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TITLE: Development and Evaluation of a Solid State Head CT

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CONTRACTING ORGANIZATION: The University of North Carolina at Chapel Hill
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14. ABSTRACT

The goal of this work is to develop a stationary head CT system that would enable head imaging at Forward Operating Bases or similar areas. Without the need for moving parts, such a system could address the clinical need of cross-sectional imaging of the brain, but in a more robust imaging system. Our design relies on linear x-ray source arrays enabled by the novel carbon nanotube x-ray source. The goals in this project extends from prototype design and development, development of reconstruction approaches and an eventual clinical trial in medically stable head trauma patients.

15. SUBJECT TERMS

None listed.

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INTRODUCTION:

The goal of this work is to develop a stationary head CT system that would enable head imaging at Forward Operating Bases or similar areas. Without the need for moving parts, such a system could address the clinical need of cross-sectional imaging of the brain, but in a more robust imaging system. Our design relies on linear x-ray source arrays enabled by the novel carbon nanotube x-ray source. The goals in this project extends from prototype design and development, development of reconstruction approaches and an eventual clinical trial in medically stable head trauma patients.

KEYWORDS:

Traumatic Brain Imaging, Computed Tomography, Trauma, Brain, Imaging, Forward Deployment.

ACCOMPLISHMENTS:

What was accomplished under these goals?

In Phase II (Year 2), the primary goal of the project is to implement the stationary Head CT system and prepare for the clinical trial.

The relevant Aims and subtasks are summarized below:

Specific Aim 2a: Construction of a fully functional prototype stationary head CT system. (Major Task 1)

- Subtask 2a.1: Finalize system design using dual source/detector pair.
- Subtask 2a.2: Acquire second tube / detector pair
- Subtask 2a.3: System integration

Milestone 2a.1: Completed s-HCT imaging prototype system

Specific Aim 2b: System Characterization (Major Task 2)

- Subtask 2b.1: Phantom acquisitions on Conventional CT
- Subtask 2b.2: Phantom acquisitions on s-HCT
- Subtask 2b.3: Quantitative image quality evaluations

Milestone 2b.1: Completed quantitative image quality evaluations comparing conventional CT to s-HCT

Specific Aim 2c: GPU implementation (Major Task 3) & Prepare for Clinical trials (Major Task 4)
Major Task 3 tasks:

- Subtask 2c.1: Implement reconstruction code for GPU
- Subtask 2c.2: Optimize acquisition code for clinical use

Major Task 4 tasks

- Subtask 2c.1: Radiation Safety Testing
- Subtask 2c.2: Obtain electrical safety approval
- Subtask 2c.3: Prepare and submit IRB for HRPO preview and IRB submission

Major Tasks 3 & 4 Milestones:
Milestone 2.c-1: Complete implementation of GPU reconstruction algorithm for fast reconstruction
Milestone 2.c-2: Submission of manuscript for publication in a peer-reviewed journal.
Milestone 2.c-3: Presentation at a military-relevant or national meeting.
Milestone 2.c-4: Completed prototype s-HCT system for clinical evaluation.
Milestone 2.c-5: Submit IRB for HRPO pre-review

Year 2 milestones addressed individually:

Milestone 1: Completed s-HCT imaging prototype system

As discussed in our quarterly progress reports, we decided to skip the "vertically" oriented prototype due to COVID-19 restrictions and delays and move directly to a horizontal single view system as a prototype, which could then be directly "transferred" to the clinical space once completed. A CAD drawing of the system in the horizontal prototype form is in Figure 1. The three x-ray tubes are marked with the colored (red, green, blue) lines, and the black hexagonal ring in the center represents the detector assemblies.

