Published in final edited form as:

IEEE Nucl Sci Symp Conf Rec (1997). 2012 ; 2012: 3564–3567. doi:10.1109/NSSMIC.2012.6551816.

The AdaptiSPECT Imaging Aperture

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Abstract

In this paper, we present the imaging aperture of an adaptive SPECT imaging system being developed at the Center for Gamma Ray Imaging (AdaptiSPECT). AdaptiSPECT is designed to automatically change its configuration in response to preliminary data, in order to improve image quality for a particular task. In a traditional pinhole SPECT imaging system, the characteristics (magnification, resolution, field of view) are set by the geometry of the system, and any modification can be accomplished only by manually changing the collimator and the distance of the detector to the center of the field of view. Optimization of the imaging system for a specific task on a specific individual is therefore difficult. In an adaptive SPECT imaging system, on the other hand, the configuration can be conveniently changed under computer control. A key component of an adaptive SPECT system is its aperture. In this paper, we present the design, specifications, and fabrication of the adaptive pinhole aperture that will be used for AdaptiSPECT, as well as the controls that enable autonomous adaptation.

Index Terms

Imaging; instrumentation; SPECT; collimator design; small-animal

I. Introduction

The AdaptiSPECT system is a 16-camera pre-clinical adaptive pinhole SPECT imaging system currently under construction at the Center for Gamma Ray Imaging. Pre-clinical SPECT systems are used for a wide range of tasks, and on a variety of small animals. Tasks could be as different as “detecting a perfusion defect in the heart of a mouse” and “estimating the uptake in a large tumor in the pancreas of a rat” for example. In a traditional

pinhole-SPECT system the imaging characteristics such as magnification, resolution and field of view are set by the geometry of the system and cannot be modified during a scan. It is therefore unlikely that such a system would be optimal for any specific task.

The AdaptiSPECT system, on the other hand, has been designed to be able to change its configuration to adapt to a preliminary scan. The general adaptation scheme is summarized on Figure 1: AdaptiSPECT acquires a first data set g_s in a scout configuration represented by the system matrix $\mathcal{H}_s$. Using information from this data set and knowledge of the task to accomplish, AdaptiSPECT reconfigures itself to optimize its task performance. This optimization could take multiple steps, and would be described by the set of system matrices $\{\mathcal{H}_i\}$. When no further optimization is possible, a final data set g_B is acquired. The task is evaluated on this data set.

In previous work, Barrett et al. [1] have derived formulations for the Hotelling and Wiener observers in the case of an adaptive SPECT system. They have also proposed various adaptation rules. Freed et al. have demonstrated the feasibility of building an adaptive SPECT imaging system with a single-camera prototype [3], and Caucci et al. have demonstrated the usefulness of the adaptive system for the task of detecting a necrotic core in a tumor [2]. In [4] and [7], we presented a preliminary design of AdaptiSPECT. Since then, we have further refined the design of the system, and finalized the imaging aperture and its controllers.

In section II of this paper, we describe the design, the specifications, and the on-going fabrication of this new aperture. We demonstrate the system's versatility in terms of magnification, resolution, and field of view, by computing these characteristics for different system configurations.

In section III, we describe the design and fabrication of the controls that enable autonomous adaptation.

II. Design and Fabrication of the Imaging Aperture

A. Design Constraints

AdaptiSPECT is based on our existing FastSPECT II system [5], so the imaging geometries of the two systems are necessarily similar. A primary difference is that on the AdaptiSPECT imaging system, the detectors are mounted on individual translating stages, and can move continuously in the radial direction, allowing for the detector distance from the center of the field of view to vary from 165.1 mm to 317.5 mm. However, the most significant difference between the FastSPECT II system and the AdaptiSPECT system is the design of the collimator. The AdaptiSPECT collimator consists of 3 rings of pinholes, where each ring is designed to achieve a different magnification and field of view when placed in the imaging position in order to accommodate different objects and imaging tasks. The collimator is thus axially segmented into different diameter bore sections such that within each ring segment, the pinholes are at a fixed distance from the center of the field of view, but this distance is different for each segment. Placing the desired ring segment into the imaging position for a particular application is achieved by translating the full imaging aperture.

