Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2013 August 25; 8853: . doi:10.1117/12.2029768.

Integration of AdaptiSPECT, a small-animal adaptive SPECT imaging system

Cécile Chaix, Stephen Kovalsky, Matthew Kosmider, Harrison H. Barrett, and Lars R. Furenlid

Center for Gamma-ray Imaging, University of Arizona, Tucson, AZ 85724

Abstract

AdaptiSPECT is a pre-clinical adaptive SPECT imaging system under final development at the Center for Gamma-ray Imaging. The system incorporates multiple adaptive features: an adaptive aperture, 16 detectors mounted on translational stages, and the ability to switch between a non-multiplexed and a multiplexed imaging configuration. In this paper, we review the design of AdaptiSPECT and its adaptive features. We then describe the on-going integration of the imaging system.

Keywords

SPECT; adaptive imaging; small-animal

1. INTRODUCTION

In a conventional SPECT system, the imaging characteristics (magnification, resolution, field of view) are set by the geometry of the system, and can be modified only by manually changing the collimator and the distance between the detector and the center of the field of view. Since the geometry of such a system is set before acquiring any data, it is unlikely that the performance of this system for a specific task is optimal. An adaptive SPECT imaging system, on the other hand, is designed to autonomously change its geometry in response to data being acquired. A task-based approach to adaptive imaging has been detailed before by Barrett *et al.*² and Clarkson *et al.*⁵

In previous work, Freed *et al.*⁷ demonstrated the feasibility of building an adaptive SPECT system with a single camera prototype, and Caucci *et al.*³ demonstrated the usefulness of adaptive SPECT in the case of the detection of a necrotic core.

Building on this first adaptive prototype, and on previous systems developed at the Center for Gamma-ray Imaging, we are now completing a fully-adaptive pre-clinical pinhole SPECT imager we call AdaptiSPECT. In this work, we will briefly review the design of AdaptiSPECT, and then describe the integration of the system: the detectors, the pinhole aperture, and the control software.

2. DESIGN OF ADAPTISPECT

AdaptiSPECT is developed with two main goals in view. The first goal is to be able to use the imager for routine pre-clinical imaging tasks. Thus, AdaptiSPECT has to be reliable, practical to use, and suited to the small-animals being imaged (rats and mice). The second goal in developing AdaptiSPECT is to use this imaging system as a demonstration tool for adaptive methods in SPECT imaging. Thus, AdaptiSPECT has to be as flexible as possible so that a rich variety of adaptation schemes can be implemented and tested.

2.1 Adaptation Schemes

There are many adaptation schemes that are possible for adaptive SPECT. Several approaches have been described by Barrett *et al.*² Here we will briefly describe three important methods of adaptation.

In the single-step adaptation scheme illustrated in Figure 1, the adaptive SPECT system acquires a preliminary dataset g_s in a scout configuration $\mathcal{H}_s$. Using the information from this scout dataset, and with knowledge of the task to accomplish, the system then computes the best configuration to achieve maximum performance on the task. The adaptive SPECT system will then reconfigure itself to diagnostic configuration $\mathcal{H}_d$ and acquire the optimized dataset g_d .

Instead of having a single adaptation step, the system could also do multiple adaptations, as illustrated in Figure 2. In this case, the adaptation could be near-continuous. For example, every two seconds, a decision could be made to move a detector, or move the object, given the data that has just been acquired, and the task to perform. This approach is well suited for adaptive SPECT in general, since the distribution of the radiotracer in the tissue is evolving continuously during the acquisition.

Finally, all adaptive systems can develop adaptation rules through machine learning methods. In this case, the system has to be trained, either through experiments or through simulations with good models. Furthermore, the system has to maintain a memory of the data acquired, the adaptation steps made, and the assessment of the acquisition.

