# Design of CT Foot Phantom for Charcot Study

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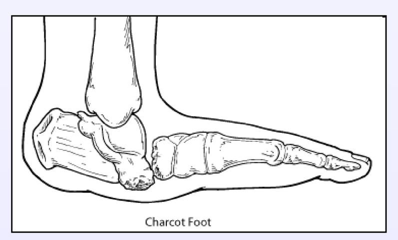
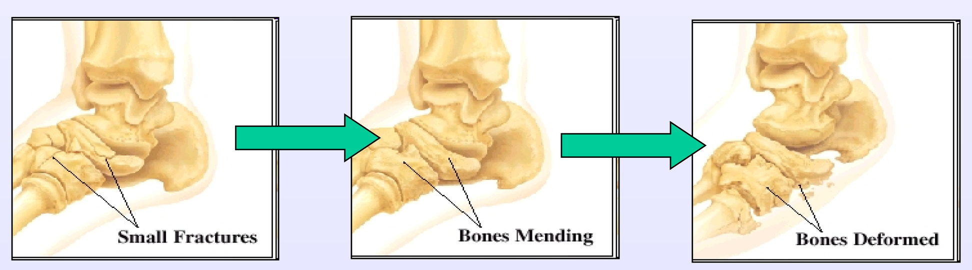
## DESIGN NEED

- Neuropathic Charcot Arthropathy (NCA) is a potentially serious complication for the ~20.8 million Americans that suffer from diabetes mellitus.
- Diagnosis often coincides with a Charcot event, such as dislocation or fracture, which often leads to fixed foot deformity, ulceration, and amputation.
- It is hypothesized that bone mineral density (BMD) is an early indicator of Neuropathic Charcot Arthropathy and that BMD predicts which patients will experience favorable treatment outcomes.
- Computed tomography (CT) may be used to measure foot BMD, but measurements are sensitive to both scanning and foot parameters and should be validated against surrogates with known standards.
- Existing BMD phantoms do not simulate cortical bone, nor do they represent the NCA foot. New phantoms that simulate foot morphology and attenuation characteristics are needed.

***Objective:*** *Design, construct, and test a solid CT phantom that is the best analogy to a Charcot foot to be used in the study of neuropathic Charcot Arthropathy.*







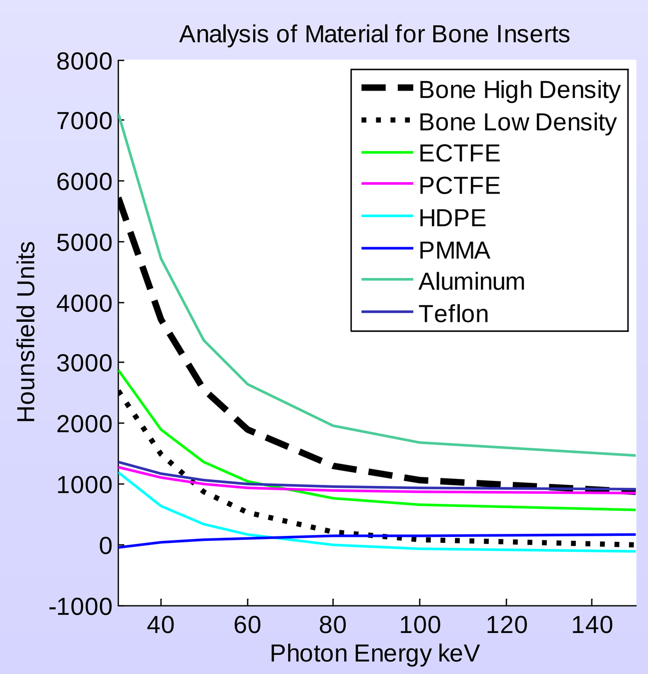

## DESIGN PROCESS

**Design Requirements**

**Phantom base**
- Phantom size - emulate differing foot cross-sections
- Phantom weight - less than 25 lbs
- Phantom shape - rounded edges, no sharp corners
- Phantom materials - emulate foot tissues radio density (approximated by radio density of water, 0 Hounsfield Units)

