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ABSTRACT

iQID is an intensified quantum imaging detector developed in the Center for Gamma-Ray Imaging (CGRI). Originally called BazookaSPECT, iQID was designed for high-resolution gamma-ray imaging and preclinical gamma-ray single-photon emission computed tomography (SPECT). With the use of a columnar scintillator, an image intensifier and modern CCD/CMOS sensors, iQID cameras features outstanding intrinsic spatial resolution. In recent years, many advances have been achieved that greatly boost the performance of iQID, broadening its applications to cover nuclear and particle imaging for preclinical, clinical and homeland security settings. This paper presents an overview of the recent advances of iQID technology and its applications in preclinical and clinical scintigraphy, preclinical SPECT, particle imaging (alpha, neutron, beta, and fission fragment), and digital autoradiography.

Key words: BazookaSPECT, iQID, CCD, CMOS, gamma camera, image intensifier, preclinical scintigraphy, clinical scintigraphy, preclinical SPECT, alpha detection, digital autoradiography

1. INTRODUCTION

Nuclear medicine imaging has become a valuable tool and a major branch of modern medical imaging. As a functional imaging modality, nuclear medicine provides early detection and diagnosis of human disease. Scintigraphy, single-photon-emission computed tomography (SPECT) and positron-emission tomography (PET) are three main nuclear medicine techniques commonly used in clinical practice. [Meikle 2005] The gamma camera, the fundamental imaging element of all three techniques, can detect gamma-ray photons emitted by the radiotracers and form a planar projection image of the radiotracer distribution. A gamma camera is basically composed of gamma-ray optics such as pinhole apertures or parallel-hole collimators to create the correspondence between points in the image and points in the object, and gamma-ray detectors with readout systems that detect each gamma-ray photon and transfer its energy into electric signals for generating a digital image. Typically there are two types of gamma-ray detectors, scintillation detectors and semiconductor detectors, each with different types of readout systems. [Peterson and Furenlid 2011, Kupinski and Barrett 2005]

Among modern gamma cameras, iQID, a novel type of CCD/CMOS-based scintillation gamma camera, was developed in the Center for Gamma-Ray Imaging and distinguishes itself from the traditional Anger-based scintillation cameras and semiconductor-based gamma cameras.[Miller et al. 2006, 2008, 2009, 2012a, 2014] With a columnar scintillator as gamma-ray detector to preserve high-spatial resolution and an image intensifier to optically amplify the weak scintillation light, iQID is able to use an optical lens to relay the amplified signal onto a consumer-grade CCD/CMOS readout sensor while maintaining a high S/N ratio. As a result, iQID cameras feature ultra-high intrinsic spatial resolution (tens of microns), millions of readout channels, portability, and easy-to-customize capability. EMCCD-based gamma cameras are another type of CCD-based scintillation gamma cameras, but they have higher cost, lower frame rates and require low-temperature refrigeration. [Miller 2006a, Nagarkar 2007, Teo 2005, Meng 2006]

Although initially developed for small-animal gamma-ray imaging, iQID cameras demonstrated many advantages over other types of gamma cameras and potentials for broader applications. During the last decade, many advances have been achieved for iQID technology, broadening its applications to include preclinical and clinical scintigraphy, preclinical SPECT, particle imaging and digital autoradiography. This paper introduces the imaging principle of iQID cameras and provides an overview of all different applications of iQID cameras. For each application, relevant camera configurations and experimental data are presented and discussed.

