Integrated PET/CT Guidance System for Oncologic Interventional Radiology

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***Abstract*–Interventional Radiology procedures such as radiofrequency ablation are a vital component of minimally invasive cancer treatment, and use of these techniques is on the rise. At the same time, PET imaging has revolutionized the care of cancer patients with its ability to rapidly and accurately screen for the presence of neoplastic disease. Our goal is to bring the full power of PET imaging into the arena of interventional radiology, by developing an integrated image guidance system using co-registered PET and CT to enable new and improved cancer therapies. Within the current system, we have several modular components built around an open source software framework. The first component is a respiratory compensation system for matching the PET image (acquired under free breathing) to the CT image (acquired at end-inspiration). The second component is a system for performing registration between CT and fluoroscopy to enable the PET information to be brought into the interventional workspace. As an alternative to fluoroscopy guidance, we have also developed a third component for using electromagnetic tracking, which can determine the position of tools in the treatment field without ionizing radiation. Finally, we have respiratory phantoms to simulate a wide variety of breathing motion and provide a robust testing platform for our system. We are currently testing the system using these phantoms in preparation for future animal and clinical trials.**

I. Introduction

Interventional Radiology (IR) procedures are a vital component of comprehensive cancer treatment. The use of image guidance (based on planar and CT fluoroscopy, as shown in Fig. 1) for percutaneous biopsy, tissue sampling, and fiducial placement is widespread. Ongoing research efforts continue to demonstrate the value of minimally invasive interventional radiology therapies such as thermal ablation (radiofrequency ablation/RFA) and it is expected that the number of these procedures will continue to rise in the future.

At the same time, PET (Positron Emission Tomography) imaging has revolutionized the care of cancer patients. Its ability to rapidly and accurately screen for the presence of neoplastic disease with whole body scanning makes it an indispensable tool for diagnosis, staging, and therapy monitoring. However, the impact of PET has been primarily felt in the arena of diagnostic radiology -- where PET images are interpreted by themselves or with co-registered x-ray computed tomography (CT) images. In this arena, the combination of PET and CT has been shown to significantly enhance the diagnostic abilities of either modality used alone. Our colleagues recently completed a retrospective study at Georgetown University Hospital of 53 consecutive whole body FDG PET/CT studies with a total of 164 lesions. They demonstrated that 41% (68/164) of PET positive lesions were unremarkable or equivocal on CT alone (Petrillo *et al*., manuscript in preparation). An example case is illustrated in Fig. 2. Examples such as these and the many others found in the literature make it clear that the biochemical information given by PET provides crucial information about the extent of disease. Thus, our goal is to bring the full power of PET imaging into the arena of interventional radiology, by developing an integrated image guidance system using co-registered PET and CT to enable new and improved cancer therapies.

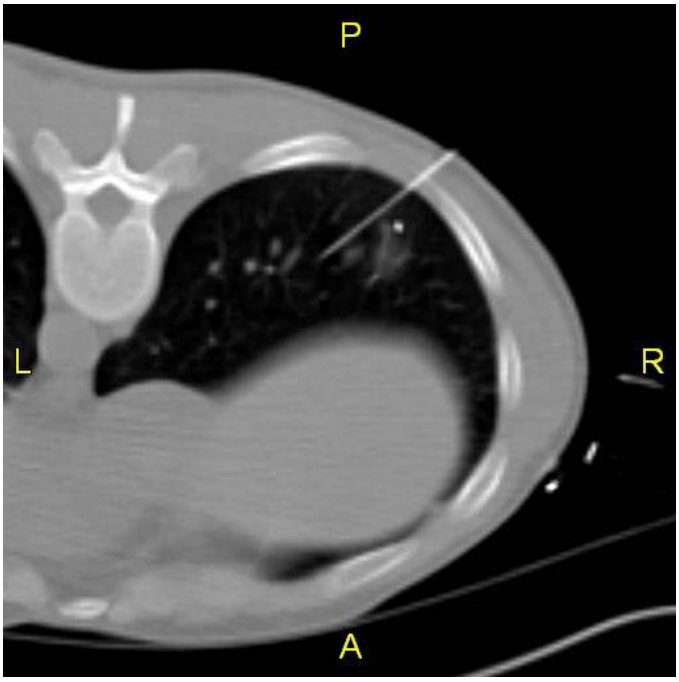

Fig. 1. Image from a CT fluoroscopy procedure showing needle insertion into the lung. The clinician is inserting tiny gold fiducials into a tumor for stereotactic radiosurgery guidance.