**Inserts and Insert holes**
- Insert size - represents 2 sizes of metatarsal bone (1 and 2 cm in diameter)
- Insert materials - emulates metatarsal bone densities (radio density of 500-2000 Hounsfield Units)
- Must be able to scan multiple bone inserts at once (up to 5)

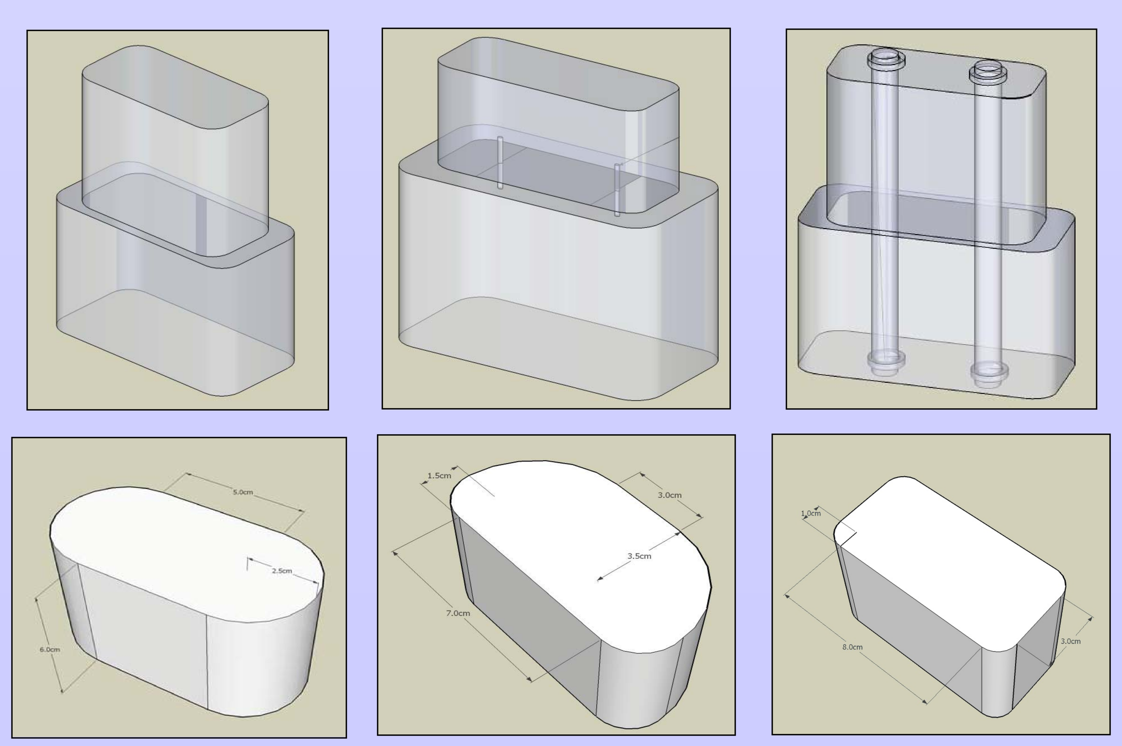
**General**
- Safe materials - cannot injure doctors or technicians
- Durable materials - non-degradable with x-ray scanning
- Cost- as determined by our mentors and grant funding