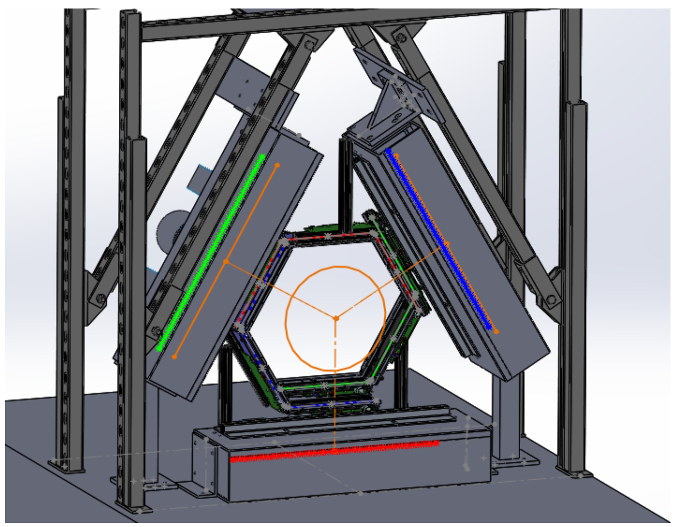

Figure 1

This is under physical construction with the lab space, pending access to clinical space for deploying the device (Figure 2). Other components, including radiation shielding, covers, etc. have been manufactured and are awaiting installation in the final location.

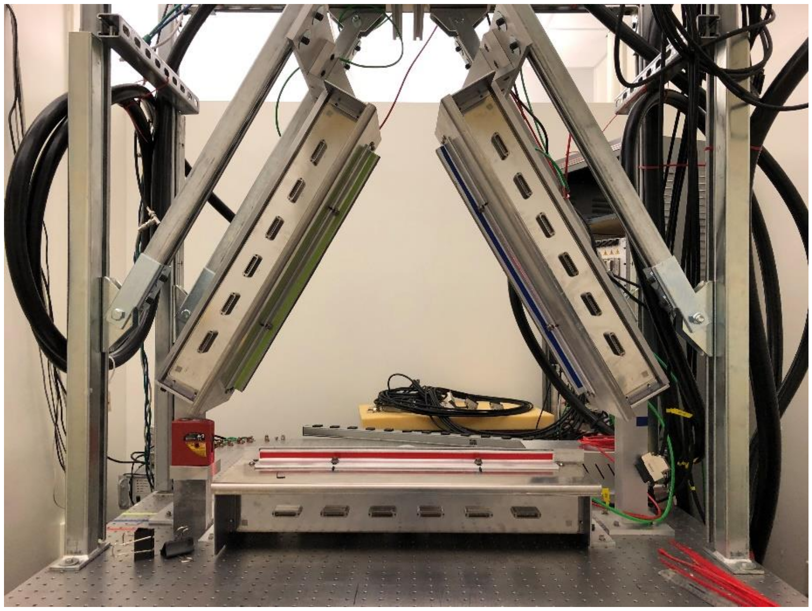

Figure 2. X-ray tubes assembled in the final system geometry assembled on an optical table in the laboratory. The room itself is lead lined, so no covers/x-ray shielding is needed for experiments performed in this space.

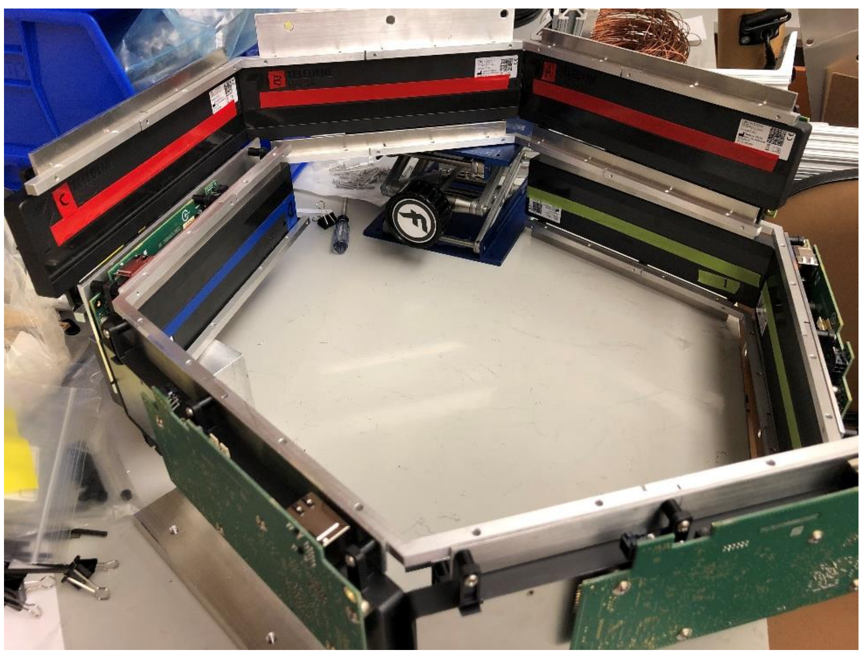

Figure 3. X-ray detector assembly: The colors on the x-ray detectors match to the corresponding x-ray tubes.