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2. IQID CAMERA

A typical configuration of an iQID camera includes a micro-columnar scintillator, image intensifier, relay lens and modern CCD/CMOS sensor, as shown in figure 1. When a gamma-ray photon interacts with the micro-columnar scintillator, scintillation light is produced and undergoes total-internal-reflection (TIR) in micro-columnar structures until it exits the scintillator, which maintains minimal lateral spread and excellent spatial resolution performance. A photocathode layer in the image intensifier transfers the energy of the weak scintillation light into electrons, which are amplified by a micron-channel plate (MCP) electron multiplier. Amplified electrons accelerated by a high voltage impinge upon a phosphor screen, transferring the electron energy back into visible light, resulting in a strong enough light signal for a consumer grade lens and CCD/CMOS sensor to read out with a high S/N ratio. Because the MCP can amplify electrons in ~10-micron diameter micro-channels, an image intensifier can provide not only high optical gain but also high spatial resolution of ~25lp/mm. Because of the use of image intensifier as the key amplifying device before signal readout, iQID is called an "intensified" quantum-imaging detector. Depending on the number of MCPs in the image intensifier, the scintillation signal can be optically amplified by factors between 10^4 to 10^7 times. With the selection of a high-resolution lens module and a matching CCD/CMOS sensor, iQID camera can provide ultra-high intrinsic spatial resolution of tens of microns.

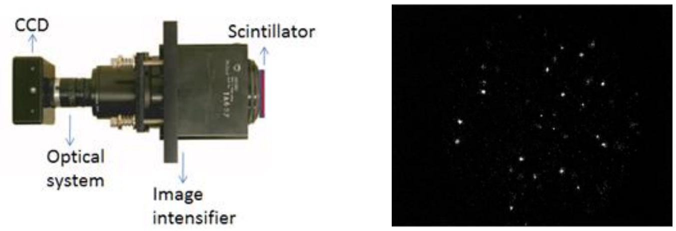

Figure 1. Left: Typical configuration of an iQID camera; Right: A frame of raw data with about 15-20 clusters, each corresponding to a gamma-ray photon detected by the scintillator

iQID cameras have many advantages over other types of gamma cameras. Because of the use of CCD/CMOS sensor as readout, iQID cameras do not require complicated read-out electronics systems. For FireWire sensors, a frame-grabber card connecting the camera and PC is enough for data acquisition. For USB 3.0 sensors, the camera can be directly connected to a PC/laptop. Since the data is acquired in the form of image frames, many image-processing algorithms and libraries can be readily applied to process the image and estimate gamma-ray photon information. With a fast frame-rate CCD/CMOS sensor, iQID cameras feature high count-rate capability and thus photon-counting capability. With the use of multi-core processing algorithms, each frame is processed in real-time and list-mode data is generated that records position, energy and raw pixel information for each gamma-ray photon. After a certain amount of time accumulating gamma-ray events, a gamma-ray image can be generated with quantitation information on radiotracer/dose distribution. Finally, iQID cameras also feature portability and easy-to-customize capability. As shown in figure 2, different configurations based on different performance requirements can be assembled using different generations image intensifiers and different resolution CCD/CMOS sensors. A fiber-optic (FO) taper can also be coupled between the entrance face of image intensifier and the exit face of the scintillator to greatly increase detection area or field of view (FOV).

Figure 2. Different configurations of iQID cameras with different image intensifiers, CCD/CMOS sensors and detection area

3. APPLICATIONS OF IQID CAMERAS

3.1 Preclinical Scintigraphy

The iQID camera was originally designed and applied for small-animal gamma-ray imaging. Because of their tens-of-microns intrinsic spatial resolution, iQID cameras, when equipped with high-resolution parallel-hole collimator, are able to provide high-resolution planar images of the subjects, such as mouse, rat, rabbit, and their internal organs.

As an example, figure 3 shows a mouse scintigraphy experiment using an iQID camera. Both mice bear introduced human breast tumors on their right shoulders. Approximately 60μCi of I-125 labeled hyaluronic acid w×as injected into the mice prepared with the tumor cells. A 180-minute acquisition time was used to produce the planar image of both mice simultaneously. The iQID configuration included a low-energy, high-resolution parallel-hole collimator to produce a high-resolution mapping of the radioisotope distribution of the mouse, an ~80μm-thick Kodak Lanex screen as the gamma-ray detector, and a 3:1 magnification fiber-optic taper to de-magnify the image onto a Proxivision 2-MCP image intensifier, the output of which was imaged via a 6mm CCTV lens onto a Point Grey CCD camera with 640×480 pixel resolution. The image reveals clearly the thyroids of both mice from free iodine absorption, liver clearance path and apparent uptake in the tumor regions.

