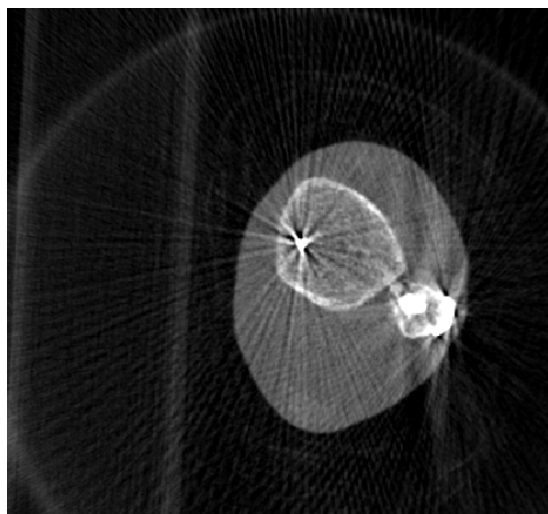


Figure 1: CT scan of cadaver ankle from iStar Lab

There are two types of methods for metal artifact reduction: correction methods and model-based reconstruction methods.

Correction methods involve replacing projection data with metal with computer-generated projections based on surrounding projection data through interpolation. This interpolation typically uses non-metal data. There have been many approaches based on correction methods, such as using prior imaging studies to replace missing data and refined interpolation through a second scan. In general, these methods involve an algorithm that must be able to first identify the projections with metal and then replace those projections with computer-generated projections. The flaw of these methods is that the regions adjacent to the metal are still low quality or have missing features. The example below illustrates the result of an interpolation algorithm used to reconstruct the image. While metal is reduced significantly, it's still unclear where the edge of the fibula is.



Figure 2: Metal reduction of cadaver ankle image in

iStar Lab

Model-based reconstruction methods involve incorporating specific key metal components into various models and reconstructing CT images based on these shape models. Many of these methods are complemented with interpolation to fill in the empty spaces in the projection data. Some papers have found ways to avoid interpolation and to only use metal artifact model reconstruction, but this usually requires knowledge of material compositions.

Regardless, these methods all lack information in regions near metal. In order to address this, one could integrate the knowledge of the shape and composition of typical metal components into the reconstruction algorithm (i.e. known component reconstruction). Usually, the exact implants, surgical tools, and other devices are known prior to images, and shape models and material compositions could be gathered as a result. The material compositions are important because metal artifacts with high atomic numbers such as iron or platinum are very noticeable while low atomic number metals, such as titanium, are less noticeable. This process consists of a registration of the known metal components to placing the metal artifact model in the correct position in the anatomy as well as a reconstruction of the surrounding material.

The problem is that residual artifacts remain when a simple monoenergetic model is used, meaning that a monoenergetic model can only be used when there is only one metal component involved.

Hence, polyenergetic forward models have been introduced to incorporate multiple types of metal artifacts into one model. Polyenergetic system models typically require a parameterization of the energy dependence of the materials in the scan and a model of the x-ray spectrum and detector energy sensitivity. Other extensions of this have included to integrate knowledge for devices whose shape is not exactly known. Ultimately, these strategies typically involve much complexity and computational burden and increased information required of the reconstruction algorithm.

In this paper, the authors introduced a polyenergetic KCR approach that separates the CT volume into the physical effects in the patient anatomy and the effects due to metal components. In this mixed-fidelity system model, metal components were modeled with high exactness using a spectral transfer function, while the patient anatomy was modeled with a monoenergetic model. This approach was adopted with the polyenergetic KCR technique, and does not involve the need for material component composition knowledge or calibration of the x-ray beam, reducing the computational burden, complexity, and information required of the reconstruction algorithm.

## **Methodology**

In terms of running the algorithm, the authors first constructed a shape model for the pedicle screw with CAD. They then applied a 3D-2D registration of the shape model to the position of the screw in the cadaver/phantom. Using the shape model registration parameters, the path length as well as the spectral coefficients and background anatomy was determined. Given all of these parameters, the CT image was reconstructed, and this process was iterated until the RMSE hit a plateau. These results were compared with other metal reduction techniques.