As discussed in the quarterly reports, the imaging dose with this current setup is significantly lower than that of a conventional head CT. There is ample room to increase the dose, if necessary, to improve image quality.

For comparison, an image of the electronics and rotating gantry mechanism of a conventional CT system is shown in Figure 4, demonstrating the complexity of a conventional system.

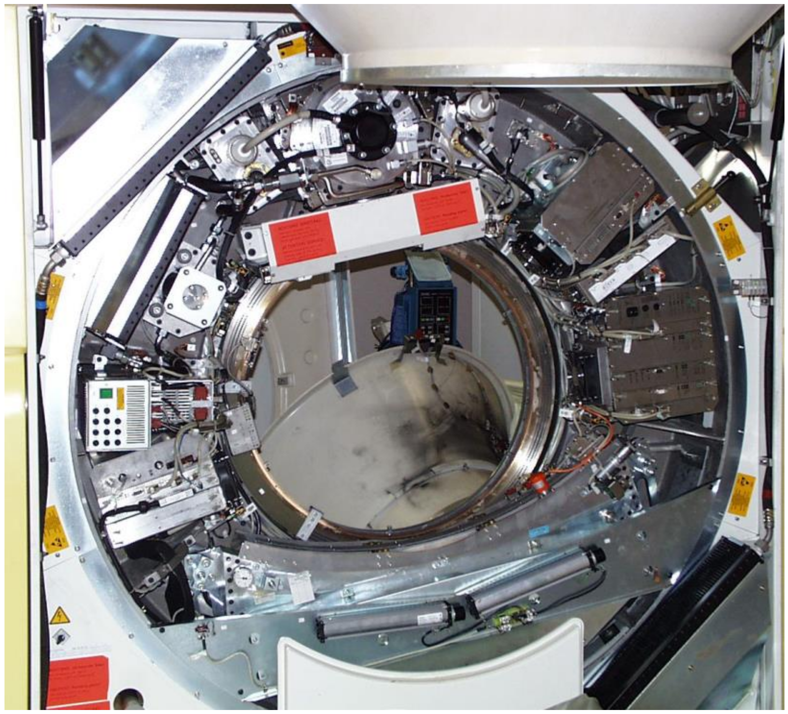

Figure 4. Image of the gantry and hardware of a conventional CT scanner with the single x-ray source (black circle above the collimator (red patches)) opposite the detector.

Milestone 2b. Completed quantitative image quality evaluations comparing conventional CT to s-HCT

We will complete the final characterization of the imaging system once it is completed (either within the lab or final clinical space). An example of our studies on the conventional CT geometry, but implemented with a CNT source is shown in Figure 5, demonstrating signal to noise of the CNT setup relative to a cone beam scanner of the jaw of a CT imaging phantom. This setup has been used to evaluate the x-ray sources themselves, independent of novel stationary geometry.

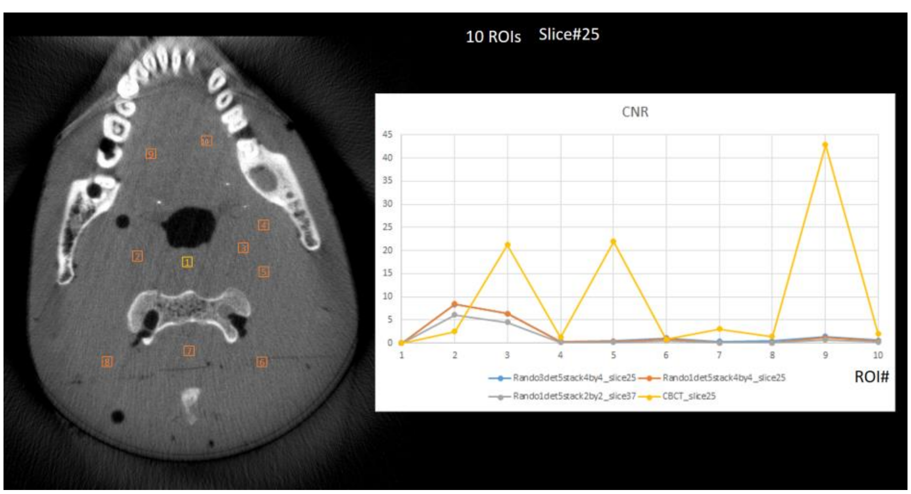

Figure 5. Comparison of contrast to noise ratios for a conventional cone beam CT (yellow curve) to a rotational CT (conventional geometry)

As mentioned in the last quarterly report, our initial dosimetry measurements are about 4.6 mGy, approximately 15% of a typical head CT imaging protocol (40 mGy) with a conventional CT. The dose for our Ceretom commercial portable system is 60 mGy. Our dosimetry may increase for the final imaging protocol, but this confirms our ability to perform low dose imaging.