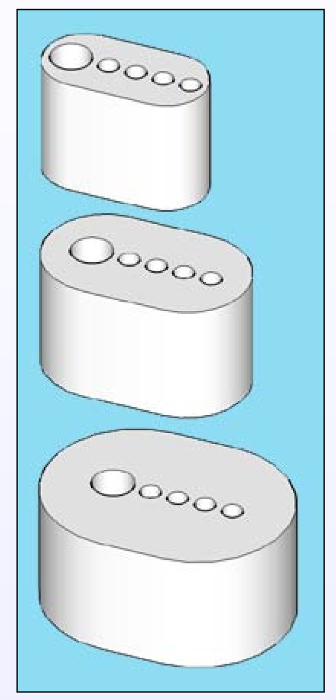

***Upper Right Graph****: Analysis for bone insert materials*

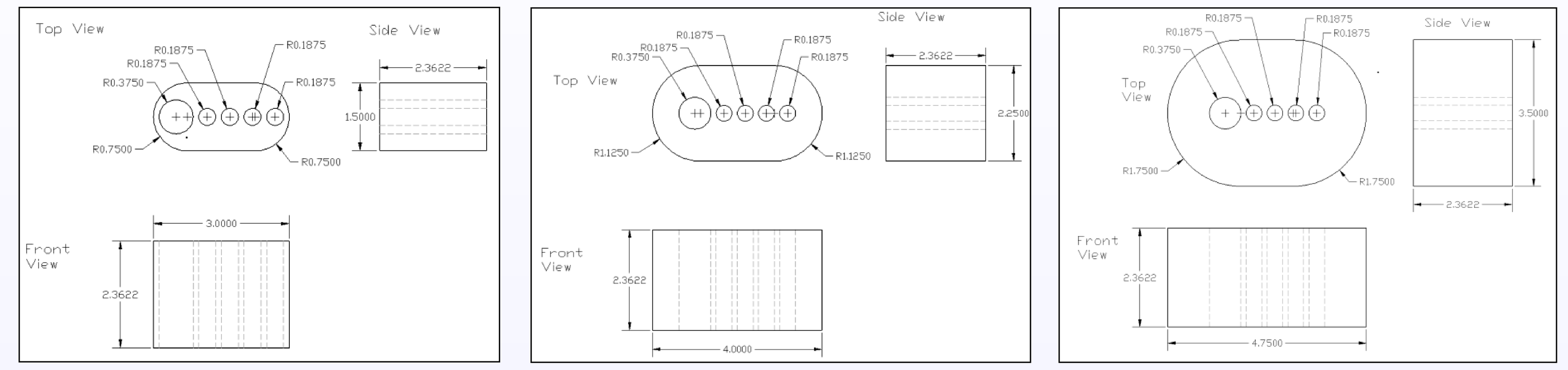
***Right****: Design alternatives for attachment method*

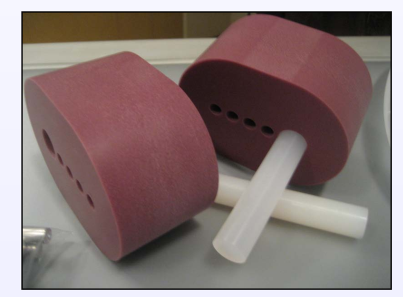
***Lower Right****: Design alternatives for cross-sectional area*

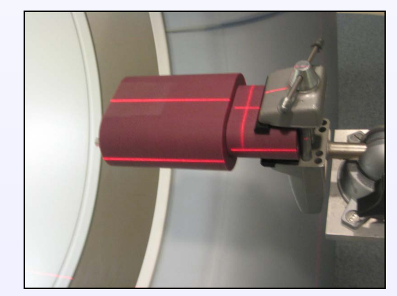


## FINAL DESIGN







| | Width (in) | Depth (in) | Height (in) |
|---|---|---|---|
| **Small** | 3 | 1.5 | 2.3622 |
| **Medium** | 4 | 2.25 | 2.3622 |
| **Large** | 4.75 | 3.5 | 2.3622 |

| Number of Inserts | Length (in) | Diameter (in) |
|---|---|---|
| 8 | 2.3662 | 0.375 |
| 2 | 2.3662 | 0.75 |
| 1 | 4.7244 | 0.375 |
| 1 | 4.7244 | 0.75 |

- Three sizes of phantoms were made from Solid Water, with two of each size resulting in a total of six phantoms. Each phantom had a cross section of a rectangle terminated with a half circle on each side.
- In each phantom, there are five holes: four with a diameter of 3/8 inches, and one with a diameter of 3/4 inches.
- The bone inserts were made from four different materials: ECTFE, PCTFE, HDPE, and Aluminum.
- The phantoms posed minimal safety concerns due to its limited contact with patients and users.