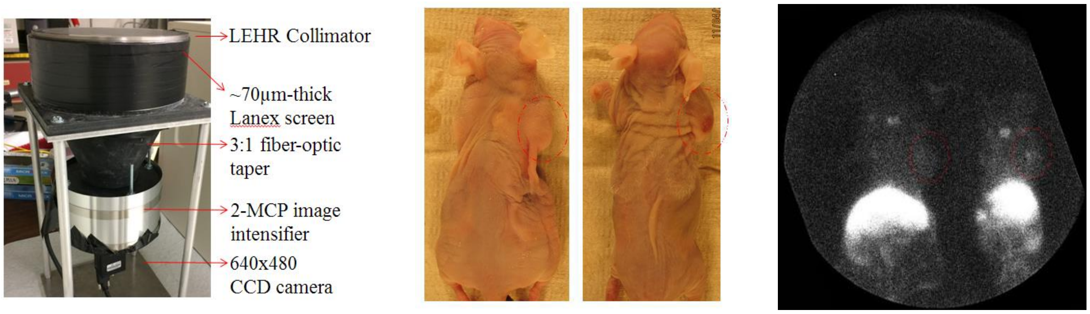

Figure 3. Mouse scintigraphy experiment using iQID camera. Left: the iQID configurations; Middle: two mice with human breast tumor implanted to the right shoulder; Right: the scintigraphy image of both mice with ~60μci I-125 labeled radiotracers and 3hours acquisition

3.2 Preclinical SPECT

To apply iQID technology in preclinical SPECT imaging, FastSPECT III, which was developed at the Center for Gamma-Ray Imaging, consists of 20 identical iQID cameras arranged in three rings to acquire projection images from 20 different directions as shown in figure 4. 250μm-diameter platinum pinholes were manufactured and used for high-resolution gamma-ray imaging. The system FOV is ~15×15×15mm^3 with ~50 cps/MBq sensitivity. After a set of projection images are acquired, maximum-likelihood expectation-maximization (MLEM) algorithm is used to carry out 3D reconstructions of radiotracer distributions.

Figure 4 [Miller 2012b]. The FastSPECT III system with 20 iQID cameras arranged in three rings (left), control system and data acquisition station (right)

A micro-resolution phantom that has six different sets of bores with different diameters and spacings was reconstructed with FastSPECT III to demonstrate the 3D imaging performance. Figure 5 shows a slice of the reconstructed image of the micro-resolution phantom. In this experiment, the phantom was filled with ~2mCi ^{99m}Tc radiotracers and the projection images were acquired in 15 minutes. 100 iterations were used to reconstruct the 3D image of the phantom. The FASTSPECT III system demonstrates better than 350μm isotropic spatial resolution.

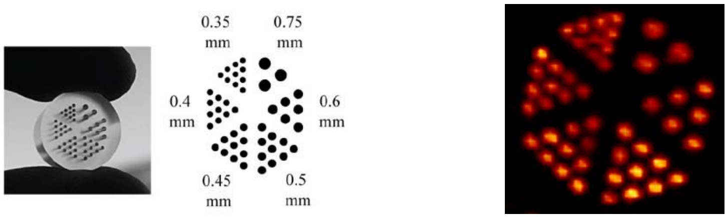

Figure 5. Imaging experiment of a micro-resolution phantom using FastSPECT III system. Left: the micro-resolution phantom with 6 sets of bores of different diameters and spacing; Right: a slice of the reconstructed 3D image of the phantom demonstrating better than 350 micron isotropic spatial resolution

With recent advances in the FastSPECT III system, full-body high-resolution mouse imaging was also accomplished and the results will be presented elsewhere.