Subtask 2c.2 Optimize acquisition code for clinical use

The clinical code is nearly completed for clinical use; we are finalizing development with coordinating the acquisition hardware, and have incorporated low cost micro-controllers to reduce the computer requirements for control. A single high-end computer has been shown to be capable of receiving data from all 9 detectors with sufficient bandwidth to perform the final scanning. This significantly simplifies the system configuration and was an important technical accomplishment.

We are finalizing bed control with the hardware, which will rely on a combination of Arduino micro-controllers integrated with the detector control computer.

Subtask 2c.3: Radiation Safety Testing

Initial testing demonstrates a dose approximately 15% of a conventional head CT; further testing will occur once we have completed the system, to also include radiation emissions from the system. We will adhere to standard guidelines for dosimetry, and our institutional radiation safety service will have to certify the system.

Subtask 2c.4: Obtain electrical safety approval.

We will seek electrical safety approval for the system once it is installed.

Subtask 2c.5: Prepare and submit IRB for HRPO preview and IRB submission

We are awaiting IRB approval, which is anticipated in the next 4 weeks. All stipulations raised by the IRB were addressed after their initial review, and we are awaiting final board approval. We were told that HRPO preview was not necessary. We will submit the institutionally approved protocol once approval is received.

Milestone 2.c-1: Complete implementation of GPU reconstruction algorithm for fast reconstruction.

We are fully GPU capable now with our advanced reconstruction algorithms, especially important with the more advanced iterative reconstruction algorithms (SIRT_GPU). As a comparison, 100 iterations with the prior CPU based reconstruction algorithms was approximately 2500 seconds. Additional speed gains can be achieved with more advanced GPUs and further parallelization through multiple GPU systems. However, our focus will shift to potentially incorporating more advanced, and possibly machine learning based reconstruction approaches.

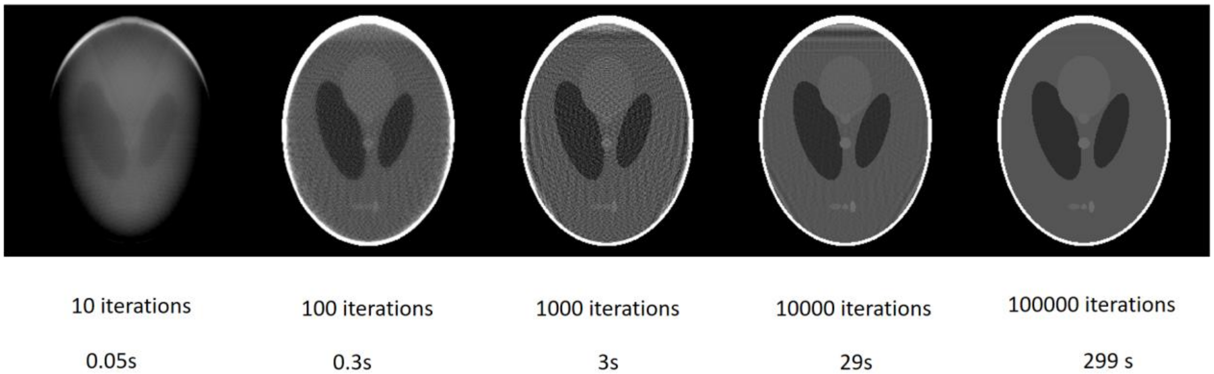

Figure 6. Example iterative reconstruction algorithm applied to our modified Shepp-Logan phantom demonstrating the image improvement over increased iterations. 100,000 iterations takes 299 seconds; as a comparison, our original tested approach, CPU based, required 2500 seconds for image quality equivalent to approximately 1 second of the GPU system.

Milestone 2.c-2: Submission of manuscript for publication in a peer-reviewed journal.