## IMPLEMENTATION AND ANALYSIS

On Tuesday, November 18th, the phantoms were scanned in 14 configurations, varying height in the scanner, inclination angle in the scanner, phantom size, and scanning energy. The data, shown below, were analyzed and compared to a beam-hardening computer model.

**Intensity Comparisons Over Materials** (in HU)

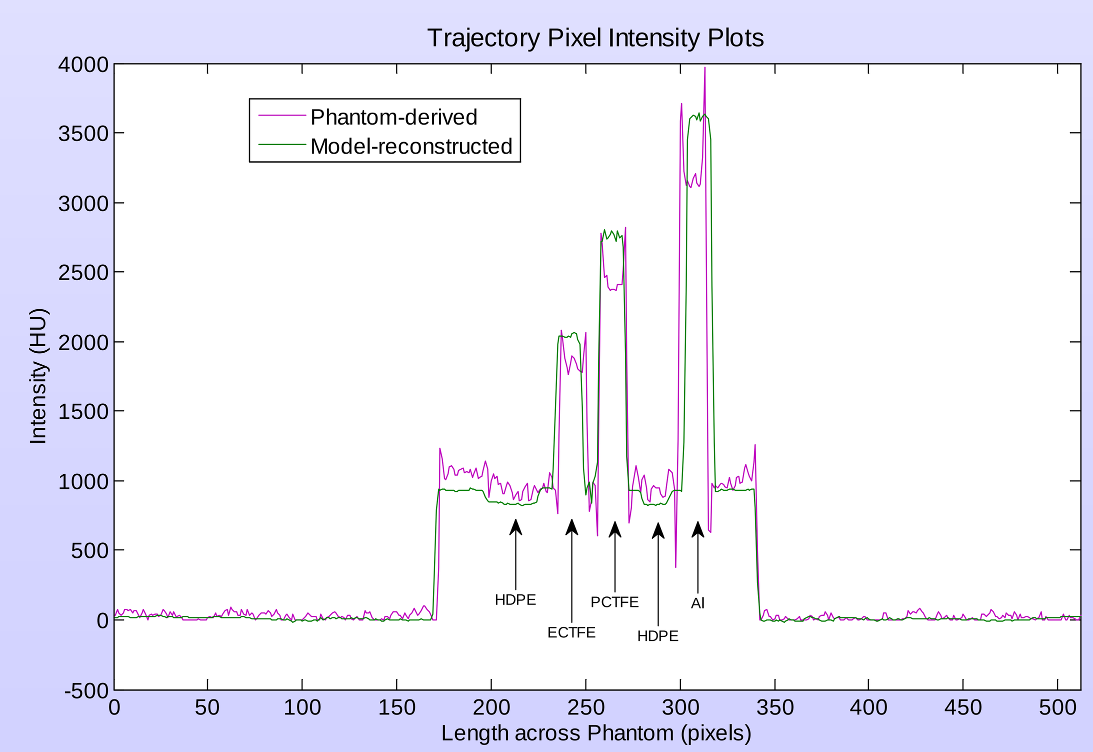
HDPE trough min in position 1:
- Phantom scan: 855.0
- Reconstruction: 823.9

ECTFE trough min in position 2:
- Phantom scan: 1763.0
- Reconstruction: 2028.0

PCTFE trough min in position 3:
- Phantom scan: 2369.0
- Reconstruction: 2722.0

HDPE trough min in position 4:
- Phantom scan: 846.0
- Reconstruction: 823.8

Aluminum trough min in position 5:
- Phantom scan: 3108.0
- Reconstruction: 3585.0