3.3 Particle Imaging

By proper selection of the scintillation crystal, the iQID camera can also be used in particle imaging applications, including alpha-particle, beta-particle, neutron and fission fragment detection. Figure 6 illustrates an imaging experiment for alpha-particle detection. The iQID configuration used a 40mm-diameter image intensifier and a 3:1 FO taper in front to increase the detection area to 115mm diameter. A ZnS:Ag screen was used as the alpha-particle detector because of its high yield of ~90photons/keV. Droplets of ^{252}Cf source that emit ~6MeV alpha particles and 80-105 MeV fission fragments were places on the ZnS screen. Each droplet contained ~1Bq of activity. The image frame demonstrates the detection of alpha-particles and fission fragments with high S/N ratio. Because of the large energy deposition by charged particles and the large energy difference between alpha-particles and fission fragments, the iQID camera can work effectively in alpha-particle-detection mode or fission-fragment-detection mode by simply applying an amplitude threshold. By adding another layer of ZnS:Ag screen on top of the ^{252}Cf source, iQID can also provide ~100% efficiency in alpha particle detection. [Miller 2014]

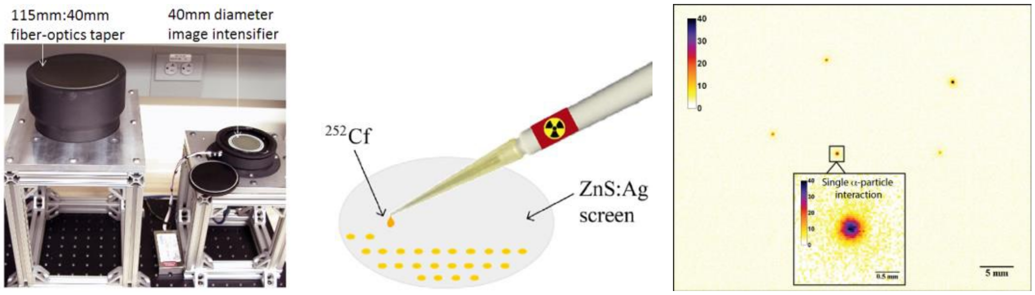

Figure 6. Alpha detection experiment using iQID camera. Left: the iQID configurations; Middle: the use of a ZnS:Ag screen for alpha particle detection from ~1Bq droplets of 252Cf source; Right: A single frame of data showing detected alpha particle with high S/N ratio

3.4 Digital Autoradiography

Alpha-emitting radionuclides have potential advantages over traditional radionuclides in cancer treatment because of the high ionizing energy and short range (50-80μm) of alpha-particles, leading to localized DNA breaks for tumor cells without damaging many normal cells. The capability of high-contrast alpha-particle detection with iQID cameras makes it a valuable tool for digital radiography, which can be used to visualize and quantify radioactivity distribution of alpha-emitting radiotracers in different tissues and cells. To demonstrate the digital-radiography capability of iQID cameras, 1.85MBq anti-CD20 monoclonal antibody labeled with ^{211}At alpha-emitting source was injected into 12 mice bearing human B-cell lymphoma xenografts. 10μm slices of different organs were harvested 4 hours after injection and placed onto a 25μm-thick ZnS:Ag screen. Using an iQID camera with the same configuration as used in alpha-particle detection, a digital radiography image of multiple slices was simultaneously acquired with 580-minute acquisition time. As shown in figure 7, the image demonstrated high resolution and contrast because of low alpha-emission background, and high alpha-detection sensitivity. Many details of radiotracer distribution can be visualized and quantitative estimation of radiation dose also proved to be highly accurate, with only ~3% error. [Miller 2015]