2.2 Design of AdaptiSPECT

AdaptiSPECT has been designed to be able to implement all three adaptation schemes described in section 2.1. The general design of the system¹⁰ is based on the existing FastSPECT II system⁸ developed at the Center for Gamma-ray Imaging and currently used as routine imager for pre-clinical studies. The imaging geometries of the two systems are therefore very similar. Both systems have 16 detectors arranged in two rings of 8 detectors, which achieves enough angular sampling for tomographic dynamic studies to be performed. This makes AdaptiSPECT especially well suited for continuous adaptation schemes. The general gantry design and detector arrangement is shown in Figure 3.

In contrast to FastSPECT II, where the detectors are at a fixed distance from the center of the field of view, the detectors on AdaptiSPECT are mounted on individual translation stages, which allows continuous radial variation of the distance between the detector and the

center of the field of view. Another key difference between the two systems is the adaptive imaging aperture.⁴ To allow for an autonomous change of the distance of the pinholes to the central axis, the aperture on AdaptiSPECT has been designed as three rings of pinholes of different diameter sections, aligned on a common axis. Selection of the desired ring segment is carried out by axial translation of the entire imaging aperture. In addition to having different diameters, each ring segment has pinholes of different diameters and is intended for different use. The largest ring segment (low-magnification) will be used for initial data acquisition. The medium ring segment (mid-magnification) accommodates rats and mice. The smallest ring segment (high-magnification) is intended for mouse studies. The dimensions are summarized in Table 1.

The imaging characteristics of the aperture are summarized in Table 2. In summary, the magnification ranges from x1 to x11, the resolution ranges from 700 μ m to 3 mm, and the transaxial field of view ranges from 10 mm to 90 mm.

On the mid-magnification and low-magnification ring segments, the aperture is equipped with shutters that enable autonomous switching from a one-pinhole-per-camera configuration to a five-pinhole-per-camera configuration, thus increasing sensitivity at the cost of possible multiplexing. Each shutter can be actuated individually, allowing for more flexibility in the adaptation. A CAD rendering of the entire aperture is shown in Figure 4.

AdaptiSPECT is well suited to implement the different adaptation schemes we have discussed. For the single-step adaptation scheme, for example, a set of fifteen **H** matrices could be pre-measured (five camera positions per ring segment). During the adaptation step, the **H** matrix that provides the highest performance would be selected. The fact that cameras can move independently makes it possible to implement near-continuous adaptation.

3. INTEGRATION OF ADAPTISPECT

3.1 Detectors and Acquisition Electronics

AdaptiSPECT uses the modular gamma-ray scintillation cameras that have been developed over the last 20 years at the Center for Gamma-ray Imaging (CGRI).^{1, 12} These detectors are in use in various systems developed at CGRI such as FastSPECT II,⁸ M3R,⁹ and ModPet.¹³

The detectors consist of a 5-mm-thick NaI(Tl) scintillation crystal (114-mm $\times$ 114-mm area), a fused quartz light guide, and a 3 $\times$ 3 array of 1.5-inch diameter PMTs. The entrance face of the scintillation crystal is coated with a reflective material, and the sides are blackened. A schematic drawing of the cameras is shown in Figure 5. Each detector has its own programmable high-voltage power supply.

Each detector in AdaptiSPECT is mounted on its own linear stage, which allows for the distance between the detector and the center of the field of view to be changed autonomously. A photograph of a camera in its mount is shown in Figure 6. The detectors can be moved independently or as a group, thus allowing for various adaptation possibilities.

AdaptiSPECT uses the list-mode acquisition electronics specifically developed for the modular gamma-cameras. The drivers for the acquisition electronics have recently been revised to be compatible with 64-bit WinOS operating systems, allowing for a higher number of events to be acquired and read out at faster rates. The back-end acquisition cards are now hosted in an external expansion crate, which permits four cards supporting 8 cameras to require only a single PCIe slot. This enables the use of modern motherboards that support general purpose GPU computing cards, as well as creating a very compact system. Only one computer is needed for the acquisition of data from 16 cameras in AdaptiSPECT, whereas two interlinked computers were originally needed for FastSPECT II.