**Analysis of Edge-Cupping Artifacts** (in HU)

Solid water edge Δ(intensity):
- Phantom scan: +228.0
- Reconstruction: +14.6

HDPE edge Δ(intensity) in position 1:
- Phantom scan: +290.0
- Reconstruction: +108.5

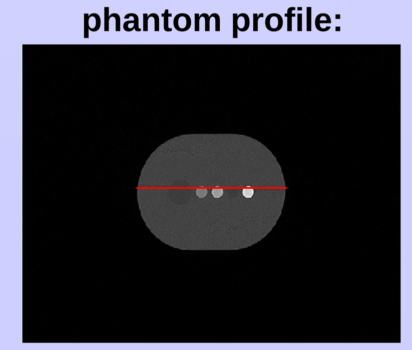
ECTFE edge Δ(intensity) in position 2:
- Phantom scan: +318.0
- Reconstruction: +40.0

PCTFE edge Δ(intensity) in position 3:
- Phantom scan: +449.0
- Reconstruction: +80.0

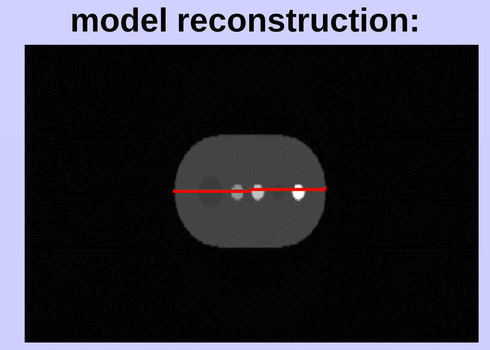
HDPE edge Δ(intensity) in position 4:
- Phantom scan: +263.0
- Reconstruction: +99.5

Aluminum edge Δ(intensity) in position 5:
- Phantom scan: +865.0
- Reconstruction: +44.0