We have one recent paper acceptance focused on utility of the CNT x-ray tubes in a stationary setup, and a second paper on reconstruction algorithms that is submitted. Two proceedings papers were presented in early 2020.

Milestone 2.c-3: Presentation at a military-relevant or national meeting.

Two proceedings papers were presented in early 2020. We will submit to MSHRS for the next meeting in 2021, as well as other scientific meetings.

Milestone 2.c-4: Completed prototype s-HCT system for clinical evaluation.

This milestone is pending a final decision on where the system will be placed for the imaging trial. The most likely location will be in a former radiology space within an outpatient clinical facility. This space was identified a few months prior, and we are awaiting final institutional approval. It previously held a CT scanner, and no significant renovation is needed. The alternate placement is adjacent our existing clinical trial space.

Milestone 2.c-5: Submit IRB for HRPO pre-review.

We are awaiting final approval of the IRB protocol; this is anticipated within the next 4 weeks. All stipulations by the IRB have been addressed, and we will forward the final protocol for review when it is IRB approved.

What opportunities for training and professional development has the project provided?

Two graduate students were recruited within the Department of Physics and Astronomy at UNC Chapel hill to participate in the development of this hardware. Two additional post-doctoral fellows have assisted in the development of the programming necessary to run the system. Mentorship by the three faculty, Zhou, Lu and Lee continues from both direct and group interactions.

How were the results disseminated to communities of interest?

Two abstracts have been presented to SPIE Medical Imaging, 2020 (in person, just before the pandemic) related to the hardware and software reconstruction work associated with this project. A paper has been accepted to Medical Physics pending minor revisions regarding the capability of the x-ray tubes for this application. An additional paper is pending submission to a medical imaging journal. Additional abstracts have been submitted to SPIE Medical Imaging, 2021, and an additional abstract will be submitted to the American Society of Neuroradiology in November 2020 for the 2021 meeting.

What do you plan to do during the next reporting period to accomplish the goals?

We will finish installation of the system and initiate the clinical trials.

IMPACT:

What was the impact on the development of the principal discipline(s) of the project?

The potential for a stationary CT system has been proposed or suggested by a number of groups in the field, with significant recent interest from a number of groups, both domestically and internationally. However, implementation of such a system is difficult, given the requirements of a clinical need, capable x-ray source and reconstruction expertise. We feel that our work in this area will bring the field forward beyond “simulated” systems, to an actual complete system capable of imaging. This will likely convince others in the field that these systems are truly feasible, and will result in innovation for other medical imaging applications. Furthermore, this will enhance interest in improved reconstruction approaches.

Overall, our system demonstrates both the potential of stationary imaging systems, and addresses many of the technical difficulties other groups have yet to encounter, based on their published work.

What was the impact on other disciplines?

Nothing to Report.

What was the impact on technology transfer?

Nothing to Report.

What was the impact on society beyond science and technology?

Nothing to Report

CHANGES/PROBLEMS:

We are currently awaiting approval of the space for performing the clinical study. The preferred space is within the Ambulatory Care Center, at the site of a former CT scanner. We are hoping to install in this space since there will be appropriate radiation shielding in place, as well as being adjacent to other clinical spaces. If this falls though, we will utilize our existing research space in Marsico Hall, where there is dedicated human imaging research space, as well as appropriate technologist shielding.

Construction of the system is nearly complete, with the entire setup being constructed in our laboratory space. Construction was mildly delayed due to the COVID pandemic, but assembly should be completed within approximately a week. This will allow for full configuration and testing and once the clinical space is decided, transferring the system will require approximately one or two weeks. I anticipate a fully functional system before the end of the Year 3 Quarter 1 update.

The IRB protocol is awaiting final official approval, which should occur at their next full board meeting. All stipulations raised during the submission process were addressed, and we fully expect approval at that time. A copy of the approved protocol will be forwarded once that is confirmed.

Unfortunately, due to the competitive environment for post-doctoral fellows with engineering experience, our first post-doctoral fellow left earlier than anticipated for an industry job opportunity that was brought on by the pandemic. Fortunately, we were able to hire one of her former colleagues at 50% effort, so there was no significant loss of productivity and it was a relatively straightforward transfer of knowledge. The new post-doctoral fellow has made significant progress in programming for the final software that we will use in the clinical system.