To investigate the performance of the model, this paper conducted studies involving a simulated CBCT system and a real test bench system. This paper introduced two approaches: a polyenergetic model with pre-estimated component registration coefficients and a polyenergetic model with pre-calibration of the coefficients using in-air component scans (PreCal-KCR). Initially, this paper concentrated on the single metal component scenario. Other reconstruction methods were compared.

The Poly-KCR approach was compared with a Mono-KCR approach where the metal component only had a single energy-independent attenuation value. A traditional filtered-back projection (FBP) approach was tested along with a model-based reconstruction approach. An interpolation based metal reduction approach was also implemented along with FBP.

The authors used a physical phantom composed of plastics, and human skeleton, and emptiness to emulate the lung region. The screws were placed into the vertebra region to simulate spine fixation intervention. The pedicle screw emulated titanium metal composition, with a known true value for its spectral transfer function coefficients.

The position and pose of the known components was known exactly and the authors took note of the true registration parameters for each component. The authors used root mean square error between the anatomical background reconstruction (consisting of no components) and the known truth. The spectral transfer function estimate was also compared with the true value.

Physical data experiments were conducted on a CBCT test-bench in a realistic setting with unknown beam spectrum and unknown material compositions (i.e. unknown STF). An investigation of a pedicle screw placed inside a phantom and a study involving a

screw in a cadaveric torso sample was used. Both experiments used the same shape model of the titanium pedicle screw.

### Results and Significance (Figures)

The reconstruction of a digital phantom was compared between a filtered back projection algorithm and the Poly-KCR approach:

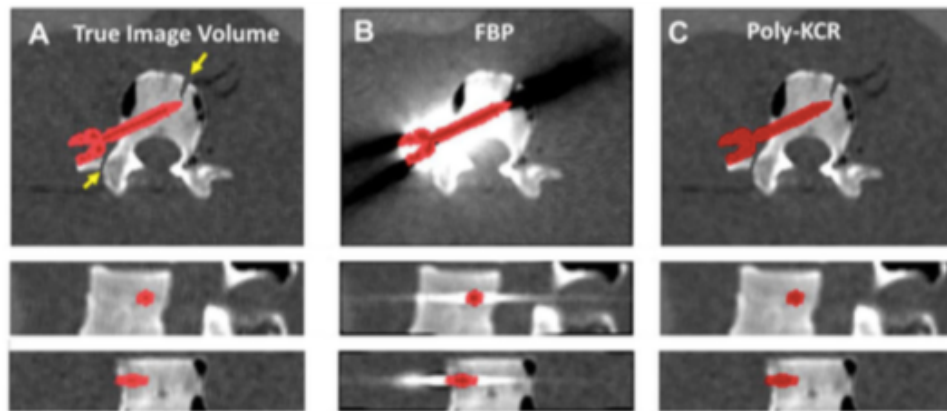


Figure 3: True Image (A) vs FBP (B) vs Poly-KCR (C) (Xu et al. 24)

In figure 3, while the FBP algorithm fails to show the edges marked in the true image volume, the Poly-KCR model reduced all of this noise. This is significant due to the fact that the fractures in the bone denoted by the arrows can still be seen in the Poly-KCR reconstructed image.