The main constraint in the design of the aperture derives from the intended imaging application of each ring of pinholes. The smallest-diameter ring segment (high-magnification) is sized for mouse studies. The diameter of the high-magnification ring is sized such that any organ in a 20g–30g mouse can be placed in the center of the field of view, and the ring's length is long enough to permit whole-body scans. Similarly, the diameter of the middle ring segment (mid-magnification) is sized such that any organ of a 250g rat may be placed in the center of the field of view. The middle ring segment is again long enough to allow for whole-body rat scans. The spacing between the ring segments is set such that no leakage occurs through the pinholes of other rings while one ring is in the imaging position.

The final constraint is on the thickness of the aperture. For SPECT, the most commonly used isotope is ^{99m}Tc , which has a γ -ray energy of 140 keV. The aperture has to be thick enough that leakage photons are a small fraction of the total number of photons reaching the detectors. The attenuation factor A is given by:

$$A = e^{-\mu\rho L}, \quad (1)$$

where μ is the mass attenuation coefficient of the material for a specific energy, and L is the path length through the absorbing media. The AdaptiSPECT pinhole aperture has a thickness of 9 mm; the density ρ of the tungsten-epoxy composite that composes it is 9 g/cc; and therefore its attenuation factor is:

$$A = 2.710^{-8} \text{ for } ^{99m}\text{Tc at 140 keV}$$

$$A = 5.210^{-6} \text{ for } ^{123}\text{I at 159 keV}$$

$$A = 3.010^{-4} \text{ for } ^{111}\text{In at 171 keV}$$

$$A = 0.02 \text{ for } ^{111}\text{In at 245 keV}$$

B. New design and specifications

The constraints on the size of the animal described in the previous section have a direct impact on the distance of the pinholes to the center of the field of view. It is tempting to reduce this distance to increase magnification, but this would reduce the ability to position the animal inside the collimator. Keeping these constraints in mind, we used ray tracing methods to compute the sensitivity, magnification, resolution and field of view of the system for various designs.

The final dimensions of each ring segment of the aperture are summarized in Table I. The imaging characteristics achieved with this design for various configurations are presented in Table II. The magnification of the system ranges from *1 to *11, the resolution ranges from 700 μm to 3 mm, and the transaxial field of view ranges from 10 mm to 90 mm. A rendering of the aperture is shown in Figure 2.

The mid-magnification ring and the low-magnification ring can be switched from a single-pinhole-per-camera configuration to a five-pinhole-per-camera configuration, thus increasing the sensitivity at the cost of multiplexing.

C. Fabrication of the aperture

The pinhole aperture was fabricated using a tungsten-epoxy casting method described previously in [6]. The method allows for the inexpensive fabrication of aperture designs with complex geometries that would be impossible or cost-prohibitive to realize through machining. For example, pinholes with oblique view angles are straightforward to create. The pinholes themselves are cast separately in platinum with a lost-wax process [6].

III. Design and Fabrication of the Controls for the Adaptation

A. Design Constraints

The total travel distance required to move the three separate ring segments — low-, mid-, and high-magnification — into the imaging position is 370 mm. There are three mechanical issues which constrain the design of the motion system:

1. The low-magnification ring-segment of the aperture has to remain clear, since it is from this end that an animal is inserted into AdaptiSPECT. Therefore, the motion *has to be driven from the high-magnification ring-segment*.
2. The aperture has a mass of 43kg, and its center of gravity is located within the low-magnification ring-segment. Therefore, it is necessary to also support the aperture from the low-magnification end to avoid sag.
3. The linear translation of the aperture must provide high-precision placement and excellent repeatability in order to maintain the validity of our measured calibration.

In addition to the motion controllers, we have designed shutters to enable switching from a five pinhole-per-camera configuration to a single pinhole-per-camera configuration for both the low-magnification and the mid-magnification ring-segments. The shutters have been designed with the following constraints in mind:

1. The shutters need to have a low-clearance, because the space between the aperture and the shielding shrouds is limited.
2. The shutters need to be easy to machine.
3. The shutters need to have a good resistance to wear, and their motion needs to be reliable and reproducible.
4. The shutters need to be easy to mount on the aperture, and they should not obstruct the entrance on the low-magnification side of the aperture.

B. Design of the motion controls

On the high-magnification side of the aperture, we have chosen to use a Velmex stage that has 508 mm of travel. We designed a ring that clamps on the end of the aperture, with a groove to help the clamp grasp, as shown in Figure 2. The clamp is attached to a bar that is driven by the Velmex stage. There are springs between the clamp and the bar to allow for some flexibility, such that the motion is not over-constrained. A CAD rendering of this motion system is shown in Figure 3.