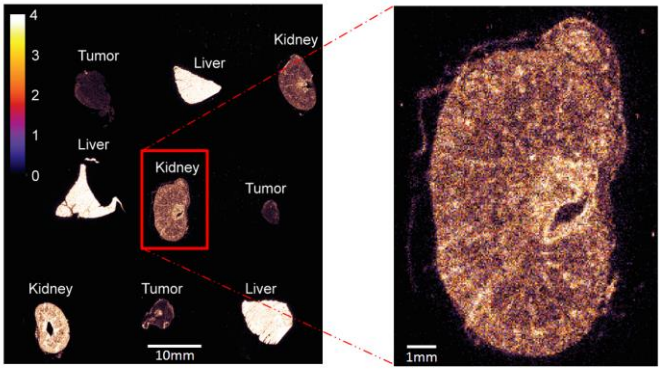

Figure 7. Digital autoradiography image of multiple slices of different organs of mice using iQID camera

3.5 Clinical Scintigraphy

Recently, a large-area iQID (LA-iQID) camera designed for dedicated clinical scintigraphy applications is being developed in the Center for Gamma-Ray Imaging. The idea involves coupling large-magnification tapers between a large scintillator and multiple image intensifiers, thus tiling multiple identical iQID cameras to achieve a large-enough FOV for dedicated clinical applications. Figure 8 shows a SOLIDWORKS rendering along with a recent picture of the camera assembly. The effective FOV of the LA-iQID camera is about 18.8×18.8 cm^2. A circular projection image is also shown which was produced by a ^{57}Co 122keV gamma-ray source placed far from the camera and a ~150μm Lanex screen as the gamma-ray detector with a circular pinhole aperture in-between. The circular projection image shows that the camera is able to provide a single seamless and uniform image across the whole FOV. The intrinsic resolution of the LA-iQID is ~410μm, which is 5-6 times better than commonly used clinical gamma cameras (2-3mm).[Han 2015] A customized LEUHR parallel-hole collimator has also been manufactured and is expected to provide ~1mm spatial resolution clinical scintigraphy image for ^{99m}Tc (140 keV) sources at 2cm distance.

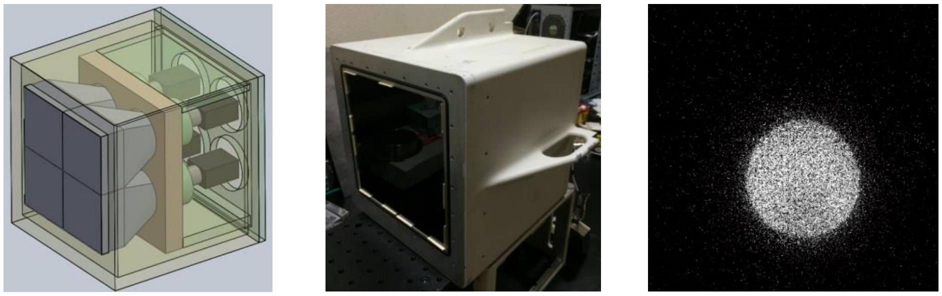

Figure 8. Left: SOLIDWORKS rendering of the LA-iQID camera; Middle: picture of LA-iQID assembly; Right: a circular projection image demonstrating the capability of LA-iQID to capture a seamless and uniform image across whole FOV

CONCLUSIONS

In this paper, we discussed the imaging principle of a novel CCD/CMOS-based intensified quantum imaging detector called iQID. The advantages of iQID cameras compared to other gamma cameras are primarily in much higher spatial resolution. We illustrated the application of iQID technology in preclinical and clinical scintigraphy, preclinical SPECT, particle imaging and digital autoradiography. Detector configurations and experimental results were shown that confirmed the feasibility of applying iQID cameras in a variety of novel applications.

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REFERENCE

[Barrett 2005] H. H. Barrett and W. C. J. Hunter, “Detectors for Small-Animal SPECT I”, ch.2 in “Small Animal SPECT Imaging”, M. A. Kupinski and H. H. Barrett, editors, Springer Science+ Business Media, 2005.

[Han 2015] Ling Han, Brian W. Miller, H. Bradford Barber, and Lars R. Furenlid, “Advances in iQID: Upgraded Algorithms, Thicker Scintillators and Larger Area”, IEEE/MIC, 2015.