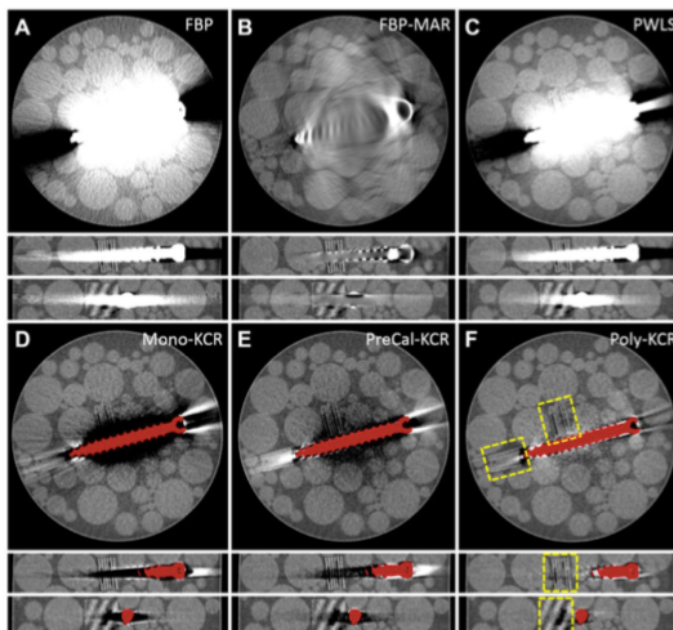


Figure 4: Phantom Experiment - FBP (A) vs FBP-MAR (B) vs PWLS (C) vs Mono-KCR (D) vs PreCal-KCR (E) vs Poly-KCR (F) (Xu et al. 28)

In figure 4, which are images of a phantom, FBP still showed significant metal artifacts due to beam hardening and noise. FBP-MAR reduced the blooming effects, but features are unclear to see near the screw. PWLS reduces the noise but there's still substantial noise. Mono-KCR and PreCal-KCR greatly reduce artifacts, but there are still spectral differences (i.e. beam hardening due to background object). Poly-KCR exhibited the best results, with minimal artifacts, though some small artifacts remained.