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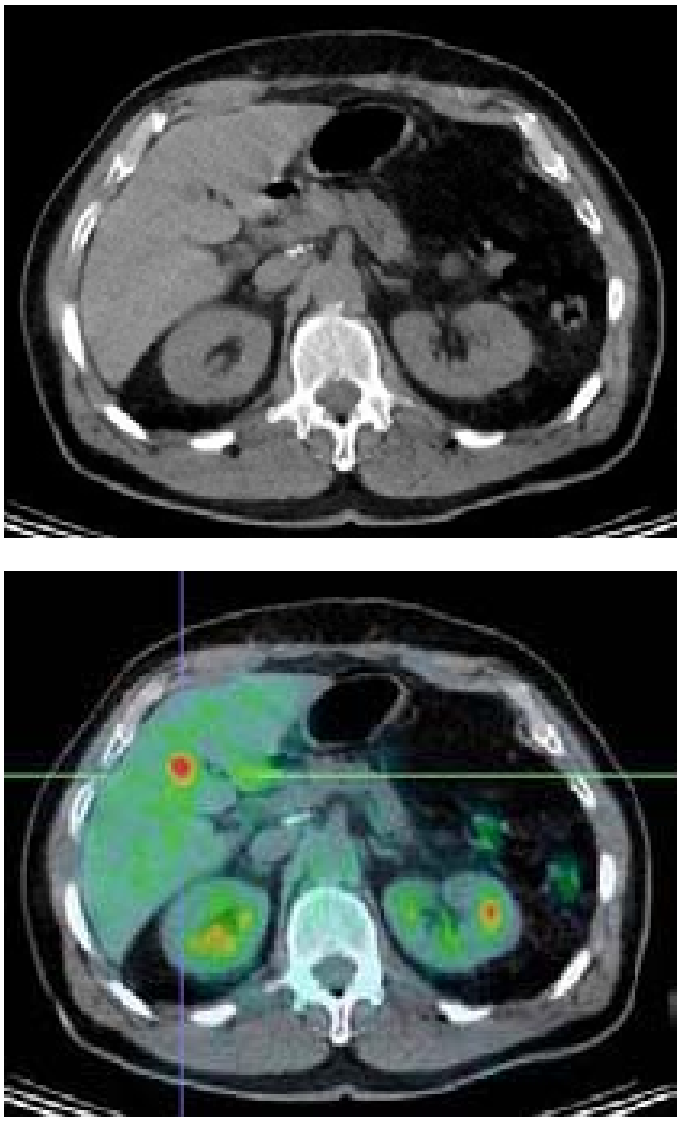

Fig. 2. In the standard CT image (above) , the liver appears normal. Combined FDG PET/CT imaging (below) clearly reveals a focus of increased metabolic activity. Based on this information, closer inspection of the CT image reveals a slightly hypointense region corresponding to the region of increased PET tracer uptake.

II. System Components

A. Open Source Software

The integrated PET/CT/IR system that we envision contains several components and is tied together with open source software and workflow analysis.

The foundation of the system is the Image-Guided Surgery Toolkit (IGSTK) developed in our laboratory and based on other successful open source efforts such as VTK (Visualization Toolkit) and ITK (Insight Segmentation and Registration Toolkit). IGSTK provides abstractions of common components of image guidance systems, enabling modularity and interoperability. At the same time, the toolkit is based on a state machine architecture, which provides a formal process for setting up transitions between different operating modes of the software and ensuring robustness.

Fig. 3 provides a high level view of an IGSTK application using a UML (Unified Modeling Language) diagram. From left to right, the principal components are (1) View class for presenting results and displays to the physician; (2) Spatial Object Representation class, which provides connection between Spatial Objects & View classes; (3) Spatial Objects class, which models physical objects including image data, tools, and simple geometrical shapes; (4) Tracker class to store data from localizers.