3.2 Pinhole aperture

Because of its mass, and the fact that the pinhole aperture has to translate axially while being supported only at its ends, the manufacturing of this component is more complex than the rest of the system. We have considered and experimented with three different approaches, and we will review their relative advantages and disadvantages.

3.2.1 Casting technique—The first manufacturing technique we considered and tried for the adaptive aperture consisted of casting the body of the aperture in tungsten-epoxy and using separately-cast platinum inserts for the pinholes. This method was successfully used to manufacture the aperture in FastSPECT III, and has been described by Miller *et al.*¹¹ In this technique, a plastic mold is created using a rapid prototype printer, and a tungsten-powder-epoxy-resin is poured into that mold. Unfortunately, the large size of the molds that were created for the AdaptiSPECT aperture led to poor results, since the concomitantly higher weight of the tungsten epoxy deformed the mold slightly during the casting process. This led to imprecise pinhole emplacement, as can be seen in Figure 7. We concluded that the AdaptiSPECT aperture is too big to use this simple method.

3.2.2 Additive manufacturing—The second method that we considered is direct additive manufacturing in metal. This method enables the production of a tungsten object with a precision comparable to rapid prototyping in plastic, albeit at a higher cost. It has already been used by Deprez *et al.*⁶ to manufacture pinhole collimators with complex shapes. This technique would enable the fabrication of the entire aperture, including the pinholes and their complicated shapes, with excellent precision. However, the mechanical properties of the finished material are not adequate for our application; the AdaptiSPECT collimator has to be able to support its own weight since it can only be supported at its ends. Figure 8 shows results of a finite-element analysis carried out with Solidworks™ to assess deformation of the aperture. Even though the deformations are not extreme, there is a risk of failure due to the reduced strength of the laser-sintered powdered tungsten relative to the solid metal. Limitations on the maximum dimensions of objects created with additive manufacturing would also require the aperture to be manufactured in four pieces that would have to be joined together with an adhesive. We decided against this technique because we could not model how strong the bond between sections of the aperture would be.

3.2.3 Mixed technique—We settled on a hybrid technique for manufacturing the aperture. The body of the aperture will be fabricated using conventional machining

techniques and solid tungsten alloy whereas the pinholes will be fabricated using additive manufacturing. The pinholes will then be inserted in the machined assembly, as is shown in Figure 9. With this approach, for each ring of pinholes, a set of load-bearing plates are machined out of tungsten alloy and arranged to form a cylinder, as shown in Figure 10. This technique allows for a strong aperture body while still using precision manufactured pinholes.

4. SOFTWARE AND CONTROLLERS

The software of AdaptiSPECT has to be as flexible as the hardware is. Since we want to use the system to implement and evaluate multiple adaptation schemes, the algorithms that compute the next desired imaging configuration on the basis of the current data have to be independent from the core software that controls moving parts in the system. We are implementing a programming model in which the adaptation algorithms send requests to the adaptive layer of the system. This layer is responsible for safely adjusting the various adaptive parts of the system, such as the detectors and aperture locations. Everything that is not movable or adjustable is controlled by the basic data-acquisition layer of the system.

4.1 Detector Controllers

Detector controller software controls everything that involve the 16 independent detectors. This includes the adaptive feature of the radial motion of the detector, and the non-adaptive features such as the high-voltage (HV) and acquisition electronics. The organization of these controllers is shown in Figure 11.

Each detector and its linear stage, which are mounted on a backplate to form a modular unit that is bolted to the system gantry, together comprise the moving part. The programmable HV unit and the acquisition electronics are mounted on the module, but do not move when the detectors move. The software sends commands to the HV units, to the acquisition electronics and to the linear stage.