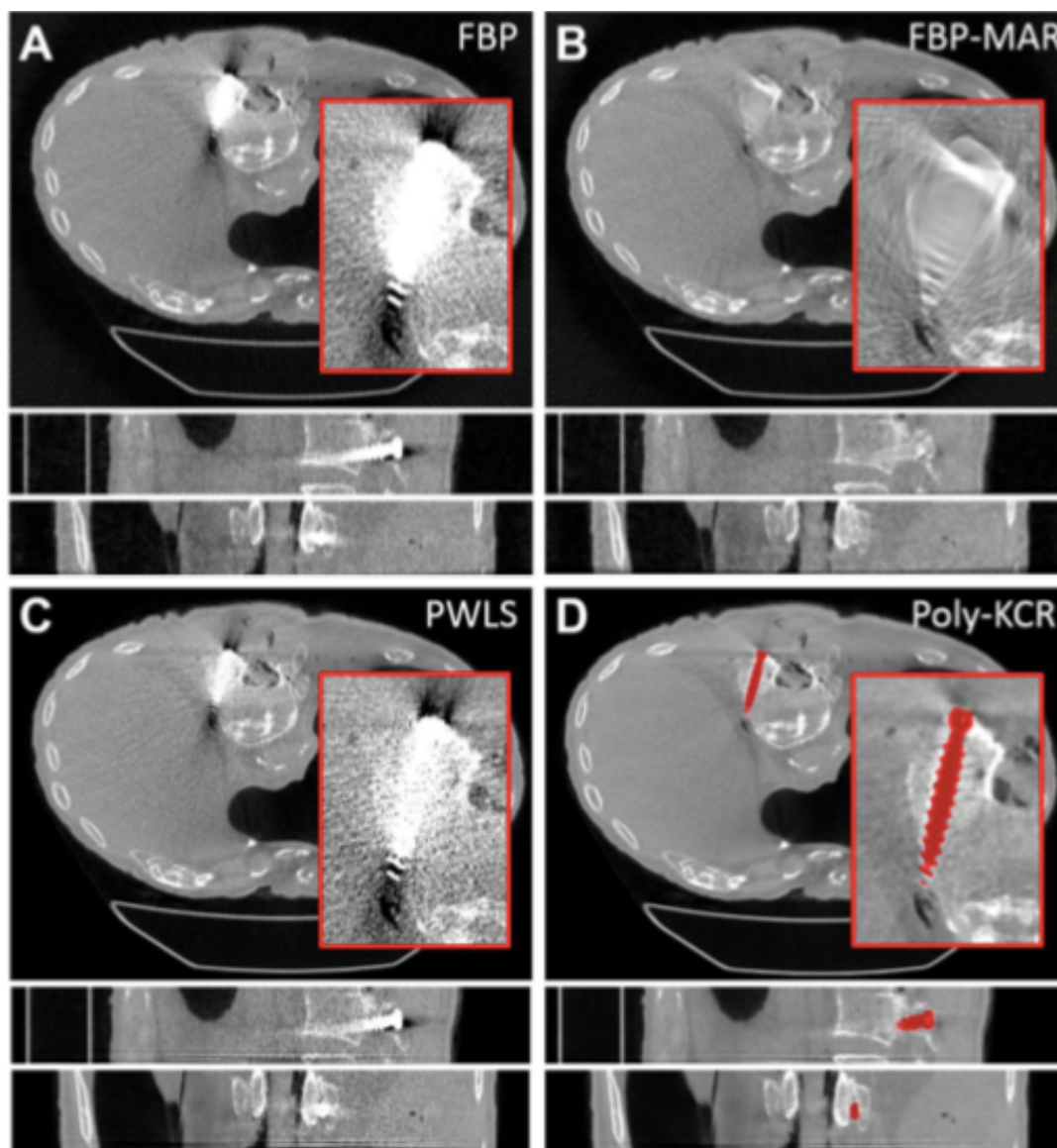


Figure 5: Cadaveric Torso Experiment - FBP (A) vs FBP-MAR (B) vs PWLS (C) vs Poly-KCR (F) (Xu et al. 29)

Similar to the phantom experiment, Poly-KCR exhibited the best image resolution in comparison to FBP, FBP-MAR, and PWLS.

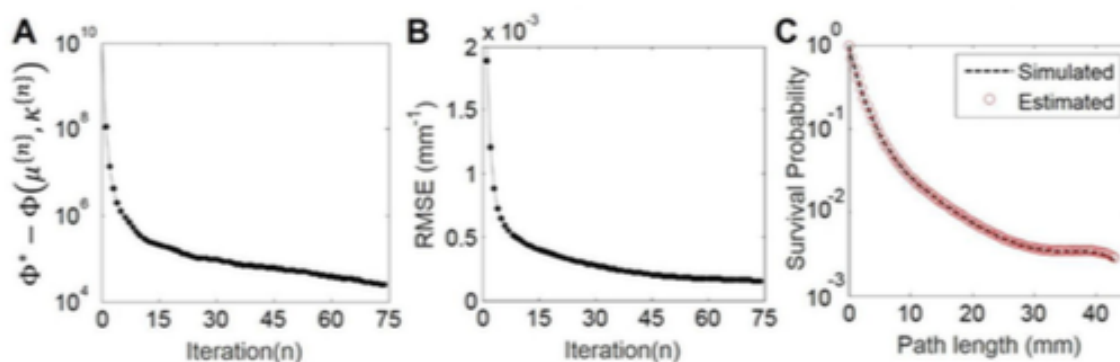


Figure 6: Root Mean Squared Error between truth image and reconstructed image (Xu et al. 25)

The algorithm went through an iterative reconstruction process where component registration was performed, then the error between the truth image and the reconstructed image was calculated. In figure 6, we see a plateau of the root mean squared error between the truth image and the reconstructed image, suggesting a fast convergence of this model.

## Assessment

This paper validated the utility of a polyenergetic KCR model to perform metal reduction in CT scans. It also helped that this paper provided pseudocode for readers to use in order to apply and replicate their work. The paper also illustrated the equations necessary to perform this experiment, and it walked through the construction of its equations step by step. However, one limitation of this paper is that it tested the model only on pedicle screws, but it did not implement this algorithm on larger pieces of metal. For example, a metal rod, which is much longer in comparison to a metal screw, could yield different results. Furthermore, even though the polyenergetic KCR model is meant to work for multiple metal components in comparison to the monoenergetic KCR model, this paper did not perform experiments with multiple metal components in the CT image.