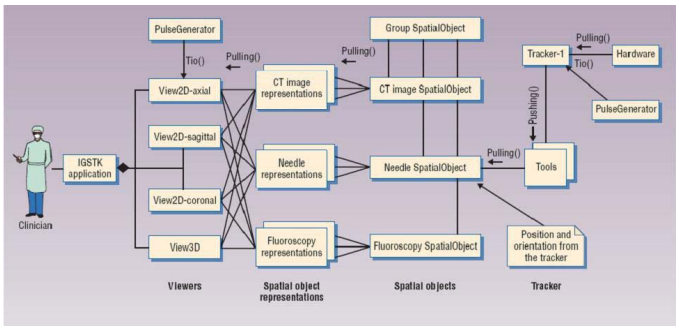

Fig. 3. UML (Unified Modeling Language) diagram of an application based on IGSTK (Image Guided Surgery Toolkit).

B. Respiratory Motion Compensation

It is well known that the differences in acquisition time between CT and PET create problems when attempting to co-register the two images together. CT images can be obtained rapidly and are typically acquired during a single breath hold, whereas PET images require several minutes and are acquired under free breathing. Furthermore, the imaging performed in the interventional radiology suite can be taken during free breathing or breath hold. Thus, one important area of investigation is methods for respiratory motion compensation. We have tested optical tracking of the skin in the PET scanner using a Polaris Vicra system with reflective markers. The Vicra is compact and thus can easily view the motion of the skin when placed at one end of the gantry (Fig. 4). Although the current version of the PET/CT scanner does not have a respiratory gating package, we can use the information from the Polaris Vicra and a deformable motion model derived from CT scans to retrospectively reconstruct an activity distribution vs. time. This time varying activity distribution can then be matched to the respiratory signal in order to determine the activity distribution at end-inspiration, corresponding to the respiratory phase from the CT scan. We are currently also in the process of acquiring a manufacturer-based respiratory motion compensation system that will integrate more fully with the scanner hardware.

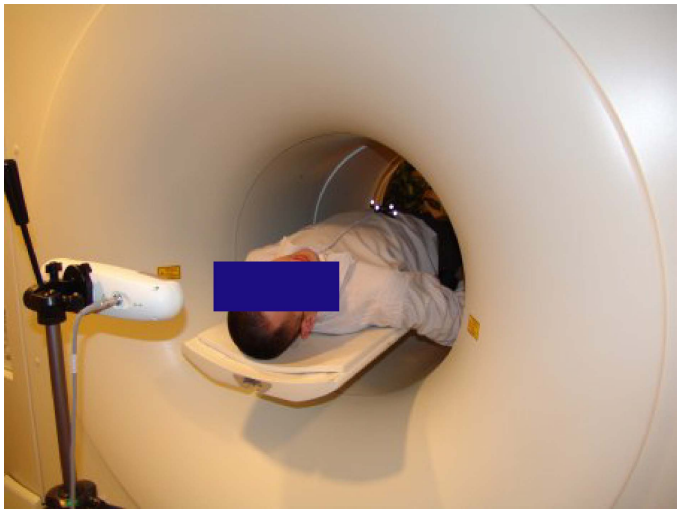

Fig. 4. Illustration of CT/PET system and Polaris Vicra optical tracker for monitoring respiratory motion.

We are also investigating software-based methods for PET/CT registration that do not depend on explicit recording of the respiratory cycle. These methods are based on the work of our collaborator Raj Shekhar (University of Maryland) and utilize a volume subdivision approach that registers subvolumes using normalized mutual information and rigid transformations. At each level, the amount of motion allowed in a subvolume is constrained by the previous level, imposing a realistic overall constraint on how much a voxel can shift. Because of this piecewise approach, the algorithm can handle deformations in the anatomy that are characteristic of breathing motion while still making use of computationally efficient rigid transformations. The algorithm is also being implemented in a hardware solution which should dramatically shorten the time necessary to calculate the registration.