[Meikle 2005] S. R. Meikle, P. Kench, M. Kassiou and R. B. Banati, Small animal SPECT and its place in the matrix of molecular imaging technologies, Physics in Medicine & Biology, vol. 50, no. 22, 2005

[Meng 2006] L.J. Meng, An intensified EMCCD camera for low energy gamma ray imaging applications, Nuclear Science, IEEE Transactions on 53 (2006), no. 4, 2376-2384.

[Miller 2006] Brian W. Miller, H. Bradford Barber, Harrison H. Barrett, Donald W. Wilson and Liying Chen, “A Low-Cost Approach to High-Resolution, Single-Photon Imaging Using Columnar Scintillators and Image Intensifiers”, IEEE/NSS, 2006.

[Miller 2006a] B.W. Miller, H.B. Barber, H.H. Barrett, I. Shestakova, B. Singh, and V.V. Nagarkar, Single-photon spatial and energy resolution enhancement of a columnar CsI(Tl)/EMCCD gamma camera using maximum-likelihood estimation, Proc. Of SPIE 6142 (2006), 61421T-1.

[Miller 2008] Brian W. Miller, Harrison H. Barrett, Lars R. Furenlid, H. Bradford Barber, Robert J. Hunter, “Recent advances in BazookaSPECT: Real-time data processing and the development of a gamma-ray microscope”, Nuclear Instrument and Methods, 2008.

[Miller 2009] Brian W. Miller, H. Bradford Barber, Lars R. Furenlid, Stephen K. Moore, Harrison H. Barrett, “Progress in BazookaSPECT”, SPIE, 2009.

[Miller 2012a] Brian W. Miller, H. Bradford Barber, Harrison H. Barrett, Zhongling Liu, Vivek V. Nagarkar, and Lars R. Furenlid, “Progress in BazookaSPECT: High-Resolution, Dynamic Scintigraphy with Large-Area Imagers”, SPEI, 2012.

[Miller 2012b] Miller, B. W. (2012). High-resolution gamma-ray imaging with columnar scin-tillators and CCD/CMOS sensors, and FastSPECT III: A third-generation stationary SPECT imager. Ph.D. thesis, University of Arizona.

[Miller 2014] Brian W. Miller, Stephanie J. Gregory, Erin S. Fuller, Harrison H. Barrett, H. Bradford Barber, Lars R. Furenlid, “The iQID camera: An ionizing-radiation quantum imaging detector”, Nuclear Instruments and Methods, 2014.

[Miller 2015] Brian W. Miller, Sofia H. L. Frost, Shani L. Frayo, Aimee L. Kenoyer, Erlinda Santos, Jon C. Jones, Damian J. Green, Donald K. Hamlin and D. Scott Wilbur, Darrell R. Fisher, Johnnie J. Orozco, Oliver W. Press, John M. Pagel, and Brenda M. Sandmaier, “Quantitative single-particle digital autoradiography with a-particle emitters for targeted radionuclide therapy using the iQID camera”, Med.Phys. 42 (7), 2015.

[Nagarkar 2007] V.V. Nagarkar, I. Shestakova, V. Gaysinskiy, B. Singh, B.W. Miller, and H.B.Barber, Fast X-ray/ -ray imaging using electron multiplying CCD-based detector, Nuclear Inst. and Methods in Physics Research, A 563 (2007), no. 1F, 45-48.

[Peterson 2011] T. Peterson and L. Furenlid, _SPECT detectors: the Anger camera and beyond,_ Phys. Med. Biol., vol. 56, p. R145, 2011.

[Teo 2005] B.K. Teo, I. Shestakova, M. Sun, W.C. Barber, B.H. Hasegawa, and V.V. Nagarkar, Evaluation of an EMCCD detector for emission-transmission computed tomography, Nuclear Science Symposium Conference Record, 2005 IEEE 5 (2005), 3050-3054.