4.2 Aperture Controllers

The aperture of AdaptiSPECT is fully adaptive, and therefore is controlled by the adaptive layer of the aperture controller software. The adaptive layer issues commands to the linear stage that enables the translation of the entire aperture, thus selecting the appropriate ring of pinholes for imaging. The adaptive layer also controls the shutter controller's electronics, opening or closing each shutter individually to switch between a five-pinhole-per-camera configuration and a single-pinhole-per-camera configuration. The shutters are actuated by pneumatic pistons. The shutter controller powers the solenoids in the valves that regulate the air supply to these pistons. The organization of the controllers is shown in Figure 12.

4.2.1 Shutters—The shutters consist of four tungsten blocks that are bonded to a circular aluminum plate that can rotate on a bearing in a fixed aluminum mount. The rotation of the plate enables the covering and the uncovering of the peripheral pinholes. The forward rotation of the circular plate is actuated by a miniature air piston from Clippard Minimatics; the return rotation of the plate is spring driven. A rendering of the shutter system is shown in Figure 13.

4.2.2 Shutter controllers—The piston driving each shutter is actuated via a solenoid. Each solenoid is driven by a custom electronic circuit, connected to a National Instruments USB-interface digital I/O module. The software sends a command to the USB device, and the output is converted into an open/close state for this valve. Each valve can be controlled individually, which means that each shutter can be controlled individually. Four shutter controller circuit boards are needed, each controls 8 valves. The circuit boards have LEDs that show the open/closed state of the valve for visual confirmation. A controller circuit is shown in Figure 14.

5. CONCLUSION

In this paper, we have reviewed the design and system integration of an adaptive pre-clinical SPECT imaging system. We found that the tungsten-powder-epoxy-resin casting technique was not precise enough due to the heavy-weight of this large aperture. The large size and weight also discouraged us from manufacturing the entire aperture using additive metal printing via laser sintering, but instead settled on a hybrid technique of a machined skeleton populated with printed metal pinhole inserts. We also described the development and integration of the electronics and software necessary for AdaptiSPECT.

We are still awaiting a final set of cameras to complete AdaptiSPECT, but will soon be able to acquire first images and test the system.

ACKNOWLEDGMENTS

This work has been supported by NIBIB grant P41-EB002035 “The Center for Gamma-ray Imaging” and by the State of Arizona Technology and Research Initiative Fund (TRIF).

References

1. Aarsvold N, Barrett H, Chen J, Landesman L, Milster D, Rowe K, Strimbu M, Patton DD, Roney TJ. Modular Scintillation Cameras: A Progress Report. *SPIE Medical Imaging II*. 1988; 914:319–325.
2. Barrett HH, Furenlid LR, Freed M, Hesterman JY, Kupinski MA, Clarkson E, Whitaker MK. Adaptive SPECT. *IEEE Trans. Med. Imag.* 2008; 27:775–88.
3. Caucci L, Kupinski MA, Freed M, Furenlid LR, Wilson DW, Barrett HH. Adaptive SPECT for Tumor Necrosis Detection. *IEEE Nuc. Sci. Symp. Conf. Record*. 2008:2782–2784.
4. Chaix C, Moore JW, Van Holen R, Barrett HH, Furenlid LR. The AdaptiSPECT Imaging Aperture. *IEEE Nuc. Sci. Symp. Conf. Record*. 2012:3564–3567.
5. Clarkson E, Kupinski MA, Barrett HH, Furenlid LR. A Task-Based Approach to Adaptive and Multimodality Imaging. *Proc. IEEE*. 2008; 96(3):500–511.
6. Deprez K, Vandenberghe S, Van Audenhaege K, Van Vaerenbergh J, Van Holen R. Rapid additive manufacturing of MR compatible multipinhole collimators with selective laser melting of tungsten powder. *Med. Phys.* 2013; 40:12501–12511.
7. Freed M, Kupinski MA, Furenlid LR, Wilson DW, Barrett HH. A prototype instrument for single pinhole adaptive SPECT imaging. *Med. Phys.* 2008; 35(5):1912–25. [PubMed: 18561667]
8. Furenlid LR, Wilson DW, Chen Y-C, Kim H, Pietraski PJ, Crawford MJ, Barrett HH. FastSPECT II: A Second-Generation High-Resolution Dynamic SPECT Imager. *IEEE Trans. Nucl. Sci.* 2004; 51:631–635. [PubMed: 20877439]
9. Hesterman JY, Kupinski MA, Furenlid LR, Wilson DW, Barrett HH. The multi-module, multi-resolution system (M^3R): A novel small-animal SPECT system. *Med. Phys.* 2007; 34(3):987–993. [PubMed: 17441245]