C. PET/CT to Fluoroscopy Registration

Matching the PET/CT data to the interventional radiology workspace is facilitated by the newly installed Siemens AXIOM Artis fluoroscopy system. This system has a flat panel x-ray detector, which gives improved dynamic range and less spatial distortion. This detector also enables cone-beam CT reconstruction, providing the interventionalist with cross-sectional imaging during the procedure. The principal advantage of the cone-beam CT system is that we are able to acquire a CT scan of the patient immediately before treatment and rapidly register the pre-treatment PET/CT scan to the interventional CT scan. The physician then has a 3D data set, complete with biochemical information, which can be used to guide the intervention.

Fig. 5. Photograph of the Siemens AXIOM Artis fluoroscopy system in the Interventional Radiology Service at Medstar Georgetown University Hospital. The flat panel detector (top end of the C-arm) replaces the image intensifier typically used in fluoroscopy systems, providing higher dynamic range and significantly less spatial distortion.

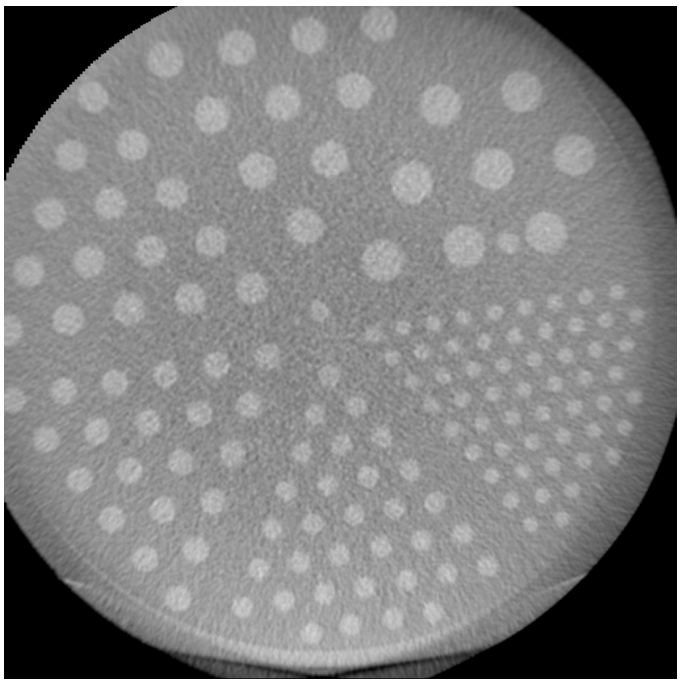

Fig. 6. Reconstructed DynaCT image of standard Data Spectrum cold rod test pattern acquired on the AXIOM Artis fluoroscopy system. The capacity for in-room CT enables us to quickly map the previously acquired PET/CT into the interventional radiology workspace, providing the physician with the capability to visualize functional information overlaid on intra-procedural imaging.

D. Electromagnetic Tracking Guidance Systems

As an alternative to direct x-ray imaging guidance, we are developing guidance systems based on electromagnetic tracking, which can be done without ionizing radiation and which does not require a clear line of sight between the tracker

and the object being tracked. This last factor is especially important in interventions where the tool (such as an RFA probe) may be deep inside the body. Key clinical applications for this technology include lung biopsy, management of hepatocellular carcinoma prior to hepatic transplantation, radiofrequency ablation for cancer treatment, and fiducial placement for image guided CyberKnife radiosurgery. Within this context, we have developed a system based on the Aurora electromagnetic tracking device for image-guided system abdominal interventions. The graphical user interface displays multiple cutplanes as well as a "needle's eye view" targeting window, and is shown in Fig. 7.

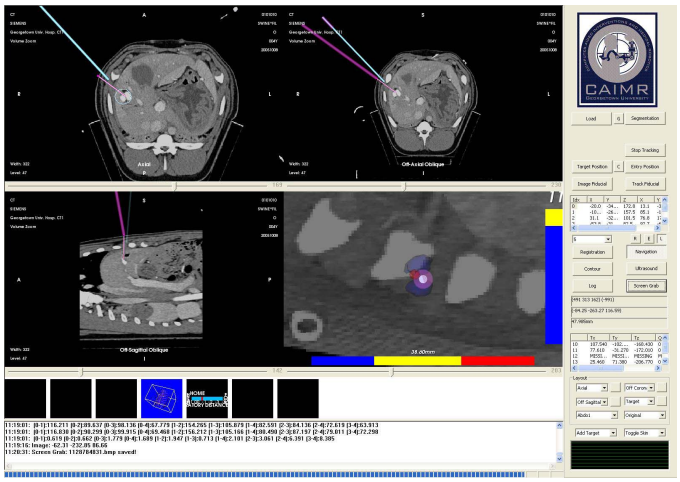

Fig. 7. Graphical user interface for an electromagnetically guided interventional radiology system. By registering the tracker space to a pre-acquired CT image, the position and orientation of tools such as needles and catheters can measured in real time and overlaid on the image