**Trajectory through phantom profile:**

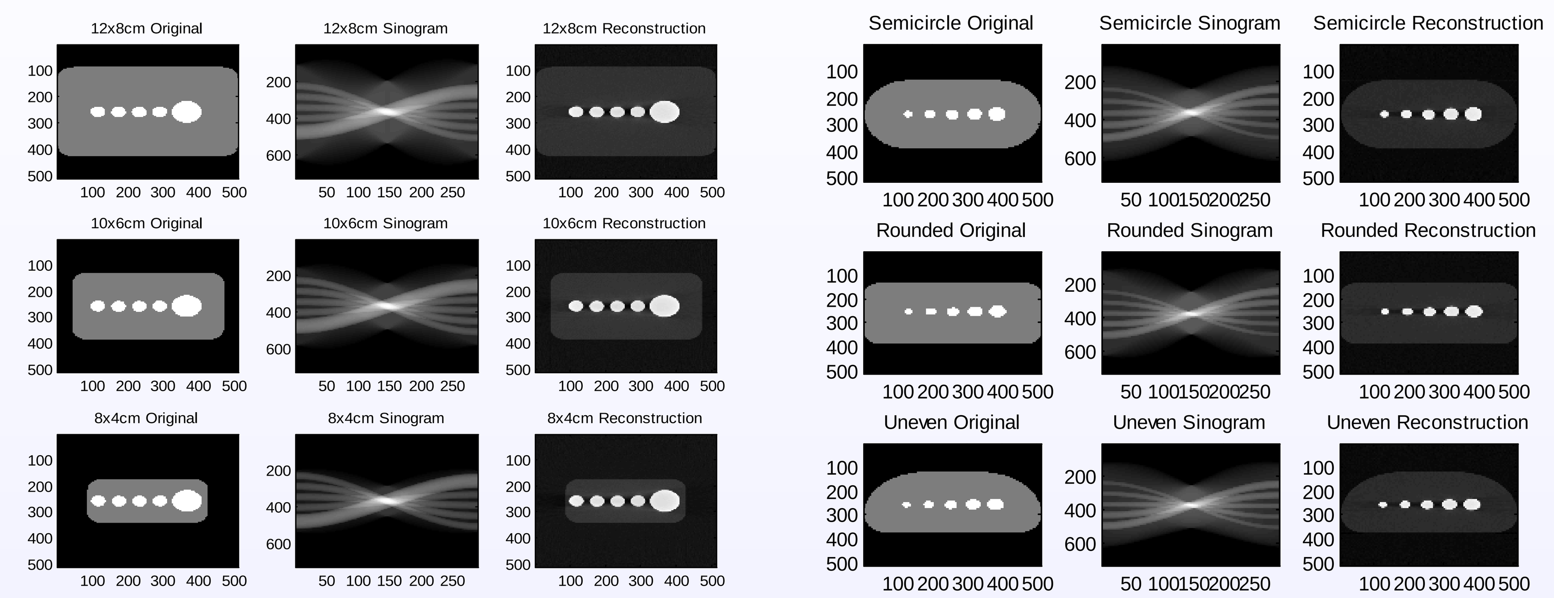


**Trajectory through model reconstruction:**



**Derived Conclusions:**
- The phantom produces accurate attenuation data when compared with the use of beam hardening computer-simulated reconstruction
- Use of the phantom provides additional information beyond what is producible using computer simulation, including estimates of potential edge cupping artifacts and a realistic characterization of signal noise

## ANALYSIS USING COMPUTER CT MODELING




***Left****: Original generated image* ***Center****: Sinogram* ***Right****: Reconstructed image*

A MATLAB beam-hardening CT-projection program using polyenergetic modeling was used to analyze the three phantom shapes and the possible cross sections to see if there were any image artifacts or problems with the designs.

In order to ensure that our selection of phantom geometry would yield successful reconstructions using the methods of back-projection, a profile was generated that we considered as a two-dimensional gray-scaled density cross section.

Then, using the *radon* transform encoded in MATLAB's image processing toolbox, a set of simulated CT scans were generated over an entire sweep of angular orientations. At every angular orientation, the intensity profile is produced as an n x 1 column vector, where n is the pixel height of the original supplied image. Each entry in this vector represents the reading of a single detector in a CT detector array. *Radon* then assembled the intensity profiles from every orientation into a sinogram.

Finally, the reconstructed image was simulated using a CT reconstruction algorithm through the use of MATLAB's inverse radon transform *iradon*.

## CONCLUSIONS

### Did we solve the problem?

- The three different phantom sizes simulate the various foot sizes and amounts of swelling.
- Each phantom is very lightweight (less than a pound).
- The shape includes only round edges.
- The radiodensity of the Solid Water is very close to the radio density of the muscle and fat tissues in the foot, and is the industry standard for representing fat and tissue in CT bones scans.
- The phantom accommodates two sizes of bone inserts: the 0.75 inch diameter hole represents the first metatarsal, and the four 0.375 inch diameter holes represent the 2nd-5th metatarsals. Up to five metatarsals can be scanned at once.
- The insert materials represent a range of bone radiodensities common to metatarsals in the foot.
- All of our materials are safe to be handled by doctors and technicians, and are very durable. The phantoms and inserts will not degrade with scanning.

*Based on these requirements, we have successfully completed the project*

### Future Directions

Based on scanning results, we may need to augment our design. Future directions could include a solid water or alternate material sleeve to represent feet with higher levels of swelling than the large phantom allows. Phantoms with other insert sizes or arrangements could be used instead of a foot with just one large metatarsal and four small metatarsals. Other possibilities for bone inserts include simulating marrow in the bones by creating inserts with two concentric cylinders of different materials representing cortical bone filled with bone marrow. We would also like to perform a more thorough analysis.

**Acknowledgements**

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