10. Holen RV, Moore JW, Clarkson EW, Furenlid LR, Barrett HH. Design and Validation of an Adaptive SPECT System : AdaptiSPECT. IEEE Nuc. Sci. Symp. Conf. Record. 2010:2539–2544.
11. Miller BW, Moore JW, Barrett HH, Fryé T, Adler S, Sery J, Furenlid LR. 3-D printing in x-ray and gamma-ray imaging: A novel method for fabricating high-density imaging apertures. Nucl. Inst. and Meth. A. 2011; 659:262–268.
12. Milster TD, Selberg LA, Barrett HH, Easton RL, Rossi GR, Arendt J, Simpson RG. A Modular Scintillation Camera. IEEE Trans. Nucl. Sci. 1984:578–580.
13. Moore, SK. ModPET : Novel Applications of Scintillation Cameras to Preclinical PET. PhD dissertation. The University of Arizona; 2011.

Figure 1.

Flowchart for single step adaptation. A scout scan is performed at first, the best configuration to achieve maximum performance on the task is computed, and the system is re-configured before acquiring the diagnostic data.

Figure 2.

Flowchart for continuous adaptation. A decision is made every few seconds to change the configuration of the system or to stay in the same configuration. The diagnostic scan consists of the entire acquisition.

Figure 3. CAD rendering of the AdaptiSPECT system. The 16 detectors are arranged in two rings of 8 detectors. The shielding and aperture supports are not shown.

Figure 4.
CAD rendering of the pinhole aperture for AdaptiSPECT showing the three ring-segments and the shutters.

Figure 5.
Schematic drawing of the gamma camera used for AdaptiSPECT.

Figure 6.

One of the AdaptiSPECT detectors mounted on its linear stage. Each detector has its own front-end electronics and high-voltage power supply, which are not shown here.

Figure 7.

In this photo, the pinhole emplacements are clearly imprecise: they are bigger than designed.

Figure 8.
Study of the deformation in the aperture under the influence of gravity.

Figure 9.

Illustration of the mixed-fabrication technique: the body of the aperture is machined in a strong tungsten-alloy, and the pinholes are manufactured using additive manufacturing. These pinholes are then bonded to the tungsten-alloy body with a suitable adhesive.

Figure 10.

Illustration of the assembly process: the plates supporting each ring of pinholes are fastened to two supporting end cylinders. Only a subset of the 16 sides comprising the low magnification ring are shown.

Figure 11.
Schematics of the communication system for the detector controllers.

Figure 12.

Schematics of the communication system for the aperture controllers.

(a) Single-pinhole configuration

(b) Five-pinhole configuration

Figure 13.

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, yielding single-pinhole projections. In (b) the actuated piston rotates the circular plate and opens the peripheral pinholes, yielding a five pinhole-per-camera configuration

Figure 14.

Components of the shutter controllers. The NI USB controller is connected to the computer via a USB interface. The circuit board shows the open or closed state of the valves (green LED is for an open valve), and delivers the necessary current to energize the valve solenoids. Each circuit board can control 8 valves. In this photograph, only two valves are shown: the top one is in the open state and the bottom one is closed.

Table 1

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 variable, from 165.1mm to 317.5mm, each pinhole ring yields a range of magnifications, resolutions, and fields of view.

Table 2

Imager Configuration	Low-Mag		Mid-Mag		High-Mag	
detector distance (mm)	165.1	317.5	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