We are exploring the use of machine learning based reconstruction algorithms for the system, to further reduce dose or artifacts. Though beyond the scope of our original specific aims, we felt it would be a lost opportunity with our relatively complex reconstruction system.

PRODUCTS:

Two conference proceedings were presented at SPIE Medical Imaging 2020, one covering the hardware development, the second covering reconstruction.

1. Spronk D, Lu Y, Inscoe C, Billingsley A, Lee YZ, Lu J, Zhou O. Feasibility of a stationary head CT scanner using a CNT x-ray source array. In: Bosmans H, Chen G-H, editors. Medical Imaging 2020: Physics of Medical Imaging [Internet]. Houston, United States: SPIE; 2020 [cited 2020 Mar 19]. p. 115. Available from: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11312/2549335/Feasibility-of-a-stationary-head-CT-scanner-using-a-CNT/10.1117/12.2549335.full

2. Luo Y, Spronk D, Lee Y, Zhou O, Lu J. Simulation and optimization of system configuration for the stationary head CT using CNT x-ray source array: reconstruction and quality evaluation. In: Bosmans H, Chen G-H, editors. Medical Imaging 2020: Physics of Medical Imaging [Internet]. Houston, United States: SPIE; 2020 [cited 2020 Mar 19]. p. 116. Available from: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11312/2549996/Simulation-and-optimization-of-system-configuration-for-the-stationary-head/10.1117/12.2549996.fullthe reconstruction algorithms.

An accepted paper to the journal Medical Physics is pending final revisions. Additional abstracts were submitted to SPIE Medical Imaging 2021.

No other products at this time.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Name: Yueh Lee
Project Role: Principal Investigator
Research Identifier: ORCID 0000-0003-1846-7680
Nearest person month worked: 3
Contribution to Project: Dr. Lee is leading the project as PI.

Name: Otto Zhou

Project Role: Co-Investigator
Nearest person month worked: 1
Research Identifier: 0000-0003-1476-5517
Contribution to Project: Dr. Zhou is assisting Dr. Lee in supervising graduate students in both system construction and design.

Name: Jianping Lu
Project Role: Co-Investigator
Nearest person month worked: 1
Research Identifier: ORCID 0000-0001-9963-9741
Contribution to Project: Dr. Lu is assisting with the develop of reconstruction algorithms for the system.

Name: Deanna Sasaki-Adams
Project Role: Co-Investigator
Nearest person month worked: 1
Research Identifier: N/A
Contribution to Project: Dr. Deanna Sasaki Adams (neurosurgeon) is the PI of the clinical study. She has been managing IRB protocol development and approval.

Name: Sean Montgomery
Project Role: Co-Investigator
Nearest person month worked: 1
Research Identifier: N/A
Contribution to Project: Dr. Montgomery (Trauma Surgeon, Duke University) is assisting the team in maintain the military relevance of the project, and will assist in interpretation of images in the trial.

Name: Christina Inscoe
Research Identifier: 0000-0001-8681-9030
Project Role: Co-Investigator / Laboratory Manager
Nearest person month worked: 3
Contribution to Project: Dr. Inscoe is assisting in system development and construction, and will coordinate radiation and electrical safety testing of the system.

Name: Derrek Spronk
Research Identifier: Not available
Project Role: Research Assistant
Nearest person month worked: 12
Contribution to Project: Mr. Spronk is developing the CAD models and selecting hardware for construction of the prototype system.

Name: Yueting Luo
Research Identifier: 0000-0002-9217-4002
Project Role: Research Assistant
Nearest person month worked: 12

Contribution to Project: Ms. Luo is developing the simulation and reconstruction software for the novel geometries.

Name: Ruofei Bu
Project Role: Postdoctoral fellow
Research Identifier: 0000-0003-1014-3737
Nearest person month worked: 6
Dr. Bu assisted with the hardware integration of the system, including bed positioning and detector control. She has left for industry.

Name: Lin Yang
Research Identifier: 0000-0002-3983-557X
Nearest person month worked: 2
Dr. Yang is assisting with the hardware integration and program control of the x-ray detectors and patient bed.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to Report.

What other organizations were involved as partners?

Provide the following information for each partnership:

Organization Name: Duke University, Durham NC USA

Partner's contribution: Dr. Sean Montgomery is a trauma surgeon with military experience, and is assisting on system design and capability in the military context.

SPECIAL REPORTING REQUIREMENTS

Quad chart will be enclosed as an attachment