E. Respiratory Motion Phantoms

Initial testing of the system uses devices for respiratory motion simulation to evaluate system performance without the need to image patients, which would of course expose them to additional risk from increased radiation dose. For testing deformable respiration-based changes in the anatomy, we use a phantom designed by our collaborator Dan Stoianovici (Johns Hopkins University). This phantom (Fig. 8) contains an anatomically accurate plastic skeleton, inflatable lungs, accessible abdominal cavity, and flexible diaphragm. The system is driven by a standard ventilation pump for large animals. The phantom provides a realistic model of the type of anatomical changes observed in breathing, although its variability is limited since the pump is designed for regular, repeatable stroke volumes and speeds.

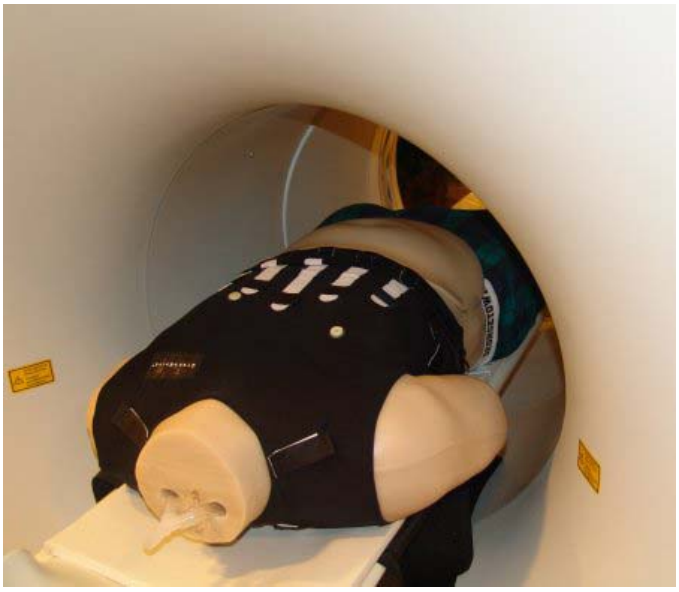

Fig. 8. Respiratory motion phantom developed by Dan Stoianovici, URobotics Laboratory, Johns Hopkins University. The phantom has bronchi, lungs, a diaphragm, and a skeleton inside a lifelike silicone figure to simulate deformable changes due to breathing.

We also have a computer controlled 3-axis respiratory motion simulator (Fig. 9) that can create precisely controlled motion paths of arbitrary form, thereby allowing us to simulate irregular breathing, phase changes between skin and internal motion, and abrupt deviations such as coughing. This simulator was designed and constructed by our group at Georgetown University. This simulator has a much higher degree of precision, but obviously does not provide a realistic simulation of thoracic anatomy.

Fig. 9. Three-axis computer controlled respiratory motion simulator designed by our group at Georgetown University. The system uses servo motors and linear slides to provide precise *x,y,z* motion to simulate the path of an internal organ target during respiration.

III. Conclusions

PET imaging can provide crucial, enabling information to improve anti-cancer therapies. Bringing biochemical and functional information into the interventional radiology environment places this vital information into the hands of physicians at the point of intervention, where it is most needed. Key components of this capability are image registration, respiratory motion compensation methods, respiratory phantoms, and open source software. We are using these resources to develop a fully integrated system to support PET-guided interventional radiology procedures. This system should prove useful for needle biopsies, fiducial placement, thermal/chemical ablation, and many other minimally invasive therapies. We are now testing the system using respiratory phantoms in preparation for future animal and clinical trials.

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