On the low-magnification end, we support the aperture and guide it during its motion with two SKF ball transfer units. The ball transfer units are directly threaded into the aperture, They are adjustable in height, and therefore allow for correct horizontal alignment of the aperture. The two ball transfer units run on precision-ground stainless-steel rails: one is a plain rail and the other one has a v-groove that defines the linear trajectory of the aperture. The two ball transfer units are mounted with a 45 degree angle, providing stability. A CAD rendering of this system is shown in Figure 4.

C. Design of the shutters

To enable an easy switch between the single pinhole-per-camera configuration to the five pinhole-per-camera configuration, we have designed the shutters as four tungsten blocks glued on a circular plate that can rotate in a fixed mount. This ensemble is directly mounted on the aperture above a group of five pinholes. The rotation of the circular plate enables the covering or uncovering of the four peripheral pinholes of the group-of-five, thus enabling the configuration switch. A miniature air piston from Clippard Minimatic is used to actuate the circular plate into the open configuration. The return of the plate to the closed position is driven by a spring. A rendering of this shutter system can be seen on Figure 5.

The shutters are machined in aluminum, and anodized for good wear resistance. The shutters are mounted individually on the aperture. They are all mounted in the same orientation, so that the tubings necessary to actuate the air pistons are all directed towards the high-magnification ring segment of the aperture.

IV. Conclusions

In this paper we have described the final design of the imaging aperture for the adaptive SPECT imaging system being assembled at CGRI, as well as the controls that enable the autonomous adaptation of the system. The aperture consists of three ring segments with different imaging characteristics. The selection of the appropriate ring is done by linear translation of the entire aperture. The combination of aperture selection and camera position provides a wide range of imaging properties, as summarized in table II. We anticipate that most adaptive imaging methods will begin with a large field of view, and then proceed to more detailed measurements at the higher-magnification limit.

We have designed the aperture, the shutters and all the parts related to the aperture motion in their final versions. We have cast the three ring-segments of the aperture, and we are now in process of assembling them. We have machined all the parts for the motion controls. We are in the process of machining the shutters, and once this is done, we will have all the components ready for mounting the aperture.

Acknowledgments

The authors would like to thank L. Acedo and R. Willwater from the University of Arizona Research Instrumentation Center for their valuable help with the machining aspects of this work.

This work was supported by the TRIF Imaging fellowship, the Research Foundation - Flanders, Belgium, and by the National Institutes of Health under NIBIB P41-EB002035, and R37-EB000803.

R. Van Holen is supported by a fellowship of the Research Foundation Flanders.

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Fig. 1.
General adaptation scheme.

Fig. 2.
CAD rendering of the pinhole aperture showing the three ring-segments, the shutters, and some of the motion controllers.

Fig. 3.
CAD rendering of the aperture support and motion control on the high magnification ring segment side.

Fig. 4.
CAD rendering of the aperture support and motion system on the low-magnification ring segment side.

(a) Single-pinhole configuration

(b) Five-pinhole configuration

Fig. 5.

Rendering of the shutters for the mid-magnification ring-segment. In (a) the piston is not actuated and the four peripheral pinholes are covered by tungsten blocks, enabling for a single pinhole-per-camera configuration. In (b) the actuated piston pushes the circular plate and opens the peripheral pinholes, enabling for a five pinhole-per-camera configuration

TABLE I

Aperture dimensions. The pinhole aperture consists of three ring segments: low-magnification, mid-magnification and high-magnification.

	Low-M	Mid-M	High-M
pinhole distance (mm)	76.2	50.8	26.1
pinhole diameter (mm)	1.5	1	0.6
total length (mm)	140	315	140

System Properties of AdaptiSPECT. Since the detector distance to the central axis is also variable, from 165.1 mm to 317.5 mm, each pinhole-ring has a range of magnifications, resolutions, and fields of view.

TABLE II

Imager Configuration	Low-Mag	Mid-Mag	High-Mag			
detector distance (mm)	165.1	317.5	165.1	317.5		
magnification	1.2	3.2	1.7	4.2	5.3	11.1
resolution (mm)	3.48	1.95	2.40	1.60	0.8	0.7
transaxial FOV (mm)	90	37.5	48	24	20	10.5